COMPARISON OF ENVIRONMENTAL PERFORMANCE OF STEEL AND REINFORCED CONCRETE BUILDINGS BY LINEAR AND NONLINEAR ANALYSIS

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CERTIFICATE OF ORIGINALITY

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____________________________ (Signed)

YU Han (Name of student)

To my husband & son

for their love, support and encouragements

ABSTRACT

There has never been a better time to save energy, but every start would be smart. Buildings play a remarkable role in human civilization, however, at the same time, are responsible for the largest energy consumption and Green House Gas emissions around the globe.

Due to the alarmingly increased concern raised towards the environmental sustainability, engineering design trends change mildly during the past few decades and efforts have never been enough towards the realization of real energy-efficiency improvement. The energy efficiency of municipal landmarks, residential buildings and commercial high-rises has increasingly been improved in different ways and fields to combat the battle towards energy sustainability, supply security and economic competitiveness. Many countries and cities, including Hong Kong, have launched policies or actions to control and reduce the embodied energy and emissions of buildings by the application of low-carbon construction materials. In view of this, the Construction Industry Council has launched a Carbon Labelling Scheme for Construction Products for industry players to select 'low carbon' materials'. On top of that, alternative structural design might further reduce the embodied carbon at a building system level. In addition to the essential requirements on quality and safety of a building, embodied carbon can be integrated in the structural optimisation process to generate low carbon construction design.

Nonlinear analysis method has showed its advantages in many areas along its developing history. As its application has been more and more popularly recognized and suggested by officially published design codes, the advantage of nonlinear analysis in terms of environmental performance enhancement would be worth of further exploration.

This thesis serves as a fulfilment of the final assessment of the PhD research study, aiming at addressing this environmental advantage that nonlinear analysis would be able to bring to the field of structural design, due to its capability to optimise the use of building materials in construction without over-designing redundant members and under-designing critical members. Based on this technique, the environmental impact of using steel, composite and reinforced concrete structures will be evaluated in a scientific manner.

The importance of environmental performance would be addressed firstly followed by an overview of the background and literature preparation for the basis formation for the comparison study to be carried out. Structural models in both steel and reinforced concrete would be established to be analysed and designed through both conventional linear method and nonlinear method.

Typical building design cases fulfilling Hong Kong design background and requirements have been analysed and demonstrated. Results have been collated through the quantification and mitigation of total embodied carbon (EC) in a system level for all steel, reinforced concrete (RC) design buildings and even with composite floor system at different heights, with or without underground consideration, through the scientific integration of low carbon materials and Nonlinear Structural optimisation. An environmental advantage target is to be achieved through the comparison in terms of material consumption, embodied energy and embodied carbon, followed by a potential economic aspect, nonlinear analysis would be able to bring to the field of structural design. Low carbon building design options in terms of different design purpose or materials will be provided for the future reference of developers and engineers.

PUBLICATIONS

Conference Papers:

1) Han Yu and Siu-Lai Chan, *Comparison of Environmental Performance of Steel and Reinforced Concrete Buildings by Linear and Nonlinear Analysis*, 2nd International Conference on Sustainable Urbanization – Symposium 1: International Symposium on Emerging Materials and Technologies for Sustainable Infrastructure (ICSU 2015), Hong Kong, 7-9 January 2015.

2) Julian Lee, Siu-Lai Chan and Han Yu, *Embodied Carbon of Concrete / Steel – Building Structures Using Nonlinear Optimisation*, Materials Science and Technology in Engineering Conference – Frontiers of Sustainable Materials (MaSTEC 2015), Hong Kong, 24 – 25 June 2015.

3) Julian Lee, Siu-Lai Chan and Han Yu, *Embodied Carbon of Concrete / Steel – Building Structures Using Nonlinear Optimisation*, Construction Industry Council Carbon Labelling Scheme for Construction Products – Acknowledgement Reception and Colloquium, Hong Kong, 26 June 2015.

4) Julian Lee, Siu-Lai Chan and Han Yu, *Carbon Footprint for Steel – Composite and Reinforced Concrete Buildings,* CEEAA 20th Anniversary Symposium –

Development vs. Conservation: Is Engineering a Solution? Hong Kong, 5 December 2015.

5) Julian Lee, Siu-Lai Chan and Han Yu, *Embodied Carbon of Concrete / Steel – Building Structures Using Nonlinear Optimization*, ACI Convention Spring 2016 – An International Session Host by ACI China Chapter: "At the Frontiers of Concrete Technology and Sustainable Development in China", Milwaukee, Winsconsin, USA, 17 – 21 April 2016.

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$\mathbf{a_i}$	Coefficients for the polynomial shape function in the lateral direction of an element
$\mathbf{A_c, A_r, A_s, A_o}$	Total area of concrete, reinforcing bars, structural steel and openings, respectively
$\mathbf{b_i}$	Coefficients for the polynomial shape function in the axially shortening direction of an element
$\mathbf{c_1, c_2}$	Parameters for the stability functions
$\mathbf{d_n}$	Depth of neutral axis of a cross section
D	Overall width of a cross section
e	Axial deformation of an element
$\mathbf{E_c, E_{c,c}}$	Young's modulus of unconfined concrete and confined concrete, respectively
$\mathbf{E_t}$	Yong's modulus of concrete in tension
$\mathbf{E_s}$	Young's modulus of steel
EA	Axial rigidity
EI	Flexural rigidity
f	Vector of the generalized force
$\mathbf{f_c, f_{c,c}}$	Compressive stress of the unconfined and confined concrete, respectively
$\mathbf{f_r}$	Characteristic strength of reinforcing bars; or the confining stress
$\mathbf{f_s}$	Characteristic strength of structural steel

$\mathbf{f_v}$	Vertical stress induced by the friction between the steel and concrete interface
$\mathbf{f_y}$	Design strength of steel
$\mathbf{F}$	Vector of the external forces
$\mathbf{F^{EQV}}$	Vector of the equivalent nodal forces
$\bar{\mathbf{F}}$	Force vector at the member local axes
G	Shear modulus of elasticity
GJ	Torsional rigidity
i	Iteration number
$\mathbf{I_{cr}}$	Second moments of area for the cracked section
$\mathbf{I_e}$	Effective second moments of area as adopted in analysis
$\mathbf{I_{un}}$	Second moments of area for the uncracked section
$\mathbf{k^*}$	Condensed tangent stiffness matrix
$\mathbf{k_e}$	Element stiffness matrix
$\mathbf{k_L}$	Linear stiffness matrix
$\mathbf{k_G}$	Geometric stiffness matrix
$\mathbf{k_S}$	Spring stiffness matrix for considering the material yielding at the internal plastic hinge location
$\mathbf{K_e}$	Element stiffness matrix in the global coordinate system
L	Length of the element
$\mathbf{L_0}$	Original length of the element
$\mathbf{L_i}$	Updated member length at the last known configuration
R	Vector of the resisting forces

M_1, M_2	Bending moments at the left and right ends of the element, respectively
M_1^*, M_2^*	Condensed member resisting moments at two ends
M_{cr}	Cracking moment of a section composing of concrete
M_t	Torsional moment
M_u, M_v	Bending moments about two major axes by referring to the uov axes
M_y, M_z	Bending moments about two major axes by referring to the yoz axes
M_{py}, M_{pz}	Bending moments by referring to the local axes yoz with the origin of the plastic centroid
M_e^ζ, M_p^ζ	Initial yield and failure moment capacities under current axial load
n	An exponent in the concrete constitutive model in Eurocode 2
n_c	Number of vertices of the compression zone
n_L	Number of the sectional layers
$n_v(i)$	Number of intersection points in the corresponding layers
N_x	Axial force by referring to uov axes
N_{xd}	Current design axial loading
N(x)	Shape function for the proposed element
N_1 and N_2	Vector of the shape function parameters
N_{11}, N_{12}, N_{13}, N_{21}, N_{22}, N_{23}	Parameters for shape functions
NELE	Total number of the element

P	Axial force
$\mathbf{P}^*$	Condensed member axial force
$\mathbf{P_{cr}}$	Euler's buckling load as $\pi^2 EI/L$
$\mathbf{q(x)}$	An arbitrary lateral distribution forces
R	Internal resisting loads which can be calculated by the function of the nodal displacement u; or spring stiffness at the mid-span and connects the two sub-elements; or plasticity parameter related to the loading state
$\mathbf{R_g}$	External resisting forces at global axes
$\mathbf{R_i}$	Local resisting forces at member local axes
$\mathbf{R_m}$	Plasticity parameter related to the loading state at the internal plastic hinge
S	Initial arc-length distance
$\mathbf{S_k}$	Current stiffness parameter
$\mathbf{S_m}$	Spring stiffness at the middle hinge
$\mathbf{S_L}$, $\mathbf{S_R}$	Spring stiffness at the left and right hinges respectively
TOL	A value for the acceptable accuracy and usually assumed to be 0.1% in conventional practice
u	Degree of freedoms in an element; or the coordinates in uov axes
$\mathbf{u_e}$, $\mathbf{u_i}$	External and internal degree of freedoms in an element respectively
$\mathbf{u_g}$	Total displacement at the external nodes in global directions
U	Strain energy

v	Lateral displacement function of an element; or the coordinates in uov axes
$\mathbf{v_0}$	Lateral displacement function of the initial member curvature
$\mathbf{v_{m0}}$	Amplitude of initial imperfection at the mid-span
V	Work done due to the external loads
x, y, z	Coordinates in the element local axes
$\mathbf{X1_0, X2_0}$ $\mathbf{Y1_0, Y2_0}$ $\mathbf{Z1_0, Z2_0}$	Coordinates of the element in the original position
$\mathbf{Y_{gc}, Z_{gc}}$	Coordinates of geometric centroid of the whole section
$\mathbf{Y_{pc}, Z_{pc}}$	Coordinates of plastic centroid of the whole section
$\gamma_c, \gamma_r, \gamma_s$	Partial safety factors for concrete, reinforcement and steel respectively
$\boldsymbol{\delta}$	Lateral deflection along element length
$\boldsymbol{\delta_0}$	Pre-defined displacement increment at the steering DOF; or the magnitude of the initial curvature at mid-span
$\boldsymbol{\Delta f}$	Vector of the incremental condensed nodal forces
$\mathbf{\Delta F}$	Vector of the unbalanced force; or the incremental shear force at the mid-span
$\mathbf{\Delta F}_i, \mathbf{\Delta F}_e$	Vectors of the internal and external unbalanced forces respectively
$\mathbf{\Delta \bar{F}}$	An arbitrary force vector parallel to the applied load

$\boldsymbol{\Delta_m \bar{u}_1}$	Displacement vector associated with an arbitrary load parallel to the applied loads
$\boldsymbol{\Delta_m u_i}$	Load increment due to the unbalanced force at the iterations
$\boldsymbol{\Delta u}$	Vector of the unbalanced displacement
$\boldsymbol{\Delta u_g}$, $\boldsymbol{\Delta u_i}$	Vectors of the incremental displacements at external and internal nodes respectively
$\boldsymbol{\Delta \bar{u}}$	Corresponding displacement vector conjugate to $\Delta\bar{F}$
$\Delta\mathbf{v}$	Incremental lateral displacement at the mid-span
$\Delta\mathbf{v_{1i}}$, $\Delta\mathbf{v_{2i}}$	Incremental displacement at member local axes along y-axis
$\Delta\mathbf{w_{1i}}$, $\Delta\mathbf{w_{2i}}$	Incremental displacement at member local axes along z-axis
$\boldsymbol{\Delta X1_i}$, $\boldsymbol{\Delta X2_i}$	Incremental displacements in global axes
$\boldsymbol{\Delta Y1_i}$, $\boldsymbol{\Delta Y2_i}$	
$\boldsymbol{\Delta Z1_i}$, $\boldsymbol{\Delta Z2_i}$	
$\Delta\boldsymbol{\alpha}_{\mathbf{y1i}}$, $\Delta\boldsymbol{\alpha}_{\mathbf{y2i}}$	Incremental rotations about the last known configuration
$\Delta\boldsymbol{\alpha}_{\mathbf{z1i}}$, $\Delta\boldsymbol{\alpha}_{\mathbf{z2i}}$	
$\Delta\boldsymbol{\beta}_{\mathbf{yi}}$, $\Delta\boldsymbol{\beta}_{\mathbf{zi}}$	Incremental rigid body rotations
$\boldsymbol{\Delta\theta_b}$, $\boldsymbol{\Delta\theta_s}$	Incremental rotations at the element and the section spring respectively
$\boldsymbol{\Delta_1\theta_1}$, $\boldsymbol{\Delta_1\theta_2}$ $\boldsymbol{\Delta_2\theta_1}$, $\boldsymbol{\Delta_2\theta_2}$	Incremental element rotations at the left and right sub-elements, respectively
$\boldsymbol{\Delta\lambda}$	Load correction factor for imposing the constrain condition
$\boldsymbol{\theta_m}$	Rotation at the middle hinge
$\boldsymbol{\theta_t}$	Twist angle along with torsional moment
$\boldsymbol{\theta_{11}}$, $\boldsymbol{\theta_{22}}$	Rotations at two external ends

$\boldsymbol{\theta_{12}}, \boldsymbol{\theta_{21}}$	Rotations at the left and right sides of the internal hinge respectively
$\boldsymbol{\varepsilon}, \boldsymbol{\sigma}$	Strain and stress
$\boldsymbol{\varepsilon_0}, \boldsymbol{\varepsilon_{0,c}}$	Strain at reaching the maximum strength for the plain and confined concrete respectively
$\boldsymbol{\varepsilon_{ce}}, \boldsymbol{\varepsilon_{ce,c}}$	Elastic limit strain at reaching the maximum strength for the plain and confined concrete respectively
$\boldsymbol{\varepsilon_{cu}}, \boldsymbol{\varepsilon_{cu,c}}$	Compressive fracture strain for the plain and confined concrete respectively
$\boldsymbol{\varepsilon_{t0}}$	Concrete strain at the peak tensile strength
$\boldsymbol{\varepsilon_{tu}}$	Concrete strains at the peak tensile fracture
$\boldsymbol{\xi}$	Location of the internal plastic hinge; or the dimensionless coordinate along the element
$\boldsymbol{\Pi}$	Total potential energy function
$\boldsymbol{\sigma_2}$	Effective lateral compression due to confinement
$\boldsymbol{\Omega}$	Indexed strength interaction surface

CHAPTER 1

INTRODUCTION

“ It is often more cost-effective to invest in end-use energy-efficiency improvement than in increasing energy supply to satisfy demand for energy services”, as noted by the authoritative Intergovernmental Panel on Climate Change (IPCC) in their previous publications [67].

Driven by a combination of El Nino and human-induced warming, 2015 was recorded to be Earth’s hottest year ever by the end of that year [34], and The year 2016 has been confirmed as the hottest year on record once more, surpassing the exceptionally high temperatures of 2015, according to a consolidated analysis by the World Meteorological Organization (WMO) [81] (Data from [28, 62, 63 & 66]). The year to date is also the hottest on record. To make the scenario even worse, the global concentration of carbon dioxide, which results in the most greenhouse gas emissions to the global atmosphere, was the first time reaching 400 parts per million (ppm) in recorded history [80].

Globally, building and construction sectors, as a major consumer of energy, are responsible for the largest energy consumption and the most greenhouse gas (GHG) emissions. However, on the other hand, the biggest consumer has the greatest potential in bringing these records down if given proper guidance and control towards the global climate change battle [32]. Especially upon the establishment of the Paris Agreement by authorities in the COP21 climate conference by the end of 2015, which was also regarded as an international historical turning global climate milestone in human history, leading the world a step forward onto a path towards a zero-carbon future.

The construction industry consumes 40% of materials entering the global economy, with its GHG generation and energy consumption accumulates almost the same percentage of the worldwide picture [64]. Hong Kong, due to its serviced based nature of economic environment, building construction acts as the largest energy consumer compared with all other sectors in the past decades. The total carbon emissions of buildings increased from 44% in 1994, 54% in 2004 to over 60% in 2013, while the percentage is still rising and much over those of other industrial sectors. Within this international and national scenario, the construction industry is facing the most serious situation, but has the greatest potential in bringing down this large figure of energy use and carbon emissions. Cutting the energy use and carbon emissions from buildings is the most imminent challenge that cities like Hong Kong are facing towards the goal of sustainable development.

To react in the way of structural engineers and architects, during the last few decades, the environmental concern has become every bit as strong as the structural safety and economic efficiency for the realization of end-use energy-efficiency improvement from the design phase. Modern building designers, structural engineers and researchers including those from the world's top consulting companies and research institutions have already raised the awareness of environmental sustainability on top of the conventional structural safety and economic efficiency in the past decades. Arup published one of their researches in 2012 introducing the concept of embodied CO_2 to their engineering design, as well as aiming to provide a general guideline showing what kind of typical structural frames for non-residential buildings would generate low carbon burden to the construction environment [44].

From developed to developing countries, more and more environment or energy friendly concepts like ecological design and green technology [48] have been disseminated by either scholars or a number of governmental/non-governmental associations in order to guide the trends of engineering design. Along with environmental management and sustainable design, though such green design technology is no longer new to us in the combat against the environmental challenges posted by the building environment [43], it encourages us to better advance the building design methodology: using slender sections, less material and labour, faster erection process, longer design life, less natural resource adoption for operation and less hazardous effects to environment. Especially for government buildings, city landmarks and commercial high-rises. There are many approaches having been or to be implemented in the design stage to achieve the goal of green buildings, e.g. to use green construction materials, to have solar panels or gardens on roofs, windows lined with heat-trapping film and energy-efficient heating, ventilating and air conditioning (HVAC) systems. However, few have been attempted to increase the energy efficiency from the angles of building structure and envelope by structural engineers.

1.1. Research objectives

As part of the research of the Carbon Labelling Scheme carried out collaboratively between the Hong Kong Construction Industry Council and the Hong Kong Polytechnic University, study results from this thesis would be able to reveal the quantification and mitigation of total embodied carbon in a system level for steel, reinforced concrete (RC) and composite design buildings at different heights with the scientific integration of low carbon materials and Nonlinear Structural optimisation. The study provided structural engineers a scientific method on the assessment of various environmental impacts, either embodied carbon or energy, of complex building systems designed in different methods or configurations but serving the same purpose. On the other hand, there arises another approach towards green building concepts from the aspect of structural design, i.e. the energy efficiency increase could be achieved through the environmental impacts evaluation of buildings designed in different methods or configurations to serve the same design purpose.

The advantages of advanced nonlinear analysis over conventional linear analysis have been emphasized in various perspectives in the design of different types of structures by ages. Moreover, the application of the advanced nonlinear analysis in the practical design field has become progressively more popular over the last decade all over the world and is regarded as indispensable especially for the fulfilment of clients and architects' ambitions of unconventional new landmarks. However, few were addressed in an environmental way. Nonlinear analysis would also be able to make remarkable contributions, both for steel and reinforced concrete buildings, towards the reduction of material use in the short run and the provision of more options for building design that would make more use of natural resources and save the operational building energy in the long run, hence better achieving the balance of safety, economics, aesthetics and sustainability.

This thesis takes this opportunity to have a deep exploration through the environmental performance of steel, reinforced concrete and composite buildings designed by linear and nonlinear analysis. Comparisons will be made to illustrate the advantage of nonlinear analysis in the building ecology, and to further bring us a direct understanding of the relative advantage of buildings in different materials, in terms of embodied carbon, i.e. environmental impacts.

Thus in this thesis, the integration of the optimised structural design method and the Hong Kong based carbon labelling scheme would probably bring the industry a clear picture of how to achieve the lowest carbon footprint of the whole building structure. Furthermore, a scientific relationship would be able to be established between material consumption, structural design optimization, selection and use of low carbon material, together with the associated building's total carbon footprint.

1.2. Layout of the thesis

This thesis contains nine chapters and the layout is presented as follows,

Chapter 1 introduced the current environmental background for which initiated every current environmental action towards stopping the global warming crisis, addressed the important role building sections play in the energy consumption and greenhouse gas emissions and pointed out a new way to reduce this part of energy consumption and greenhouse gas emissions from the angle of structural engineers in a scientific manner. The research objectives are also detailed and the content outline of this thesis is discussed.

Chapter 2 reviews the background of this research project, where the role of building sector in the world energy distribution is to be introduced as well as the actions taken towards energy efficiency worldwide. The development of Hong Kong Local Carbon Labelling System would be detailed thereafter. Literatures would be reviewed regarding similar environmental evaluation as well as building design and comparison methodology in this chapter, further indicating the benefits the efficient nonlinear structural design would bring to the field of environmental performance evaluation and improvement. In addition, the method of environmental impacts comparison by embodied carbon which would integrate the nonlinear structural design and analysis method with the carbon-labelling system would be introduced as well, providing a guidance and theory foundation for the following comparison studies.

Chapter 3 takes the material factor into consideration and examines the environmental performance of different forms of steel and reinforced concrete structures in terms of the embodied carbon and energy designed in different methods. The advantage of the well-known accurate and efficient nonlinear analysis applied in the design process would be explored in terms of the environmental impacts evaluation, which would also form a basis for the following comparisons of building models integrating the environmental parameters with different configurations and design methods.

Chapter 4 illustrates a systematic integration of the above verified optimised structural design method with the UK based ICE Carbon Footprint Database using a pair of 25-storey commercial buildings designed in steel or reinforced concrete with only superstructure part taken into account for analysis. Comparisons would be conducted in terms of the total embodied carbon emission values between this set of models designed in different concrete strength and with different percentages of recycled steel scrap included. It is determined to figure out what kind of material combinations should be applied to this kind of mid-rise commercial building designed in Hong Kong so as to make their environmental impacts more competitive.

Chapter 5 applied the same structural design method with the UK based ICE Carbon Footprint Database using the same pair of 25-storey commercial buildings designed in steel or reinforced concrete, including not only the superstructure, but also the underground parts for analysis. Same sets of comparisons would be conducted in terms of the total embodied carbon emission values between this set of models designed in different concrete strength and with different percentages of recycled steel scrap included. It is determined to figure out what kind of material combinations should be applied to this kind of mid-rise commercial building designed in Hong Kong so as to make their environmental impacts more competitive even with underground design taken into account.

Chapter 6 applied the same structural design method and comparison analysis method to the same pair of building models considering the superstructure part or including the underground design as well, however, integrated with a set of Hong Kong based carbon labelling scheme. Comparisons would be carried out for different sets of carbon footprint values applied to the same set of building models, thereafter the potential of the Hong Kong local construction industry would be evaluated in terms of the environmental effects reduction under this local material supply situation.

Chapter 7 examines the environmental performance of building models again in different construction materials and designed by different methods with the UK based ICE Carbon Footprint Database applied, however, for building models designed in different heights or levels to make the whole study more consistent and complete. The relative material advantage of either steel or concrete for buildings in different heights is to be explored on the basis of the previously established scientific relationship between material consumption, structural design optimization, selection and use of low carbon material, together with the associated building’s total carbon footprint.

Chapter 8 extends the comparisons in terms of the total embodied carbon values in a system level to a different set of building models, which includes a steel building designed specifically with composite floor systems included compared with a nonlinear steel design solution, with the same integration method applied of low carbon materials and nonlinear structural optimisation. The advantages of composite designed buildings in application are to be extended to environmental sustainability, in the hope of providing an additional environmental friendly design option for future reference of developers and engineers.

Chapter 9 is the final chapter which concludes the study of this thesis and presents the significance of this research project. Furthermore, the recommendations for future works are also given.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEWS

2.1. Background

2.1.1. Role of Building Sector in the World Energy Distribution in the 2010s

There is a considerable number of statistics available showing the percentage of energy consumption and green house gas (GHG) emissions in different parts of the world.

The steel construction institution of UK recently published the investigation result that over half of the total primary energy (and CO_2 emissions) is consumed in the building construction and operation. The number for the European countries in average is 40% of the EU total energy consumption and about 36% of the total CO_2 emissions [31].

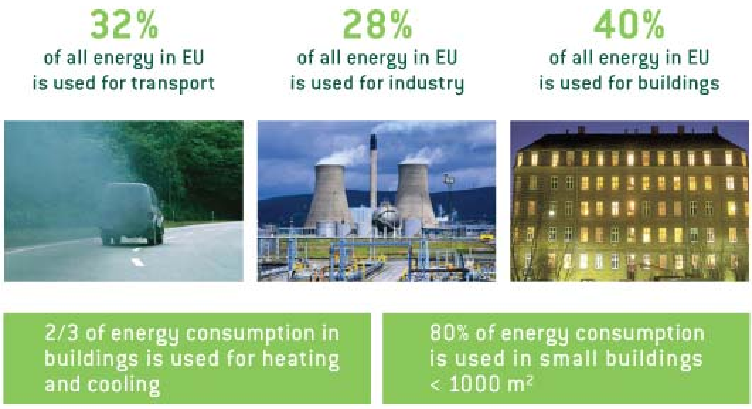


Figure 2. 1 Energy Consumption by Different Sectors in EU [31]

According to the Buildings Energy Data Book published by the U.S. Department of Energy, 41% of U.S. primary energy was consumed by the buildings sector, compared to 30% by the industrial sector and 29% by the transportation sector [77].

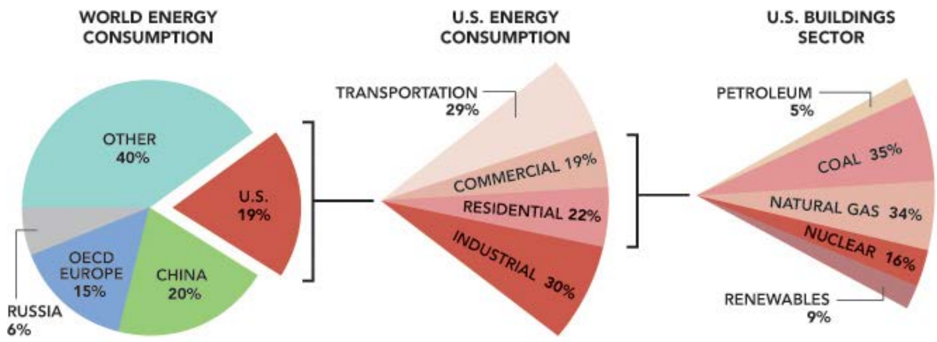


Figure 2. 2 World Energy Consumption, U.S. Energy Consumption & U.S. Buildings Sector Energy Consumption [77]

Case in China is more complicated since the numbers lie within a large range due to the vast variety of city types, sizes, locations and development stages. However, due to the rapid revolution in the last two decades, it is not surprizing that China has already changed the previous energy consumption structure of the whole world [2]. Increasing number of rural areas is undergoing urbanization; cities are facing modernization, while relatively developed regions are bursting to be shaped as international financial centres, like Beijing, Shanghai and Hong Kong, the most vertical and densely populated places in China and even in the world. From a macroscopic view of the entire nation, China took the place of the world's largest energy consumption country instead of the United States and was even expected to make up four times as much of the absolute energy consumption growth as the United States [2].

Unlike other cities in China where the industrial sector accounts for 30~50% of the total energy consumption, Hong Kong, due to its service-based nature of economic environment, has a shrinking industrial sector with the percentage decreased from 20% in 1994 to 10% in 2004. As the largest energy consumer, on the contrary, building sector energy consumption accounts for 44% in 1994 but 54% in 2004, while the percentage is still rising and much over those of the other sectors [2]. Adding an astonishing 90% of this city's electricity and 97% of gas being used, buildings here are responsible for at least 60% of the total local carbon emissions [32].

It is apparent that cutting the energy use and carbon emissions from buildings is the most imminent challenge that cities like Hong Kong are facing towards the goal of sustainable development. Building efficiency at the moment determines the future of the planet. Within this international and national scene, the construction industry, along with all other industrial sectors, has to consider how future design and construction can be changed to better address the achievement of sustainable development [24].

2.1.2. Actions Taken towards Energy Efficiency Worldwide

The production, supply and consumption of energy are associated with harmful pollution and negative climatic effects and the most prevalent sources of energy are finite and non-renewable. Climate change not only presents unprecedented problems for our environment, economy and well-being, but also inextricably linked with energy policy. To address the challenges of sustainable energy, security of supply and economic competitiveness, leaders from different parts of the world have been trying to act in the most immediate and effective way to produce energy policies according to the nations' present conditions and future development.

In Europe, all EU Member States made a commitment to produce national action plans that would implement the agreed environmental actions or agendas after the 'Earth Summit' Conference in Rio de Janeiro in June 1992 [84]. The UK government committed to return its CO_2 emissions to 1990 levels by 2000 and carried out its national plans for sustainable development. Likewise, following the introduction of Green Building Labels from the US such as "Leadership in Energy and Environmental Design" (LEED), which is going to be addressed in the later part, a new generation Sustainable Building Labels such as "Deutsches Gutesiegel Nachhaltiges Bauen" (DGNB) was adopted for the evaluation and labelling of industrial buildings in Germany in 2009 [69]. Similar actions were taken by other EU governments.

Most recently in 2010, European Member States promised a 20% reduction in primary energy consumption and GHG emissions by 2020 during the world's premier forum "Toronto Summit of the G-20" for international economic development. The need for global solutions to the climate change in the long run was once more addressed for the challenges of energy sustainability, supply security and economic competiveness [32]. To start with the biggest energy consumer, changes to the building sector should be considered from the phase of design and construction.

In the U.S., the United States Green Building Council (USGBC) emerged in 1993 and started the development of its Leadership in Energy and Environmental Design (LEED) standards from 1994. Since its launch in 2000, LEED has grown from a single rating system for new construction to a series of nine interrelated rating systems covering all aspects of the development and construction process. In addition, its development triggered the introduction of such green building rating systems in other countries like the previously mentioned DGNB labelling system in Germany and many others in Asian countries to be discussed later. However, LEED is still the most widely accepted one around the world promoting expertise in green building through a comprehensive system offering project certification, professional accreditation, training and practical resources. The development of such rating systems like LEED aims to provide guidance for design, construction and operational practices that significantly reduce the environmental impact of the development so as to encourage and recognize the design and construction of buildings with superior environmental performance [2].

In Asia, the concept of green building was imported following the western movements and in a similar trend. Among the 11 Asian economies reviewed in the study of Building Energy Efficiency by Asia Business Council, Japan, Singapore, South Korea, Taiwan, Hong Kong, India and China all have green building rating systems [2].

In 1997, Japan started to strengthen its building energy policies since the Kyoto Protocol by the United Nations Framework Convention on Climate Change (UNFCC), in order to realize the national goal of CO_2 emissions reduction [76]. Voluntary energy standards for both residential and non-residential buildings were revised in 1999 and were then made mandatory by the government after 2007. The Housing Quality Assurance Law and a voluntary energy-efficiency labelling system were indorsed in 2000, followed by the Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) in 2004 and updated in 2006 [2].

As a result of the Kyoto Protocol negotiation, the GHG emissions reduction policies have been carried out and enforcement of relevant provisions will follow in a Post-Kyoto Regime in countries classified as developing [49]. Such as the Singapore Building and Construction Authority (BCA) launched the Green Mark for Buildings Scheme to promote environmental sustainability in buildings in 2005 [68].

In China, authorities started to notice building energy-efficiency issues since mid-1980s. However, though a comprehensive appliance standard and labelling program were developed for coping with the large-scale urban construction nationwide, the application was not popularized due to the lack of continuous monitoring and follow-ups [2].

Later in 2008, a new green building rating system called “Green Olympic Building Assessment System (GOBAS) was developed based basically on Japan’s Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) and LEED for achieving a Green Olympics [2], with its implementation being inspected by the Central Government.

2.1.3. Development of Hong Kong Local Carbon Labelling System

Hong Kong has started to pay attention to the development of building energy standards since 1990 [2]. Non-government building energy-efficiency programs are available on voluntary basis like the Building Environmental Assessment Method (BEAM) which was previously the most widely used green building scheme in Asia and had been adopted in over 100 premises [2]. In 1995, a voluntary energy-efficiency labeling scheme for appliances, home and office equipment and vehicles was initiated by the Energy Efficiency Office. Thereafter, energy efficiency registration of buildings and building rating system were also released and encouraged though on voluntary basis over again.

Figure 2. 3 Policies and Actions Launched in other Countries towards Carbon Emissions Control of Buildings [53]

As stated in section 2.1.1 & 2.1.2, in many other countries and cities, policies or actions have already been launched to control and reduce the embodied energy and emissions of buildings by the application of low-carbon construction materials, but none of them was designed especially for construction materials.

CIC Carbon Labelling Scheme for Construction Products
建築產品碳標籤計劃

Figure 2. 4 Label for CIC Carbon Labelling Scheme for Construction Products [53&64]

Due to the important role construction industry plays in GHG emissions and energy consumption in Hong Kong, the Construction Industry Council (CIC) initiates the Carbon Labelling Scheme for Construction Products (the "Scheme") in 2014 January especially missioned to promote green building practices and sustainable development [53].

The construction industry in the world is primarily dominated by the use of steel and reinforced concrete as building materials, but the production of steel and concrete relates to intensive energy consumption and harmful climate effects. As reported by the Intergovernmental Panel on climate Change (IPCC) in 2001, the cement industry alone generated approximately 5% of the global anthropogenic CO_2 emissions. Similarly, the International Energy Agency (IEA) reported in 2008 that the iron and steel industry is responsible for about 10% of worldwide CO_2 emissions from fossil fuel use. Thereafter, the selection and application of low carbon materials is undoubtedly a critical part towards the goal of green building construction.

The Scheme aims to provide the communication of verifiable and accurate information on the carbon footprint of construction products available in the current Hong Kong construction materials market for client bodies, designers, contractors and end users to select 'low carbon' materials. Though still carried out on a voluntary basis, in the long term, the 'Scheme' intends to encourage the demand for, and supply of, low carbon products, speeding Hong Kong's transition to a low carbon economy, so as to better combat against the global warming and to make Hong Kong's district contribution towards the global Sustainable Development Goals.

The Scheme simplifies the GHGs generated from the production of these construction materials available for application in Hong Kong construction market into a single quantifiable parameter as CO_2 equivalents (CO_2e). Six types of GHGs having significant impact on global warming have been taken into consideration as cited from the Kyoto Protocol, including CO_2, methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6) [76]. The development of the Scheme was based on the ISO 14025:2006 "Environmental Labels and Declarations - Type III Environmental Declarations - Principles and Procedures". The quantification and reporting of the carbon footprint of products (CFP) under the Scheme shall comply with the ISO/TS 14067:2013

"Greenhouse Gases – Carbon Footprint of Products – Requirements and Guidelines for Quantification and Communication". In accordance with ISO/TS 14067, the CFP study shall include the four phases of life cycle assessment (LCA), i.e. goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and life cycle interpretation.

By the end of 2014, due to the diverse increase in construction products covered in the Carbon Labelling Scheme database, the development of the Scheme entered a new phase. The CIC started to promote the application of the carbon footprint of these Hong Kong based construction materials by their implementation in building design and environmental impacts analysis. Our research in 2015 formed a pilot study on the quantification and mitigation of total embodied carbon in a system level for steel and reinforced concrete (RC) design buildings with the scientific integration of low carbon materials and Nonlinear Structural optimisation. This study enabled the advance of the LCA results from every low carbon material level to a building system level, bringing the industry a clear picture of how to achieve the building structure with lowest carbon footprint. Moreover, a scientific relationship and guidance was established between material consumption, structural design optimization, economic consideration, selection and use of low carbon material, together with the associated building's total carbon footprint forming a theory basis to continue with my PhD study.

Within this international and national scene, the construction industry, along with all other industry sectors, has to address the sustainable development issues and consider how changes can be made to future design and construction in every effort in every minute. The nonlinear advanced analysis and design of steel and reinforced concrete building would hopefully bring a bright tomorrow for our energy sustainability, well-beings and economic competitiveness in the long way.

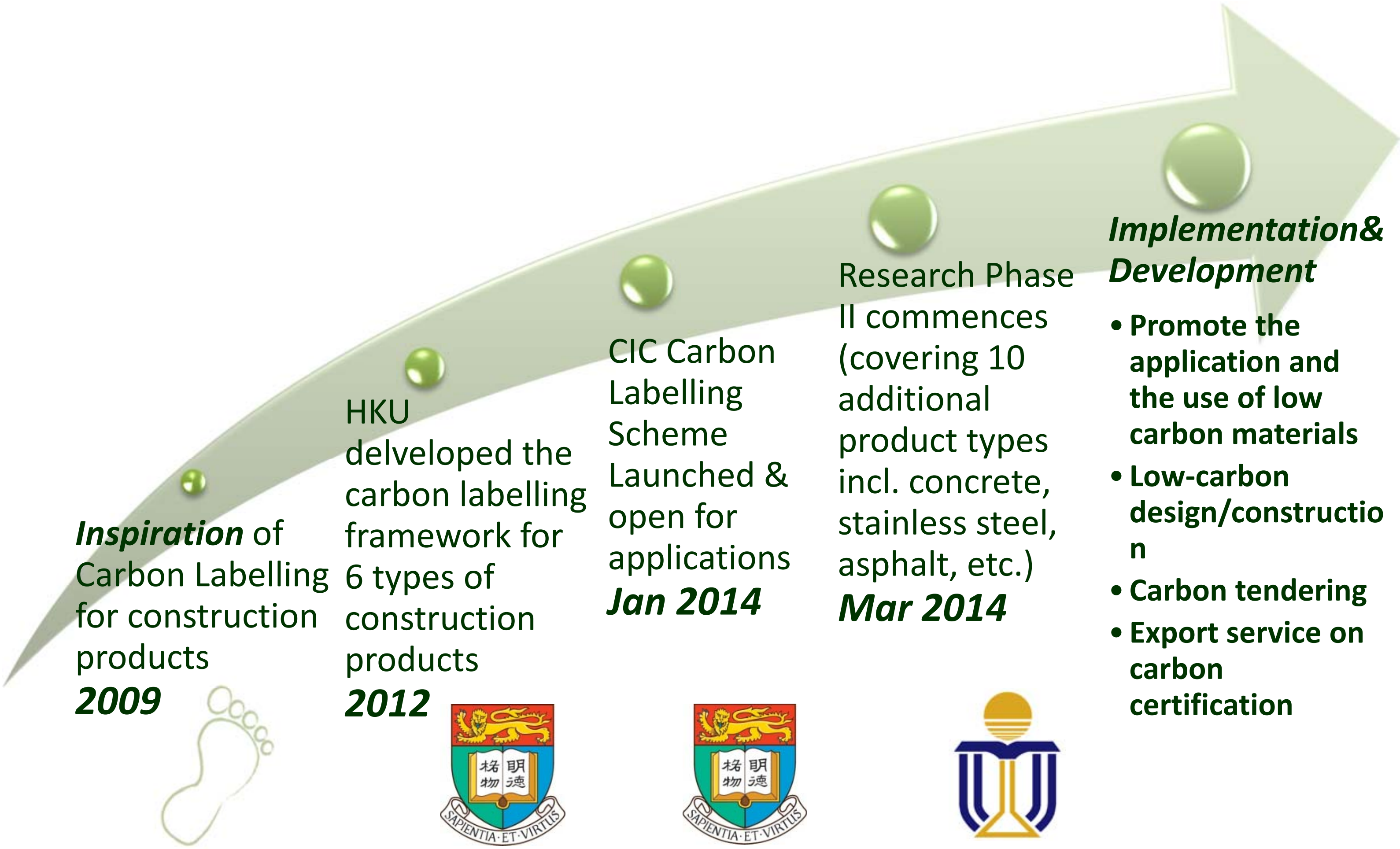


Figure 2. 5 The Development of the CIC Carbon Labelling Scheme [63]

2.2. Literature Reviews on Environmental Evaluation

2.2.1 Embodied Energy

Building energy consumption can be categorized into two types: 1) embodied energy, which is defined as the total energy inputs consumed throughout a product's life-cycle, usually in its construction and pre-use phase; and 2) operational energy, which is defined as the amount of energy required to operate and maintain the structure, including providing heat, air-conditioning, lights, water and so on to meet the needs of building occupants [6]. Both are typically expressed in mega joules per kilogram, i.e. MJ/kg.

Among the majority of existing buildings, as noted in several studies in this field, operational energy far outweighs embodied energy accounting for an estimated 80% to 90% of total energy consumption during their whole life spans [19 & 52]. It seems that embodied energy contributes little to the whole energy consumption, however, for the first 15 to 20 years of a building's whole life-cycle, embodied energy dominates a building's total energy consumption. Due to the decreasing of average building life spans nowadays and again the increasing alert raised by the architecture and engineering professions, as mentioned in the above section, in bringing down the energy buildings consume in their life-long operations, operational energy efficiency is improving and therefore the relevant importance of building embodied energy over a building's total energy footprint cannot be underestimated [5].

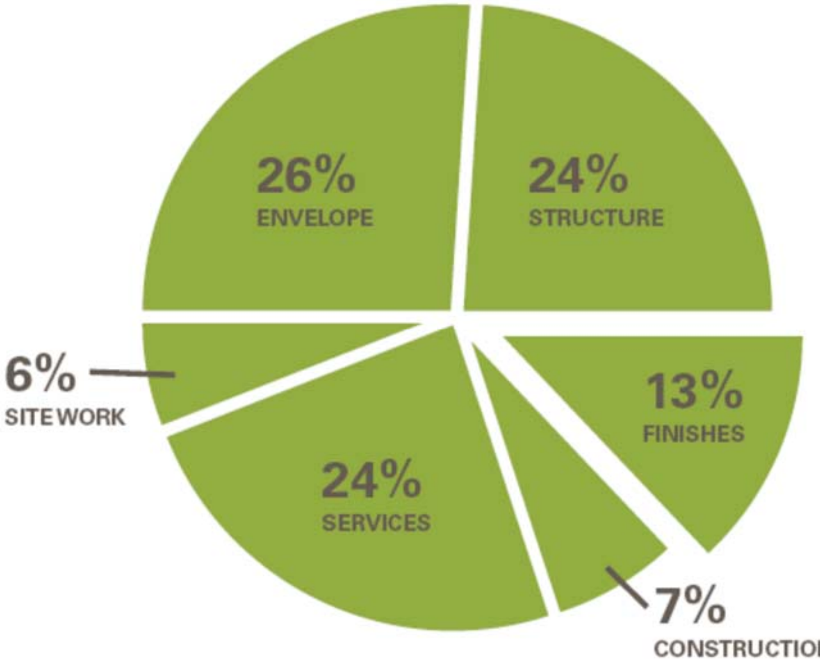


Figure 2. 6 Average Initial Embodied Energy of an Office Building [5 & 19]

Question would be raised here: What could we structural engineers do to reduce embodied energy? Study carried out by Cole and Kernan [19] yields the results for average total initial embodied energy as shown in the above figure, based on a 4620m^2 three-storey office building with underground parking and considering construction systems in wood, steel and concrete. As the results for three types of building obtained were similar, the averaged data for all the construction systems showed that, the envelope and structure alone account for approximately a half of a building's total initial embodied energy [5]. Suggestions were made like those in Material LIFE to select existing buildings for interior building-outs, renovations, or adaptive reuse projects which were more related to the work of architects and interior designers [6]. This limits the reduction of energy footprint depended on the material selection to a large extent. In the view of structural engineers, what we can do to the envelope and structure parts of embodied energy so as to facilitate the application of high quality eco-friendly materials could not only bring a significant reduction to the embodied energy footprint but also benefit the ecological operation of the building in the long term. These are the benefits advanced nonlinear analysis would be expected to be of with regard to the buildings' environmental performance.

2.2.2 Life Cycle Assessment

As the importance of building embodied energy over a building's total energy footprint has been stated in the above section, environmental burdens of the building during its whole life cycle is on demand of a systematic, objective and well-regulated quantification so as to be applied in assistance to the study of industrial ecology along with environmental management and sustainable design. One of the most popular utilized methods is Life Cycle Assessment (LCA) firstly established by the Society of Environmental Toxicology & Chemistry (SETAC) and then formalized by the International Standards Organization (ISO) as a mean to assess environmental impacts of a product system. In definition, LCA is referred as a technique for assessing the environmental aspects and potential impacts associated with a product, process or activity, including the entire life-cycle encompassing extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use, maintenance, recycling and final disposal [41 & 52]. The application of this method would enable the comparison of different materials in adherence with regard to either data collection and evaluation or results interpretation.

2.2.3 Selection of Construction Materials

Steel and reinforced concrete have dominated the world's major building material market of the commercial construction industry for years since the beginning of the 20th century, wherever in the United States, the Europe and Asia. In the meantime, they have competed for their construction market share almost throughout their history [43]. Steel and concrete have very diverse characteristics in terms of strength, stiffness, density, constructability, therefore, engineers and architects usually select the most suitable material fulfilling their requirements based on the above mentioned characteristics and with due considerations on different labour skill level and wages, material availability and cost, building type, location and structural performance, etc. Due to the recent trend towards the environmental sustainability in the worldwide construction industry, many official organizations related to steel and concrete have incorporated such topic in their official websites and in associated journals, including the American Institute of Steel Construction (AISC), American Concrete Institute (ACI), Portland Cement Association (PCA), the Steel Construction Institution (SCI), etc. In the meantime, various material/product manufacturers and material interest groups have competed to exploit the environmental advantages of their products in order to interest clients and architects on environmental concern for more market share. The environmental concern thereby becomes a new but definitely important criterion for the determination on the choice of material.

The development of a series of environmental policies, regulations and standards such as LEED triggers more severe competition between these two traditional materials. Either steel or concrete claims itself to be the better choice over the other in terms of their environmental performance and sustainability. Many researches have been carried out with the adoption of such standards like LEED in order to search for a result between their comparisons. However, it seems still be quite difficult to obtain a definite result on which one stands out to have absolute advantages over the other despite many of research publications available regarding such comparisons. In the comparisons reviewed as background for the thesis, it is still difficult to have an absolute conclusion drawn between steel and concrete though all based on the application of life cycle assessment. An overview would be presented in the following section, in terms of their goals, scopes, methodologies, assumptions made, legislations followed and conclusions drawn.

2.2.3.1 A Comparative Environmental Life Cycle Assessment of Modern Office Buildings by the Steel and Construction Institute

The Steel and Construction Institute (SCI) published “A Comparative Environmental Life Cycle Assessment of Modern Office Buildings” study conducted by Dr K J Eaton and Dr A Amato of the SCI aiming to present a methodology framework in conformity with ISO Life Cycle [24] Assessment procedures rather than a verification of individual numerical results. The study was firstly introduced by British Steel and the Department of the Environment, Transport and the Regions in 1994, under external peer review by members of the advisory group and by Battella in the USA, and the full results of this study were submitted as a PhD thesis of Dr. A Amato to Oxford Brookes University.

The commercial office buildings assessed covered a series of structural alternatives that were previously characterized in an earlier SCI study together with a range of service options that are considered to be relevant to the current construction environment. Two generic building types were adopted: Building A of small to medium size, with no air-conditioning, ranged from natural ventilation through to enhanced mechanical heating and ventilation systems, built to a developer's standard specification; Building B designed to be a large size headquarters building to a prestigious standard with full air-conditioning as the only service option. The collection of 10 out of the 15 original structural alternatives including steel, composite, reinforced concrete and precast concrete systems was selected for this comparative environmental parameter evaluation with all the building details and assumptions presented in the Appendix A of the corresponding study. The study was praised by Battelle in the US as a very well done publicly available life-cycle inventory analysis, producing quantitative building life cycle energy and building life cycle CO_2 profiles of the above buildings applicable to a wide range of building forms over a notional 60 year life with its weather condition specified as a standard year located in the South-East of the UK. Modification might be required in other climate conditions, applied in other building detailing varieties and in other countries where energy generating fuel mix and transportation infrastructure are significantly different.

The authors concluded their study as follows:

Firstly, energy consumption and CO_2 emissions can be used as relevant environmental parameters for life cycle assessment for the investigation of comparative performance of alternative materials.

Throughout the study results, no significant difference was observed between the various types of construction in terms of the embodied energy/CO_2 emission values, operational energy/CO_2 emission values and total life cycle energy/CO_2 values. Therefore, it can be concluded that there is no significant benefit of either steel or concrete framed office buildings over the other kind in terms of their environmental performance up to the end of design life. No specific material advantage was shown of either steel or concrete in the combat towards environmental sustainability, however, the relative values of embodied energy as compared with operational energy have now been assessed to enable designers to make improvements in the building fabric assisting the future energy planning.

Data extracted from this SCI study, for example the material embodied energy/CO_2 values of steel and concrete, would be of value for the quantification of the environmental performance of the structures to be compared in this study between linear and nonlinear analysis [24]. Details of the specific values to be utilized in accordance to the particular case would be referenced in the later parts of this thesis.

2.2.3.2 Similar Life Cycle Assessment Comparisons Conducted by Other Researchers

In 2006, Timothy Werner Johnson carried out an educational comparative study on the environmental impacts of steel and concrete as building materials using the life cycle assessment method in partial fulfilment of the MSc degree submitted to the Massachusetts Institute of Technology [43]. This study and life-cycle assessment aim to compare the environmental impacts created by steel and cast-in-place concrete construction industry at the lowest common performance level, i.e. the structural shell of a typical multi-storey building in the City of Boston as a basis Functional Unit in terms of the three targeted environmental impacts: CO_2 emissions, energy consumption and resource depletion. A material flow called “most widely used” (MWU) method was used for the modelling of the material manufacture, shipping and erection on a typical construction-site in the metro-Boston area in the current steel and concrete market, so as to make the study results as comparable as those in other studies with respect to the assumptions, scope and boundaries.

From a sustainability perspective, steel is concluded to be a relatively ‘better’ building material than cast-in-place concrete in the pre-use phase of a building development based on the three targeted environmental impacts. In terms of total CO_2 emissions and resource depletion, steel stood out to have obvious advantages over cast-in-place concrete with 25% less total CO_2 emissions and 68% less total natural resources adoption recorded. Results of the total energy consumption showed no clear difference between the two materials, thereafter it is considered that the energy consumption is not a crucial parameter in the determination and conclusion of the LCA comparison.

The above conclusion is barely based on the raw data collected from interviews with corresponding manufacturers in the studied area by the researcher and analysed on an un-weighted basis for the pure evaluation of specific environmental impact though the relative importance of each particular environmental impact has been controversial in the standpoints of different people. This enables a tangible comparison of the above mentioned study (A) with other existing studies more directly when the raw data were normalized with respect to the building total floor area in square foot. The works referred to in the comparison include those done by Bjorklund et al from Sweden (B), Guggemos et al from the U.S. (C) and Junnila et al from Finland (D). The normalized results are summarized in the following Table 2.1.

	CO_2 emissions (kg/SF)		Energy Consumption (MJ/SF)		Resource Depletion (million·kg)	
	Steel	Concrete	Steel	Concrete	Steel	Concrete
Current Study	12.4	16.4	102.1	102.5	270 27.7*	885 89.3*
Bjorklund et al., 1996	8.1	11.9	84.7	110.6	-	-
Guggemos et al., 2005	57.6	51.1	882.6	771.1	-	-
Junnila et al, 2003	-	-	-	-	-	20.4

* total results (in million·kg) without water resource included

Table 2. 1 Comparison of Normalized Environmental Impact Values [43]

From the comparison, it is obviously observed that only Timothy's study encompassed all the three environmental parameters related to the sustainability consideration, i.e. CO_2 emissions, energy consumption and resource depletion while study B and C are most similar to the Timothy's in terms of the LCA comparison done between steel and concrete used as building materials in the pre-use phase. The absolute values of CO_2 emissions and energy consumption of both steel and concrete do not vary too much between study A and B and in particular concrete is perceived to create more severe environmental impacts in CO_2 emissions and energy consumption. However, in terms of study C, the normalized values are several times larger than those corresponding ones in study A and B while concrete seems to behave more environmental friendly.

From the above comparisons, all these LCA comparisons, including the firstly revealed SCI one done in the UK, the Timothy's and the Guggemos' done in America and the Bjorklund's done in Sweden, seem to be able to draw fairly close conclusions following the LEED standards and ISO regulations and solely based on un-weighted raw data. However, the potential diversities have already been witnessed according to the above tangible comparison. To look back into the details in the assumptions made and uncertainties in the raw data utilized by different researchers, sources of differences might lie in several areas.

Firstly, scopes of the studies might vary in a large scale like study C included more comprehensive parts like foundation slab and exterior cladding which might play a large role in affecting the results due to the large material and construction procedures required but adding no total floor area to the total building, leading to a large scale of difference in the functional unit and MWU method compared with those in study A though both were conducted in America. Another consideration lies quite obvious in the location where the study conducted. With the location specified in the South-East of the UK of the SCI comparison, in the metro-Boston area of the Timothy's study, in the Midwest United States of that by Guggemos, quite a lot of sources of difference might be easily traced either in terms of weather or transportation condition and the applicability of their research results were all limited to the condition under similar assumptions. Modifications have been suggested by all of them in case of variety in application. Hence the conclusions of the relative advantages of either steel or concrete might be viewed and utilized in an objective fashion.

The one by Junnila et al done in 2004 was the only one considering resource depletion as the environmental impact parameter that was of value in comparison with the Timothy's. The study covered a life cycle study of only a cast-in-place concrete office building located in Finland. Since no comparison was done between steel and concrete, neither relative nor tangible comparison results could be drawn for the purpose of environmental evaluation of these two building materials.

2.2.4 Conclusion Remarks

To conclude the above several parts, material selection and structural design could both make contributions to the potential decrease of the buildings' environmental impacts in terms of sustainability management. As what has been emphasized, it is fairly difficult to differentiate the difference between the environmental performance of steel framed office buildings and that of concrete framed office buildings throughout their life cycle. Furthermore, it was also addressed that the importance of the building envelope and structure overweighs all of the others in terms of total building embodied energy. Hence, the benefits of more efficient nonlinear design of commercial building construction would not only be limited to the structural performance, but also the preference of materials in the sense that their environmental performance is not that reliable; the continuous eco-friendly advantage that nonlinear analysis would bring to the modern building construction and design unquestionably deserves further exploration. In the following section, details of the nonlinear analysis would be introduced followed by the proposed analyses for comparison.

2.3. Literature Review on Building Design and Comparison Methodology

The conventional limit state design method has been used extensively over the past decades in which the second-order effects and material yielding are considered separately according to design specifications. However, the second-order analysis design method is also suggested in many national design codes such as Eurocode-3 (2005), Code of Practice for Structural Uses of Steel 2005&2011 (HKSC), BS5950(2000) and AS4100(2000). The latter method makes it possible to eliminate the necessity of assumption of effective length factors, but directly take the second-order geometric and material nonlinearities into consideration, integrating the effects of fire, temperature variation, seismic, impact load and progressive collapse into the design and analysis process. However, due to the limited capability of computer programs available in the previous market, accuracy and reliability of these computer analyses cannot be fully guaranteed while the application of such computer analysis programs and the concept of second-order analysis have not been greatly accepted by experienced engineers.

For this thesis, the method adopted for model assessment is primarily based on the direct second-order elastic and inelastic analysis methods developed by Professor

S. L. Chan. The underlying principle is very different from the first-order linear analysis using the effective length, but to simulate the process of structural performance with the section capacity checked along the length of every member. The computer software programme applied for the comparison study is NIDA developed by Chan since 1996, approved by the Buildings Department for nonlinear and second-order analysis to Code of Practice to Structural Uses of Steel, Hong Kong 2005 and 2011. It is able to overcome the shortcomings of most commercial and academic computer packages for second-order analysis allowing for only P-Δ effect and requiring extensive manual checking. Section capacity check is performed globally with the system imperfection, member imperfection, material yielding and member buckling effects all incorporated. Furthermore, to carry out the analysis for frames connected semi-rigidly, the semi-rigid behaviour of connections could be modelled as required directly in NIDA so that the structural response modelling is no longer limited to those with simply rigid or pinned connections which follows the conventional assumption used in the conventional design. On the other hand, the accuracy and efficiency of such simple direct second-order inelastic analysis brings great convenience for both academic and practical applications and makes the comprehensive and time-consuming finite element modelling no longer the only reliance.

2.3.1 Modelling Techniques

The examples for direct second-order inelastic analysis is produced with the aid of computer programme NIDA, approved by the Buildings Department for nonlinear and second-order analysis to Code of Practice to Structural Uses of Steel, Hong Kong

2005 and 2011. In this section, modelling techniques together with the associated assumptions made and related insights of computer analysis are discussed, while the modelling of semi-rigid beam-column connections would be emphasized.

2.3.2 Second-Order Design Approach

Second-order method of analysis, which is also called as direct analysis method in AISC (2010) [4], is a nonlinear and simulation-based approach allowing for various types of nonlinear effects for structural strength and stability, such as initial member and global frame imperfections, material residual stresses and so on. Therefore, the forces distribution and the deformations from the analysis are closed to the actual situation that a safe and reliable result can be obtained. Since the P-Δ and P-δ effects as well as the initial imperfections have been directly considered in analysis, the member strength check can be simply conducted by a cross section capacity check at the critical locations of a member. Unlike the conventional linear design method, which requires assumptions of column effective lengths associated with the tedious calculation of the K-factors, this design approach is efficient and the cumbersome assumptions are eliminated.

2.3.2.1 Consideration of Initial Imperfections

Imperfections unavoidably exist in all the members and frames due to fabrication, construction, transportation and assemblage, e.g. welding, and therefore the perfectly straight assumption in the analytical model is unavailable in practice. In the second-order analysis method of design, the considerations of these effects are essential [17].

Two types of imperfections are usually taken into account namely as the initial member curvature and the frame out-of-plumpness. In a correct second-order design method, both these imperfections are needed to be considered in order to ensure the design results will be adequately safe.

The research on modelling of geometric initial imperfections was started in 1980s. A curved beam element was proposed for buckling analysis of arc members [78]. Later, an investigation on the buckling and post-buckling behaviours due to the initial imperfections were carried out [7]. A member tangent stiffness matrix was proposed for consideration of geometrical imperfections [45] and an incremental-interactive procedure was intoduced to trace the load-displacement path of the frames. An element with initial curvature was developed for large deflection analysis of the thin and curved planar beam [70]. However, the P-δ effect due to the member imperfections was not properly considered in their element formulations and the common types of frames had not been investigated in detail in their research.

Several sophisticated elements with the direct incorporation of the initial member imperfection have been derived and proposed in 1990s. A curved PEP (Pointwise Equilibrating Polynomial) element was derived for second-order analysis of steel frames [16] which was based on the finite element method with the high-order shape function. The stability function element was further developed allowing initial member curvature for practical design of framed structures [12]. These elements are stable and widely accepted in many contemporary engineering practices.

2.3.2.2 Current Codes for Second-Order Design

Research on the second-order design method for steel frames has been extensively studied in the past few decades and this method has been well-documented in most modern design codes such as AS4100 (1998) [71], AISC (2010) [4], Eurocode 3 (2005) [26], Hong Kong Steel Code (2011) [38]. Further, AS4100 (1998) [71] was the first national design code allows the use of nonlinear analysis approach for the design of steel frames and it was termed as “Advanced analysis”. This approach is also called as the “direct analysis method (DAM)” in AISC (2010) [4] which recommends its use in place of the traditional linear design method. Numerous steel frames have been designed by the second-order analysis method of design in the last ten years which was proven to be efficient, economical and adequately safe in engineering practice.

Several national codes, including AS5100 (2004) [71], Eurocode 4 (2004) [27], BS5400 (2005) [73] and Hong Kong Steel Code (2011) [38] can be utilized in the design of steel and concrete composite structures. The current approaches for the stability design of compression members are still based on the linear analysis method associated with the assumptions of the effective length or the moment amplification factors. However, the recently published Eurocode 4 (2004) [27] accepts the second-order analysis method and the initial imperfections for various types of sections were also given. This method has been successfully adopted in design of composite members and portal frames [33].

The second-order effects of slender reinforced concrete (RC) columns are required to be considered in the design codes, such as Eurocode 2 (2004) [25], ACI

318 (2008) [3], Hong Kong Concrete Code (2013) [37] and so on. Nevertheless, these design methods are still based on the linear assumption and the considerations of these nonlinear and buckling effects are done indirectly by the indirect methods, such as the nominal stiffness and the nominal curvature methods in Eurocode 2 (2004) [25]. However, the concept and theoretical consideration of these P-Δ and P-δ effects as well as the initial imperfections are the theoretically same regardless of the members in different materials but the values of these imperfections may vary with respect to the types of materials and forming processes. Therefore, the second-order analysis method of design for RC columns and frames was then investigated and developed by Liu et al. in 2012 [56&57].

2.3.3 Advanced Analysis Method

Advanced analysis method is considered as an accurate simulation-based technique for investigating the ultimate behaviours of a structure under some extreme events, such as seismic attacks, progressive collapse and accidental occasions and so on. In order to obtain reliable analysis results, various types of important effects inherent to a real structure should be considered and they include initial imperfections, geometric and material nonlinearities, residual stress and concrete cracking. In the past decades, this method has been extensively studied and many researchers have proposed their analytical models for advanced analysis of framed structures.

White developed plastic hinge methods for advanced analysis of steel frames [79]. He defined the term “advanced” as a method that sufficiently captures the limit states such that checking of the specification equations was not needed. Two plastic hinge methods had been discussed and the consideration of geometric imperfection effects was also studied.

Kim and Chen proposed an advanced analysis method for planar un-braced steel frames [46]. In order to consider the initial frame imperfection, three types of methods were discussed as (a) an explicitly modelling method by offsetting the nodes; (b) an equivalent notional force method and (c) a tangent modulus reduction method. According to their studies, all these methods could produce accurate analysis results by comparing to the plastic-zone analysis approach for the simple planar portal frames. However, these methods were only suitable for the regular planar frames and the P-δ effects induced by the member initial imperfection is modelled by using several elements that the modelling is complicated and inconvenient.

Liew *et al*. developed an advanced analysis technique for the large-displacement inelastic analysis of spatial structures [54]. An imperfect strut model with one elastic-perfectly-plastic hinge placed at mid-span was proposed for simulating both the geometric and material nonlinearities. The structural instability due to initial imperfections can also be checked in their analytical model. They observed that the method predicts not only the limit load of the structure, but also assists to study the load sharing and force distributions of the framed system and to identify the critical members that their failure leads to progressive collapse.

Liew *et al*. summarized the recent development of advanced analysis of spatial structures [55], where the modeling of inelasticity in beam-column members had been investigated. Further, the inelastic analysis methods for composite beams and the modeling of semi-rigid connections were also reviewed. They claimed that the use of the advanced design philosophy could help the understanding about the system behavior so that a more rational and cost effective design could be achieved.

Kim and Choi proposed an advanced analysis method by accounting for the semi-rigid connections between beams and columns [47]. The stability function element was introduced to capture the P-δ effect and the gradual material yielding was considered by the stiffness degradation model. The shear deformation was also included in their analytical model and the effects of the semi-rigid connections based on the Kishi & Chen power model was studied [51]. From the comparisons with the plastic zone analysis, it showed a more accurate result could be obtained by their method.

Trahair and Chan reviewed methods for studying the out-of-plane behaviours of two-dimensional frames under in-plane loading [75], where the inelastic lateral buckling effects involving the residual stresses, initial member imperfections , twists and so on. The difficulties in the method were discussed and the suggestions had also been made for testing the accuracy of an analytical model.

Chan *et al*. reported a robust advanced analysis method based on a finite-element procedure for the large deflections and inelastic analysis of the imperfect frames with semi-rigid base connections [13]. They introduced the refined plastic hinge approach for modelling of section yielding. The simulations of the framed global imperfections are specially considered and studied by two methods as the notional horizontal force method and the Eigen-buckling mode method. They found that, the Eigen-buckling mode method was more suitable for engineering practice since the assumption of most adverse directions of imperfections was skipped. Furthermore, it was also addressed that the semi-rigid base connection significantly affected the overall behaviour of a structure.

2.3.4 Conclusion Remarks

In this section, the modelling techniques was introduced for analysing the building models in need for comparison study in this thesis. The theories of the analysing methods adopted were then detailed, where the development of the nonlinear advanced analysis and the associated design codes were described in detail as well.

2.4. Environmental Impacts Comparison by Embodied Carbon Footprints

From the discussion and comparison of section 2.1 and 2.2 of this thesis, it was concluded that material selection and structural design could both make contributions to the potential decrease of the buildings' environmental impacts in terms of sustainability management. It was also addressed that the importance of the building envelope and structure overweighs all of the others in terms of total building embodied energy throughout the building's life cycle. Therefore, to explore the benefits of the more efficient nonlinear design method, either for steel or concrete structures, the reduction in embodied energy and embodied carbon obtained would definitely provide a proof for the continuous eco-friendly advantage of nonlinear analysis over the conventional linear analysis.

The Inventory of Carbon & Energy (ICE) [35] Version 2.0 from the University of Bath's embodied energy & embodied carbon database was referred as embodied energy and embodied carbon coefficients for building materials based on Life Cycle Assessments and the collection from other secondary resources in the public domain. The embodied energy coefficients exhibit a higher accuracy over those of embodied carbon with the boundary conditions all specified to be Cradle-to-Gate. Due to the complexity of the specification of boundary conditions, the variation of the sources of these data as well as the variation of the same kind of building materials, data would more likely to be located in a range for quite a large part of building materials studied, which, on the other hand, is difficult for the application of calculation as required in this comparison study. Uncertainty is therefore regarded as a natural part of embodied energy and carbon analysis even from the most reliable data resource. To apply the embodied energy and embodied carbon values to this comparison study, data was obtained from the material profile for steel and concrete.

The quantification of the construction buildings' total carbon footprint is contributed by the accumulation of the carbon footprints of all the construction materials. Basically, in Hong Kong, the structural frameworks fall into the categories of ready-mixed concrete and steel.

Most of the GHG generated from construction products are emitted from raw material acquisition, production process, and transportation. The quantification and reporting of the carbon footprint of products (CFP) under this Scheme is thus based on a "cradle-to-site" approach, covering all GHG emissions and removals of the product arising from raw material acquisition, transportation, production process, storing/packaging and finally to the border of Hong Kong [53].

The development of the Scheme was based on the ISO 14025:2006 "Environmental Labels and Declarations - Type III Environmental Declarations - Principles and Procedures". The quantification and reporting of the CFP under the Scheme shall comply with the ISO/TS 14067:2013 "Greenhouse Gases – Carbon Footprint of Products – Requirements and Guidelines for Quantification and Communication". In accordance with ISO/TS 14067 (2013), the CFP study shall include the four phases of life cycle assessment (LCA), i.e. goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and life cycle interpretation [53].

Based on various worldwide data sources collected, carbon footprint values in a unit of $kgCO_2e/kg$ would generally fall in a general range: (1) 0.1~0.2 for concrete depending on strength, SCM rate, cement carbon footprint, etc; (2) 1.5~3.5 for virgin steel depending on the manufacturing furnace type, fuel type and usage, etc; (3) 0.5~1.5 for recycled steel depending on recycled scrap usage, furnace type, fuel type and usage, etc. These three sets of carbon footprints would be applied in the calculation of the system total carbon footprints of the building models in this study.

Current CIC carbon labelling data system includes rebar and structural steel products as well as concrete products ranging from C30 to C60. The lowest carbon footprint values are 0.55 and 2.08 $kgCO_2e/kg$ for rebar and structural steel section available in Hong Kong construction material market [64]. However, due to the limitation of the product varieties and availability of the particular recycled percentage of different products provided in the CIC carbon labelling data system, a more consistent and systematic database, Bath Inventory of Carbon & Energy (ICE) Version 2.0 [35], provided a major reference regarding the carbon footprint values for ready-mixed concrete in various grades, steel rebars and sections with different recycling levels. The ICE database formed a source of reference in the early stage of the establishment of Hong Kong CIC carbon labelling system, use similar cradle-to-gate boundaries but based on UK or world steel construction industry market. Though there might result in many possible variations for application in Hong Kong, the study would still lead to a similar trend in the results, creating a picture of how much recycled material applied would help make an environmental decision on the preference of concrete or steel as major construction material.

2.5. Integration of Environmental Evaluation Method with Nonlinear Structural Design Method

From the above discussion, conclusions could be drawn that material selection and structural design could both make contributions to the potential decrease of the buildings’ environmental impacts in terms of sustainability management. As what has been emphasized, it is fairly difficult to differentiate the difference between the environmental performance of steel framed office buildings and that of concrete framed office buildings throughout their life cycle. Furthermore, it was also addressed that the importance of the building envelope and structure overweighs all of the others in terms of total building embodied energy. Hence, the benefits of more efficient nonlinear design of commercial building construction would not only be limited to the structural performance, but also the preference of materials in the sense that their environmental performance is not that reliable; the continuous eco-friendly advantage that nonlinear analysis would bring to the modern building construction and design unquestionably deserves further exploration. In this section, details of the nonlinear analysis would be introduced followed by the proposed analyses for comparison.

The conventional limit state design method has been used extensively over the past decades in which the second-order effects and material yielding are considered separately according to design specifications. However, the second-order analysis design method is also suggested in many national design codes such as Eurocode-3 (2005), Code of Practice for Structural Uses of Steel 2005&2011 (HKSC), BS5950(2000) and AS4100(2000). The latter method makes it possible to eliminate the necessity of assumption of effective length factors, but directly take the second-order geometric and material nonlinearities into consideration, integrating the effects of fire, temperature variation, seismic, impact load and progressive collapse into the design and analysis process. However, due to the limited capability of computer programs available in the previous market, accuracy and reliability of these computer analyses cannot be fully guaranteed while the application of such computer analysis programs and the concept of second-order analysis have not been greatly accepted by experienced engineers.

Frames are the most primarily and commonly utilized idealization for the analysis of the majority of man-made engineering structures. Although it is widely accepted that the actual behaviour of frames is nonlinear and complex, different types of analysis with different degrees of accuracy, limitation and refinement could be adopted with respect to the purposes of analysis. Advanced analysis combines the effects of material yielding and geometrical change with sufficient accuracy for practical purposes so that isolated member capacity checks can be avoided. Thus, “Advanced analysis” can be defined as any analysis method that does not require specific member capacity check. Instability, P-Δ and P-δ effects, and frame and member initial imperfections should be accounted for so that the nonlinear structural behaviour can be captured in the analysis.

For this study, the method adopted for model assessment is primarily based on the direct second-order elastic and inelastic analysis methods developed by Professor S. L. Chan [50]. The underlying principle is very different from the first-order linear analysis using the effective length, but to simulate the process of structural performance with the section capacity checked along the length of every member (HKSC2011, Equation 4.20&4.21). The computer software programme applied for the comparison study is NIDA developed by Chan since 1996, approved by the Buildings Department for nonlinear and second-order analysis to Code of Practice to Structural Uses of Steel, Hong Kong 2005 and 2011. It is able to overcome the shortcomings of most commercial and academic computer packages for second-order analysis allowing for only P-Δ effect and requiring extensive manual checking. Section capacity check is performed globally with the system imperfection, member imperfection, material yielding and member buckling effects all incorporated. On the other hand, the accuracy and efficiency of such simple direct second-order inelastic analysis brings great convenience for both academic and practical applications and makes the comprehensive and time-consuming finite element modelling no longer the only reliance.

CHAPTER 3

COMPARISON OF ENVIRONMENTAL PERFORMANCE OF STEEL & REINFORCED CONCRETE STRUCTURES BY LINEAR AND NONLINEAR ANALYSIS

The Hong Kong steel code and Eurocode 3 are the few of the majority of available design codes worldwide allowing for the use of both the first-order linear and second –order nonlinear analysis methods for the purpose of structural design and analysis. For cases with elastic critical factor λcr not less than 5, geometry changes and buckling effects should both be incorporated either following the codified method or in the nonlinear design software. For cases with elastic critical factor λcr less than 5 or in special irregular shape, second-order analysis becomes necessary for capturing the structural response efficiently and accurately.

Unlike the first-order linear analysis using the effective length assumption while determining the column resistance, second-order $P-\Delta-\delta$ analysis carried out by NIDA which is used in this thesis takes the increase in stress due to the second-order and buckling effects into consideration throughout the loading process. This section aims at illustrating the difference between the codified linear analysis and computer nonlinear analysis in terms of structural design for the environmental friendly purpose. Models selected range from single element, planer structure to space structure.

The beginning two chapters, which could also be regarded as the theory foundation of this study, aims at addressing this advantage that nonlinear analysis would be able to bring to the field of structural design because it could optimise the use of building materials in construction and would not over-design redundant members and under-design critical members. Based on this technique, the environmental impact of using steel, composite and reinforced concrete structures will be evaluated in a scientific manner.

The Inventory of Carbon & Energy (ICE) [35] Version 2 from the University of Bath's embodied energy & embodied carbon database was referred as embodied energy and embodied carbon coefficients for building materials based on Life Cycle Assessments and the collection from other secondary resources in the public domain, with the boundary conditions all specified to be Cradle-to-Gate.

To apply the embodied energy and embodied carbon values to this comparison study, data was obtained from the material profile for steel and concrete. Assume all the steel sections used in this study are in the category of UK typical general steel. Embodied energy value is taken as 24.4MJ/kg within +/-30% range of uncertainty. Embodied carbon value is taken as 1.77kgCO_2/kg within +/-30% range of uncertainty [35]. Typical structural forms have been chosen below for the illustration of environmental impacts comparison.

Material Profile: Steel

Embodied Energy (EE) Database Statistics - MJ/Kg

Main Material	No. Records	Average EE	Standard Deviation	Minimum EE	Maximum EE	Comments on the Database Statistics:
Steel	180	31.25	[illegible]	[illegible]	95.70	None
Steel, General	154	29.36	13.45	6.00	77.00	
30% Recycled	2	32.75	20.86	18.00	47.50	
Market Average	11	25.68	5.92	18.20	36.00	
Other Specification	2	19.40	0.71	18.90	19.90	
Predominantly Recycled	33	13.60	4.86	6.00	23.40	
Unspecified	49	31.96	10.61	12.50	77.00	
Virgin	57	37.48	12.07	12.00	63.42	
Steel, Stainless	21	45.68	28.84	8.20	95.70	
Market Average	3	48.36	6.22	40.20	51.48	
Predominantly Recycled	2	11.00	0.00	11.00	11.00	
Unspecified	8	43.10	32.21	8.20	95.70	
Virgin	8	57.80	28.76	12.00	81.77	
Steel, Structural	5	30.91	3.74	25.50	35.90	
Unspecified	2	28.67	4.48	25.50	31.83	
Virgin	3	32.40	3.10	30.00	35.90	

Selected Embodied Energy & Carbon Values and Associated Data

Material	Embodied Energy - MJ/Kg			Embodied Carbon - Kg CO2/Kg			Boundaries	Best EE Range - MJ/Kg		Specific Comments
	UK Typical	Primary	Secondary	UK Typical	Primary	Secondary		Low EE	High EE	
General Steel	24.4	35.3	9.50	1.77	2.75	0.43	Cradle to Gate	(+/- 30%)		Estimated from UK's consumption of types of steel, and worldwide recycled content 42.7%
Bar & rod	24.6	36.4	8.8	1.71	2.68	0.42				
Engineering steel	-	-	13.1	-	-	0.68				
Pipe	-	34.4	*NTMR*	-	2.7	*NTMR*				NTMR = Not Typical Manufacturing Route
plate	-	48.4	*NTMR*	-	3.19	*NTMR*				NTMR = Not Typical Manufacturing Route
Section	25.4	36.8	10.0	1.78	2.78	0.44				
Sheet	-	31.5	*NTMR*	-	2.51	*NTMR*				NTMR = Not Typical Manufacturing Route
Sheet - Galvanised	-	39.0	-	-	2.82	-				
Wire	-	36.0	-	-	2.83	-				
Stainless	56.7	-	-	6.15	-	-		11	81.8	4.3 MJ/kg Feedstock Energy (Included). World average data from Institute of Stainless Steel Forum (ISSF) was selected due to the large extent of the study. Values specified are for the most popular grade (304).
Comments	Assumed 42.7% worldwide recycled material, as used to estimate the typical market values. The best data resource was from the International Iron & Steel Institute (IISI), who completed to most detailed steel LCI to date. Some of the IISI data has been processed to fit into the categories (Primary, secondary material). The results of this study are in line with that expected from other sources. **Please see note on recycling methodology at the front of the document.**									

Table 3. 1 ICE Carbon Footprint Database: Material Profile for Steel [35]

Material Profile: Concrete

Embodied Energy (EE) Database Statistics - MJ/Kg

Main Material	No. Records	Average EE	Standard Deviation	Minimum EE	Maximum EE	Comments on the Database Statistics:
Concrete	122	2.91	8.68	0.07	92.50	None
Concrete, General	112	3.01	9.07	0.07	92.50	
Unspecified	85	2.12	2.85	0.07	23.90	
Virgin	27	6.02	18.24	0.59	92.50	
Concrete, Pre-Cast	10	1.89	0.43	1.20	2.72	
Unspecified	6	2.01	0.43	1.36	2.72	
Virgin	4	1.72	0.42	1.20	2.19	

Selected Embodied Energy & Carbon Values and Associated Data

Boundaries	Cradle to Gate	Data Range (+/- 30%)	Specific Comments
Material	Embodied Energy - MJ/Kg	Embodied Carbon - Kg CO2/Kg	
General Concrete	0.95	0.130	Selection of a specific concrete type will give grater accuracy, please see comments
1:1:2 Cement:Sand:Aggregate	1.39	0.209	(High strength)
1:1.5:3	1.11	0.159	(used in floor slab, columns & load bearing structure)
1:2:4	0.95	0.129	(Typical in construction of buildings under 3 storeys)
1:2.5:5	0.84	0.109	
1:3:6	0.77	0.096	(non-structural mass concrete)
1:4:8	0.69	0.080	
REINFORCED CONCRETE (ICE CMC Model Values)			
For reinforcement add to selected coefficient for each 25kg steel reinforcement	0.26	0.018	For each 25 kg Steel per m3 concrete
EXAMPLE: Reinforced RC30 (See Below) with 100kg Rebar	2.12 (1.08 + 0.26 * 4)	0.241 (0.153 + 0.018 *4)	

Table 3. 2 ICE Carbon Footprint Database: Material Profile for Concrete [35]

3.1. Fixed-Pinned Column under Axial Compression

A typical steel column in 88.9x3.2CHS is to be analyzed subjected to an axial compression of 200kN, with one end fixed and the other end pinned, in the length of 5m and of grade S355.

For the effective length method according to Hong Kong Steel Code 2011 linear design, effective length factor (L_e/L) = 0.7 (Table 8.6,HKSC(2011)) and curve "a" (Table 8.7,HKSC(2011)) of was selected.

[EQ(8.79),HKSC(2011)] is MORE critical.

The Max. Section Capacity Factor:

| Fc/Pc+(m.Mr)/Mc | = |-1.74(100.0%) "+" 0.00(0.0%) | = 1.740 > 1 NOT O.K.

Fc/Pc = -200 / Pc = -1.74

Column resistance by effective length method:

Pc = 200 / 1.74 = 114.9425 kN

For the second-order analysis, imperfection δ_0 = L/500 (Table 6.1) was adopted

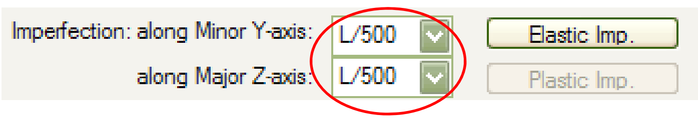
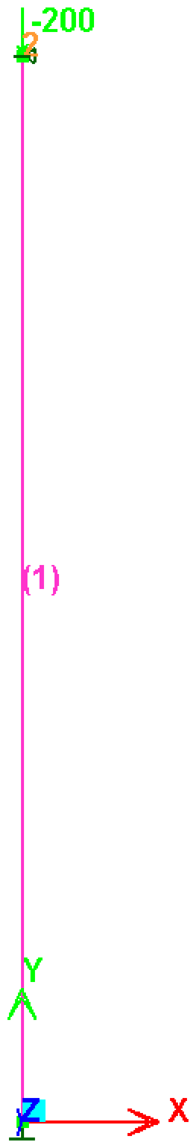


Figure 3. 1 Member Imperfection of Section 88.9x3.2CHS according to HKSC2011

Column resistance by second-order elastic analysis:

200 x 0.5212 = 104.24 *kN* < 114.9425 *kN* by effective length method.

From this example, it is observed that second-order analysis is more conservative than the conventional codified linear design. The environmental advantage of second-order analysis could not really be illustrated through a single element structure, and therefore, complexity is increased to the model to be examined.



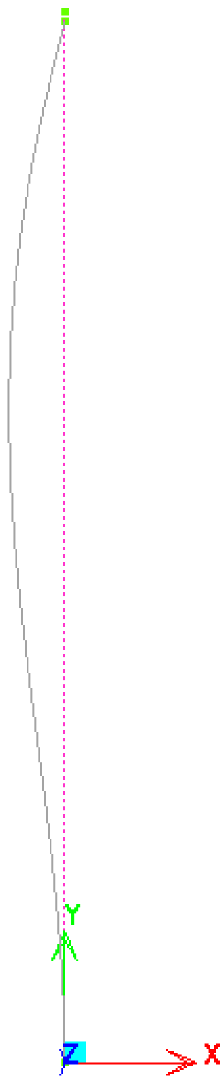


Figure 3. 2 Fixed-Pinned Column under Axial Compressive Load

Figure 3. 3 Second-Order Elastic Analysis

3.2. An Unbraced Portal Frame

An unbraced portal frame of a height of 10m and grade S275 in uniform section is to be designed to a vertical loading of 1000kN downward and a horizontal loading of 60kN as shown in Figure 5.4. Joint 2 and 3 are moment joints while 1 and 4 are pinned to base. With the width to height ratio equals to 3, the portal frame is highly sensitive to sway.

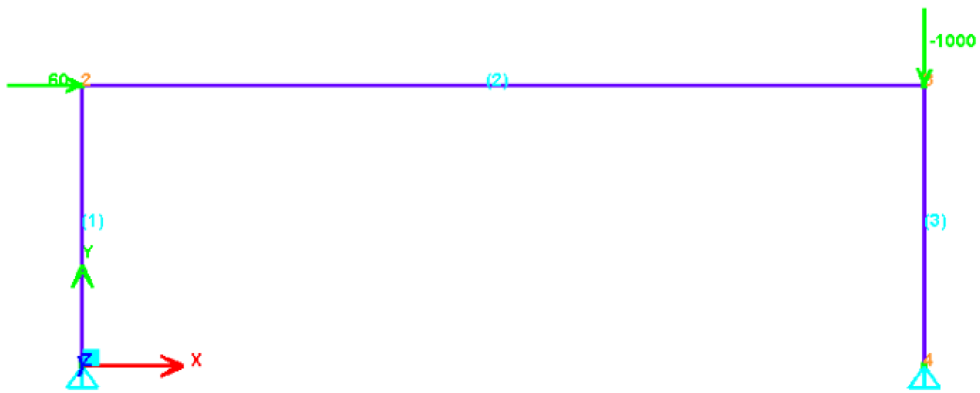


Figure 3. 4 Loading and End Conditions for Unbraced Portal Frame

Moment amplification method according to HKSC2011:

Vertical reaction on the left: R_L = 60 x 10 / 30 = 20kN ↓

Vertical reaction on the right: R_R = 1000 + 20 = 1020kN ↑

Horizontal raction of both base joints: $H_L = H_R$ = 60 / 2 = 30 kN ←

$M_1 = M_4 = 0$

$M_2 = M_3$ = 30 x 10 = 300 kNm

Moment amplification method to Equation 8.80, clause 8.9.2, section UC 356 x 368 x 153 kg/m is tried first,

Top deflection at 0.5% load is 22.3mm,

Equation 6.1, λ_{cr} = 10000/22.3/200 = 2.24 < 5,

This is a sway-sensitive frame, first order analysis could not be used unless member size is increased or second order analysis should be used.

To increase the section size, portal frame failed in the linear analysis in section UC 356 x 368 x 177 kg/m, but is safe for section UC 356 x 368 x 202 kg/m.

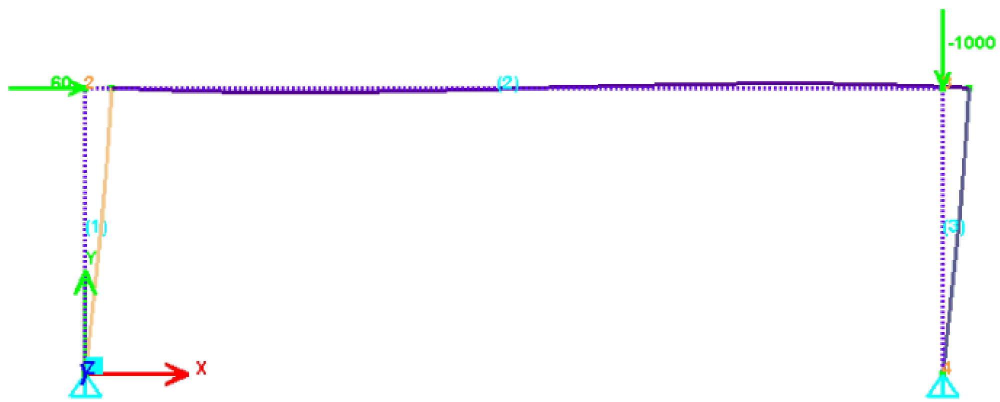


Figure 3. 5 Deformed Shape of Unbraced Portal Frame by Second-Order Analysis

However, when the analysis of portal frame in section UC 356 x 368 x 153 kg/m is carried out in NIDA second-order analysis with plastic hinge enabled, Newton-Raphson method adopted and eigen-buckling mode in both directions selected for the incorporation of geometry change.

When λ=1, all members reach their moment capacity with the 1st plastic hinge inserted when λ=1.06, i.e. the structure is safe under the design load in section UC 356 x 368 x 153 kg/m. Load deflection curve and moment rotation curve of Node 3 are shown as below. Obvious load-deflection curve reverse could be observed after load cycle 212, the maximum load which the frame can sustain is 1.06 times the design load, since the incremental load factor equals 0.005.

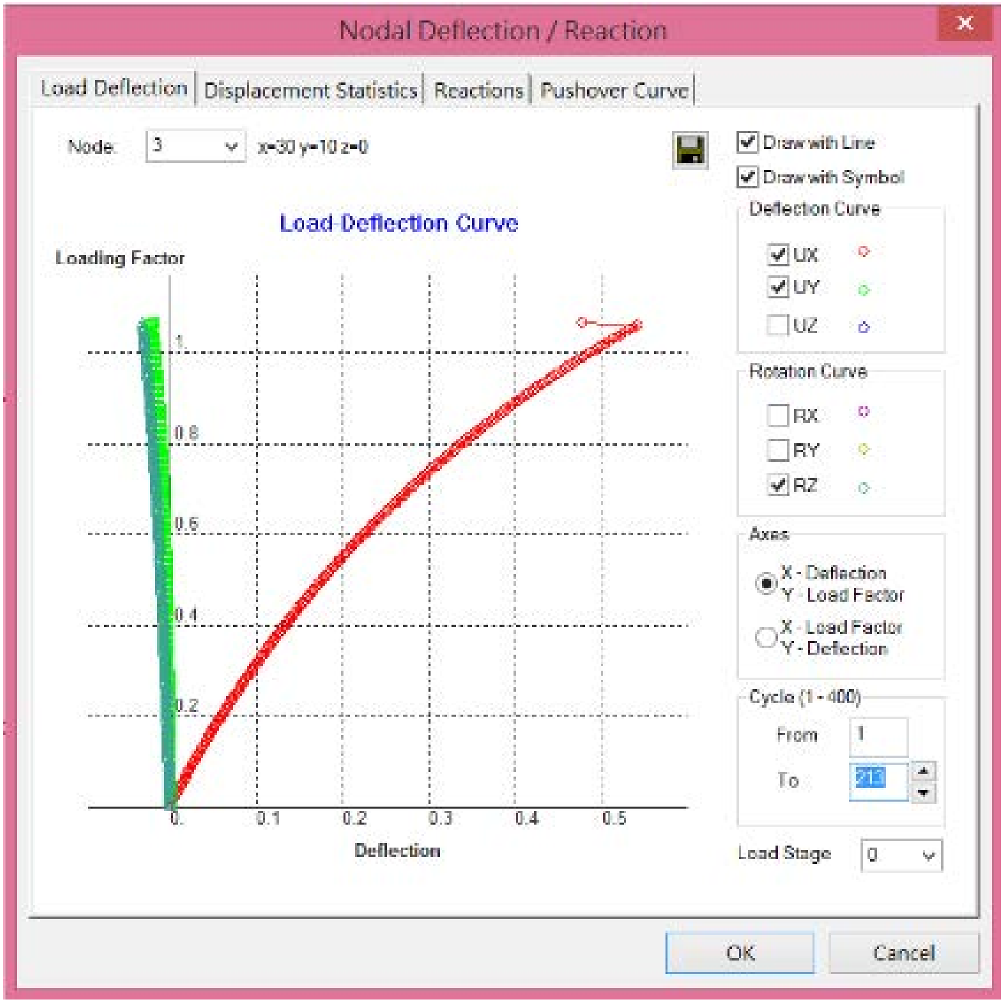


Figure 3. 6 Load-Deflection Curves of Node 3 in UX, UY & RZ directions

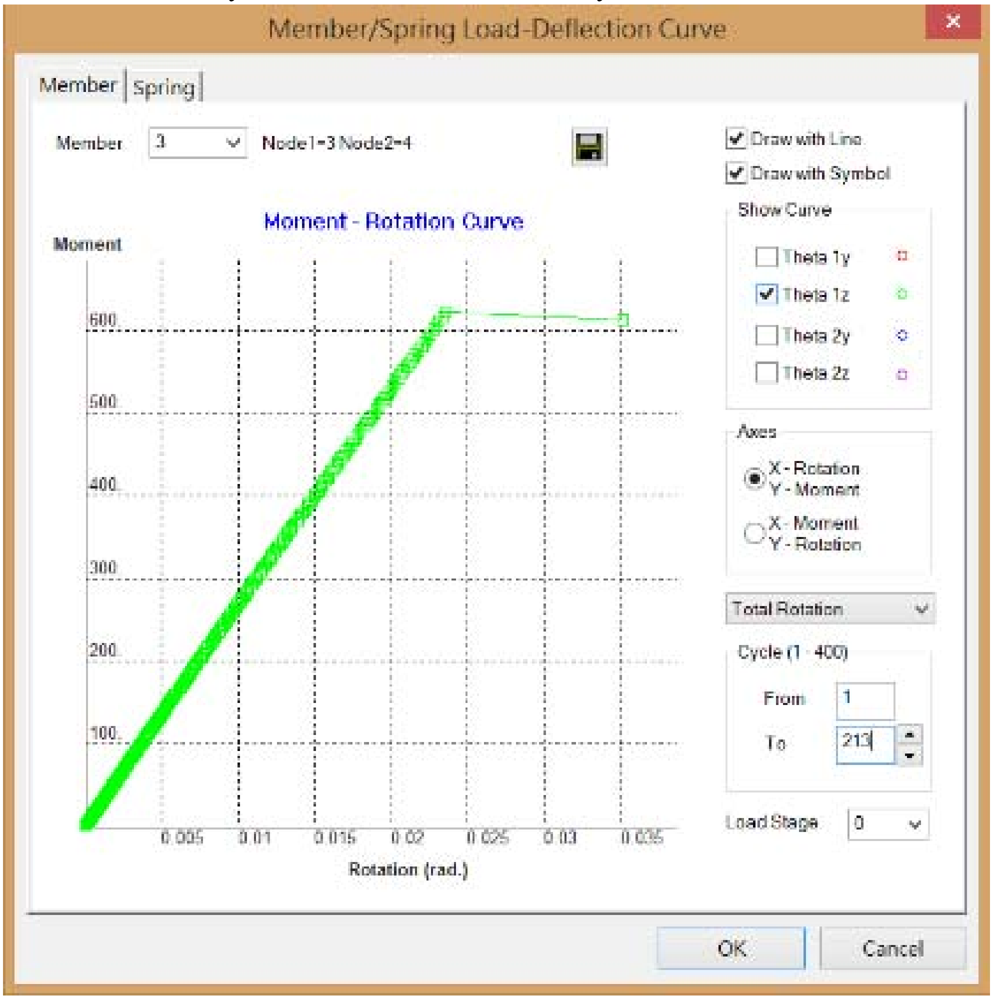


Figure 3. 7 Moment-Rotation Curve of Node 3 about Z-Axis

Compare the section used for linear and nonlinear design, from UKC 356 x 368 x 202 kg/m to UKC 356 x 368 x 153 kg/m, around 24% of material in weight, i.e. (202kg/m – 153kg/m) x 50m=2450kg steel, could be saved due to the adoption of nonlinear analysis. As the structure of this portal frame is simple, having low degree of indeterminacy and little strength reserve. When the moment redistribution becomes more complex in terms of more complex structure upon reaching the plastic section capacity, a more obvious advantage of nonlinear analysis could be expected.

3.3. A Space Moment Resisting Frame

A 3-storey frame of steel grade S275 with uniform beam sections and uniform column sections is a moment resisting frame with rigid member connections and pinned bases. Given designed dead load being 2kN/mm^2 and live load being 4.5kN/mm^2, design load combination equals 1.4x2+1.6x4.5=10kN/m^2 is applied to the two frame floors according to the HKSC 2011.

NIDA linear analysis gives the result of beam all in section UKB 406x178x60kg/m and column all in section UKC 356x368x129kg/m for the frame to be safe to resist the designed loads.

While for the second-order elastic-plastic analysis conducted in programme NIDA, all beam sections could be reduced to UKB 305x165x46kg/m and column sections could be reduced to UKC 254x254x73kg/m. The load factor λ_{2nd} could reach 1.33 under the design loads. Load deflection curves of node 17 and moment rotation curves of member 25 at node 17 are provided below. Likewise, after load cycle 664, the load-deflection curve reverses indicating the failure of the system, the maximum load the structure could sustain should be 663 times the incremental load factor 0.005, which gives the load factor λ_{2nd} = 1.33 designed by nonlinear method.

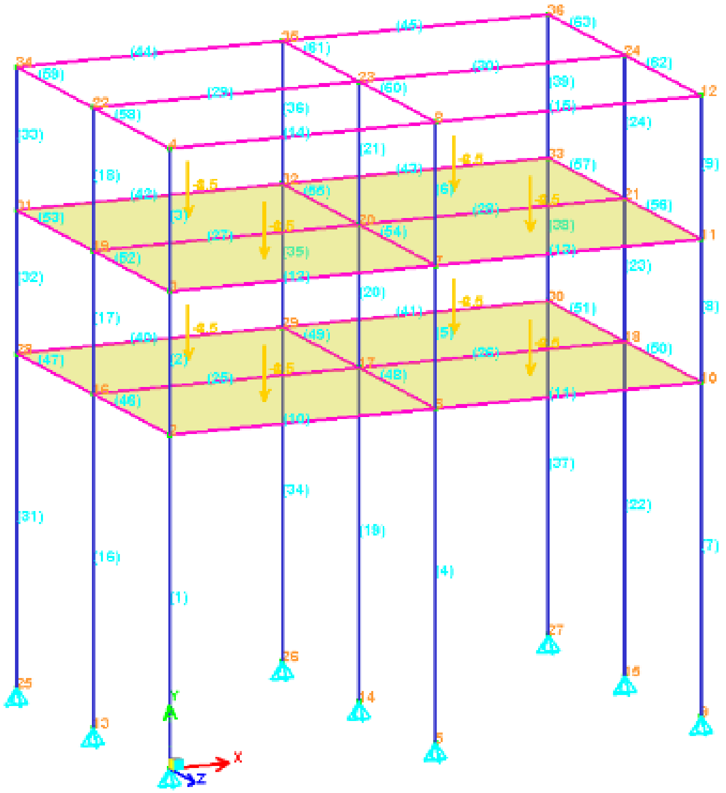


Figure 3. 8 Loading and End Conditions for Space Frame

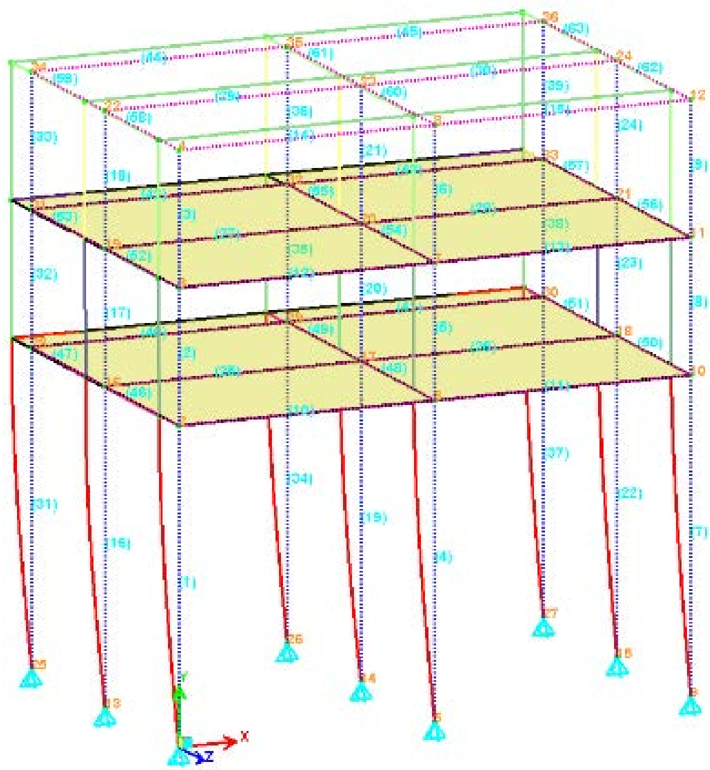


Figure 3. 9 Deformed Shape of Space Frame by Second-Order Analysis

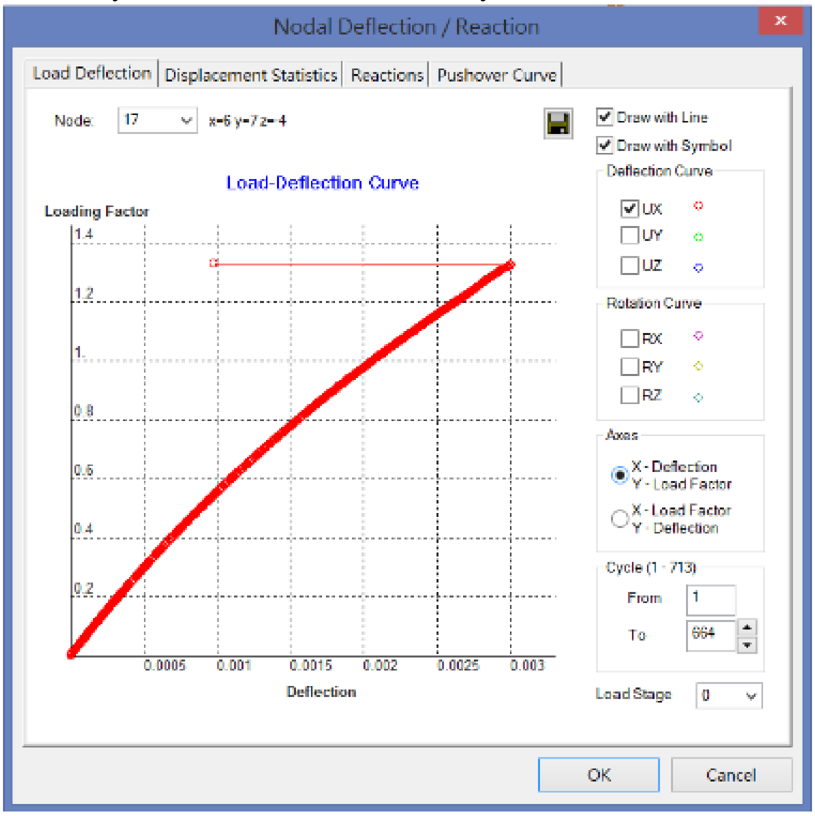


Figure 3. 10 Load-Deflection Curves of Node 17 in UX direction

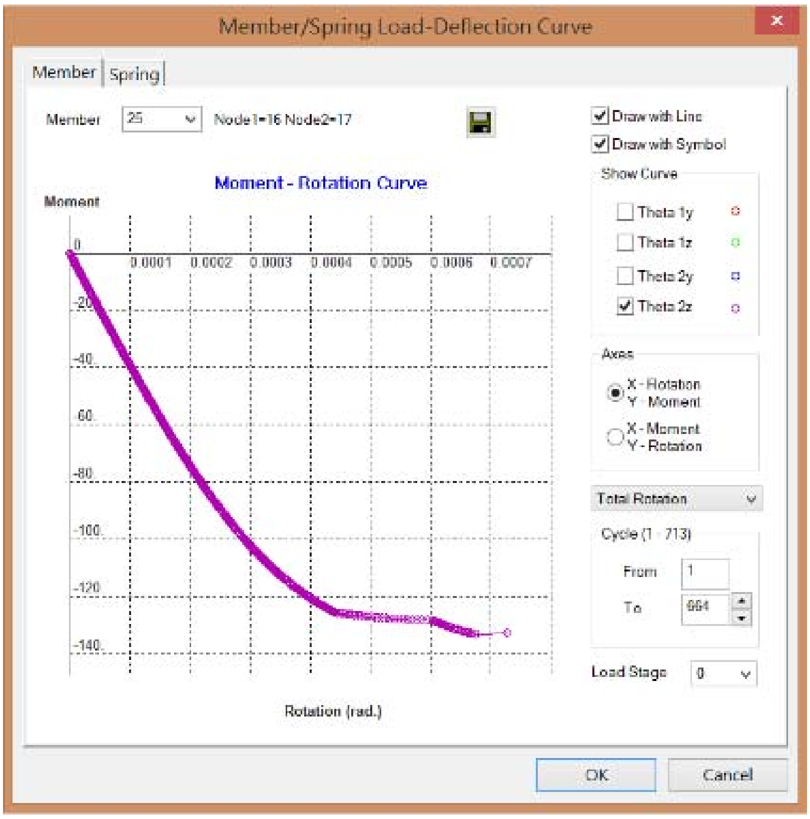


Figure 3. 11 Moment-Rotation Curve of Node 17 about Z-Axis 2

Unlike the portal frame, this multi-storey space frame exhibits moment-redistribution after the first section capacity is reached, which can be seen from the moment-rotation curve, and continues to sustain the increasing loading until drastic rotation occurs after load cycle 663 which is at the same time of load-deflection curve reverse.

To summarize the reduction percentage, the materials used for the beams and columns could be calculated thereafter:

Linear analysis: 60kg/mx180m(beam) + 129kg/mx117m(column) = 25893kg;

Nonlinear analysis: 46kg/mx180m(beam) + 73kg/mx117m(column) = 16821kg.

The material saved here is 25893-16821=9020kg

The percentage of material reduction hence obtained is

(25893-16821)/25893x100% = 35%.

As indicated from the portal frame example, as the complexity of structure and degree of indeterminacy increases, more strength reserve could be made use of through the adoption of nonlinear analysis. With the system behaviour more accurately captured, nonlinear analysis captures the real failure of the whole system and reduces the section size required to sustain the design loading.

3.4. Formulation of the three hinges element

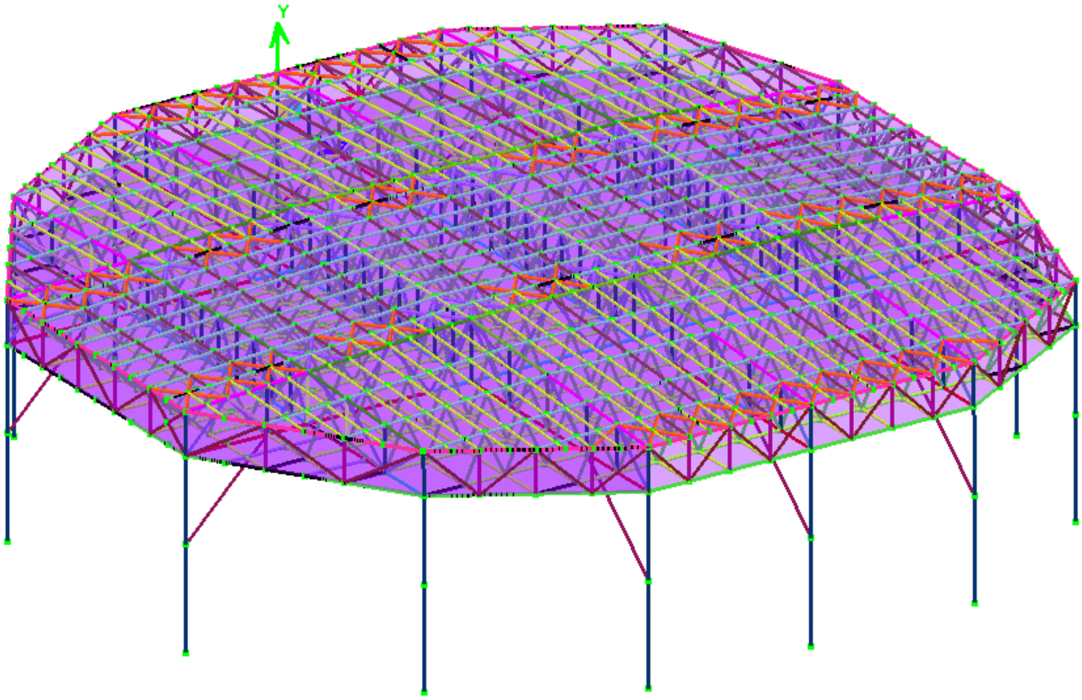


Figure 3. 12 Steel Roof Structure

A steel roof structure was selected first for the evaluation of the above comparison in terms of environmental impacts. Load cases considered are listed below. Both linear and nonlinear analyses were carried out on the 28 serviceability limit state cases and 60 ultimate limit state cases.

Load Cases
- DL(Steel+Slab)(1.00)
- SDL(Roof = 2+1 kPa)(1.00)
- SDL(Acoustic Panel = 1.0 kPa)(1.00)
- SDL(Catwalk = 0.5 kN/m)(1.00)
- SDL(Permanent Ceiling = 1.5 kPa)(1.00)
- SDL(Pulley Grid = 1.5 kPa)(1.00)
- SDL(Technical Grid = 1.5 kPa)(1.00)
- LL(Roof = 1 kPa)(1.00)
- LL(Acoustic Panel = 1.0 kPa)(1.00)
- LL(Technical Grid = 3.0 kPa)(1.00)
- LL(Hanging Wall = 30 kN/m)(1.00)
- LL(Catwalk = 0.5 kN/m)(1.00)
- DL+LL (factored 4100 kN)(1.00)
- TP(+30)(1.00)
- TP(-20)(1.00)
- WX(+)(1.05)
- WZ(+)(1.05)
- WY(+ Uplift)(1.05)
- WY(- Downward)(0.00)

Combined Load Cases
- [SLS1]1.0(DL+SDL)+0.6LL+0.3T(+30)
- [SLS2]1.0(DL+SDL)+0.6LL+0.3T(-20)
- [SLS3]1.0(DL+SDL)+0.4LL+0.5T(+30)
- [SLS4]1.0(DL+SDL)+0.4LL+0.5T(-20)
- [SLS5]1.0(DL+SDL)+0.4LL+0.4WX+0.3T(+30)
- [SLS6]1.0(DL+SDL)+0.4LL-0.4WX+0.3T(+30)
- [SLS7]1.0(DL+SDL)+0.4LL+0.4WZ+0.3T(+30)
- [SLS8]1.0(DL+SDL)+0.4LL-0.4WZ+0.3T(+30)
- [SLS9]1.0(DL+SDL)+0.4LL+0.4WX+0.4WY+0.3T(+30)
- [SLS10]1.0(DL+SDL)+0.4LL-0.4WX+0.4WY+0.3T(+30)
- [SLS11]1.0(DL+SDL)+0.4LL+0.4WZ+0.4WY+0.3T(+30)
- [SLS12]1.0(DL+SDL)+0.4LL-0.4WZ+0.4WY+0.3T(+30)
- [SLS13]1.0(DL+SDL)+0.4LL+0.4WX-0.4WY+0.3T(+30)
- [SLS14]1.0(DL+SDL)+0.4LL-0.4WX-0.4WY+0.3T(+30)
- [SLS15]1.0(DL+SDL)+0.4LL+0.4WZ-0.4WY+0.3T(+30)
- [SLS16]1.0(DL+SDL)+0.4LL-0.4WZ-0.4WY+0.3T(+30)
- [SLS17]1.0(DL+SDL)+0.4LL+0.4WX+0.3T(-20)
- [SLS18]1.0(DL+SDL)+0.4LL-0.4WX+0.3T(-20)
- [SLS19]1.0(DL+SDL)+0.4LL+0.4WZ+0.3T(-20)
- [SLS20]1.0(DL+SDL)+0.4LL-0.4WZ+0.3T(-20)
- [SLS21]1.0(DL+SDL)+0.4LL+0.4WX+0.4WY+0.3T(-20)
- [SLS22]1.0(DL+SDL)+0.4LL-0.4WX+0.4WY+0.3T(-20)
- [SLS23]1.0(DL+SDL)+0.4LL+0.4WZ+0.4WY+0.3T(-20)
- [SLS24]1.0(DL+SDL)+0.4LL-0.4WZ+0.4WY+0.3T(-20)
- [SLS25]1.0(DL+SDL)+0.4LL+0.4WX-0.4WY+0.3T(-20)
- [SLS26]1.0(DL+SDL)+0.4LL-0.4WX-0.4WY+0.3T(-20)
- [SLS27]1.0(DL+SDL)+0.4LL+0.4WZ-0.4WY+0.3T(-20)
- [SLS28]1.0(DL+SDL)+0.4LL-0.4WZ-0.4WY+0.3T(-20)
- [ULS1]1.35(DL+SDL)+1.5T(+30)
- [ULS2]1.35(DL+SDL)+1.5T(-20)
- [ULS3]1.35(DL+SDL)+1.5LL+0.9T(+30)
- [ULS4]1.35(DL+SDL)+1.5LL+0.9T(-20)
- [ULS5]1.35(DL+SDL)+1.05LL+1.5WX+0.9T(+30)
- [ULS6]1.35(DL+SDL)+1.05LL-1.5WX+0.9T(+30)
- [ULS7]1.35(DL+SDL)+1.05LL+1.5WZ+0.9T(+30)
- [ULS8]1.35(DL+SDL)+1.05LL-1.5WZ+0.9T(+30)
- [ULS9]1.35(DL+SDL)+1.05LL+1.5WY+0.9T(+30)
- [ULS10]1.35(DL+SDL)+1.05LL-1.5WY+0.9T(+30)
- [ULS11]1.35(DL+SDL)+1.05LL+1.5WX+1.5WY+0.9T(+30)
- [ULS12]1.35(DL+SDL)+1.05LL-1.5WX+1.5WY+0.9T(+30)
- [ULS13]1.35(DL+SDL)+1.05LL+1.5WZ+1.5WY+0.9T(+30)
- [ULS14]1.35(DL+SDL)+1.05LL-1.5WZ+1.5WY+0.9T(+30)
- [ULS15]1.35(DL+SDL)+1.05LL+1.5WX-1.5WY+0.9T(+30)
- [ULS16]1.35(DL+SDL)+1.05LL-1.5WX-1.5WY+0.9T(+30)
- [ULS17]1.35(DL+SDL)+1.05LL+1.5WZ-1.5WY+0.9T(+30)
- [ULS18]1.35(DL+SDL)+1.05LL-1.5WZ-1.5WY+0.9T(+30)
- [ULS19]1.35(DL+SDL)+1.05LL+1.5WX+0.9T(-20)
- [ULS20]1.35(DL+SDL)+1.05LL-1.5WX+0.9T(-20)
- [ULS21]1.35(DL+SDL)+1.05LL+1.5WZ+0.9T(-20)
- [ULS22]1.35(DL+SDL)+1.05LL-1.5WZ+0.9T(-20)
- [ULS23]1.35(DL+SDL)+1.05LL+1.5WY+0.9T(-20)
- [ULS24]1.35(DL+SDL)+1.05LL-1.5WY+0.9T(-20)
- [ULS25]1.35(DL+SDL)+1.05LL+1.5WX+1.5WY+0.9T(-20)
- [ULS26]1.35(DL+SDL)+1.05LL-1.5WX+1.5WY+0.9T(-20)
- [ULS27]1.35(DL+SDL)+1.05LL+1.5WZ+1.5WY+0.9T(-20)
- [ULS28]1.35(DL+SDL)+1.05LL-1.5WZ+1.5WY+0.9T(-20)
- [ULS29]1.35(DL+SDL)+1.05LL+1.5WX-1.5WY+0.9T(-20)
- [ULS30]1.35(DL+SDL)+1.05LL-1.5WX-1.5WY+0.9T(-20)
- [ULS31]1.35(DL+SDL)+1.05LL+1.5WZ-1.5WY+0.9T(-20)
- [ULS32]1.35(DL+SDL)+1.05LL-1.5WZ-1.5WY+0.9T(-20)
- [ULS33]1.35(DL+SDL)+1.5LL+0.9WX+0.9T(+30)
- [ULS34]1.35(DL+SDL)+1.5LL-0.9WX+0.9T(+30)
- [ULS35]1.35(DL+SDL)+1.5LL+0.9WZ+0.9T(+30)
- [ULS36]1.35(DL+SDL)+1.5LL-0.9WZ+0.9T(+30)
- [ULS37]1.35(DL+SDL)+1.5LL+0.9WY+0.9T(+30)
- [ULS38]1.35(DL+SDL)+1.5LL-0.9WY+0.9T(+30)
- [ULS39]1.35(DL+SDL)+1.5LL+0.9WX+0.9WY+0.9T(+30)
- [ULS40]1.35(DL+SDL)+1.5LL-0.9WX+0.9WY+0.9T(+30)
- [ULS41]1.35(DL+SDL)+1.5LL+0.9WZ+0.9WY+0.9T(+30)
- [ULS42]1.35(DL+SDL)+1.5LL-0.9WZ+0.9WY+0.9T(+30)
- [ULS43]1.35(DL+SDL)+1.5LL+0.9WX-0.9WY+0.9T(+30)
- [ULS44]1.35(DL+SDL)+1.5LL-0.9WX-0.9WY+0.9T(+30)
- [ULS45]1.35(DL+SDL)+1.5LL+0.9WZ-0.9WY+0.9T(+30)
- [ULS46]1.35(DL+SDL)+1.5LL-0.9WZ-0.9WY+0.9T(+30)
- [ULS47]1.35(DL+SDL)+1.5LL+0.9WX+0.9T(-20)
- [ULS48]1.35(DL+SDL)+1.5LL-0.9WX+0.9T(-20)
- [ULS49]1.35(DL+SDL)+1.5LL+0.9WZ+0.9T(-20)
- [ULS50]1.35(DL+SDL)+1.5LL-0.9WZ+0.9T(-20)
- [ULS51]1.35(DL+SDL)+1.5LL+0.9WY+0.9T(-20)
- [ULS52]1.35(DL+SDL)+1.5LL-0.9WY+0.9T(-20)
- [ULS53]1.35(DL+SDL)+1.5LL+0.9WX+0.9WY+0.9T(-20)
- [ULS54]1.35(DL+SDL)+1.5LL-0.9WX+0.9WY+0.9T(-20)
- [ULS55]1.35(DL+SDL)+1.5LL+0.9WZ+0.9WY+0.9T(-20)
- [ULS56]1.35(DL+SDL)+1.5LL-0.9WZ+0.9WY+0.9T(-20)
- [ULS57]1.35(DL+SDL)+1.5LL+0.9WX-0.9WY+0.9T(-20)
- [ULS58]1.35(DL+SDL)+1.5LL-0.9WX-0.9WY+0.9T(-20)
- [ULS59]1.35(DL+SDL)+1.5LL+0.9WZ-0.9WY+0.9T(-20)
- [ULS60]1.35(DL+SDL)+1.5LL-0.9WZ-0.9WY+0.9T(-20)

Referring to the Inventory of Carbon & Energy (ICE) [35] Version 2.0, embodied energy value is taken as 24.4MJ/kg within +/-30% range of uncertainty, while embodied carbon value is taken as 1.77kgCO_2/kg within +/-30% range of uncertainty.

The embodied energy reduction percentage and the embodied carbon reduction percentage have been obtained for the steel roof structure in terms of the building envelope and structure, the total building initial embodied energy reduction would then be estimated as shown in the bottom line of Table 7.1.

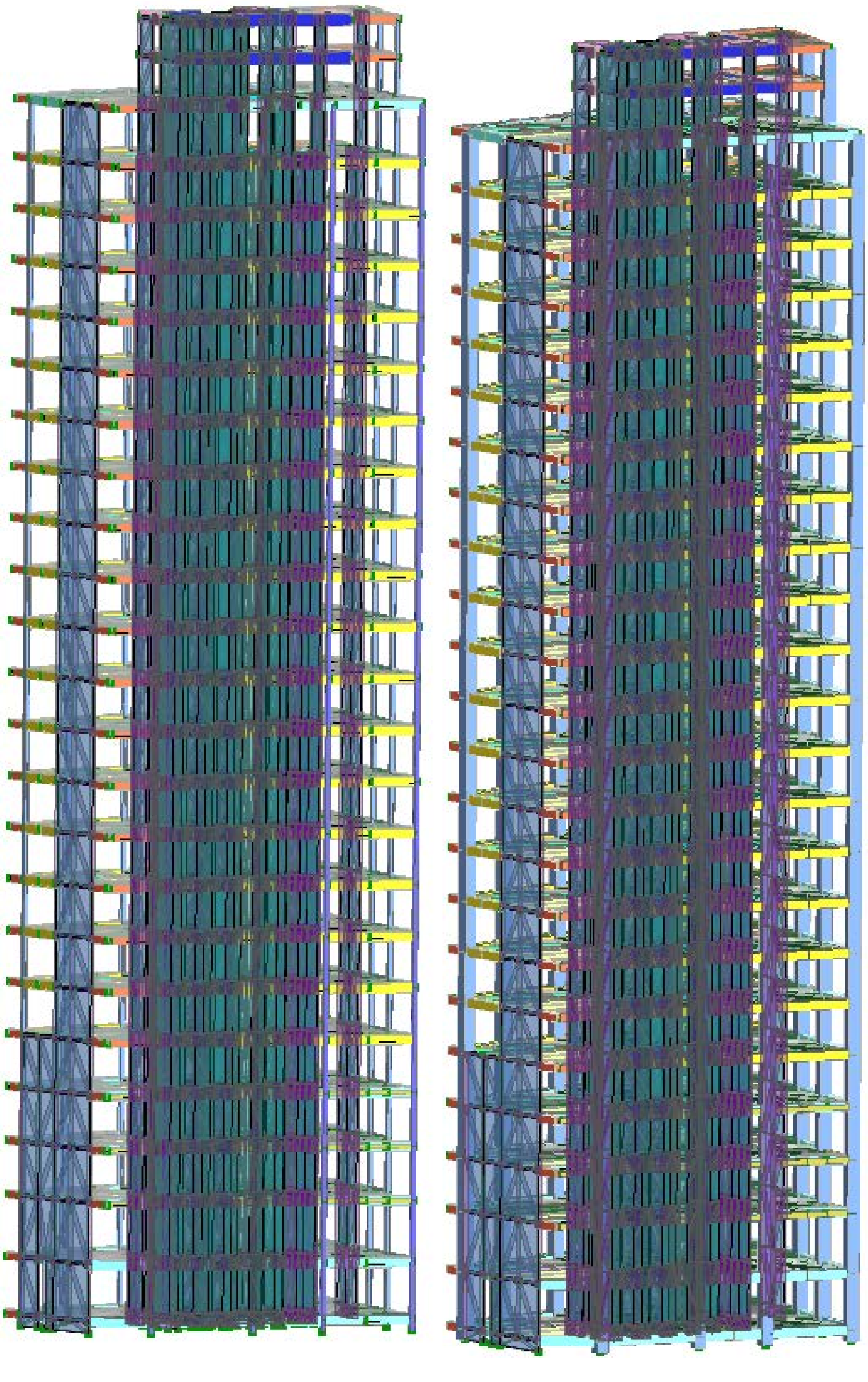
Steel Roof	Total Weight (ton)	Embodied Energy (MJ/kg)	Embodied Carbon ($kgCO_2/kg$)
Linear	2491	60.78 E+06 (±30%)	4.41 E+06 (±30%)
Nonlinear	1969	48.04 E+06 (±30%)	3.49 E+06 (±30%)
Reduction	522	12.74 E+06 (±30%)	0.92 E+06 (±30%)
Percentage	21%		

Table 3. 3 Material Consumption, Embodied Energy and Embodied Carbon Calculation Results for the Steel Roof by Linear and Nonlinear Methods

From the results of 3.1 ~ 3.3, it was concluded that around 10%-20% (with a reasonable range of uncertainty included) of total initial embodied energy reduction could be achieved for basic and elementary steel structure through the application of nonlinear analysis and design method instead of conventional linear design. For this steel roof structure, nonlinear analysis shows its advantage in reducing the material consumption, embodied energy and embodied carbon by 21%, which is at least a 21% saving in expense.

3.5. Numerical solution strategies for nonlinear analysis

This is a 25-storey model modified from a real commercial building originally designed and constructed in Hong Kong Island. The building's plan area was designed to be 27.69m by 23.26m for each storey, with the total height of the whole building to be 97.6 metres. Both steel building superstructure scheme and reinforced concrete building superstructure scheme have been carried out to simultaneously fulfil the Ultimate Limit States and Serviceability Limit States specified according to Hong Kong Steel Code 2011. The steel building solution was conducted by nonlinear analysis to achieve the best structural efficiency, including beams and columns made of steel and core walls made of concrete. On the other hand, the RC building solution done by linear analysis only designed with RC beams, RC columns and concrete core walls. Both structures were optimized to have the top total displacement over total height ratio approaching 1/500 as much as possible, so as to make the two design solutions comparable since the best structural efficiency was achieved with fairly closed reaction behaviour under the same vertical and horizontal loading circumstances.



(a) (b)

Figure 3. 13 Configuration of (a) Steel Building and (b) Reinforced Concrete Building

3.6. Results Evaluation of Frames, Roof and Buildings

According to the summary by Cole and Kernan [19], as described in section 2, the building envelope and building structure constitute half of the average initial embodied energy of an office building. As the percentage of embodied energy reduction has been obtained for all examples in terms of the building envelope and structure, the total building initial embodied energy reduction would then be estimated as shown in the bottom lines of the following tables in this section.

3.6.1 Frames

For basic and elementary steel structures, around 10~20% (with a reasonable range of uncertainty included) of total initial embodied energy reduction could be achieved through the application of nonlinear analysis and design method instead of conventional linear design.

Portal Frame	UKB & UKC (kg/m)	W (ton)	EE(±30%) (10^3MJ/kg)	EC(±30%) (tonCO_2/kg)
Linear	356 x 368 x 202	10.1	246.4	17.9
Nonlinear	356 x 368 x 153	7.7	186.7	13.5
Reduction	49	2.4	221.3	4.3

Percentage	24%
Estimated total building initial embodied energy reduction % = 24%x50% = 12%	

Table 3. 4 Material Consumption, Embodied Energy and Embodied Carbon Calculation Results for the Design of Portal Frame Example by Linear and Nonlinear Methods

Space Frame	UKB (kg/m)	UKC (kg/m)	W (ton)	EE(±30%) (10^3MJ/kg)	EC(±30%) (tonCO_2/kg)
Linear	406x178x60	356x368x129	25.9	631.8	45.8
Nonlinear	35x165x460	254x254x73	16.8	410.4	29.8
Reduction	14	56	9.1	221.4	16.1
Percentage	N/A	N/A	35%		
Estimated total building initial embodied energy reduction % = 35%x50% = 18%					

Table 3. 5 Material Consumption, Embodied Energy and Embodied Carbon Calculation Results for the Design of Space Frame Example by Linear and Nonlinear Methods

3.6.2 Roof

Steel Roof	Weight (ton)	EE(±30%) (10^6MJ/kg)	EC(±30%) (10^6kgCO_2/kg)
Linear	2491	60.8	4.4
Nonlinear	1969	48.0	3.5
Reduction	522	12.7	0.9
Percentage	21%		
Estimated total building initial embodied energy reduction % = 21%x50% = 11%			

Table 3. 6 Material Consumption, Embodied Energy and Embodied Carbon Calculation Results for the Steel Roof by Linear and Nonlinear Methods

For this steel roof structure, nonlinear analysis shows its advantage in reducing the material consumption by 21%, which is at least a 21% saving in expense, while in addition, the total building initial embodied energy reduction has been obtained as 11%.

Therefore, it could be foreseen that the reduction in the material cost, energy consumption and GHG emissions is noticeable. The advantages of nonlinear analysis over conventional linear analysis could be extended to the environmental impacts quite reasonably.

3.6.3 Buildings

For the whole building's comparison, another set of embodied energy and embodied carbon coefficients were adopted to demonstrate the environmental impacts referred from the Inventory of Carbon & Energy [35] as well. As the RC building was designed by linear analysis but the steel structure designed by nonlinear analysis, reduction in total weight and embodied carbon value could be observed under the assumption that all sections and reinforcements made up of virgin steel with relatively high levels of Embodied Energy and Embodied Carbon coefficients associated with. Given the condition that an ideal and extreme application of highly recycled steel materials to every parts of the steel building, a remarkable decrease in total Embodied Energy and total Embodied Carbon has been noticed as high as 16% and 42% accordingly due to the very low levels of Embodied Energy and Embodied Carbon coefficients.

	Materials	Weight (kN)	Weight (tons)	EE Coefficients (MJ/kg)	Embodied Energy (MJ)	EC Coefficients ($kgCO_2/kg$)	Embodied Carbon (kgCO2)
Concrete Structure	Steel	0	0	25.4	0	1.78	0
	Concrete	124558	12701	0.95	1.21E+07	0.13	1.65E+06
	Reinforcement	8314	848	24.6	2.09E+07	1.71	1.45E+06
	Total	132872	13549		3.29E+07		3.10E+06

Table 3. 7 Material Consumption, Embodied Energy and Embodied Carbon Calculation Results for the RC Building

	Materials	Weight (kN)	Weight (tons)	EE Coefficients (MJ/kg)	Embodied Energy (MJ)	EC Coefficients ($kgCO_2/kg$)	Embodied Carbon (kgCO2)
Steel Structure (Virgin)	Steel	8654	882	25.4	2.24E+07	1.78	1.57E+06
	Concrete	48226	4917	0.95	4.67E+06	0.13	6.39E+05
	Reinforcement	3219	328	24.6	8.07E+06	1.71	5.61E+05
	Total	60099	6128		3.52E+07		2.77E+06
	Reduction to Concrete Structure				-7%		11%

Table 3. 8 Material Consumption, Embodied Energy and Embodied Carbon Calculation Results for the Steel Building in Virgin Materials

	Materials	Weight (kN)	Weight (tons)	EE Coefficients (MJ/kg)	Embodied Energy (MJ)	EC Coefficients ($kgCO_2/kg$)	Embodied Carbon (kgCO2)
Steel Structure (Recycled)	Steel	8654	882	10	8.82E+06	0.44	3.88E+05
	Concrete	48226	4917	0.95	4.67E+06	0.13	6.39E+05
	Reinforcement	3219	328	8.8	2.89E+06	0.42	1.38E+05
	Total	60099	6128		1.64E+07		1.17E+06
	Reduction to Concrete Structure				16%		42%

Table 3. 9 Material Consumption, Embodied Energy and Embodied Carbon Calculation Results for the Steel Building in Recycling Materials

3.7. Conclusions and Inspiration

For basic and elementary steel structure: around 10%-20% of total initial embodied energy reduction could be achieved;

For the steel roof structure: reduction in material consumption and expense (at least) around 20%, while the total building initial embodied energy reduced by 10%;

For the recent commercial building application: steel vs. concrete design schemes showed reduction in material total weight about 50% while the embodied carbon emissions' reduction would possibly range from 11% to 42% depending on the level of recycled steel material adopted

Conclusion could be drawn from the above several comparisons and evaluation that reduction in the material cost, energy consumption and GHG emissions is noticeable by the application of nonlinear analysis in the design process. Thereafter, the advantages of nonlinear analysis over conventional linear analysis could be extended to the environmental impacts quite reasonably and scientifically.

Recycled steel seems could be able to bring a more environmental friendly solution to the field of structural analysis and design for the target of making environmental contributions in a structural way, however, due to the limitation of availability, constraints of application and uncertainties in the level of recycled scrap in different suppliers and countries, a combination of virgin and partially recycled steel materials would be applied in the majority of building construction market. To what extent the recycled steel should be utilized is worthy of further exploration, so that nonlinear analysis could best profit the design scheme either economically or environmentally.

CHAPTER 4

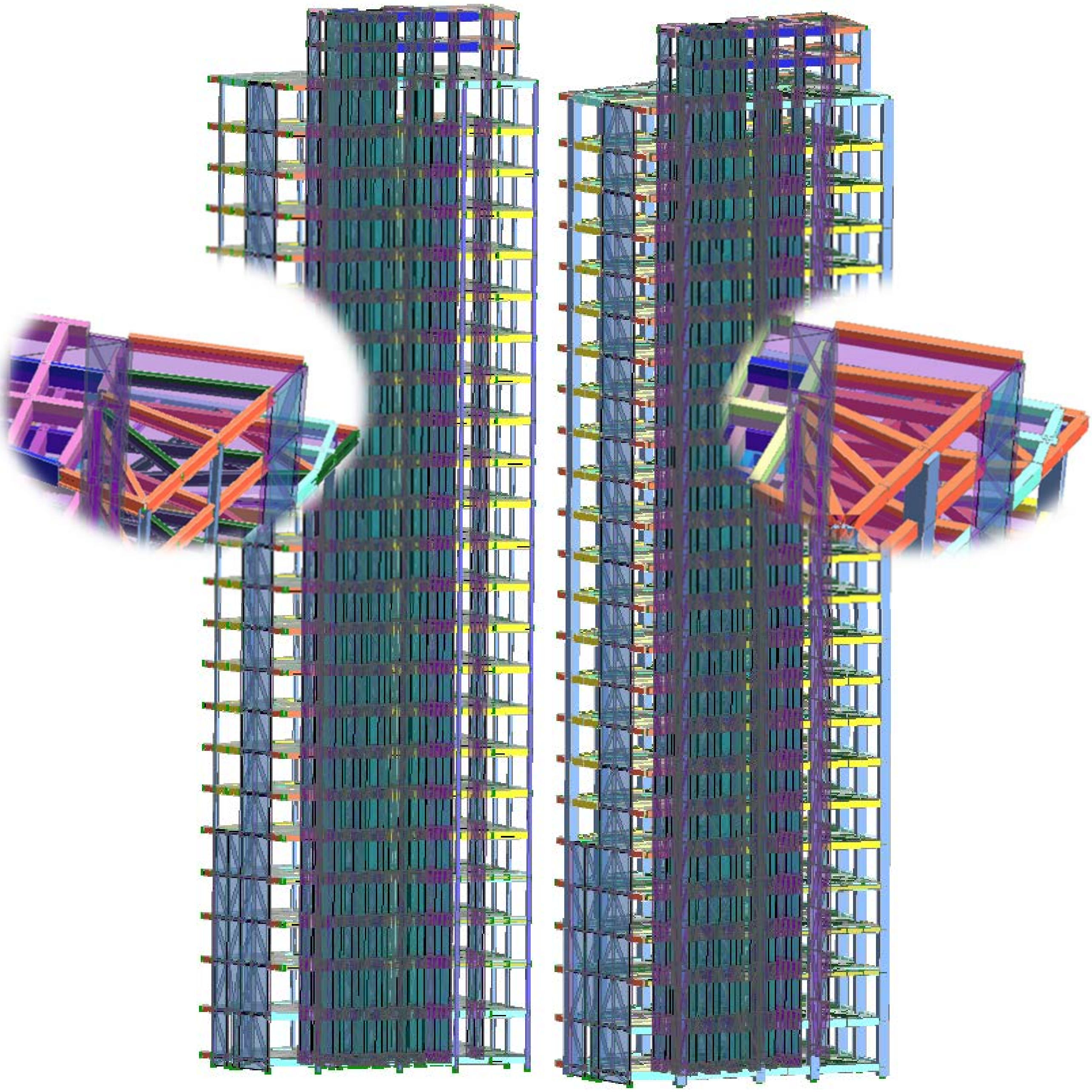
EMBODIED CARBON COMPARISON OF CONCRETE/STEEL – BUILDING STRUCTURES (SUPERSTRUCTURES ONLY) USING NONLINEAR OPTIMIZATION

Taking the material factor into consideration, in the previous Chapter 3, the environmental performance of steel and reinforced concrete structures has been examined in terms of the embodied carbon and energy. Furthermore, the advantage of nonlinear analysis has been addressed once more in terms of the building ecology and sustainable profits. As the environmental impact evaluation method has already been scientifically proved, in the following studies of this research, the environmental performance of different structural design methods, in different design configurations and different materials could then be conducted following the above stated solution.

Thus in the following study, the integration of the optimised structural design method and the Hong Kong based carbon labelling scheme would be illustrated using several series of examples and the results will bring the industry a clear picture of how to achieve the lowest carbon footprint of the whole building structure. Furthermore, a scientific relationship would be able to be established between material consumption, structural design optimization, selection and use of low carbon material, together with the associated building's total carbon footprint.

4.1. Summary of Building Models

The same set of building models were selected as those in Figure 3.12 in section 3.5. This is a 25-storey model modified from a real commercial building originally designed and constructed in Hong Kong Island. The building's plan area was designed to be 27.69m by 23.26m for each storey, with the total height of the whole building to be 97.6 metres. Both steel building superstructure scheme and reinforced concrete building superstructure scheme have been carried out to simultaneously fulfil the Ultimate Limit States and Serviceability Limit States specified according to Hong Kong Steel Code 2011 [38]. The steel building solution was conducted by nonlinear analysis to achieve the best structural efficiency, including beams and columns made of steel and core walls made of concrete. On the other hand, the RC building solution done by linear analysis only designed with RC beams, RC columns and concrete core walls. Both structures were optimized to have the top total displacement over total height ratio approaching 1/500 as much as possible, so as to make the two design solutions comparable since the best structural efficiency was achieved with fairly closed reaction behaviour under the same vertical and horizontal loading circumstances.



(a) (b)

Figure 4. 1 Configuration of Commercial Building Models (a) Steel Building and (b) Reinforced Concrete (RC) Building

The building model was firstly designed in a steel structural frame ("Steel Building") consisting of steel beams and steel columns all in steel grade of S355 coupled with RC structural core walls. Lateral stiffness is provided by RC structural core walls to resist wind actions. Vertical actions including self-weight, super-imposed dead load, live load, etc., are resisted by steel beams through which are further transferred to the steel columns down to the ground. The structural configuration is illustrated in Figure 4.1(a).

On the other hand, in the second scheme, the building model was designed to be a reinforced concrete structure ("RC Building") consisting of RC beams, RC columns coupled by concrete core walls. Lateral stiffness is provided by RC core-walls to resist wind actions. Vertical actions including self-weight, super-imposed dead load, live load, etc., are resisted by RC beams supported by RC columns and RC walls and downward to the ground. The structural configuration is illustrated in Figure 4.1(b).

However, with all the steel sections used in the Steel Building and reinforcements applied in both Steel and RC Buildings to be of Grade S355, the grade of concrete adopted for analysis and comparison vary from C60, C80 to C100 with the steel bar in various recycled rates, including virgin steel bar, 39% recycled scrap included or 59% recycled scrap included according to the carbon footprint data provided by ICE Version 2.0, which will be detailed introduced in the following contents of this section.

This preliminary appraisal assesses the structural behaviour of the building under dead, imposed and wind actions, as well as the effects due to temperature variation by direct analysis approach. All relevant loadings are considered to be applied either in individual or in such realistic combinations as to comprise the most critical effects on all the structural elements and the structure as a whole. The ultimate limit safety state and serviceability limit state cases are analysed to capture the fundamental requirements for the reliability of construction works.

4.2. Analysis Method

The second-order direct analysis suggested by the Hong Kong Steel Code 2011 was performed in this design on the deformed structures of the Steel Building. Both P-Δ sway and P-δ bow nonlinear effects were included for determination of stresses in equilibrium with the defined actions for a global analysis dependent on geometrical, structural and material properties. NAF series – Non-linear Integrated Design and Analysis (NAF-NIDA) version 9.0 was employed for the second-order elastic analysis conducted in this study, which was an already approved approach for the non-linear analysis and design to Code of Practice for the Structural Use of Steel 2011 and Eurocode-3, with a number of application in the UK, Singapore, Hong Kong, China, Macau, Taiwan, India, and Myanmar, etc, in the past decade. With a conventional linear analysis, it is difficult to determine and visualise the real action effects especially in terms of the steel-composite floor system actions in which the simple effective length assumption is no longer reliable without taking consideration of secondary stresses and buckling effects.

For the RC Building examples whichever in Grade C60, C80 or C100, conventional linear elastic analysis was adopted for all the models according to Hong Kong Steel Code 2011, satisfying the Ultimate Limit State and Serviceability Limit State simultaneously.

4.3. Embodied Carbon Footprint

4.3.1 Data

The quantification of the construction buildings' total carbon footprint (CFP) was calculated by the accumulation of all the construction materials' carbon footprints. The CFP calculated under this Scheme was based on a "cradle-to-site" approach, covering all GHG emissions and removals of the product arising from raw material acquisition, transportation, production process, storing/packaging and finally transporting to the border of Hong Kong.

Currently, the Scheme database [64] (Table 4.1) includes rebars and structural steel products as well as concrete products ranging from C30 to C60 grade concrete. The lowest carbon footprint values are 0.55 and 2.08 $kgCO_2e/kg$ for rebar and structural steel section available in Hong Kong construction material market respectively.

Applicant Region	Product Category	Carbon Footprint Value
	Rebar and Structural Steel	Unit: tonne CO_2e/tonne
Thailand	Section	0.55
Mainland China	Pipe	2.95
Taiwan	Section	1.37
Middle East	Rebar	2.08
Middle East	Section	2.36
Hong Kong	**Ready-mixed Concrete**	Unit: kg CO_2e/m^3 concrete
	C30s	240
	C40s	308
	C40s	209
	C40s	229
	C40s	233
	C40s	255
	C40s	287
	C40s	282
	C60s	310
	C60s	240

Table 4. 1 Hong Kong CIC Carbon Labelling Scheme Applicant Data [64]

However, due to the limitation of the product varieties and availability of the particular recycled rates of products provided in the Scheme database, a more consistent and systematic database, Bath Inventory of Carbon & Energy (ICE) Version 2.0 [35], was referred regarding the carbon footprint values for ready-mixed concrete in various grades, as well as steel rebars and sections with different recycled contents.

In order to achieve the purpose of application of the environmental impact evaluation method in the current Hong Kong construction market, some local carbon footprint values for all the ready-mixed concrete, steel sections and steel rebars were also shortlisted for reference and comparison.

The CFPs applied in this study are listed in the following tables:

Concrete Grade	100% OPC (Upper Limit)	50% GGBS (Lower Limit)	Average Value
C60	491	306	413
C80	598	381	507
C100 *	598	381	507

*The carbon footprint value of super high strength concrete will not be increased with the increasing strength but tending to be steady. It is assumed that the carbon footprint of C100 the same as the C80.

Table 4. 2 The Carbon Footprint Data of Concrete Applied in this Study

(Unit: kg CO_2e/m^3)

Steel Type	100% virgin steel	39% recycled scrap	59% recycled scrap
Section	3.03	2.03	1.53
Bar	2.77	1.86	1.40

*Due to the limitation of product size produced from recycled scrap, the steel products sized above 305 all applies the virgin steel.

Table 4. 3 The Carbon Footprint Data of Steel Applied in this Study

(Unit: kg CO_2e/kg)

The following Table 4.4 provides supporting references and sets the initial benchmarks for the CIC's Carbon Labelling Scheme for Ready-mixed Concrete Products [64]. The embodied carbon footprint of Ready-mixed Concrete Products in "kg CO_2e / m^3 of concrete produced" (Table 4.1) are obtained from / referenced to relevant literature, databases and worldwide concrete manufacturers' environmental product declaration (EPD) reports.

Source	Data Year	Emission Factor ($kgCO_2e/m^3$)														
		C20	C25	C30	C35	C40	C45	C50	C55	C60	C65	C70	C80	C90	C100	Remarks
UK ICE[a]	2011		310	329	348	383		442	464	491	518	545	598			100% cement
			287	306	324	357		409	431	456	481	506	556			15% FA concrete
			254	270	291	320		364	386	408	431	453	498			30% FA concrete
			244	261	280	313		360	381	405	429	452	500			25% GGBS concrete
			181	190	207	235		270	288	306	325	344	381			50% GGBS concrete
U.K. MPA	2013			316	316	369		432								CEM I concrete, include steel bar
				236	261	313		351								30% FA concrete, include steel bar

a The number is converted using a bulk density of 2350 Kg/m3.

b The numbers highlighted in yellow are extrapolated according to ICE value from C25 to C50.

Table 4. 4 Embodied Carbon Footprint of Ready-Mixed Concrete Products from Literature and Databases

After searching all the available sources, it is found that only ICE database presents the most comprehensive systematic data based on strength class and SCM substitution ranging from C20 to C50 and the values up to C80 could be extrapolated following the linear trend between the embodied carbon values and the increasing strength. Considering the authoritativeness, representativeness, sample size and data timeliness, ICE data are selected for setting the initial benchmark values for each strength category. The figures from other data bases can be used as references to verify the use of ICE for the benchmarking exercise.

In order to be consistent with the product categorization described in the Assessment Guide, the benchmark values shall be grouped based on 10 MPa difference of strength grade starting from C30. To obtain a reference value for the group of C30s, average value of the C30, C35 and C40 is taken and the same method applies to other groups of strengths (C40s to C70s). For high-strength concrete (>C80), their embodied carbon values are not simply extrapolated based on linear relationship because the achievement of high-strength is not only based on the increasing content of cement (the dominant GHG emission source in concrete), but also supplementary materials (PFA, GGBS, SF) and other chemical admixtures which are relatively less carbon-intensive. Hence, initially the embodied carbon footprint values of C80 to C100 are assumed to be the same as C70s.

4.3.2 Total EC Accumulation Methods

Results were collected, interpreted and compared in terms of both design schemes. Referring to the above databases, total carbon footprint is contributed by the accumulation of all the construction materials' carbon footprints. In the Steel Building, all the loadings are supported by steel members with structural walls taking action, while in the RC Building, the system consists of RC beams and RC columns with concrete core walls. From a system level, the total carbon footprints should include all the structural elements of the building system. Therefore, to make the two design schemes comparable, the range of structural elements included will be as shown below.

Variations	**Steel Building**	**RC Building**
Elements	steel beams steel columns Concrete Core Walls Steel Rebars	RC beams RC columns Concrete core-walls Steel Rebars
Materials	Core walls in C60, C80, C100; Steel Sections / Bars in Virgin, 39% recycled scrap, 59% recycled scraps	Beams, Columns and Core walls in C60, C80, C100; Steel Bars in Virgin, 39% recycled scrap, 59% recycled scraps

Table 4. 5 Structural Elements Included in Calculation for Commercial Steel and RC Buildings

4.4. Results Discussion

The relative advantages of Steel Building or RC Building are to be examined by comparing the environmental effects of the accumulation of all structural elements supporting the horizontal loadings and vertical loadings. Therefore, it is expected to examine how much could be saved in material used and total embodied carbon (EC) with different materials included for application.

4.4.1 Total Weight of the Models' Superstructures

The total weights of the Steel Building and RC Buildings in C60, C80 and C100 have been listed in the following Table 4.6 and plotted in Figure 4.2. The total weight of Steel Building frame is only around half of that of RC Building in C60, while one third less of that of RC Building in C100 with high strength concrete adopted. These numbers showed a great level of decrease in material consumption in the nonlinear optimized Steel Building Scheme, which further infers that the underground construction could save even more material and cost under this scheme, which will be further explored in details in the following Chapter 5.

4.4.2 Total Embodied Carbon

Based on the CFPs in Table 4.2 & 4.3, total carbon footprints of Steel Building and Comp Building have been calculated for all material combinations, in the unit of $10^6 kgCO_2e$ according to ICE database in Table 4.

Weight (kN)	Steel Building	RC Building in C60	RC Building in C80	RC Building in C100
Section	8654	0	0	0
Concrete	47636	98239	86560	76668
Bar	5163	10893	10001	9640
Total	**61452**	**109132**	**96561**	**86308**

Table 4. 6 Superstructure (Sup) Total Weights for Steel and RC Buildings in Different Concrete Grades

Figure 4. 2 Superstructure (Sup) Total Weights for Steel and RC Buildings in Different Concrete Grades

Steel Building	C60 UL	C60 Avg	C60 LL	C80 UL	C80 Avg	C80 LL	C100 UL	C100 Avg	C100 LL
	Unit: $10^6 kgCO_2e$								
Virgin	5.13	4.97	4.75	5.34	5.16	4.90	5.34	5.16	4.90
39%R	3.76	3.61	3.39	3.98	3.80	3.54	3.98	3.80	3.54
59%R	3.08	2.92	2.71	3.30	3.11	2.86	3.30	3.11	2.86
RC Building	C60 UL	C60 Avg	C60 LL	C80 UL	C80 Avg	C80 LL	C100 UL	C100 Avg	C100 LL
	Unit: $10^6 kgCO_2e$								
Virgin	5.13	4.80	4.35	5.02	4.69	4.23	4.67	4.37	3.96
39%R	4.12	3.79	3.34	4.10	3.76	3.30	3.78	3.48	3.07
59%R	3.60	3.28	2.83	3.63	3.29	2.83	3.32	3.03	2.62

Table 4. 7 Total Embodied Carbon Values Associated with Different Materials (Sup Only)

4.4.3 Variable: Concrete Carbon Footprint Value

Sorting the total EC values for comparisons, in this section, data were plotted into bar charts along rows in Table 4 in order to examine the effects of varying concrete carbon footprint data for both Steel Building and RC Building with the same steel recycled contents included. Totally nine combinations could be summarized under this category.

Combination		Steel Recycled Level		
		Virgin	39% R	59% R
Concrete Grade	C60	a	d	g
	C80	b	e	h
	C100	c	f	I

Table 4. 8 Total EC Values Comparison Combinations for Steel/RC Buildings in Different Concrete Grades

Extracting Combinations a, b and c for comparison firstly, the following Figures 4.3 a, b & c show the total EC values with varying concrete grade, as well as different CF data level applied under each concrete grade series.

As the Concrete Grade increases, observations could be made that,

Combinations a, b & c

i. From the trend of decrease of bar lengths according to the sequence of Combination a to b and then to c, total Embodied Carbons of the RC Building would decrease generally according to the increase of concrete grade, while those of the Steel Building would increase generally according to the increase of the concrete grade. However, the total Embodied Carbon values of the Steel Building from Combination b and c keep identical as the reason of same RC elements designed to Steel Building models with the only difference lying in concrete material grades. As strength increase at very high level was achieved mainly due to the chemical additives, the carbon footprint values of super high strength concrete will not be increased along with the material strength increase but tending to be steady. Therefore, the same set of carbon footprint values of C80 and C100 result in the same total Embodied Carbon values for the Steel Building models in C80 and C100 according to the bar charts in Combination b and c.

ii. The relative difference in terms of the total embodied carbon values of the entire building systems achieved by using Steel Building Scheme compared with the corresponding RC Building Scheme have been presented in the following Figure 4.3 as well. The differences are labelled in red, orange and green bars for concrete grade values according to the upper limit, average and lower limit values.

iii. In the same concrete grade, the total EC values difference between steel and RC buildings decrease as the concrete grade value level increases within the same concrete grade range. As for the same set of concrete grade comparison, the different levels of concrete grade values apply to the same set of designs for Steel and RC buildings. The contribution of concrete to the total EC value of the Steel Building is very minor compared to steel and is as little as incomparable to the contribution of concrete to the total EC value of the RC Building. Therefore, as the concrete grade value decreases, the embodied carbon footprint value of concrete decreases accordingly and then the accumulation of the total embodied carbon would decrease apparently, resulting in the increase in the total EC values difference.

iv. Taking total EC values in different concrete grades but all in the same value levels, i.e. Grade C60, C80 and C100 all using Upper Limit values, labeled in red, as a set of comparison. As the concrete grade increases, the concrete carbon footprint increases, but the member size decreases in a large scale, so the material consumption decreases. In the Steel Building, the concrete contribution is very limited, so the effect of concrete consumption decrease is very minor compared with the carbon footprint increase, thereafter the total EC values increases a bit as the concrete grade increases. However, in terms of the RC Building, the concrete contribution almost determines the total EC value trends, so the effect of large material save overweighs that of the concrete carbon footprint value increase, so the total EC value of the RC Building decreases as the concrete grade increases, and finally resulting in the difference increase between the RC building and the Steel Building in terms of the total EC values calculated.

v. The above iv trend applies to the comparison sets with Grade C60, C80 and C100 concrete all using average carbon footprint values or all using Lower Limit carbon footprint values.

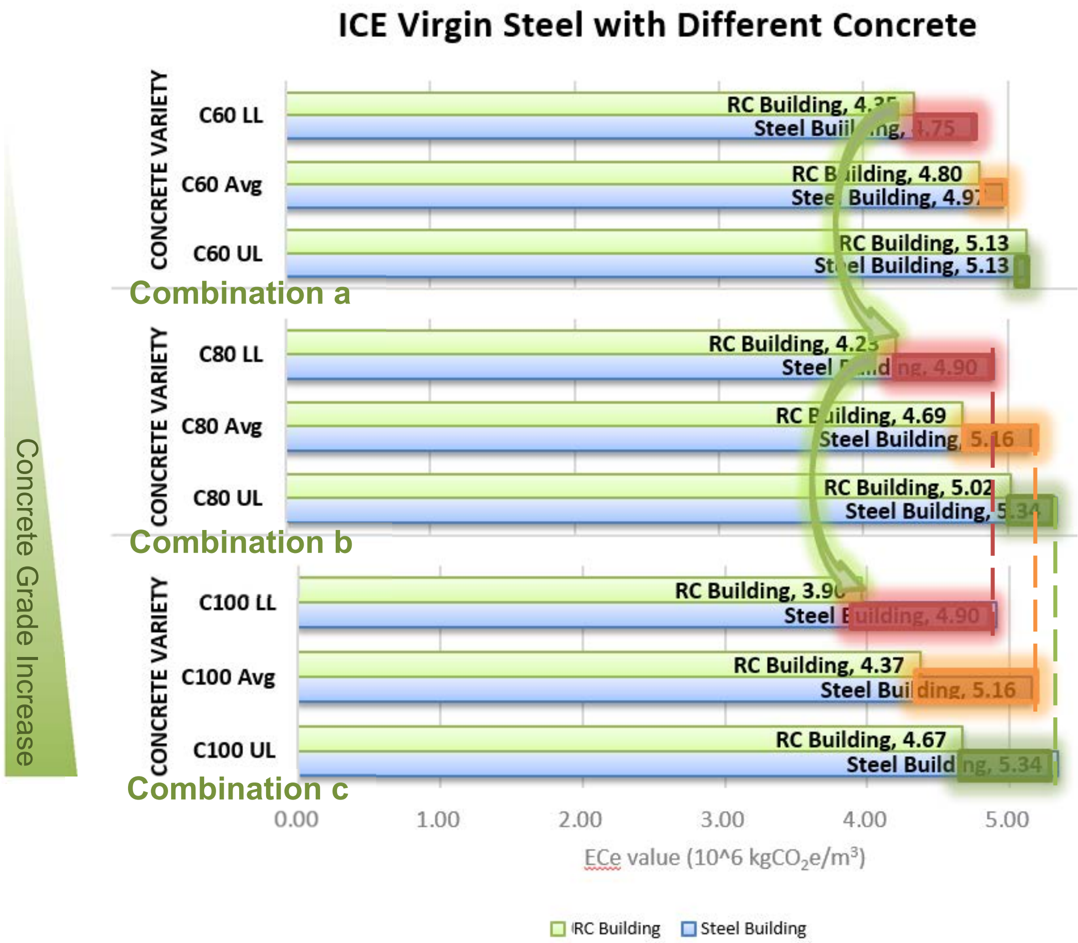


Figure 4. 3 Total Embodied Carbon Values Comparison of Steel and RC Buildings in Virgin Steel with Concrete in Different Grades: Combinations a, b & c.

vi. The above summarized results i ~ v apply not only to the Steel Building and the RC Building models using ICE virgin steel carbon footprint values, i.e. Combinations a, b & c, but also to the models using ICE carbon footprint values with different levels of recycled steel scrap, i.e. Combinations d, e & f for steel with 39% recycled scrap, as well as, Combinations g, h & i for steel with 59% recycled scrap. The results are listed in the following Figures 4.4 & 4.5 where the above mentioned trends could be thereafter examined accordingly.

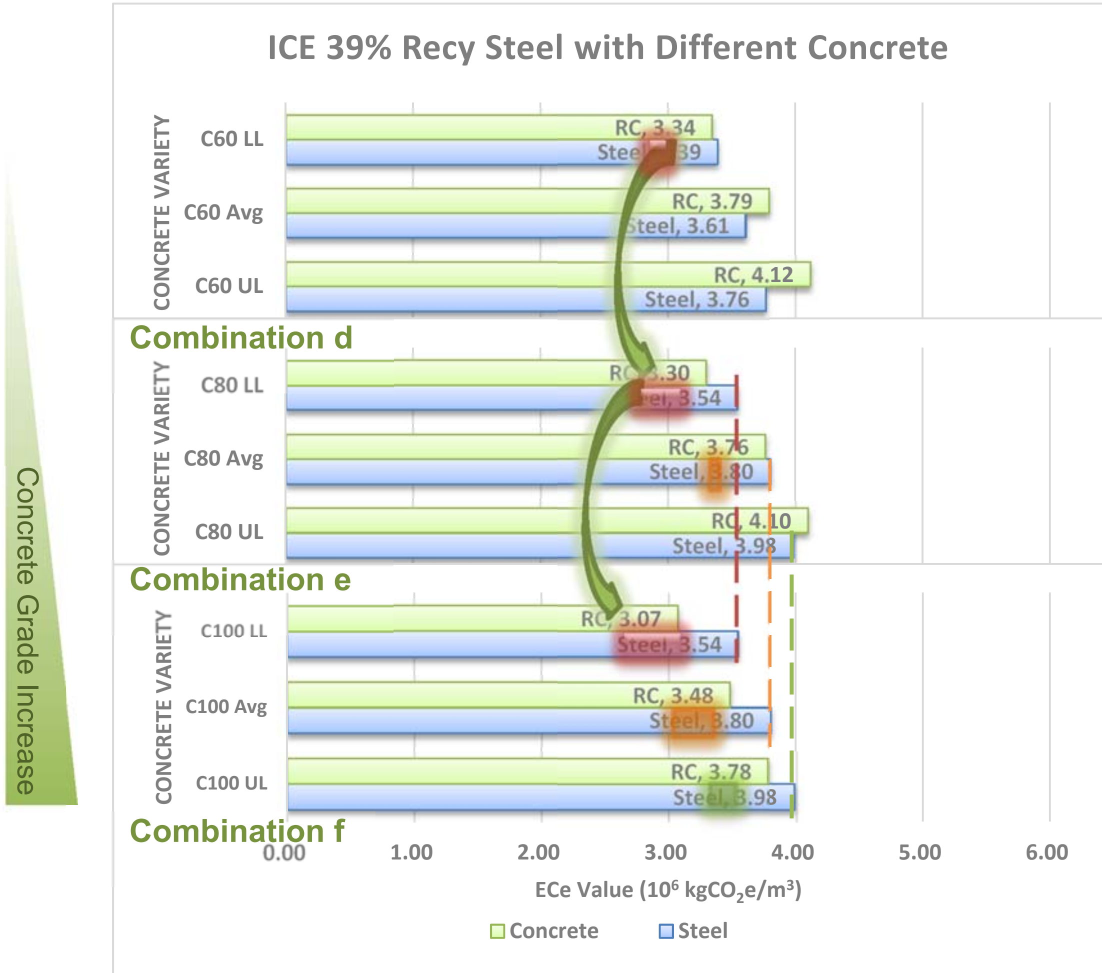


Figure 4. 4 Total Embodied Carbon Values Comparison of Steel and RC Buildings in 39% Recycled Steel (ICE) with Concrete in Different Grades: Combinations d, e & f.

Combinations d, e & f and Combinations g, h & i

vii. The trend of decrease of bar lengths according to the sequence of Combination d to e and then to f follows the same manner as stated in i, however, with the increase of recycled steel scrap inclusion in the steel material for application, this trend becomes no longer applicable. Total Embodied Carbon values of RC Building increase from Combination g to h, but decrease again from Combination h to i, which brings a new indication that with low percentage of recycled steel applied to the whole system. In the results for both the Virgin Steel and 39% Recycled Steel combinations a, b & c and d, e, & f, the increase in the concrete grade brings down the total material consumption which overweighs the little increase in the CF values of different grade concrete, while on the other hand in the results for 59% Recycled Steel combinations g, h & i, with high percentage of recycled steel scrap included, the very low CF value for recycled steel for this application makes the effects of the increase in the concrete CF overweighs those due to the material reduction with the concrete grade increase. Other than the above stated difference from result i, the total ECs of the Steel Building would increase generally according to the increase of the concrete grade as in result i, at the same time, those of the Steel Building from Combination e and f, as well as, from Combination h to i keep identical as described in result i.

viii. The relative difference in terms of the total embodied carbon values of the entire building systems achieved by using Steel Building Scheme compared with the corresponding RC Building Scheme have been presented in the following Figure 4.3~4.5 as well. The differences are labelled in red, orange and green bars for concrete grade values according to the upper limit, average and lower limit values. In the previous Combinations a, b & c in Figure 4.3, all the total EC values of Steel Building systems are larger than those of the corresponding RC Buildings. Starting from Combination d and e in Figure 4.4, bars of Steel Buildings become shorter than those of RC Buildings, further in Combinations g, h & I in Figure 4.5, more and more bars for Steel Buildings are found to be shorter than the RC Buildings' ones, which implies that the more recycled steel scrap included in the building system, the lower the total EC values the steel material could contribute to, therefore more environmental friendly especially with lower grade concrete applied to the whole system.

ix. Taking total EC values in different concrete grades but all in the same value levels, i.e. Grade C60, C80 and C100 all using Upper Limit values, labelled in red, as a set of comparison. As the concrete grade increases, the concrete carbon footprint increases, but the member size decreases in a large scale, so the material consumption decreases. In the Steel Building, the concrete contribution is very limited, so the effect of concrete consumption decrease is very minor compared with the carbon footprint increase, thereafter the total EC values increases a bit as the concrete grade increases. However, due to the significant decrease of CF values of the recycled steel included in Combinations d, e, f and g, h, i, compared with those with virgin steel applied in Combinations a, b & c, the effect of the total EC decrease is very well noticed in Steel Buildings with large percentage of steel included. As a matter of this, the result figures of these combinations could no longer follow the trends as described above in results iii, iv & v, but the effect of large material save still affect the reduction of the total EC of RC Building systems as the associated concrete grade increases.

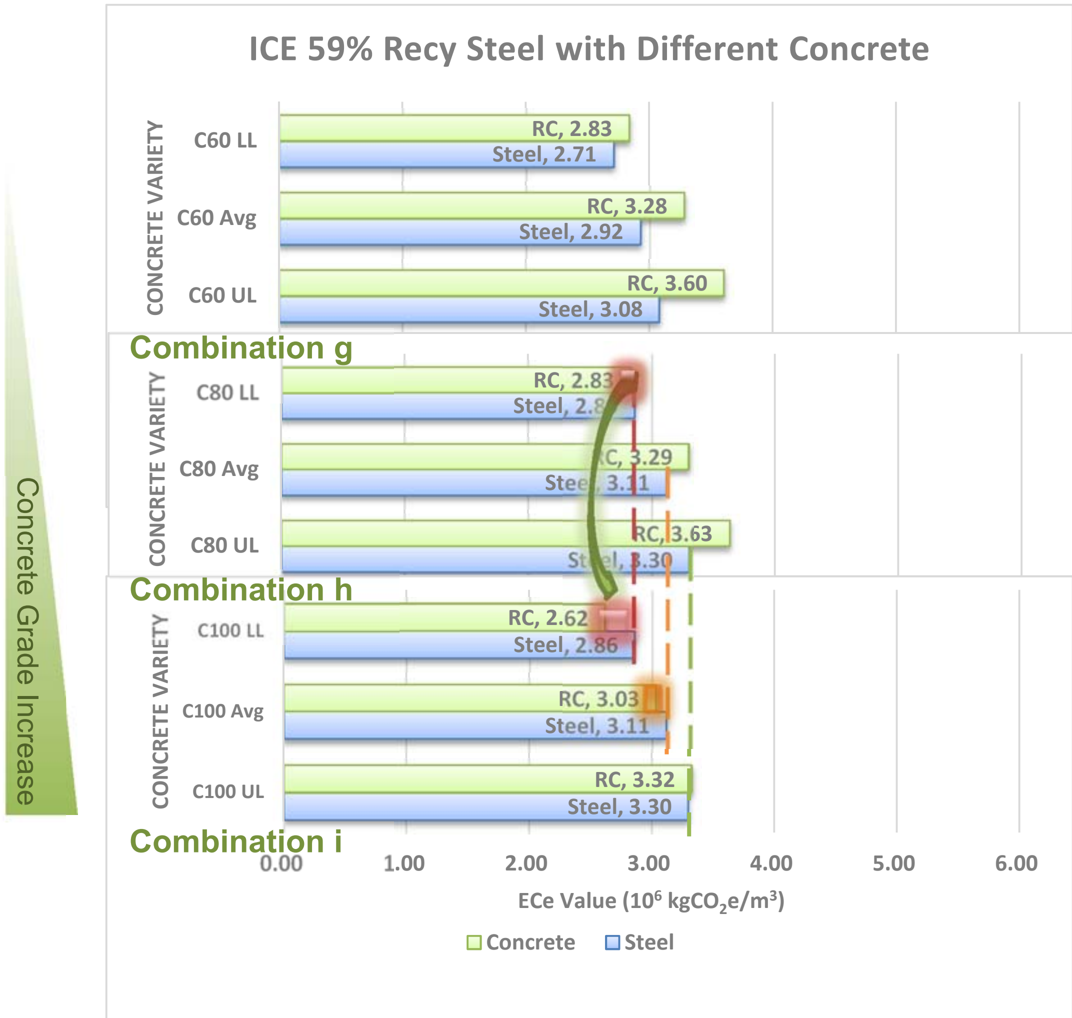


Figure 4. 5 Total Embodied Carbon Values Comparison of Steel and RC Buildings in 59% Recycled Steel (ICE) with Concrete in Different Grades: Combinations g, h & i.

4.4.4 Variable: Steel Carbon Footprint Value

Sorting the total EC values for comparisons, in this section, data were plotted into bar charts along columns in Table 4 in order to examine the effects of varying steel carbon footprint data for both Steel Building and RC Building with the same level of carbon footprint value applied to the associated concrete. Totally nine combinations could be summarized under this category.

Combination names could follow the concrete grade with different levels of CF, such as C60 Upper Limit with Different Steel could be labelled as C60_UL, the following combinations are as following, C60_Avg, C60_LL, C80_UL, C80_Avg, C80_LL, C100_UL, C100_Avg and C100_LL.

Sup Combination		Concrete Grade Series		
		C60	C80	C100
Carbon Footprint Level/Range	UL	C60_UL	C80_UL	C100_UL
	Avg	C60_Avg	C80_Avg	C100_Avg
	LL	C60_LL	C80_LL	C100_LL

Table 4. 9 Total EC Values Comparison Combinations for Steel/RC Buildings in Different Steel Recycled Level

To start the comparisons, take the C60 series combinations into consideration firstly. Figures 4.6, 4.7 & 4.8 show the total EC values with varying levels of recycled steel scrap inclusion, with different CF values applied to the different steel materials combined with each concrete grade series.

As the Recycled Content of Scrap in Steel Products Increases from 0 (virgin) to 39% and then to 59%, it could be apparently noticed from Table 4.3 that the carbon footprint values of the recycled steel products could be reduced as much as only half of the virgin ones. Therefore, as the recycled content of scrap in steel products increases, observations could be made that,

i. In Combination C60 Series, the total Embodied Carbon values of both Steel Building system and RC Building System decrease in a large scale in every concrete level combination. Due to the large decrease of the CF values for the applied steel material with more recycled content of scrap included, the contribution of the carbon footprint due to the steel material obtained a great reduction and therefore further affect the total CF values of both building system in a large scale, thereafter, resulting in the same trend applied to the total Embodied Carbon values of both Steel Building and RC Building systems in both C80 Series and C100 Series.

ii. Though the concrete material makes up the majority weights of both the Steel and RC Buildings as shown in Figure 4.2 at the beginning of this part of content, as the CF values for steel could be as large as 20-30 times of those for concrete, depending on the percentage of recycled steel scrap inclusion, the contribution of the steel material to the total CF values could not be underestimated.

iii. In all the following combinations in the Figures 4.6~4.8, lengths of arrows indicate the difference between Steel Building and RC Building systems in terms of total EC values adopting the same set of concrete and steel CF values for comparisons. Red arrows mean the total CF value of Steel Building is lower than that of the corresponding RC Building, while yellow arrows mean the total CF value of the RC Building is lower than that of the corresponding Steel Building. The one with the arrow means more environmental friendly in terms of total Embodied Carbons.

iv. In each of the nine combinations, as the recycled content of scrap in steel products increases, which is from virgin to 39% and then to 59%, it could be observed that a) the lengths of red arrows increase as in Combination C60_UL, or b) the lengths of yellow arrows decrease as in Combination C100_Avg and C100_LL, or c) the lengths of yellow arrows decrease firstly and then the arrows are switched to red with increasing lengths such as in Combination C60_LL and Combination C60_Avg. These observations could provide a conclusion that the advantage of steel building in terms of total EC increases especially with increasing recycled content of scrap in the steel products, so as the Steel Building Design would be more environmental friendly.

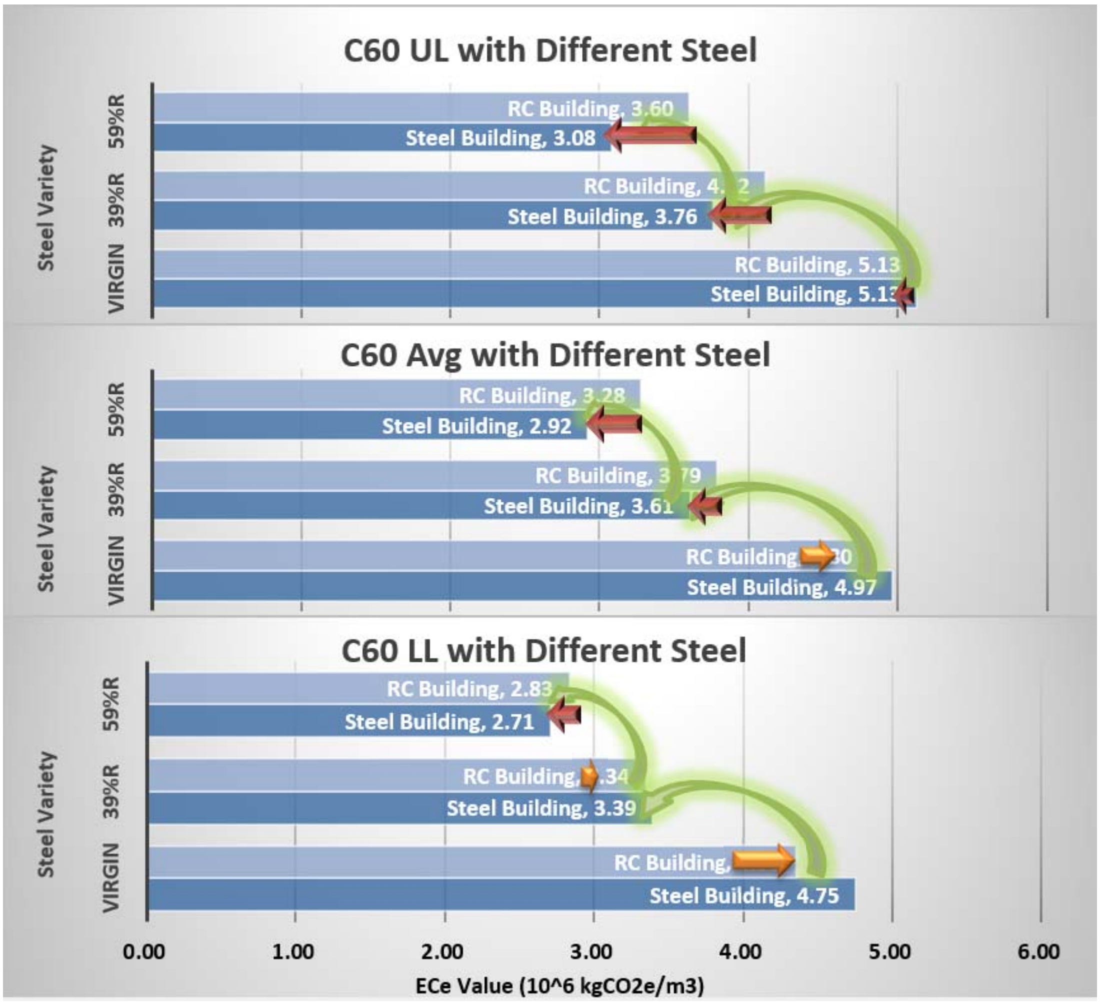


Figure 4. 6 Total Embodied Carbon Values Comparison of Steel and RC Buildings in C60 with Steel in Different Recycled Level: Combinations C60_UL, C60_Avg & C60_LL.

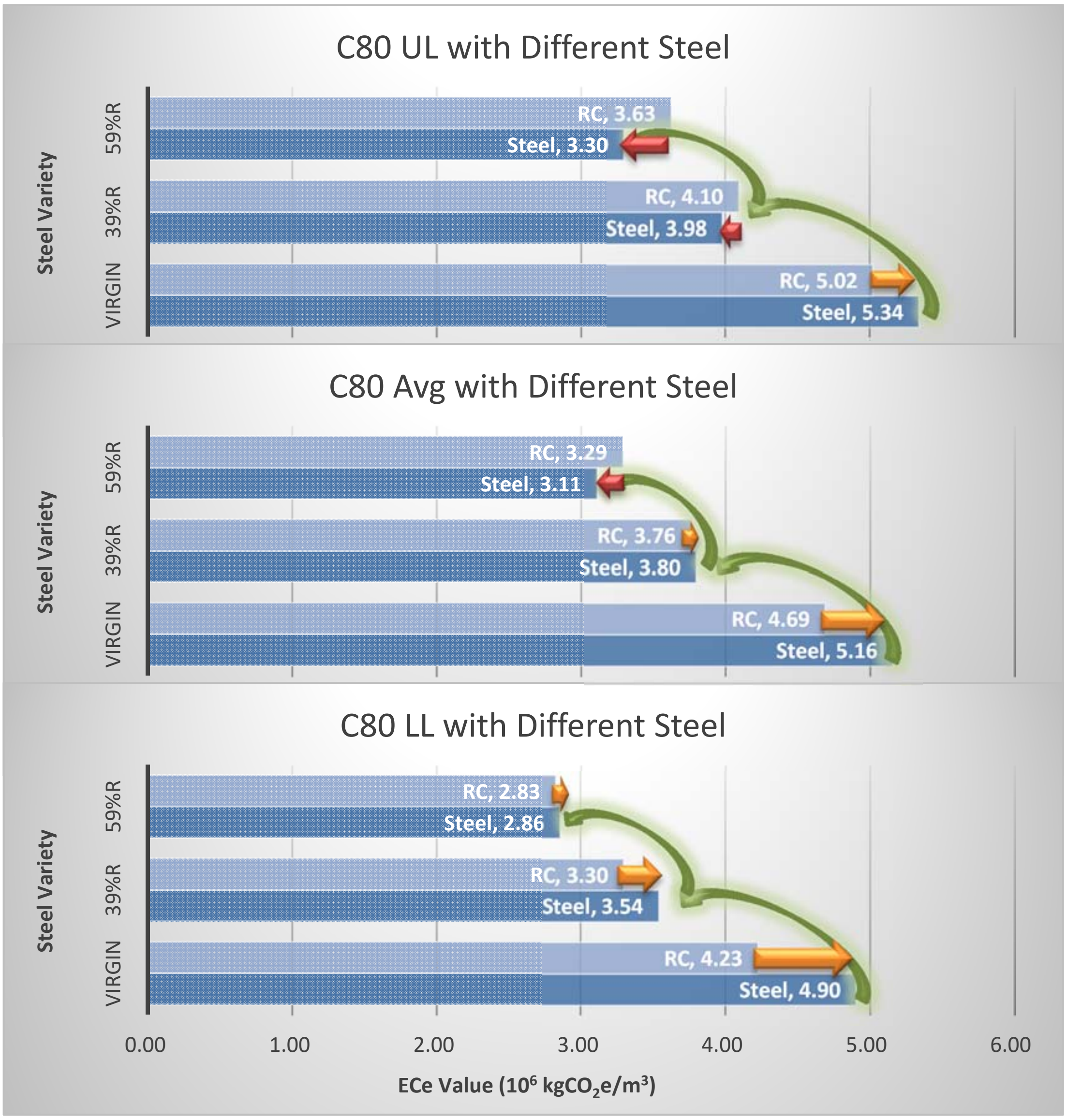


Figure 4. 7 Total Embodied Carbon Values Comparison of Steel and RC Buildings in C80 with Steel in Different Recycled Level: Combinations C80_UL, C80_Avg & C80_LL.

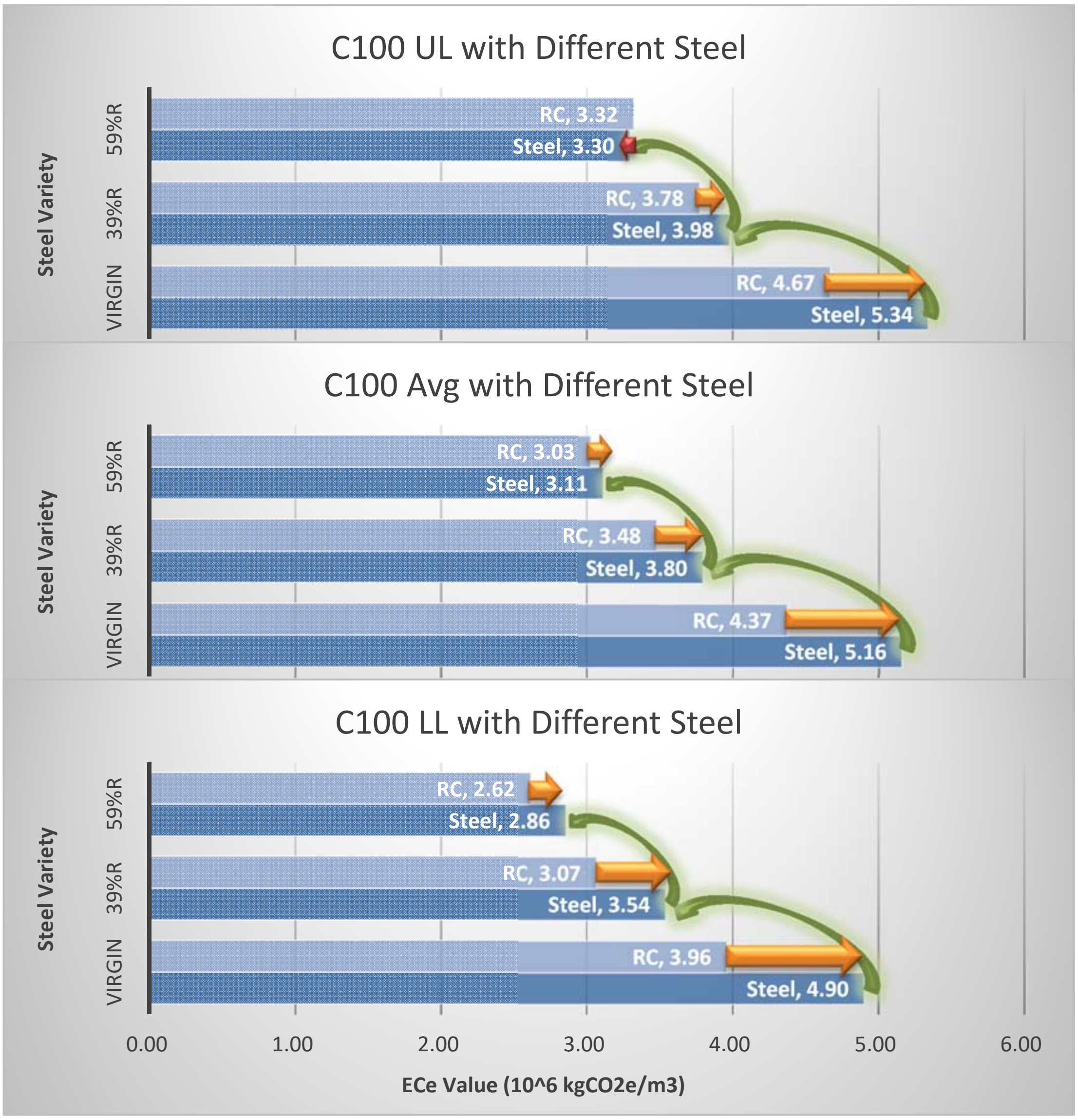


Figure 4. 8 Total Embodied Carbon Values Comparison of Steel and RC Buildings in C100 with Steel in Different Recycled Level: Combinations C100_UL, C100_Avg & C100_LL.

4.4.5 Steel Building Superstructure's Environmental Advantage Effect

The relative steel building optimization reduction rates were obtained through the following equation:

Percentage = (Total ECe Value of RC Building – Total ECe Value of Steel Building) / Total ECe Value of RC Building * 100%

Therefore, as a summary in the following Figure 4.9, when the reduction rate is positive, the corresponding pair of total ECe values of RC and Steel Buildings would be located above the x – axis as shaded in light blue, which means the steel building system is more advantageous in environmental effects in terms of Embodied Carbon equivalent values. On the other hand, when the reduction rate is negative, the corresponding pair of total ECe values of RC and Steel Buildings would be located below the x – axis as shaded in light orange, which means the RC building system is more advantageous in environmental effects in terms of Embodied Carbon equivalent values..

It could be observed from the Figure 4.9 that, the higher the grade of concrete in use, which is, the higher the embodied CF in use for the part of concrete products, the higher environmental advantage effect the steel buildings would present, especially when recycled steel is in use associated with higher grade of concrete. Therefore, this could be concluded as when the concrete CF data applied increases, the steel nonlinear optimization creates better design solution in terms of environmental performance.

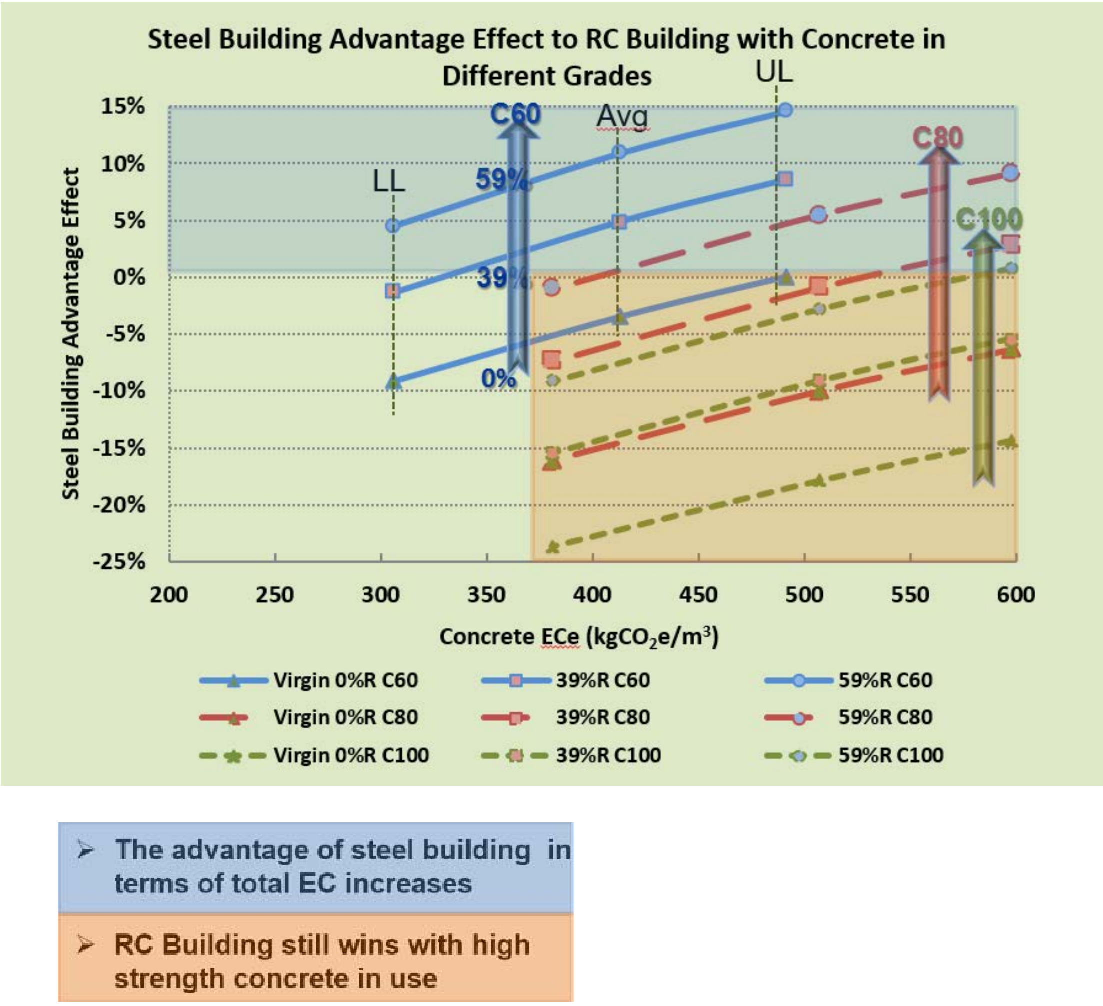


Figure 4. 9 The Steel Building optimization reduction rates: Relative Total EC Reduction of Steel Building with Respect to RC Building for concrete in C60, C80 and C100.

Furthermore, as the recycled content of scrap in steel products increases, more results would be located within the blue shade, so that the advantage of steel buildings in terms of total ECe values increases.

However, with high grade concrete products used as the major building system component, almost all resulting reduction rates would located within the orange shade, indicating that the RC Building's advantage still overtake that of the steel buildings even when very high percentage of recycled steel scrap were included for application in terms of the total Embodied Carbon equivalent value. Buildings still win with high strength concrete.

4.4.6 Effect of Recycled Steel Content Inclusion

In real application, it is not practical to use recycled steel in the whole building structure due to size limitation of recycled steel products available and also as required in the Hong Kong local construction market. For example, in Hong Kong, the size limit of recycled steel section could be adopted is UKB305, so for steel beams and columns sized above UKB305, virgin steel sections should be applied strictly. The combinations of different steel materials with various recycled rates together with the absolute virgin, absolute 39% recycled steel and the absolute 59% recycled steel solutions, constitute a recycled steel inclusion rate scale as shown along the y-axis in the following Figures 4.10~4.12. From top to bottom along the y-axis, the combinations range from the most available recycled steel inclusion 59% to absolutely virgin steel with 0%. The steel products adopted in the whole building system include steel sections and steel rebars, so the different combinations can be referred from the following illustrations:

Combinations	Steel Section > 305	Steel Section ≤ 305	Steel Rebar	Total Recycled Steel Inclusion
VS59S&59B	Virgin	59%	59%	33%
VS59S&VB	Virgin	59%	Virgin	11%
VS39S&39B	Virgin	39%	39%	22%
VS39S&VB	Virgin	39%	Virgin	7%

Table 4. 10 Total Recycled Steel Inclusion Rates for Different Steel Material Combinations for Buildings' Superstructures.

The resulting bar charts below clearly summarized the comparisons of the total EC of all buildings with the same concrete carbon footprint, as the recycled content of scrap in steel products increases, the total EC value decreases in a similar manner.

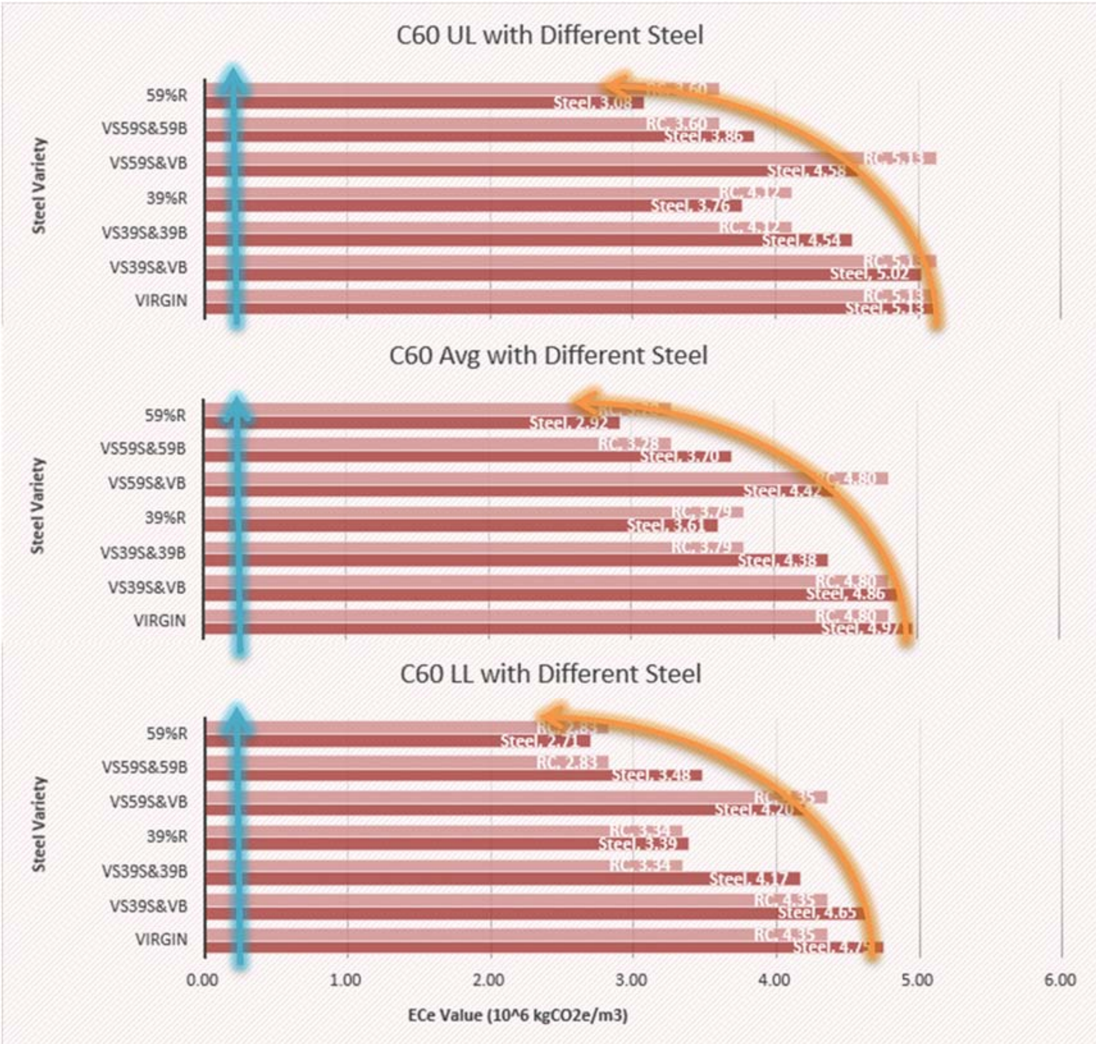


Figure 4. 10 Total Embodied Carbon Values Comparison of Steel and RC Buildings in C60 with Steel Materials in Various Recycled Steel Inclusion Scale

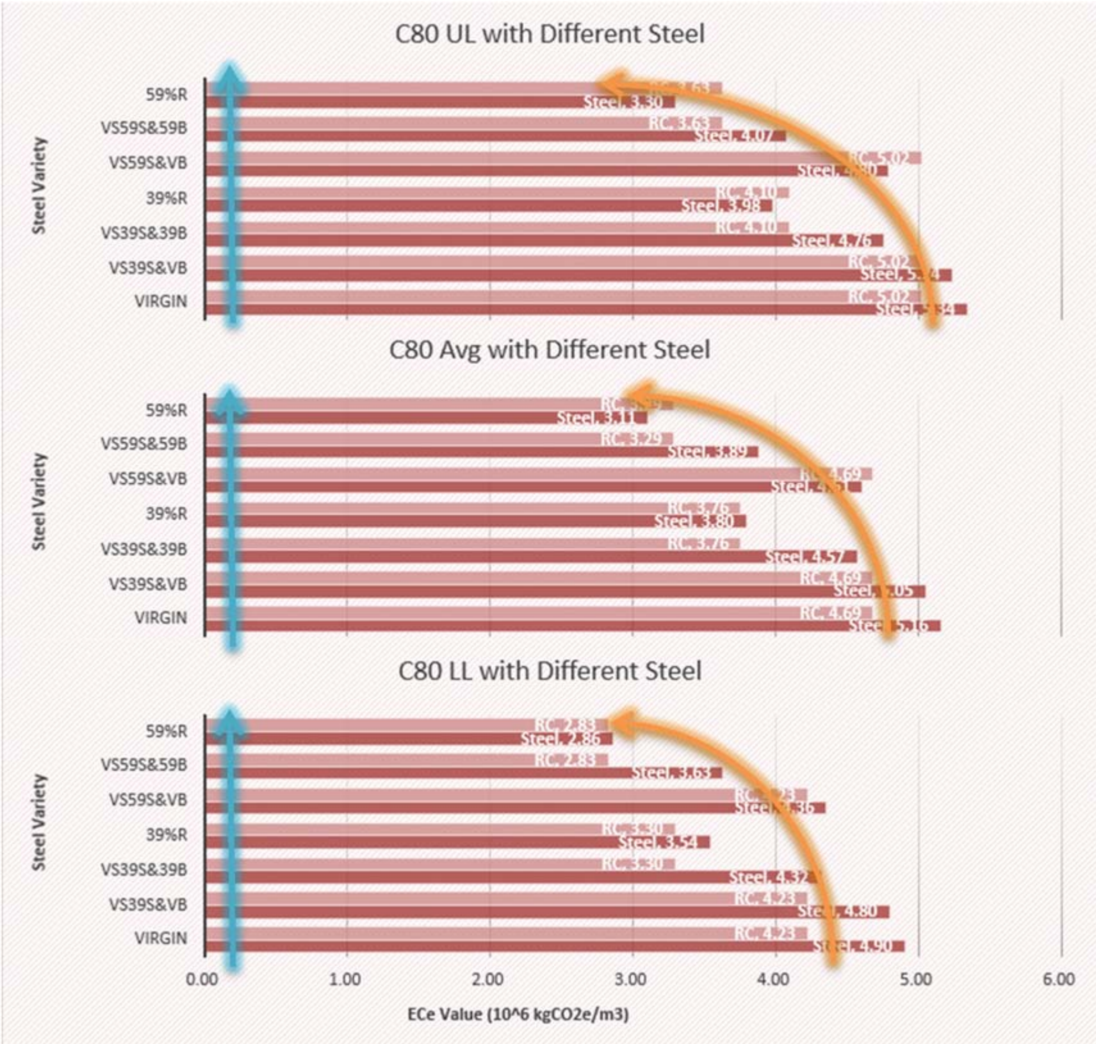


Figure 4. 11 Total Embodied Carbon Values Comparison of Steel and RC Buildings in C80 with Steel Materials in Various Recycled Steel Inclusion Scale

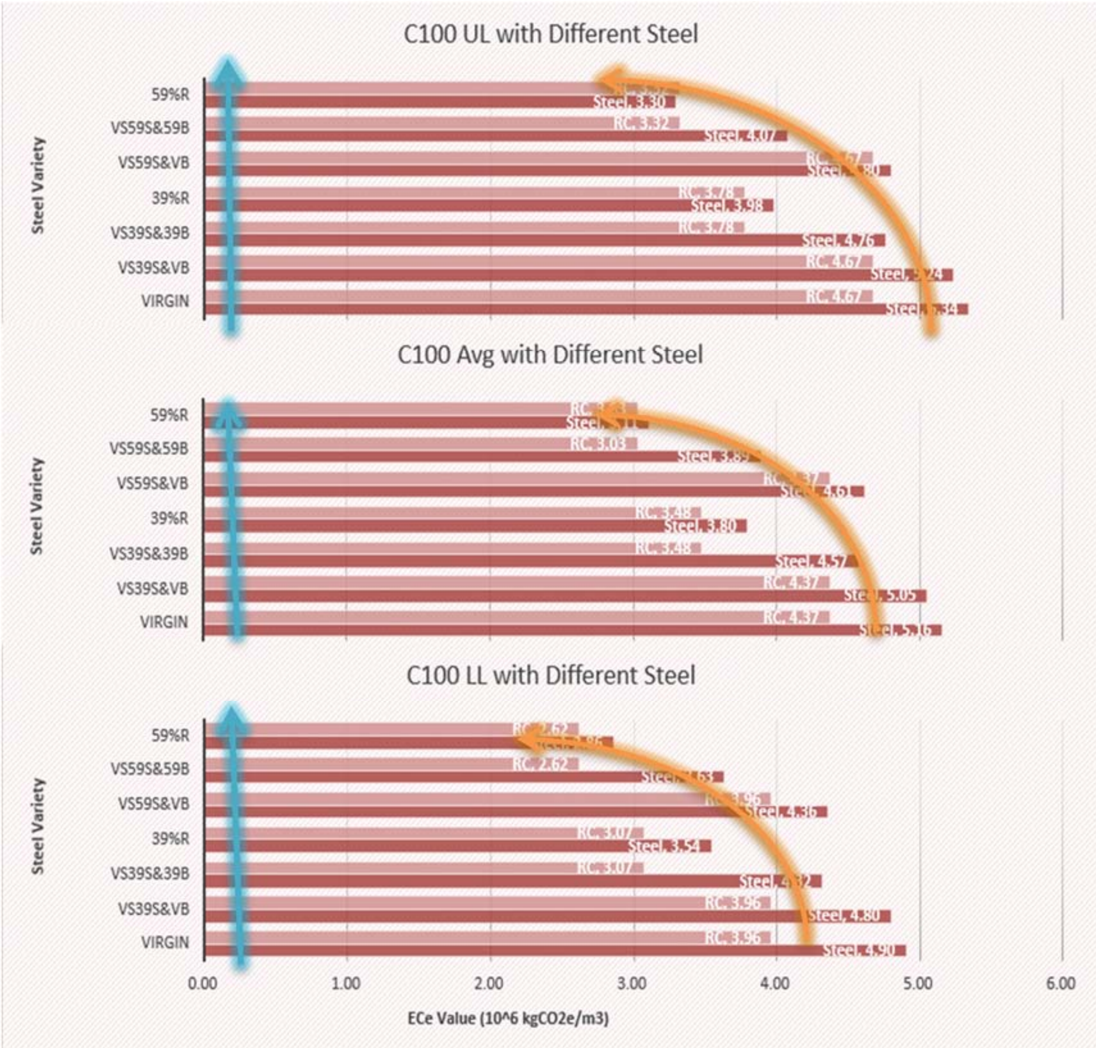


Figure 4. 12 Total Embodied Carbon Values Comparison of Steel and RC Buildings in C100 with Steel Materials in Various Recycled Scale

Plot the above mentioned total ECe values in the following Figures 4.13 (a)~(d). Figure 4.13(a) provides a summary of all the total ECe values of both building schemes designed with different concrete carbon footprint values. For concrete in different grades applied in the design, the average carbon footprint values for concrete product in each grade was selected to provide an overview of this set of comparison. As concluded above in this part, the more recycled material used, the more environmental friendly the design would be. However, due to the product availability and size limitation in the certain construction material market, it is not practical to have all the products in application to be composed of fully recycled materials for the whole building system. Therefore, for certain concrete strength adopted, it would be very well deserved to explore the percentage of the recycled steel accounting for in the overall steel consumption so as to examine the relative environmental advantage of either the Steel Building Scheme or the RC Building Scheme in terms of lower total carbon emissions.

In Figure 4.13(b)~(d), trendlines were added to each set of total ECe results for both building schemes.

In Figure 4.13(b), an interception was noticed at around 28% at x-axis, which means that RC Building generates lower environmental impacts than Steel Building when low carbon footprint (low grade) concrete is used with recycled scrap rate of steel under 28%, otherwise, Steel Building generates lower environmental impacts when low carbon footprint (low grade) concrete is used with more than 28% recycled steel applied in the design.

In Figure 4.13(c), the trendlines' interception was increased from 28% to around 52% at x-axis, which means that when the concrete grade was risen from C60 to C80, the recycled steel scrap rate should reach as high as 52% to make the Steel Building generate lower environmental impacts than the RC Building.

In Figure 4.13(d), no interception was found in the two trendlines within the given percentage range of the recycled steel scrap rates, but it could be deduced from the line trends that the interception would possibly lie around 65%-70%. As the carbon footprint value of concrete increases to C100, i.e. high strength concrete is used, Steel Building could hardly win RC Building in terms of environmental friendly since very high percentage of recycled steel is required for application together with very high strength concrete, which can barely be satisfied given the practical market availability, indicating the absolute environmental advantage of the high strength RC Building over the steel design option. From Table 4.2, though the carbon footprint value of C100 concrete increased in a large scale compared with that of C60 concrete, these carbon footprint values would still be not comparable to those of steel products.

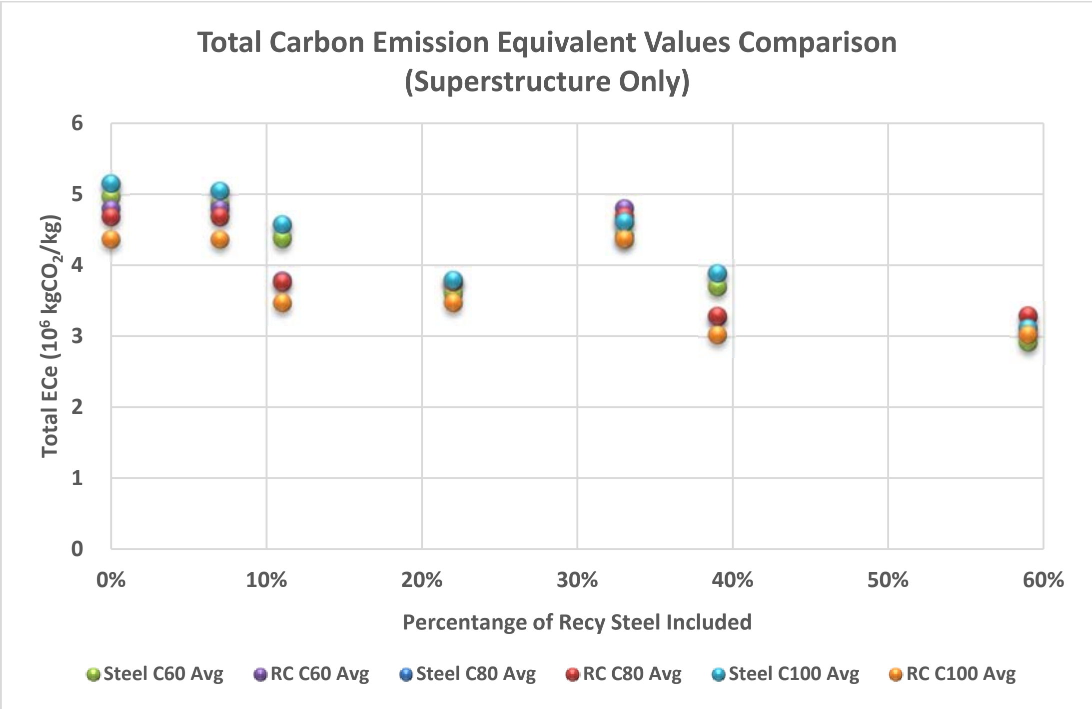


Figure 4. 13 Superstructure Total Carbon Emission Equivalent Values Comparison

(a) Summary

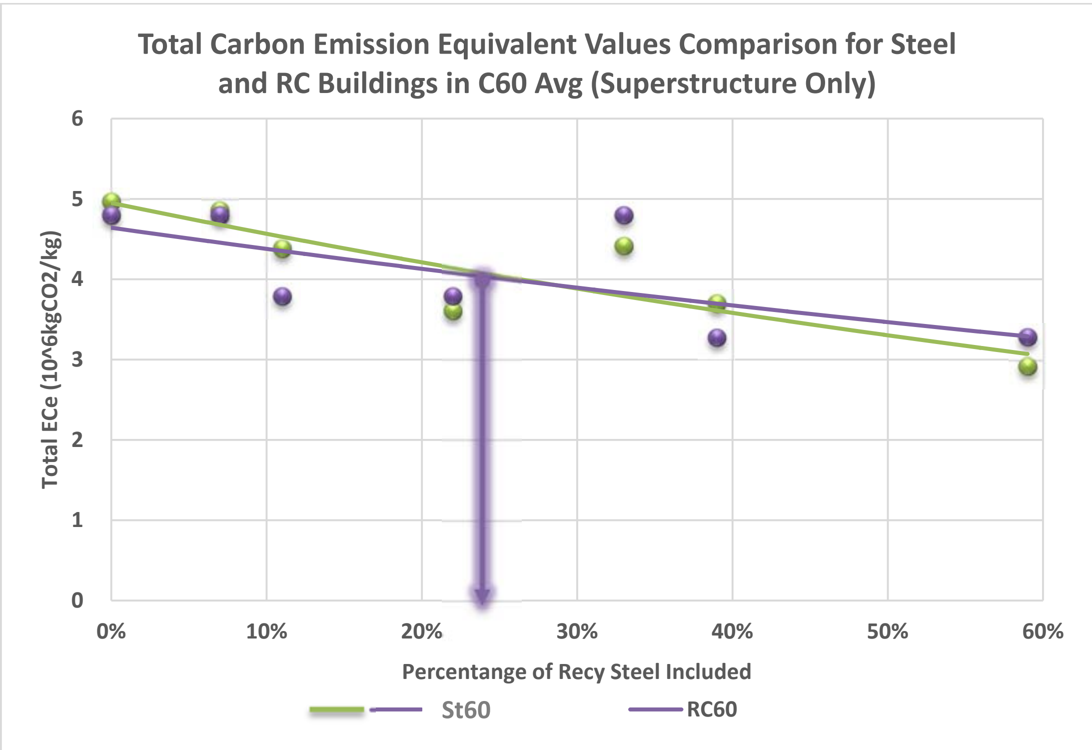


Figure 4. 14 (b) Steel and RC Buildings in C60 Avg

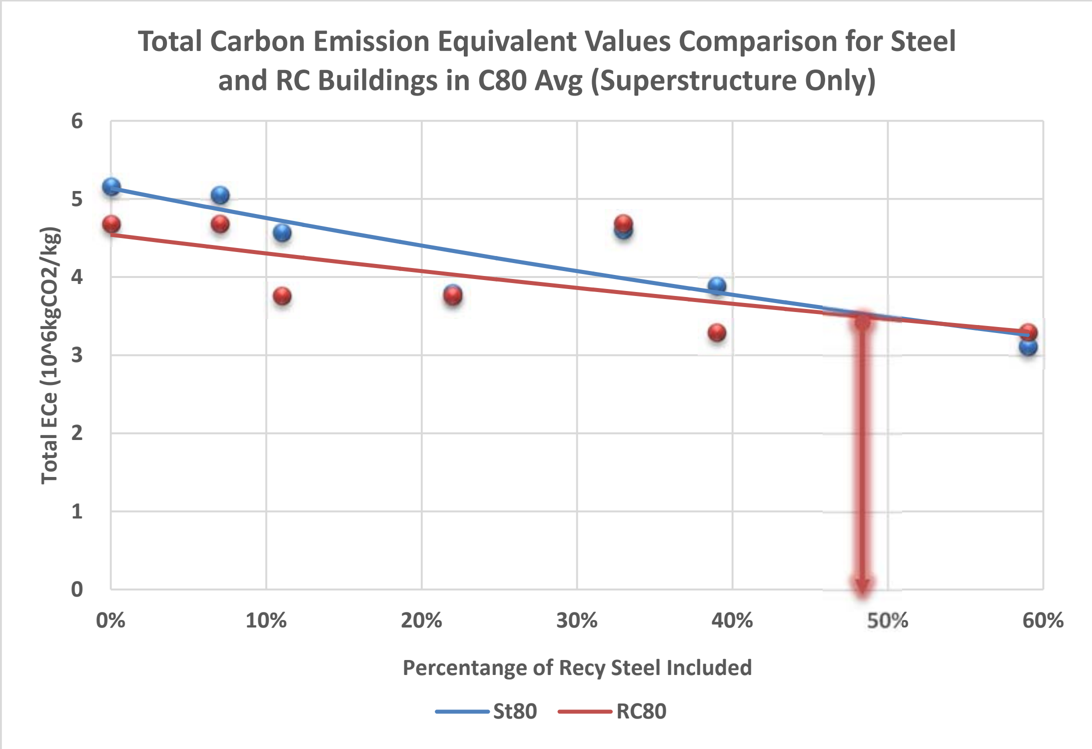


Figure 4. 15 (c) Steel and RC Buildings in C80 Avg

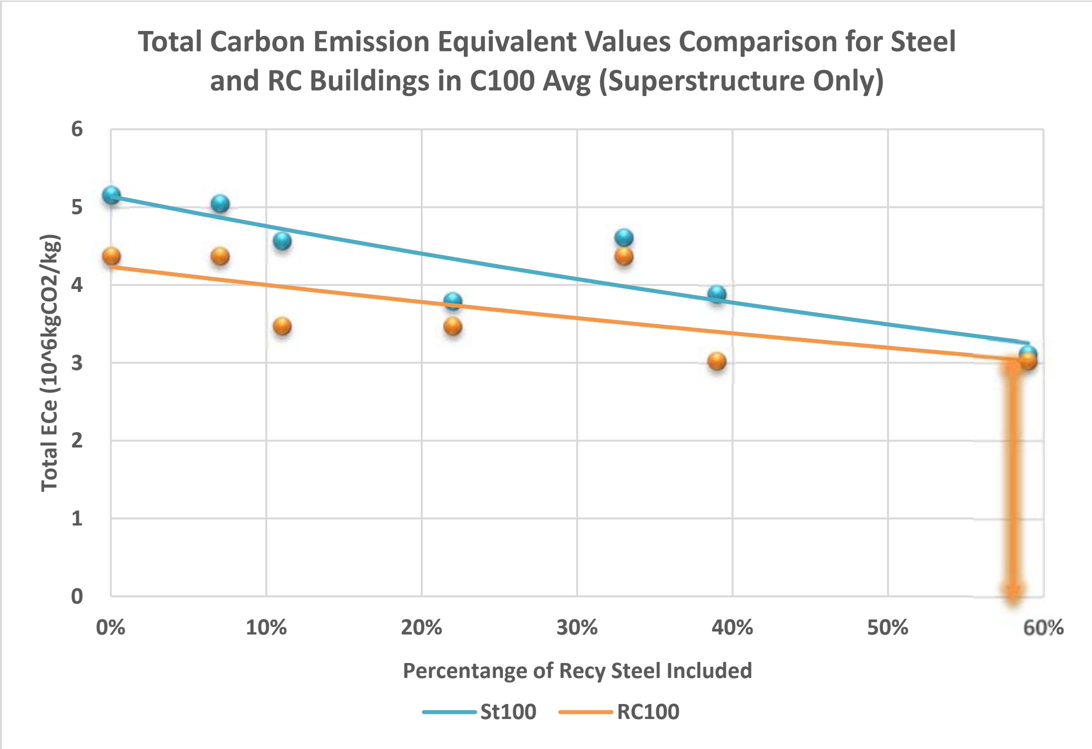


Figure 4. 16 (d) Steel and RC Buildings in C100 Avg

4.5. Concluding remarks

As a conclusion of the above observations, the higher the concrete strength in use in the RC structural design, the more recycled steel scrap is required in the steel design option to make their environmental impacts competitive for these kind of mid-rise commercial buildings designed in Hong Kong construction market, with only superstructure part taken into account for analysis or for buildings built upon existing underground foundation.

CHAPTER 5

EMBODIED CARBON COMPARISON OF CONCRETE/STEEL – BUILDING STRUCTURES (SUPERSTRUCTURE+UNDERGROUND) USING NONLINEAR OPTIMIZATION

In the previous Chapter 4, the environmental impact evaluation method has already been scientifically proved, and further in this chapter, the environmental performance of different structural design methods, in different design configurations and different materials was conducted using a superstructure design of a mid-rise commercial building satisfying the Hong Kong structural design codes, using ICE steel and concrete carbon footprint values for the consistency of comparison analysis.

This section would serve as a supplement to the previous study on the mid-rise Hong Kong based commercial building's superstructure only. In the following content, a underground foundation was assumed to be designed under the above designed Steel Building and RC Building superstructures. To take all parts of the building structure into consideration, a further relationship would be expected between material consumption, structural design optimization, selection and use of low caron material, together with the buildings' total carbon footprint including both superstructure and foundation.

5.1. Summary of Building Models

The same set of building models were selected as those in Figure 3.12 and Figure 4.1. This is a 25-storey model modified from a real commercial building originally designed and constructed in Hong Kong Island. The building's plan area was designed to be 27.69m by 23.26m for each storey, with the total height of the whole building to be 97.6 metres.

Both steel building superstructure scheme and reinforced concrete building superstructure scheme have been carried out to simultaneously fulfil the Ultimate Limit States and Serviceability Limit States specified according to Hong Kong Steel Code 2011 [38]. Both steel building underground scheme and RC building underground scheme have been carried out to fulfil the Hong Kong Code of Practice for Foundations 2004 [36]. Foundation condition in Hong Kong underground may vary in a large range. Presumed allowable bearing pressure was taken as 5000kPa in Grade III. An average column depth was assumed to apply in this underground condition, with safety factor taken to be 2 to 3.

The steel building solution was conducted by nonlinear analysis to achieve the best structural efficiency, including beams and columns made of steel and core walls made of concrete. On the other hand, the RC building solution done by linear analysis only designed with RC beams, RC columns and concrete core walls. Both structures were optimized to have the top total displacement over total height ratio approaching 1/500 as much as possible, so as to make the two design solutions comparable since the best structural efficiency was achieved with fairly closed reaction behaviour under the same vertical and horizontal loading circumstances.

The building model was firstly designed in a steel structural frame ("Steel Building") consisting of steel beams and steel columns all in steel grade of S355 coupled with RC structural core walls. Lateral stiffness is provided by RC structural core walls to resist wind actions. Vertical actions including self-weight, super-imposed dead load, live load, etc., are resisted by steel beams through which are further transferred to the steel columns down to the ground. Superstructure columns are supported by foundation column piles while core walls are located on rafts supported by four corner piles.

On the other hand, in the second scheme, the building model was designed to be a reinforced concrete structure ("RC Building") consisting of RC beams, RC columns coupled by concrete core walls. Lateral stiffness is provided by RC core-walls to resist wind actions. Vertical actions including self-weight, super-imposed dead load, live load, etc., are resisted by RC beams supported by RC columns and RC walls and downward to the ground. Superstructure columns are supported by foundation column piles while core walls are located on rafts supported by four corner piles.

With all the steel sections used in the Steel Building and reinforcements applied in both Steel and RC Buildings to be of Grade S355, the grade of concrete adopted for analysis and comparison vary from C60, C80 to C100 with the steel bar in various recycled rates, including virgin steel bar, 39% recycled scrap included or 59% recycled scrap included according to the carbon footprint data provided by ICE Version 2.0 [35], which have been detailed in section 4.3.

This preliminary appraisal assesses the structural behaviour of the building under dead, imposed and wind actions, as well as the effects due to temperature variation by direct analysis approach. All relevant loadings are considered to be applied either in individual or in such realistic combinations as to comprise the most critical effects on all the structural elements and the structure as a whole. No tension was found in underground foundation after analysis. The ultimate limit safety state and serviceability limit state cases are analysed to capture the fundamental requirements for the reliability of construction works.

5.2. Total EC Accumulation

The total EC accumulation of both the superstructure and underground parts of the Steel and RC Buildings was performed using the same set of carbon footprint values as those detailed in section 4.3. The results obtained from the linear or nonlinear analysis were collected, interpreted and compared in terms of both design schemes. Referring to the above databases, total carbon footprint is contributed by the accumulation of all the construction materials' carbon footprints. In the Steel Building, all the loadings are supported by steel members with structural walls taking action, while in the RC Building, the system consists of RC beams and RC columns with concrete core walls. Underground structures are made up of reinforced concrete piles and rafts. From a system level, the total carbon footprints should include all the structural elements of the building system. Therefore, to make the two design schemes comparable, the range of structural elements included will be as shown below.

Variations	Steel Building	RC Building
Elements	steel beams steel columns Concrete Core Walls Steel Rebars RC Column Piles RC Rafts RC Corner Piles	RC beams RC columns Concrete core-walls Steel Rebars RC Column Piles RC Rafts RC Corner Piles
Materials	Core walls, Foundation Piles and Rafts in C60, C80 and C100; Steel Sections / Bars in Virgin, 39% recycled scrap, 59% recycled scraps	Beams, Columns, Core walls, Foundation Piles and Rafts in C60, C80 and C100; Steel Bars in Virgin, 39% recycled scrap, 59% recycled scraps

Table 5. 1 Structural Elements Included in Calculation for Commercial Steel and RC Buildings' Superstructure

5.3. Results Discussion

The relative advantages of Steel Building or RC Building are to be examined by comparing the environmental effects of the accumulation of all structural elements supporting the horizontal loadings and vertical loadings. Specifically in this section, as the comparisons are to be conducted to the Steel Building and RC Building superstructures together with the supporting underground foundations. Therefore, it is expected to examine how much could be saved in material used and total embodied carbon (EC) with different materials included for application with the foundation taken into account.

5.3.1. Total Weights of the Models' Superstructures and Foundations (Sup+F)

The total Sup+F weights of the Steel Building and RC Buildings in C60, C80 and C100 have been listed in the following Table 5.2 and plotted in Figure 5.1. With the inclusion of the buildings' foundations, the total weight of Steel Building is over 60 percent of that of RC Building in C60, while one fourth less of that of RC Building in C100 with high strength concrete adopted. As indicated in Section 4.4.1, the nonlinear optimized Steel Building Scheme has already achieve a great level of decrease in material consumption in the superstructure, while in this section, the inclusion of the underground construction exhibited more material and cost reduction in total under this scheme. Details of the weights of different models would be shown in the following Table 5.2 and Figure 5.1.

Weight (kN)	Steel Building	RC Building in C60	RC Building in C80	RC Building in C100
Section	8654	0	0	0
Concrete	79178	136431	123443	112367
Bar	7808	14096	13094	12634
Total	**95640**	**150527**	**136538**	**125002**

Table 5. 2 Superstructure and Underground (Sup+F) Total Weights for Steel and RC Buildings in Different Concrete Grades

Figure 5. 1 Superstructure and Underground (Sup+F) Total Weights for Steel and RC Buildings in Different Concrete Grades

5.3.2. Total Embodied Carbon

Based on the CFPs in Table 4.2 & 4.3, total carbon footprints of the Steel Building and the RC Building encompassing both superstructures and foundations have been calculated for all material combinations, in the unit of 10^6kgCO_2e according to ICE database in Table 5.3.

Steel Building	C60 UL	C60 Avg	C60 LL	C80 UL	C80 Avg	C80 LL	C100 UL	C100 Avg	C100 LL
	Unit: $10^6 kgCO_2e$								
Virgin	**6.53**	**6.27**	**5.91**	**6.89**	**6.58**	**6.16**	**6.89**	**6.58**	**6.16**
39%R	**4.92**	**4.66**	**4.30**	**5.28**	**4.98**	**4.55**	**5.28**	**4.98**	**4.55**
59%R	**4.12**	**3.85**	**3.49**	**4.48**	**4.17**	**3.75**	**4.48**	**4.17**	**3.75**
RC Building	**C60 UL**	**C60 Avg**	**C60 LL**	**C80 UL**	**C80 Avg**	**C80 LL**	**C100 UL**	**C100 Avg**	**C100 LL**
	Unit: $10^6 kgCO_2e$								
Virgin	**6.83**	**6.38**	**5.76**	**6.83**	**6.36**	**5.70**	**6.42**	**5.99**	**5.39**
39%R	**5.52**	**5.07**	**4.45**	**5.62**	**5.14**	**4.48**	**5.25**	**4.82**	**4.22**
59%R	**4.86**	**4.41**	**3.79**	**5.01**	**4.53**	**3.87**	**4.66**	**4.22**	**3.62**

Table 5. 3 Total Embodied Carbon Values Associated with Different Materials (Sup+F)

5.3.3. Variable: Concrete Carbon Footprint Value

Sorting the total EC values for comparisons as those in the previous Section 4.4.3, data were plotted into bar charts along rows in order to examine the effect of varying concrete carbon footprint data for both Steel Building and RC Building with the same steel recycled contents included. Totally nine combinations could be summarized under this category

Combination		Steel Recycled Level		
		Virgin	39% R	59% R
Concrete Grade	C60	a’	d’	g’
	C80	b’	e’	h’
	C100	c’	f’	i’

Table 5. 4 Total EC Values Comparison Combinations for Steel/RC Buildings with Foundation in Different Concrete Grades

Extracting Combinations a’, b’ and c’ for comparison, the following Figure 5.2 a’, b’ & c’ show the total Sup+F EC values with varying concrete grade, as well as different CF data level applied under each concrete grade series.

As the Concrete Grade increases, observations could be made that,

i. From the trend of decrease of bar lengths according to the sequence of Combination a’ to b’ and then to c’, total Embodied Carbons of the RC Building Sup+F would decrease generally according to the increase of concrete grade, while those of the Steel Building Sup+F would increase generally according to the increase of the concrete grade. However, the total Embodied Carbon values of the Steel Building Sup+F from Combination b’ and c’ keep identical as the reason of same RC elements designed to Steel Building Sup+F models with the only difference lying in concrete material grades. As strength increase at very high concrete grade level was achieved mainly due to the chemical additives, the carbon footprint values of super high strength concrete will not be increased along with the material strength increase but tending to be steady. Therefore, the same set of carbon footprint values of C80 and C100 result in the same total Embodied Carbon values for the Steel Building Sup+F models in C80 and C100 according to the bar charts in Combination b’ and c’.

ii. The relative difference in terms of the total embodied carbon values of the entire building systems achieved by using Steel Building Sup+F Scheme compared with the corresponding RC Building Sup+F Scheme have been presented in the following Figure 5.2 as well. The differences are labelled in red, orange and green bars for concrete grade values according to the upper limit, average and lower limit values.

iii. Different from the observation in Section 4.4.3 iii, the total Steel Buildings Sup+F EC values becomes lower than those for RC Buildings Sup+F when Concrete was in Grade C60 Avg and C60 UL. In the C80 and C100 concrete grades, the total EC values difference between steel and RC buildings Sup+F decrease as the concrete value level increases within the same concrete grade range. The same reason applied to C80 and C100 sets of comparisons as for all in Section 4.4.3 iii, as the concrete value level decreases, the embodied carbon footprint value of concrete decreases accordingly and then the accumulation of the total embodied carbon would decrease apparently, resulting in the increase in the total EC values difference. As for the same set of concrete grade comparison, the different levels of concrete grade values apply to the same set of designs for Steel and RC buildings Sup+F together. The contribution of concrete to the total EC value of the Steel Building is no longer incomparable minor compared to steel as the great contribution due to the underground RC rafts and piles. As the total weights of the underground structures usually two to three times of those from only superstructure parts, therefore, the giant contribution of the underground RC elements could no longer be underestimated while the heavier the superstructure elements weight, the greater the underground RC elements' contribution would be to the total EC values of the whole Sup+F systems. Thus due to this big underground contribution for low grade concrete applied, the lower the concrete grade be, the heavier the total superstructure weight, there caused the C60 low grade RC Buildings Sup+F generate more total EC than corresponding Steel Ones Sup+F with C60 Avg and UL material carbon footprint levels apply.

iv. Taking total EC values in different concrete grades but all in the same value levels, i.e. Grade C60, C80 and C100 all using Upper Limit values, labelled in red, as a set of comparison. As the concrete grade increases for Sup+F structures, the concrete carbon footprint increases, but the member size decreases in a large scale, so the material consumption decreases. In the Steel Building, though the total concrete consumption weights become neglected, effect of concrete consumption decrease becomes noticeable compared with the carbon footprint increase, thereafter the total EC values increases in a larger scale as the concrete grade increases compared with the results for superstructures only. However, in terms of the RC Building, the concrete contribution almost determines the total EC value trends and the total weights difference become more significant if underground elements were taken into consideration, so the effect of large material save overweighs that of the concrete carbon footprint value increase, so the total EC value of the RC Building decreases more rapidly as the concrete grade increases, and finally resulting in the difference increase more obviously between the RC building and the Steel Building in terms of the total EC values calculated.

v. The above trend iv applies to the comparison sets with Grade C60, C80 and C100 concrete all using average carbon footprint values or all using Lower Limit carbon footprint values, with the Steel to RC Buildings Sup+F total Difference increase in a larger range from negative to positive since the total Steel Building Sup+F EC values for the C60 Avg and UL cases are lower than those for the corresponding RC Building Sup+F.

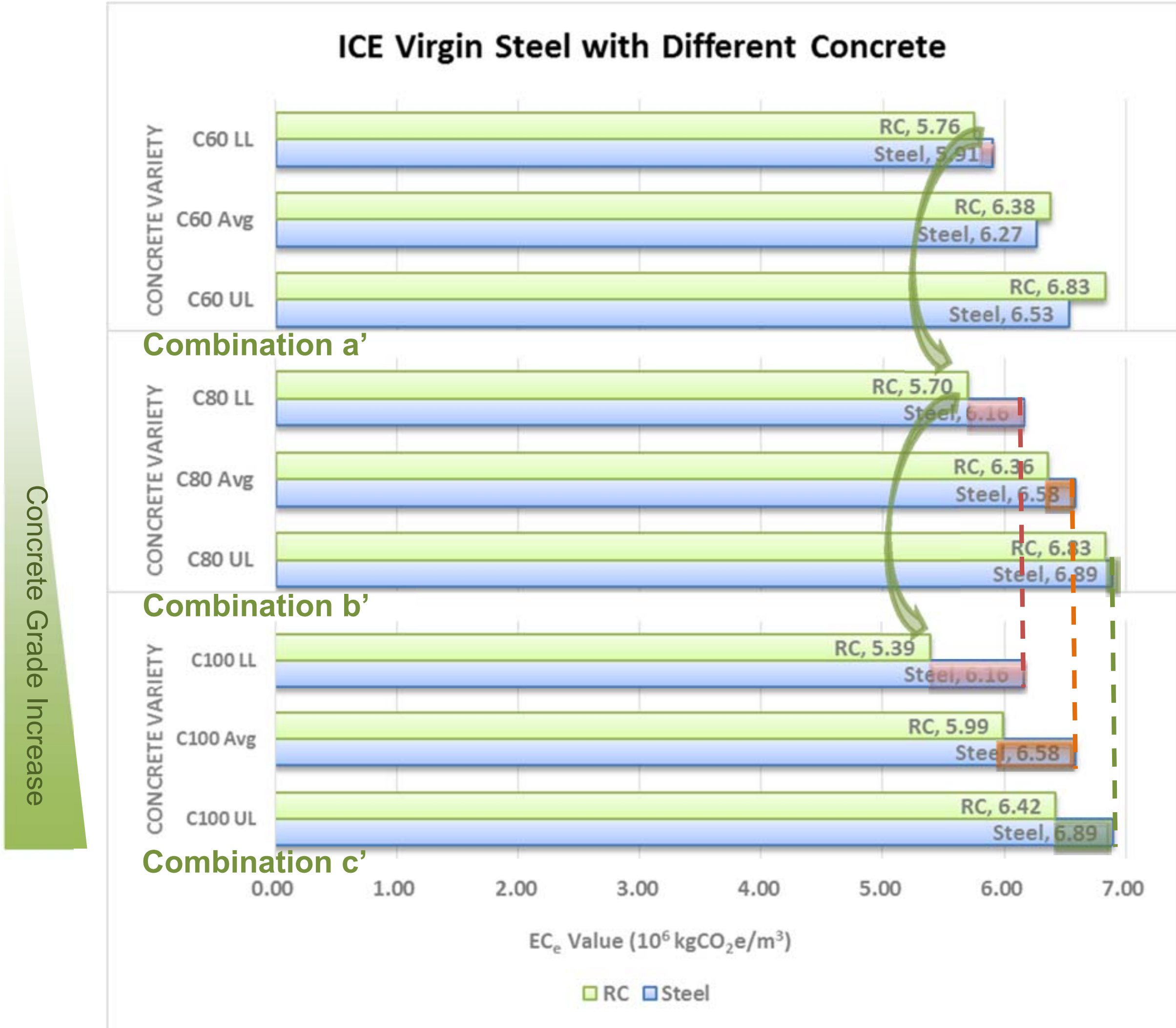


Figure 5. 2 Total Embodied Carbon Values Comparison of Steel and RC Buildings with Foundation in Virgin Steel with Concrete in Different Grades: Combinations a', b' & c'.

vi. The above summarized results i ~ v apply not only to the Steel Building Sup+F and the RC Building Sup+F models using ICE virgin steel carbon footprint values, i.e. Combinations a', b' & c', but also to the models using ICE carbon footprint values with different levels of recycled steel scrap, i.e. Combinations d', e' & f' for steel with 39% recycled scrap, as well as, Combinations g', h' & I' for steel with 59% recycled scrap. The results are listed in the following Figure 5.3 & 5.4 where the above mentioned trends could be mostly examined accordingly. A noticeable difference to be mentioned here is that due to the large contribution of RC elements to the total EC values for both Steel and RC Building models with foundation taken into considerations, the environmental advantages of Steel Buildings Sup+F become more significant if more and more recycled steel scrap could be included in the construction materials.

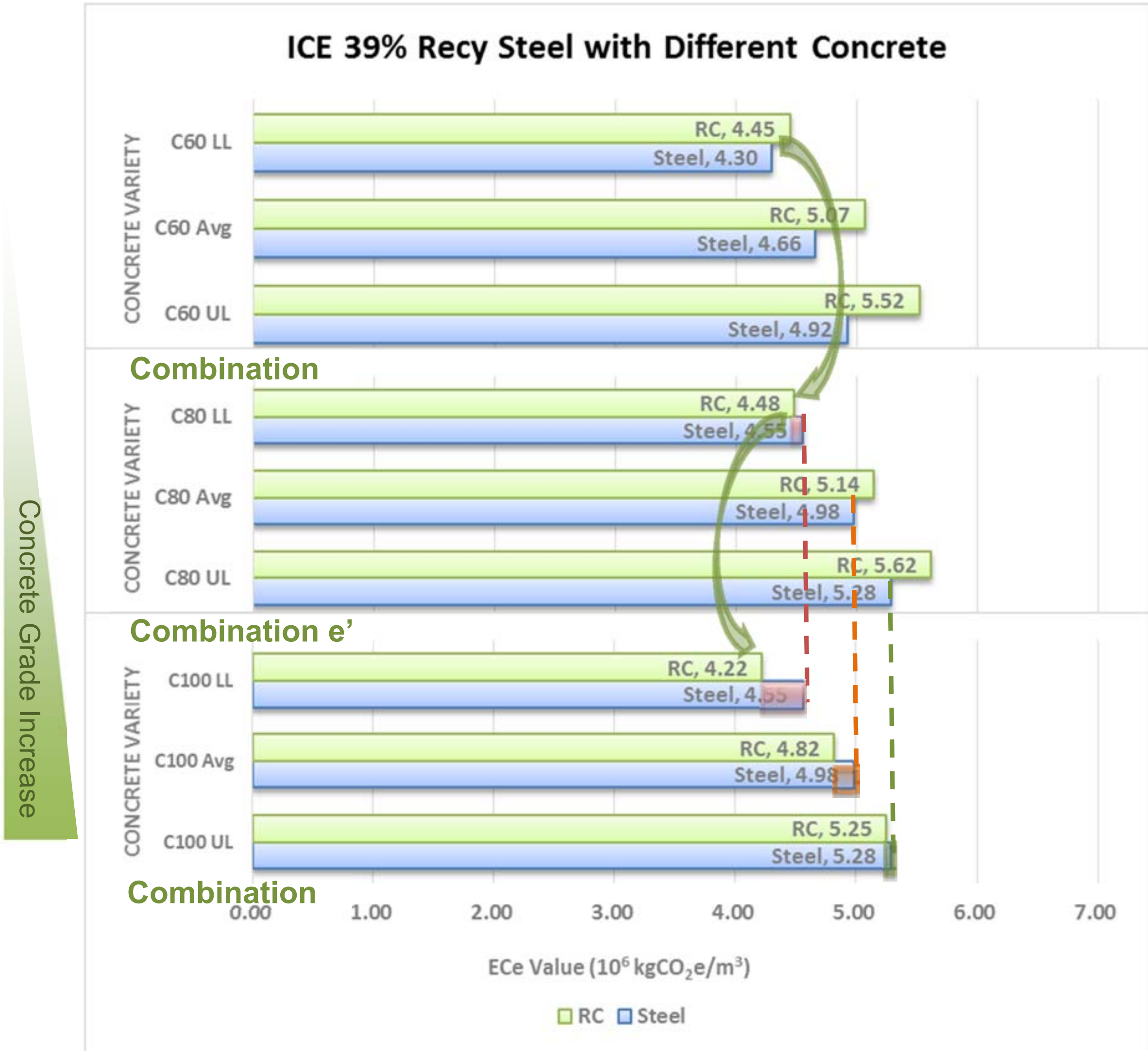


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Figure 5. 3 Total Embodied Carbon Values Comparison of Steel and RC Buildings with Foundation in 39% Recycled Steel (ICE) with Concrete in Different Grades: Combinations d', e' & f'

Figure 5. 4 Total Embodied Carbon Values Comparison of Steel and RC Buildings with Foundation in 59% Recycled Steel (ICE) with Concrete in Different Grades: Combinations g', h' & I'.

5.3.4. Variable: Steel Carbon Footprint Value

Sorting the total EC values for comparisons, in this section, data were plotted into bar charts along columns in Table 5.4 in order to examine the effects of varying steel carbon footprint data for both Steel Building Sup+F and RC Building Sup+F with the same level of carbon footprint value applied to the associated concrete. The same set of nine combinations could be applied in this category as well.

Combination names could follow the concrete grade with different levels of CF, such as C60 Upper Limit with Different Steel could be labelled as C60_UL, the following combinations are as following, C60_Avg, C60_LL, C80_UL, C80_Avg, C80_LL, C100_UL, C100_Avg and C100_LL.

Sup+F Combinations		Concrete Grade Series		
		C60	C80	C100
Carbon Footprint Level/Range	UL	C60_UL	C80_UL	C100_UL
	Avg	C60_Avg	C80_Avg	C100_Avg
	LL	C60_LL	C80_LL	C100_LL

Table 5. 5 Total EC Values Comparison Combinations for Steel/RC Buildings with Foundation in Different Steel Recycled Level

To start the comparisons, take the C60 series combinations into consideration firstly. Figures 5.5, 5.6 & 5.7 show the total EC values with varying levels of recycled steel scrap inclusion, with different CF values applied to the different steel materials combined with each concrete grade series.

As the Recycled Content of Scrap in Steel Products Increases from 0 (virgin) to 39% and then to 59%, it could be apparently noticed from Table 4.3 that the carbon footprint values of the recycled steel products could be reduced as much as only half of the virgin ones. Therefore, as the recycled content of scrap in steel products increases, observations could be made that,

i. In Combination C60 Seires, the total Embodied Carbon values of both Steel Building Sup+F system and RC Building Sup+F System decrease in a large scale in every concrete level combination. Due to the large decrease of the CF values for the applied steel material with more recycled content of scrap included, the contribution of the carbon footprint due to the steel material obtained a great reduction and therefore further affect the total CF values of both building Sup+F systems in a large scale, thereafter, resulting in the same trend applied to the total Embodied Carbon values of both Steel Building Sup+F and RC Building Sup+F systems in both C80 Series and C100 Series and furthermore, with the inclusion of the underground elements in this section, the total EC values difference between Steel Building Sup+F and RC Building Sup+F systems become larger than those for superstructures only as shown in section 4.4.4.

ii. Though the concrete material makes up the majority weights of both the Steel and RC Buildings as shown in Figure 5.1 at the beginning of this part of content, and in addition, the contribution of concrete become more significant for both Steel and RC Building Sup+F systems with the inclusion of underground elements, as the CF values for steel could be as large as 20-30 times of those for concrete, depending on the percentage of recycled steel scrap inclusion, the contribution of the steel material to the total CF values become weaker but still noticeable important.

iii. In all the following combinations in the Figure 5.5, 5.6 & 5.7, lengths of arrows indicate the difference between Steel Building Sup+F and RC Building Sup+F systems in terms of total EC values adopting the same set of concrete and steel CF values for comparisons. Red arrows mean the total CF value of Steel Building Sup+F is lower than that of the corresponding RC Building Sup+F, while yellow arrows mean the total CF value of the RC Building Sup+F is lower than that of the corresponding Steel Building Sup+F. The one with the arrow in every set of comparison means more environmental friendly in terms of total Embodied Carbons.

iv. In each of the nine combinations, as the recycled content of scrap in steel products increases, which is from virgin to 39% and then to 59%, it could be observed that a) the lengths of red arrows increase as in Combinations C60_UL and C60_Avg or b) the lengths of yellow arrows decrease as in Combination C100_LL, or c) the lengths of yellow arrows decrease firstly and then the arrows are switched to red with increasing lengths such as in Combinations C60_LL, C80_UL, C80_Avg, C80_LL, C100_UL and C100_Avg. These observations could provide a conclusion that the advantage of steel building Sup+F in terms of total EC increases especially with increasing recycled content of scrap in the steel products, so as the Steel Building Design would be more environmental friendly, especially with the inclusion of the underground structures, the environmental advantage of recycled steel scrap materials' application becomes more obvious.

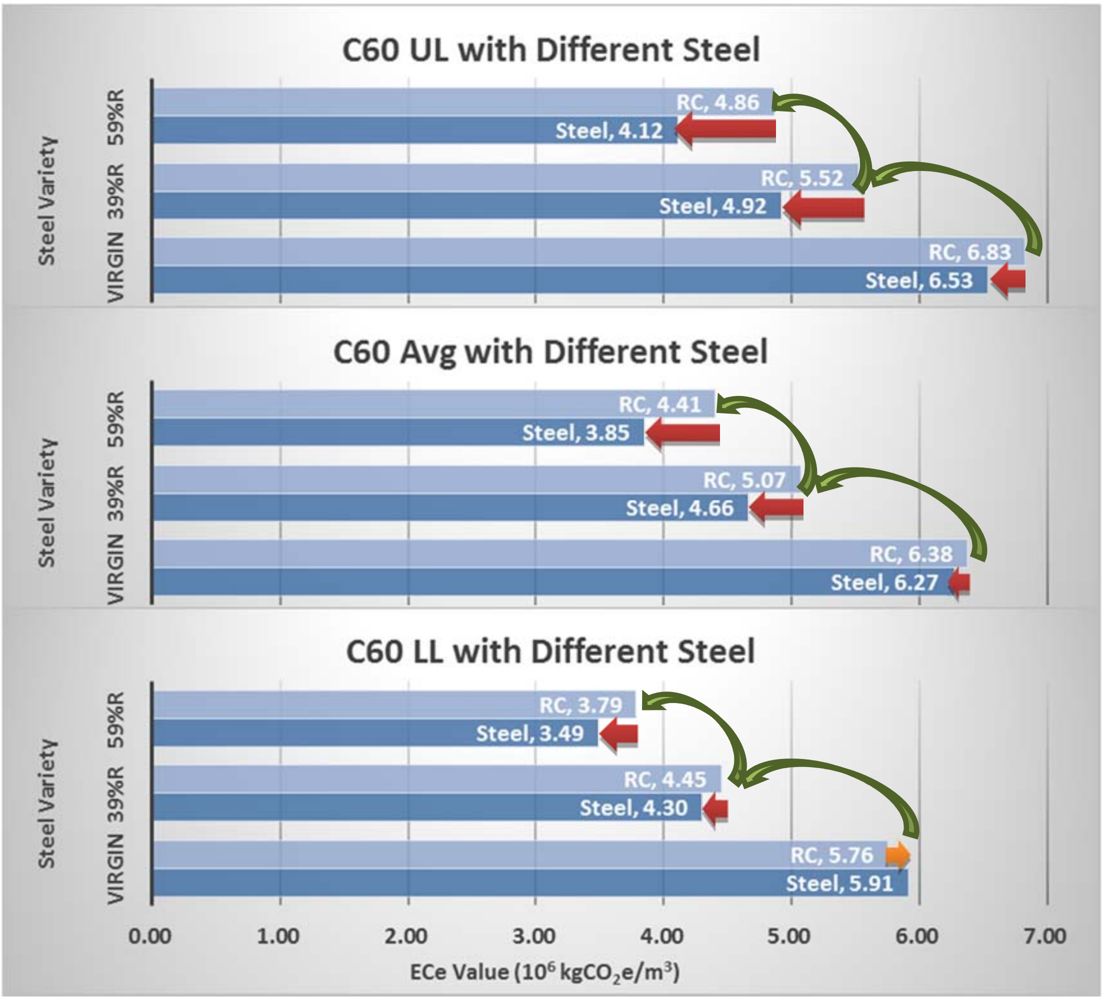

Figure 5. 5 Total Embodied Carbon Values Comparison of Steel and RC Buildings with Foundation in C60 with Steel in Different Recycled Level: Combinations C60_UL, C60_Avg & C60_LL.

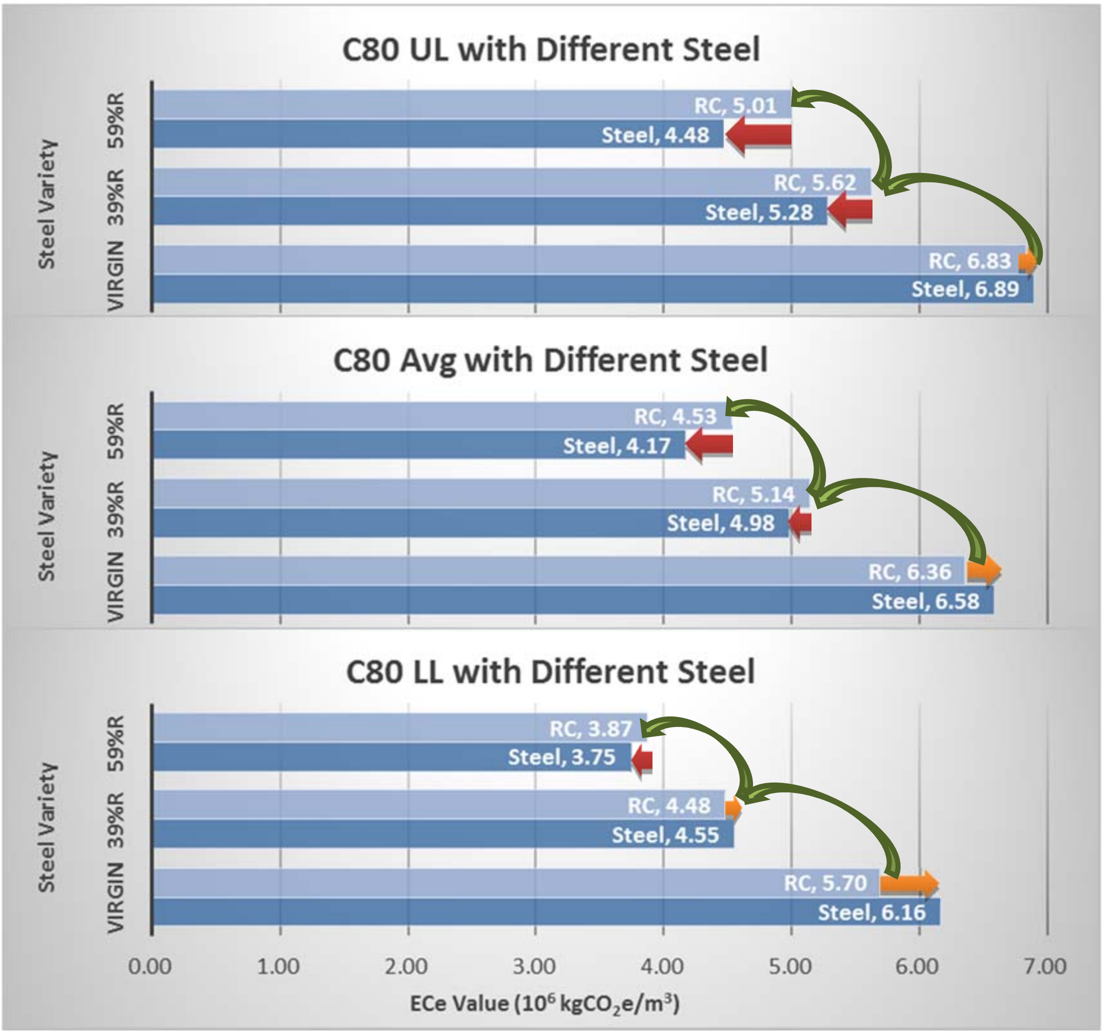

Figure 5. 6 Total Embodied Carbon Values Comparison of Steel and RC Buildings with Foundation in C80 with Steel in Different Recycled Level: Combinations C80_UL, C80_Avg & C80_LL.

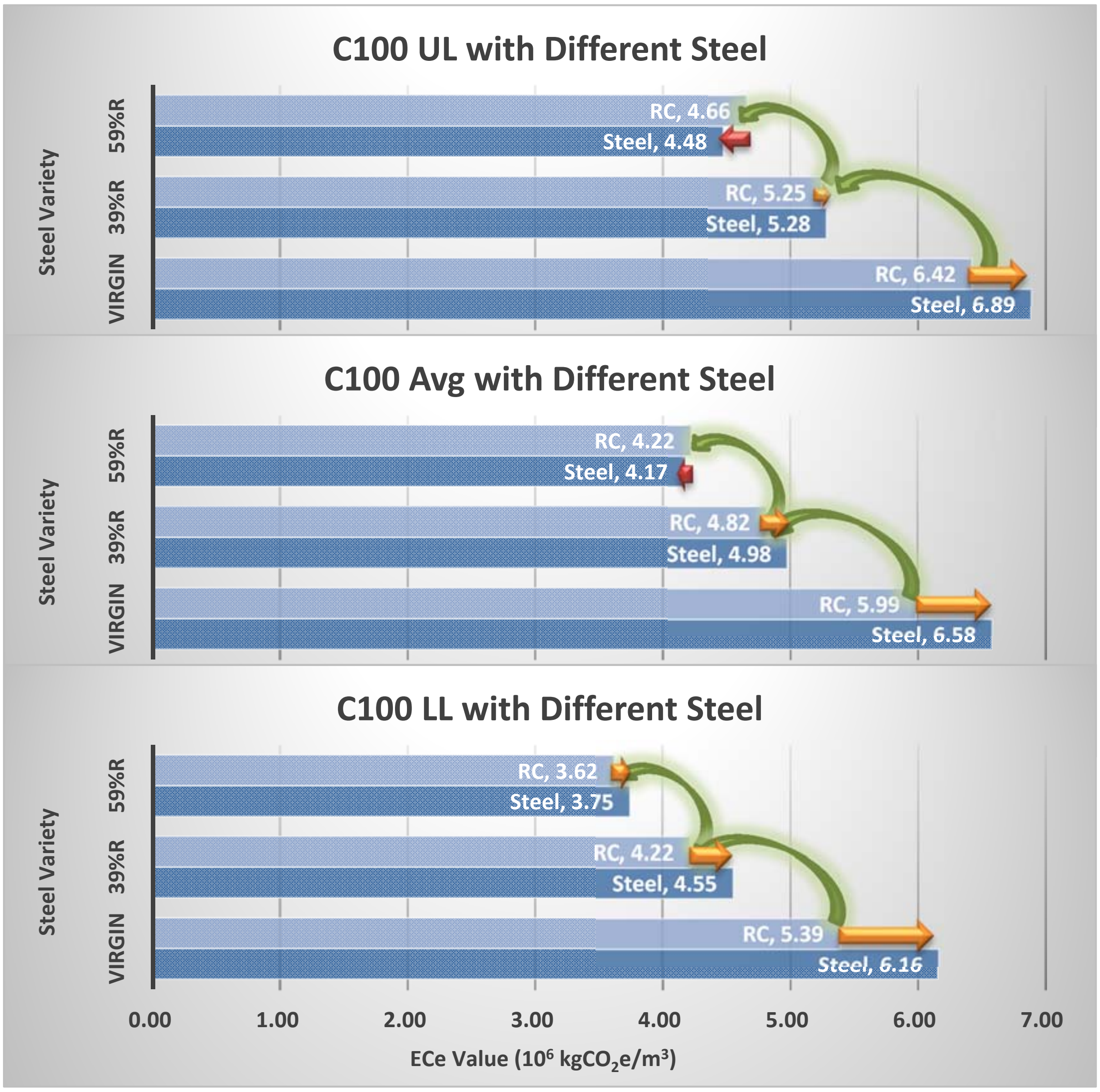

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Figure 5. 7 Total Embodied Carbon Values Comparison of Steel and RC Buildings with Foundation in C100 with Steel in Different Recycled Level: Combinations C100_UL, C100_Avg & C100_LL

5.3.5. Effect of Recycled Steel Content Inclusion

In real application, it is not practical to use recycled steel in the whole building structure due to size limitation of recycled steel products available and also as required in the Hong Kong local construction market. For example, in Hong Kong, the size limit of recycled steel section could be adopted is UKB305, so for steel beams and columns sized above UKB305, virgin steel sections should be applied strictly. The combinations of different steel materials with various recycled rates together with the absolute virgin, absolute 39% recycled steel and the absolute 59% recycled steel solutions, constitute a recycled steel inclusion rate scale as shown along the y-axis in the following Figure 5.8, 5.9 & 5.10. From top to bottom along the y-axis, the combinations range from the most available recycled steel inclusion 59% to absolutely virgin steel with 0%. The steel products adopted in the whole building system include steel sections and steel rebars, so the different combinations can be referred from the following illustrations:

Combinations	Steel Section > 305	Steel Section ≤ 305	Steel Rebar	Total Recycled Steel Inclusion
VS59S&59B	Virgin	59%	59%	37%
VS59S&VB	Virgin	59%	Virgin	9%
VS39S&39B	Virgin	39%	39%	24%
VS39S&VB	Virgin	39%	Virgin	6%

Table 5. 6 Total Recycled Steel Inclusion Rates for Different Steel Material Combinations for Buildings Sup+F.

The resulting bar charts below clearly summarized the comparisons of the total EC of all buildings Sup+F with the same concrete carbon footprint, as the recycled content of scrap in steel products increases, the total EC value decreases in a similar manner. Compared with the results for superstructures only, the absolute values of total EC values' decrease become more significant and the absolute decrease percentage in every set of combinations increases as well.

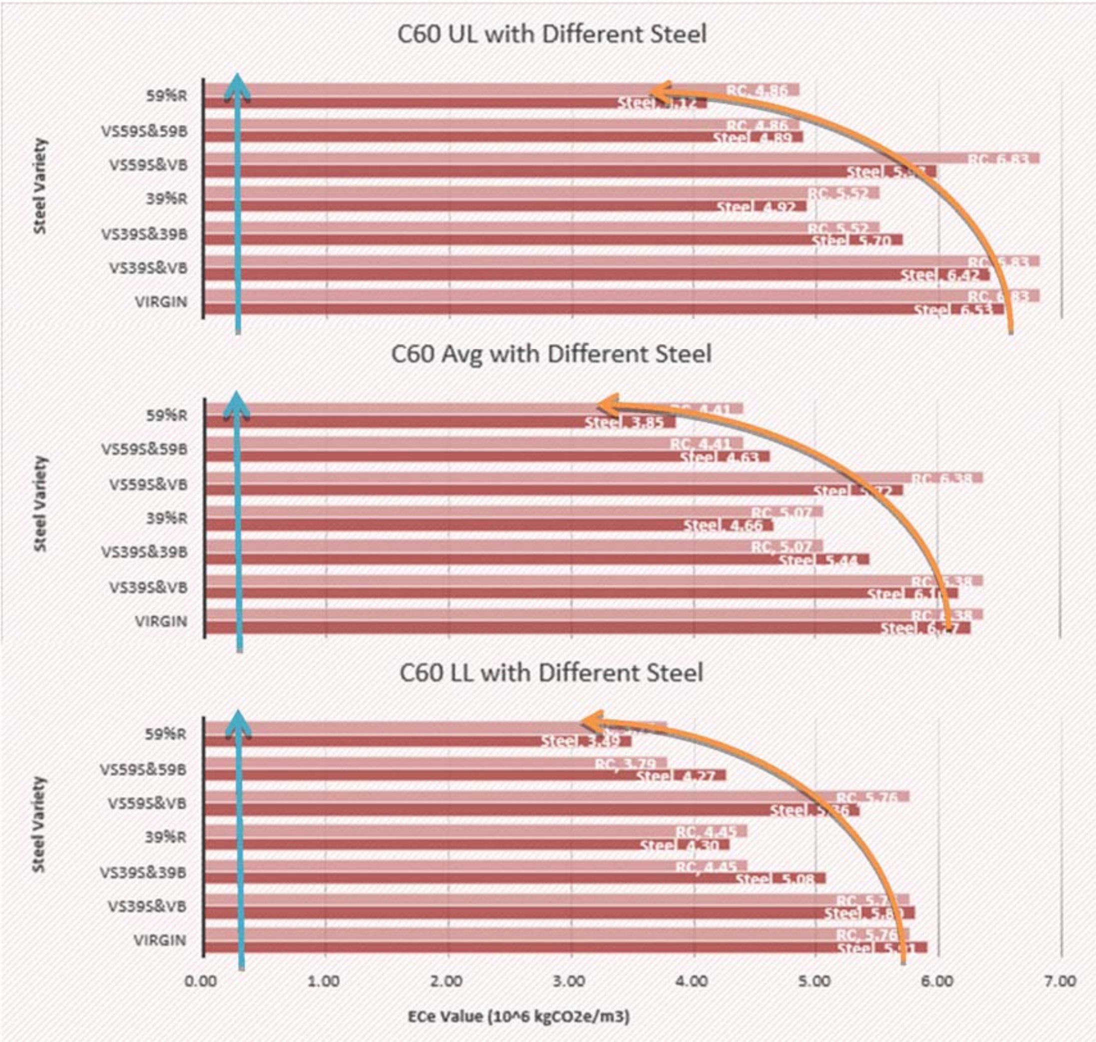


Figure 5. 8 Total Embodied Carbon Values Comparison of Steel and RC Buildings with Foundation in C60 with Steel Materials in Various Recycled Steel Inclusion Scale

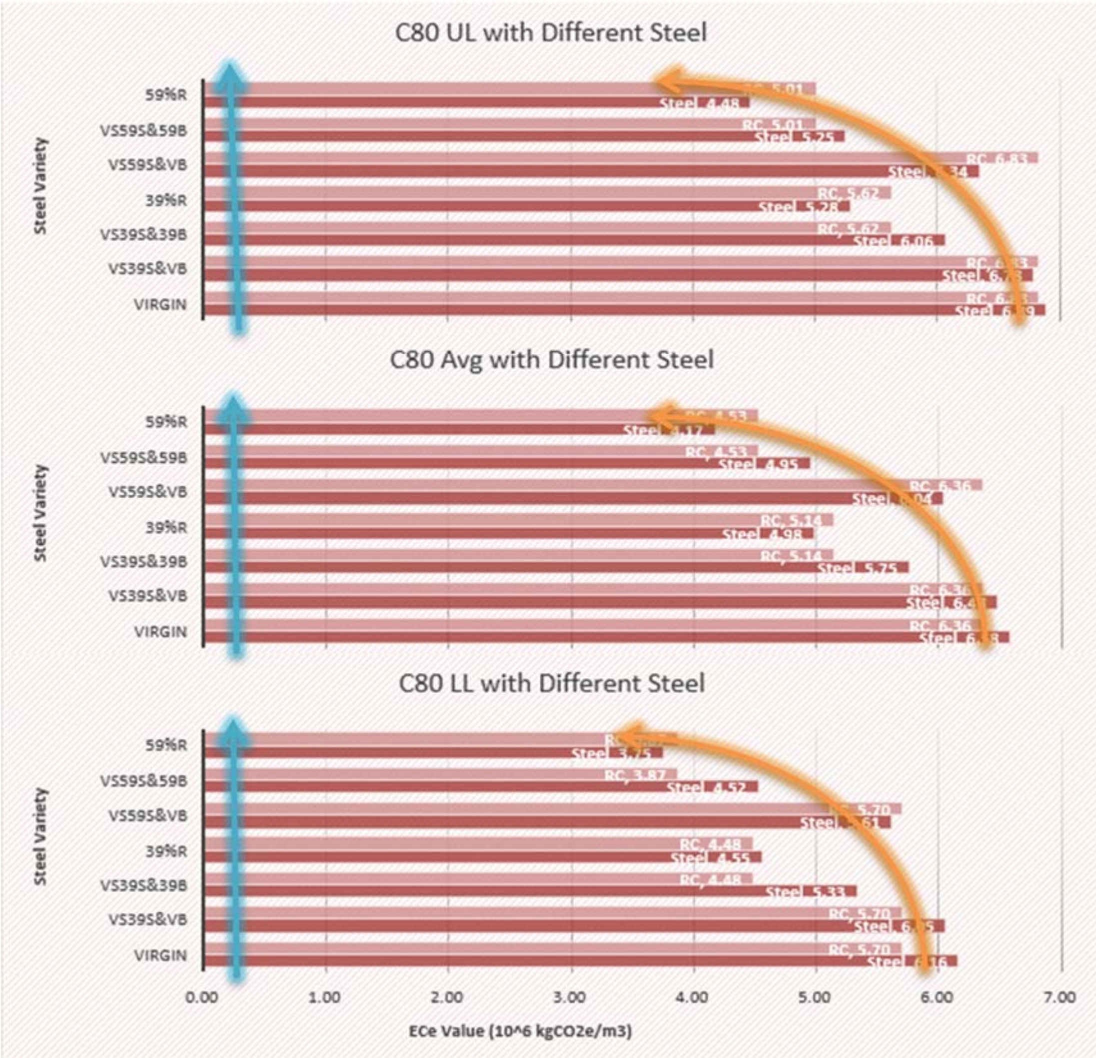


Figure 5. 9 Total Embodied Carbon Values Comparison of Steel and RC Buildings with Foundation in C80 with Steel Materials in Various Recycled Steel Inclusion Scale

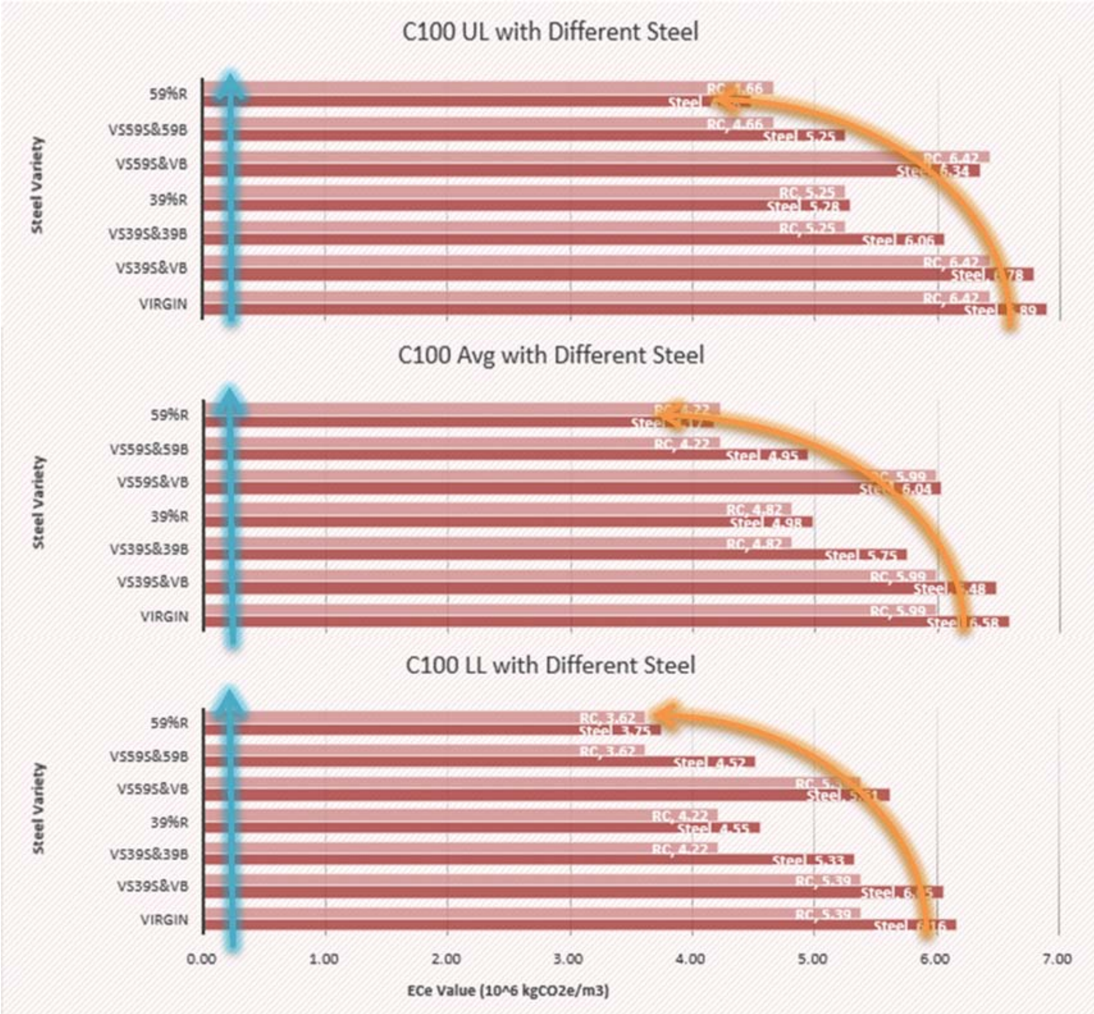


Figure 5. 10 Total Embodied Carbon Values Comparison of Steel and RC Buildings with Foundation in C100 with Steel Materials in Various Recycled Steel

Plot the above mentioned total ECe values in the following Figure 5.11 (a)~(d). Figure 5.11 (a) provides a summary of all the total ECe values of both building Sup+F schemes designed with different concrete carbon footprint values. For concrete in different grades applied in the design, the 'Average' carbon (Avg) footprint values for concrete product in each grade was selected to provide an overview of this set of comparison. As concluded above in this part, the more recycled material used, the more environmental friendly the design would be. However, due to the product availability and size limitation in the certain construction material market, it is not practical to have all the products in application to be composed of fully recycled materials for the whole building system. In the previous section 4.4.6, the percentage of the recycled steel accounting for in the overall steel consumption has been explored for certain concrete strength adopted so that the relative environmental advantage of either the Steel Building Scheme or the RC Building Scheme has been examined including the superstructure only in terms of lower total carbon emissions. To take account of the underground elements into consideration, the same series of examinations would be conducted as in the following Figure 5.11 (a)~(d) and comparisons would be displayed in Figure 5.11 (b)~(d) with the Superstructure together with Foundation results.

In Figure 5.11 (b)~(d), trendlines were added to each set of total ECe results for both building schemes. For every scheme, two sets of results were plotted. The trendlines for Buildings Sup+F are located above those for Building with Sup only because of the inclusion of underground structures' embodied carbon values.

Interceptions would still exist for the trendlines for each set of total ECe results for buildings' Sup+F models.

In Figure 5.11 (b), the interception was relocated from 28% to 5% at x-axis, which means that C60 RC Building Sup+F generates lower environmental impacts than Steel Building when low carbon footprint (low grade) concrete is used with recycled scrap rate of steel under 5%, otherwise, Steel Building generates lower environmental impacts when low carbon footprint (low grade) concrete is used with more than 5% recycled steel applied in the design, which indicates that with the inclusion of foundation elements, Steel Building design option would be more environmental efficient given 5% of recycled scrap included.

In Figure 5.11 (c), the trendlines' interception was relocated from 53% to 32% at x-axis, which means that when the concrete grade was risen from C60 to C80, with the inclusion of foundation elements, the recycled steel scrap rate should reach as high as 32% to make the Steel Building generate lower environmental impacts than the RC Building. This percentage has been lower by around 20% for C80 models, which implying that Steel Building design option including foundation would be more environmental efficient given 32% of recycled scrap included. However, the steel scrap requirement for C80 design models is still high when compared with the C60 ones for Steel Building design option to achieve the best structural and environmental efficiency.

In Figure 5.11(d), no interception was found in the two sets of trendlines within the given percentage range of the recycled steel scrap rates, but it could be deduced from the line trends that the interception for the Sup+F set would possibly lie around 60%, which is already a reduction from 65%-70% as for Sup set. As the carbon footprint value of concrete increases to C100, i.e. high strength concrete is used, Steel Building could hardly win RC Building in terms of environmental friendly since very high percentage of recycled steel is required for application together with very high strength concrete, which can barely be satisfied given the practical market availability, indicating the absolute environmental advantage of the high strength RC Building over the steel design option even the foundation elements were taken into consideration. From Table 4.2, though the carbon footprint value of C100 concrete increased in a large scale compared with that of C60 concrete, these carbon footprint values would still be not comparable to those of steel products.

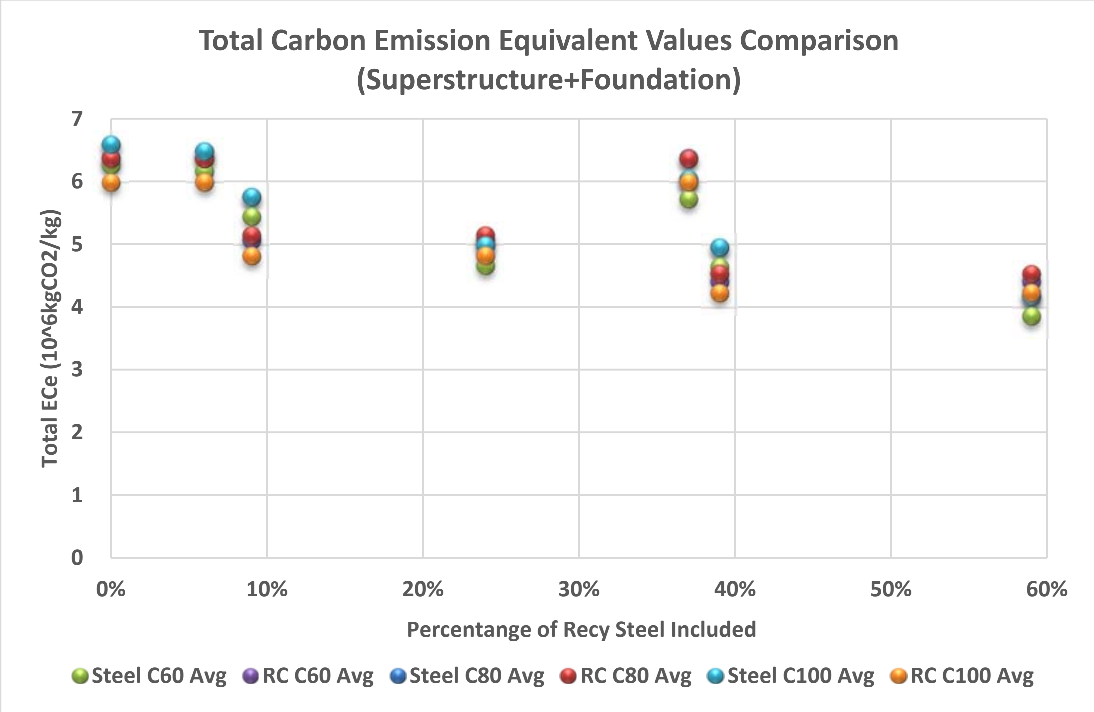


Figure 5. 11 Superstructure + Foundation Total Carbon Emission Equivalent Values Comparison (a) Summary

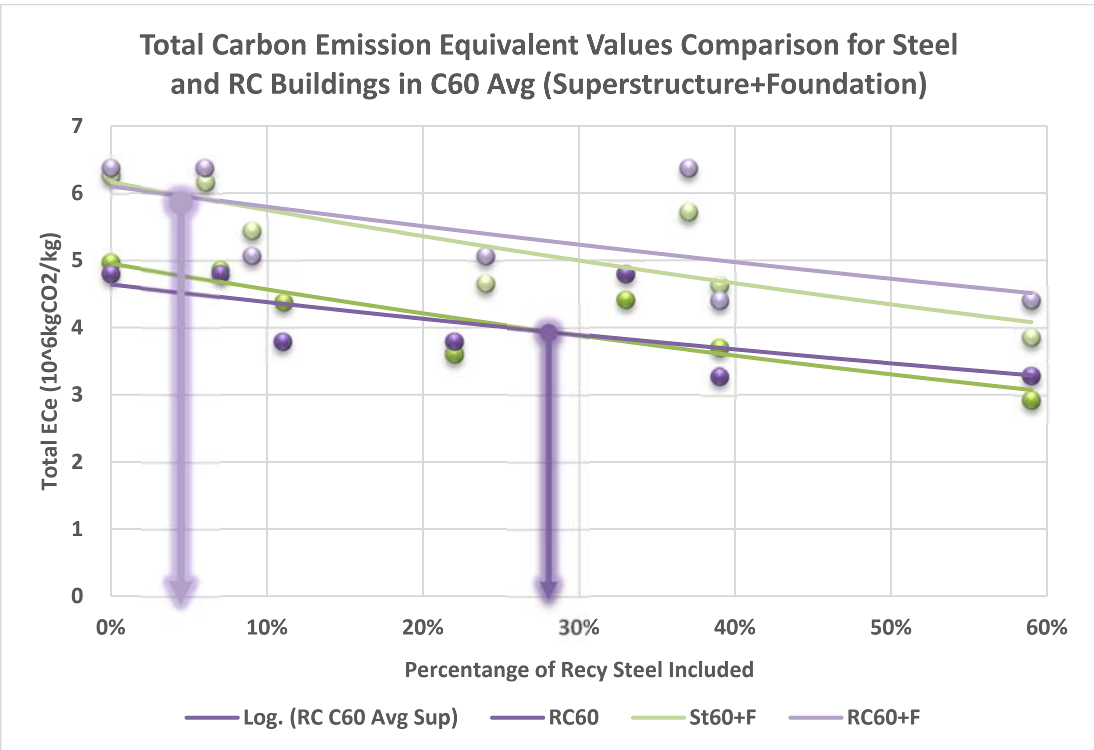


Figure 5. 12 (b) Steel and RC Buildings with Foundation in C60 Avg

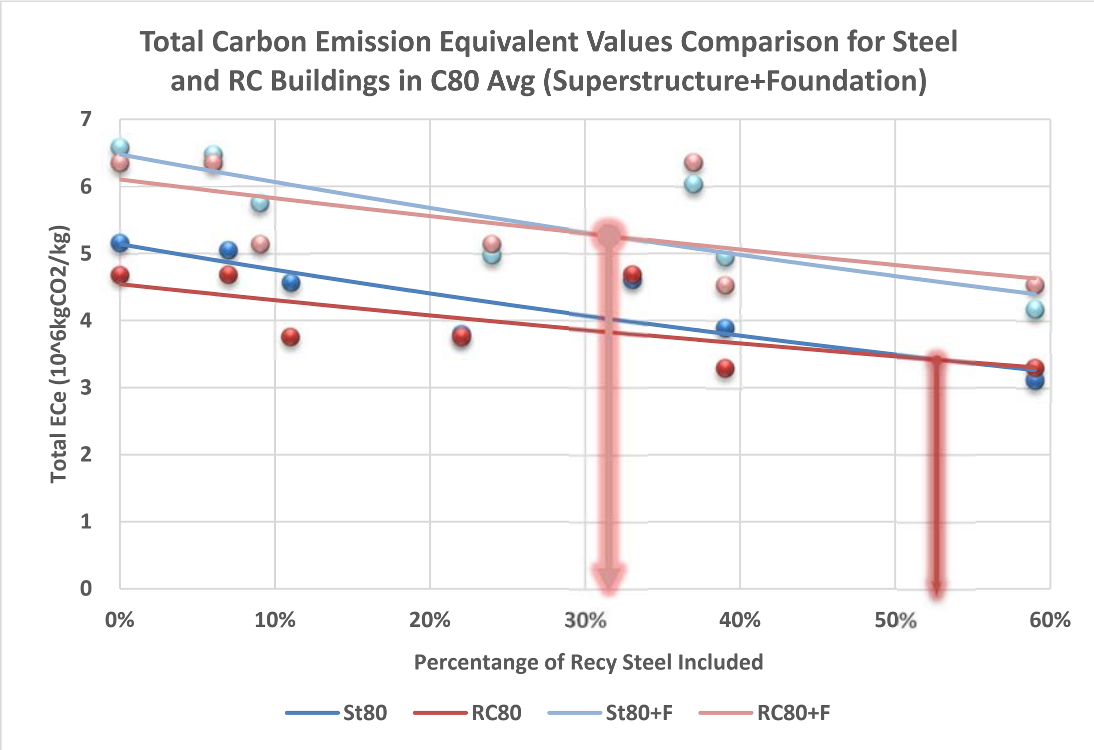


Figure 5. 13 (c) Steel and RC Buildings with Foundation in C80 Avg

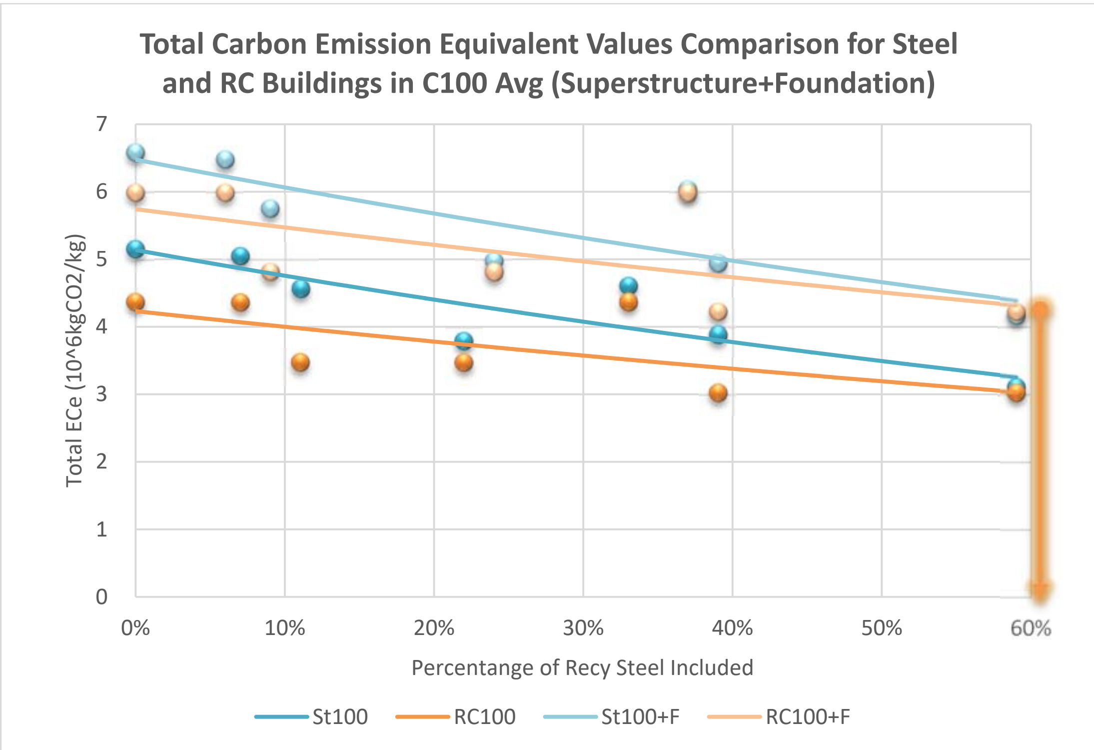


Figure 5. 14 (d) Steel and RC Buildings with Foundation in C100 Avg

As a conclusion of the above observations with all the superstructure and underground elements taken into account, the higher the concrete strength in use in the RC structural design, the more recycled steel scrap is required in the steel design option to make their environmental impacts competitive for these kinds of mid-rise commercial buildings designed in Hong Kong construction market. However, for low grade concrete RC Building design to be carried out and compared with Steel Building option correspondingly, as for C60 concrete in use, 5% of recycled steel scrap material is required, while for C80 concrete in use, 32% of recycled steel scrap material is required, so that the Steel Building design option would achieve the best structural and environmental efficiency simultaneously given the absolute material weight reduction as mentioned in the beginning of this chapter for Steel Building models. Therefore, it would be suggested to conduct a nonlinear steel building design scheme for these similar mid-rise commercial buildings in terms of their advantages in mateiral save and eco-firenliness.

CHAPTER 6

ENVIRONMENTAL IMPACTS COMPARISONS USING HONG KONG CERTIFIED MATERIALS

In the previous Chapter 4 & Chapter 5, a systematic integration has been achieved of the optimised structural design methods and the ICE carbon footprint database. Using the same set of building models as in the two sections, with superstructure only or including foundation, it is worth exploring the application of the Hong Kong based carbon labelling scheme to this commercial building originally designed in Hong Kong construction environment.

6.1 Embodied Carbon Footprint Data

The quantification of the construction buildings' total carbon footprint (CFP) was calculated by the accumulation of all the construction materials' carbon footprints. The CFP calculated under this Scheme was based on a "cradle-to-site" approach, covering all GHG emissions and removals of the product arising from raw material acquisition, transportation, production process, storing/packaging and finally transporting to the border of Hong Kong.

Currently, the Scheme database includes rebars and structural steel products as well as concrete products ranging from C30 to C60 grade concrete. The lowest carbon footprint values are 0.55 and 2.08 kgCO_2e/kg for rebar and structural steel section available in Hong Kong construction material market respectively.

In order to achieve the purpose of application of the environmental impact evaluation method in the current Hong Kong construction market, some local carbon footprint values for all the ready-mixed concrete, steel sections and steel rebars were also shortlisted already in Table 4.1 as in section 4.3.1.

The CFPs applied in this study are listed in the following tables:

Applicant from	Product Category	Embodied Carbon Value
	Rebar and Structural Steel	Unit: $kgCO_2e/kg$
Thailand	Section	0.55
Mainland China	Pipe	2.95
Taiwan	Section	1.37
Middle East	Rebar	2.08
Middle East	Section	2.36
	Ready-mixed Concrete	Unit: kg CO_2e/m^3 concrete
Hong Kong	C60 normal concrete	310

Table 6. 1 Hong Kong CIC Carbon Labelling Scheme Application: CFPs Applied in this Study

The environmental effects comparisons based on ICE database encompass material combinations of different concrete grades with different levels of carbon footprint values CFPs within each grade together with steel sections and rebars in different recycling level. In the following comparisons, the CIC carbon labelling scheme certified materials are listed to be adopted to the aforementioned Steel and RC Building models. The same concrete grade level C60 OPC was selected for the material used for the concrete constitution. In the following Table 6.2, the CFP values are listed for Carbon Labelling System certified materials and ICE database accordingly. It could be easily observed that the great difference lying between the CFP values for C60 OPC concrete following the ICE database or the CIC Carbon Labelling Scheme. The steel sections and rebars for this corresponding Steel Building with C60 RC walls in design also have different options for CFP values between ICE and CIC as shown in the following table. The ICE CFP values for steel sections and rebars in different recycled level should keep identical as those applied in the previous comparisons in Chapter 4 and Chapter 5, therefore, the difference would be examined in terms of the total Embodied Carbon values when different CFP database was referred in analysis.

	CLS Certified Materials	ICE Data		
Concrete	310 kg CO_2e/m^3 (C60 OPC)	491 kg CO_2e/m^3 (C60 OPC)		
Rebar	2.08 $kgCO_2e/kg$	59% Recycled	39% Recycled	Virgin
Structural Steel	0.55 $kgCO_2e/kg$	59% Recycled	39% Recycled	Virgin

Table 6. 2 RC Superstructure Concrete CFPs from ICE Database vs. Hong Kong CIC Carbon Labelling Scheme CFPs Applied in this Study

6.2 Total Embodied Carbon Values Comparisons

Sorting the total EC values for comparisons, in this section, data were plotted into bar charts according to the data listed in the tables below correspondingly in order to examine the effects of the application of Hong Kong certified materials with low CFP values compared to the ICE material combinations with varying steel carbon footprint data for both Steel Building Sup & Sup+F and RC Building Sup & Sup+F with C60_UL concrete in use.

Comparisons		1	2	3	4
Unit: $kgCO_2e/kg$		**CIC CLS Certified Materials**	**59% Recycled**	**39% Recycled**	**100% Virgin**
Steel Type	Section	0.55	1.53	2.03	3.03
	Bar	2.08	1.40	1.86	2.77
Unit: $kgCO_2e/m^3$		**CIC CLS C60 OPC**	**ICE C60 UL (OPC)**		
Concrete Type		310	491		

Table 6. 3 CFP Values for the CIC vs. ICE total CF Comparisons

As the Recycled Content of Scrap in Steel Products Increases from 0 (virgin) to 39% and then to 59%, it could be apparently noticed from Table 6.3 above that the carbon footprint values of the recycled steel products could be reduced as much as only half of the virgin ones. However, the lowest CFP value for steel section available in Hong Kong construction materials market has been recorded to be as low as 0.55 $kgCO_2e/kg$, which is only one third of that of the lowest CFP value available according to the ICE database. Steel bar with lowest CFP available in Hong Kong was recorded to be 2.08 $kgCO_2e/kg$, which is not as low as those for the recycled steel rebars according to ICE database.

For concrete in the same grade with the same recycling level adopted for comparisons, Hong Kong CLS certified C60 OPC has a much lower carbon footprint value than the ICE one.

Comparisons 2, 3 and 4 result in the same figures as those in the C60 series for both the Superstructure only comparisons in Section 4.4.4 and Section 5.3.4.

Given the above materials in use for comparisons, observations could be made that,

i. In these four combinations, the total Embodied Carbon values of both Steel Building system and RC Building system decrease in a large scale as the CFP values for materials decrease for both Sup and Sup+F situations. Due to the large decrease of the CF values for the applied steel material with more recycled content of scrap included in the sequence from Comparison 4 to 1, the contribution of the carbon footprint due to the steel material obtained a great reduction and therefore further affect the total CF values of both building system in a large scale.

ii. Though the concrete material makes up the majority weights of both the Steel and RC Buildings as shown in Figure 4.2 as described in Chapter 4 and Figure 5.1 in Chapter 5, as the CF values for steel could be as large as 20-30 times of those for concrete, depending on the percentage of recycled steel scrap inclusion, the contribution of the steel material to the total CF values could not be underestimated.

iii. In all the following Figure 6.1&6.2, lengths of arrows indicate the difference between Steel Building and RC Building systems in terms of total EC values adopting the same set of concrete and steel CF values for comparisons. Red arrows mean the total CF value of Steel Building is lower than that of the corresponding RC Building. The one with the arrow means more environmental friendly in terms of total Embodied Carbons. In these two sets of comparisons, all the Steel Buildings are more environmentally friendly than the RC Buildings.

iv. In each of the two sets of comparisons, as the CFP value of steel decreases from Comparison 4 to 1, it could be observed that the lengths of red arrows increase. As the length of the red arrow increases, the more decrease the total EC could achieve for the corresponding combination, especially for the case taking foundation into consideration. These observations could provide a conclusion that the advantage of steel building in terms of total EC increases especially with increasing recycled content of scrap in the steel products, so as the Steel Building Design would be more environmental friendly, while the lower the materials' CF values adopted, the more environmental friendly the design would be. Hong Kong has the potential in providing a more environmental friendly construction market in the condition that the Carbon Labelling System Certified Materials would be invested in the future design and construction. Furthermore, with the assistance of nonlinear analysis in the steel building design schemes, the advantage of nonlinear analysis has been addressed once more in terms of the building ecology and sustainable profits.

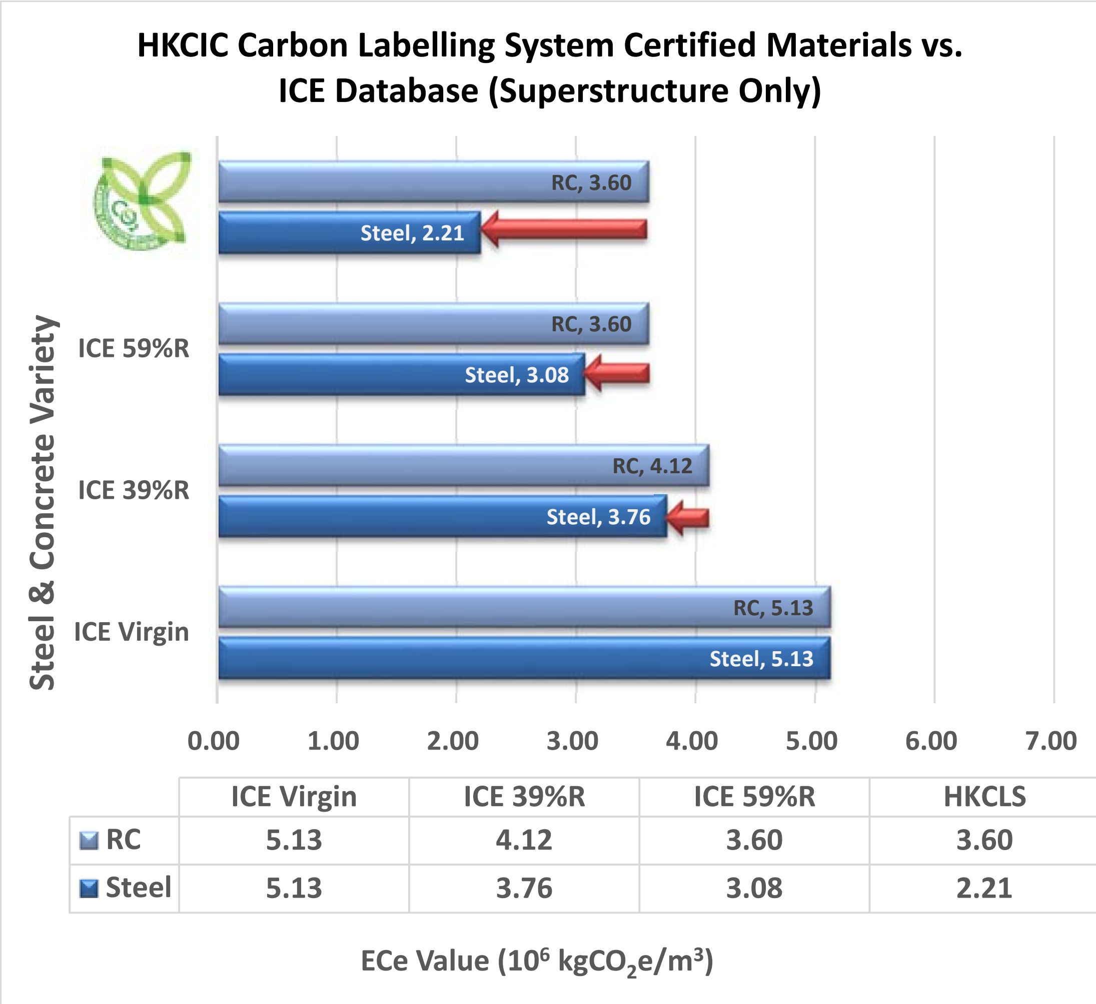
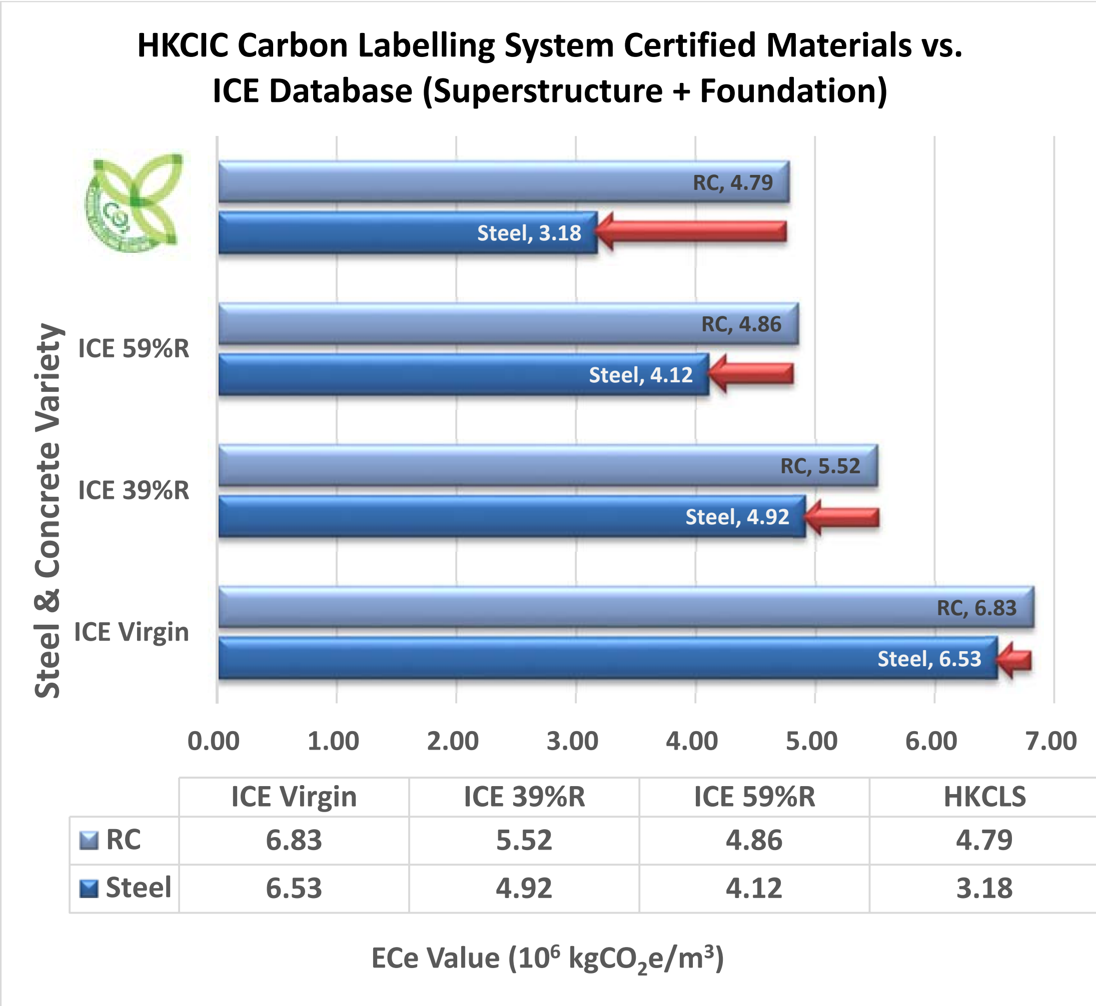


Figure 6. 1 HKCIC Carbon Labelling System Certified Material vs. ICE Database for Steel and RC Buildings with Superstructures Only



	ICE Virgin	ICE 39%R	ICE 59%R	HKCLS
RC	6.83	5.52	4.86	4.79
Steel	6.53	4.92	4.12	3.18

Figure 6. 2 HKCIC Carbon Labelling System Certified Material vs. ICE Database for Steel and RC Buildings with Superstructures and Foundation

CHAPTER 7

ENVIRONMENTAL IMPACTS OF BUILDINGS IN DIFFERENT HEIGHTS

In the previous Chapter 3, the environmental impact evaluation method adopting nonlinear analysis has been scientifically proved taking the material factor into consideration. In Chapter 4 and Chapter 5, the integration of the optimised structural design method and the ICE carbon footprint database for different design methods in different construction materials was reasonably conducted. In Chapter 6, the integration of the optimised structural design method and the Hong Kong based carbon labelling scheme was address as well. All of the above examples and results have already provided an overview of the advantages and disadvantages of either the steel or RC design solution, however, to make the study more complete in this section, the environmental performance is to be examined again of building models in different levels, in different construction materials and designed with different methods. Therefore, in this section, the relative material advantage of either steel or concrete for buildings in different heights is to be explored, in addition to the scientific relationship established between material consumption, structural design optimization, selection and use of low carbon material, together with the associated building’s total carbon footprint.

7.1 Summary of Building Models

There are three sets of building models adopted to carry out the environmental performance comparisons and categorised in terms of their storey levels, 15F, 25F and 35F.

The same set of building models were still in use for the 25F building models as those from Chapter 3 to Chapter 6. The 25F is a 25-storey model modified from a real commercial building originally designed and constructed in Hong Kong Island. The building's plan area was designed to be 27.69m by 23.26m for each storey, with the total height of the whole building to be 97.6 metres.

For the 15F and 35F building models, buildings' plan areas keep identical to those of the original 25-storey building model, but the total heights of the whole buildings were modified to be 15 storeys and 35 storeys respectively, with the storey height staying the same as the original one.

All of the three sets of steel building superstructure scheme and reinforced concrete building superstructure scheme have been carried out to simultaneously fulfil the Ultimate Limit States and Serviceability Limit States specified according to the Code of Practice for the Structural Use of Steel 2011 [38] and the Code of Practice for Structural Use of Concrete 2013 [37].

Due to the storey changes of the 15F and 35F sets of buildings, the overall configurations' change results in the overall wind profile change along both x and y directions. Therefore, for the 15F and 35F sets of building models, wind profiles were modified according to the Code of Practice on Wind Effects in Hong Kong 2004 [39]. Furthermore, the column and wall sizes should be modified again to achieve the best structural efficiency but following the requisite design codes.

The steel building solution was conducted by nonlinear analysis to achieve the best structural efficiency, including beams and columns made of steel and core walls made of concrete. On the other hand, the RC building solution done by linear analysis only designed with RC beams, RC columns and concrete core walls. Both structures were optimized to have the top total displacement over total height ratio approaching 1/500 as much as possible, so as to make the two design solutions comparable since the best structural efficiency was achieved with fairly closed reaction behaviour under the same vertical and horizontal loading circumstances.

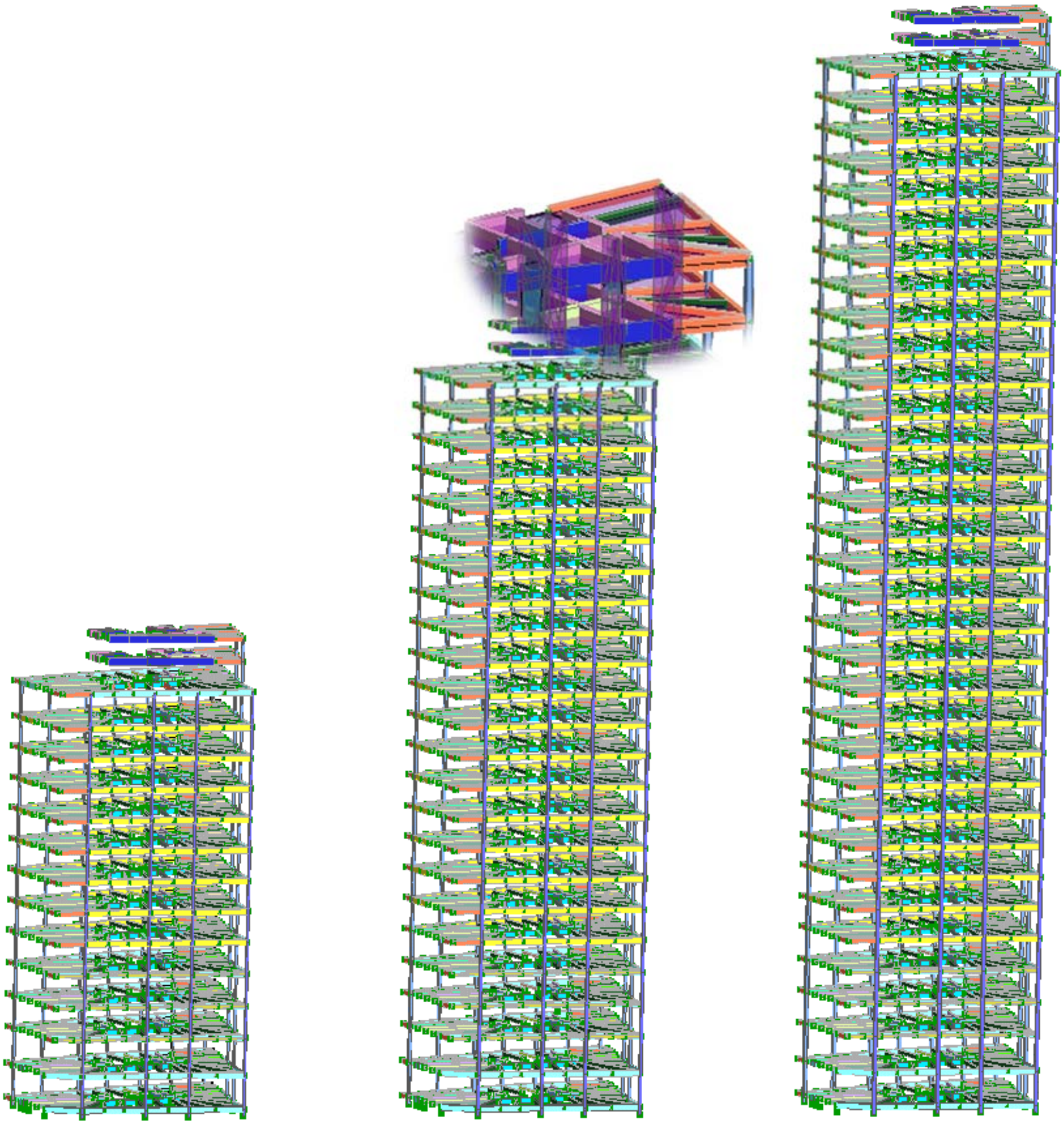


Figure 7. 1 Configuration of Steel Building in 15, 25, 35 Storeys Respectively

15F 25F 35F

Figure 7. 2 Configuration of RC Building in 15, 25, 35 Storeys respectively

The building model was firstly designed in a steel structural frame ("Steel Building") consisting of steel beams and steel columns all in steel grade of S355 coupled with RC structural core walls. Lateral stiffness is provided by RC structural core walls to resist wind actions. Vertical actions including self-weight, super-imposed dead load, live load, etc., are resisted by steel beams through which are further transferred to the steel columns down to the ground. The structural configuration is illustrated in Figure 7.1.

On the other hand, in the second scheme, the building model was designed to be a reinforced concrete structure ("RC Building") consisting of RC beams, RC columns coupled by concrete core walls. Lateral stiffness is provided by RC core-walls to resist wind actions. Vertical actions including self-weight, super-imposed dead load, live load, etc., are resisted by RC beams supported by RC columns and RC walls and downward to the ground. The structural configuration is illustrated in Figure 7.2.

Different from the comparisons in previous contents, in this section, with all the steel sections used in the Steel Building and reinforcements applied in both Steel and RC Buildings to be of Grade S355, the grade of concrete adopted for analysis and comparison was chosen to be uniform in order to emphasize the effects of building heights variation. All the concrete material adopted in this study was in grade C60, which is considered to be more commonly applied for buildings in these heights in the current Hong Kong construction environment. Concrete materials in the same grade vary in different levels of carbon footprint values were considered while steel sections and bars in various recycled rates, including virgin steel bar, 39% recycled scrap included or 59% recycled scrap included according to the carbon footprint data provided by ICE Version 2.0 [35], which will be detailed introduced in the following contents of this Chapter 7.

This preliminary appraisal assesses the structural behaviour of the building under dead, imposed and wind actions, as well as the effects due to temperature variation by direct analysis approach. All relevant loadings are considered to be applied either in individual or in such realistic combinations as to comprise the most critical effects on all the structural elements and the structure as a whole. The ultimate limit safety state and serviceability limit state cases are analysed to capture the fundamental requirements for the reliability of construction works.

7.2 Analysis Method

The second-order direct analysis suggested by the Hong Kong Steel Code 2011 [38] was performed in this design on the deformed structures of the Steel Building. Both P-Δ sway and P-δ bow nonlinear effects were included for determination of stresses in equilibrium with the defined actions for a global analysis dependent on geometrical, structural and material properties. NAF series – Non-linear Integrated Design and Analysis (NAF-NIDA) version 9.0 was employed for the second-order elastic analysis conducted in this study, which was an already approved approach for the non-linear analysis and design to Code of Practice for the Structural Use of Steel 2011 [38] and Eurocode-3 [26], with a number of application in the UK, Singapore, Hong Kong, China, Macau, Taiwan, India, and Myanmar, etc, in the past decade. With a conventional linear analysis, it is difficult to determine and visualise the real action effects especially in terms of the steel-composite floor system actions in which the simple effective length assumption is no longer reliable without taking consideration of secondary stresses and buckling effects.

For the RC Building examples whichever in Grade C60, conventional linear elastic analysis was adopted for all the models according to Hong Kong Concrete Code 2013 [37], satisfying the Ultimate Limit State and Serviceability Limit State simultaneously.

7.3 Embodied Carbon Footprint

7.3.1. Data

The same set of carbon footprint values database was adopted in this Chapter as in Chapter 5 and Chapter 5, i.e. Bath Inventory of Carbon & Energy (ICE) Version 2.0 [35], was referred regarding the carbon footprint values for ready-mixed concrete in grade C60, as well as steel rebars and sections with different recycled contents.

The CFPs applied in this study are listed in the following tables:

Concrete Grade	100% OPC (Upper Limit)	50% GGBS (Lower Limit)	Average Value
C60 **(unit: kg CO_2e/m^3)**	491	306	413

Table 7. 1 The ICE Carbon Footprint Data of Concrete Applied in Chapter 7

(Unit: kg CO_2e/m^3)

Steel Type	100% virgin steel	39% recycled scrap	59% recycled scrap
Section	3.03	2.03	1.53
Bar	2.77	1.86	1.40

Table 7. 2 The ICE Carbon Footprint Data of Steel Products Applied in Chapter 7

(Unit: kg CO_2e/m^3)

*Due to the limitation of product size produced from recycled scrap, the steel products sized above 305 all applies the virgin steel.

7.3.2. Total EC Accumulation Methods

The results obtained from the linear or nonlinear analysis as described in Chapter 4 and Chapter 5 were collected, interpreted and compared in terms of both design schemes. Referring to the above databases, total carbon footprint is contributed by the accumulation of all the construction materials' carbon footprints. In this section, three sets of building models were analysed for comparisons under the condition that only building superstructures were included. In the Steel Building, all the loadings are supported by steel members with structural walls taking action, while in the RC Building, the system consists of RC beams and RC columns with concrete core walls. Underground structures are made up of reinforced concrete piles and rafts. From a system level, the total carbon footprints should include all the structural elements of the building system, but again to emphasis the effects of heights variations, only superstructure study was carried out, but the situation with foundation could be foreseen clearly from the following superstructure study as well. Therefore, to make the two design schemes comparable, the range of structural elements included will be as shown below.

Variations	15F, 25F & 35F Steel Building	15F, 25F & 35F RC Building
Elements	steel beams steel columns Concrete Core Walls Steel Rebars	RC beams RC columns Concrete core-walls Steel Rebars
Materials	Core walls in C60; Steel Sections / Bars in Virgin, 39% recycled scrap, 59% recycled scraps	Beams, Columns and Core walls in C60; Steel Bars in Virgin, 39% recycled scrap, 59% recycled scraps

Table 7. 3 Structural Elements Included in Building Heights Variation Comparisons Calculation Considering Superstructure Design Only

7.4 Results Discussion

The relative advantages of Steel Building or RC Building in different heights are to be examined by comparing the environmental effects of the accumulation of all structural elements supporting the horizontal loadings and vertical loadings. Therefore, it is expected to examine how much could be saved in material used and total embodied carbon (EC) with different materials included for application.

7.4.1. Total Weight of the Models' Superstructures

The total weights of the Steel Building and RC Buildings in 15F, 25F and 35F in C60 have been listed in the following Table 7.4 and plotted in Figure 7.3. All of the total weights of Steel Building frame are around half of those of the corresponding RC Building models in certain levels. These numbers showed a great level of decrease in material consumption in the nonlinear optimized Steel Building Scheme, which further infers that the underground construction could save even more material and cost under this scheme, especially for higher level of buildings to be designed, the material save as well as the corresponding economic efficiency increase mean huge to the whole project.

Weight (kN)	15F Steel	15F RC C60	25F Steel	25F RC C60	35F Steel	35F RC C60
Section	4640	0	8654	0	14836	0
Concrete	25223	53728	47636	98239	82685	160164
Bar	2727	6294	5163	10893	8940	19032
Total	**32590**	**60022**	**61452**	**109132**	**106461**	**179196**

Table 7. 4 Superstructure (Sup) Total Weights for Steel and RC Buildings in C60 Concrete for Models in 15F, 25F and 35F Respectively

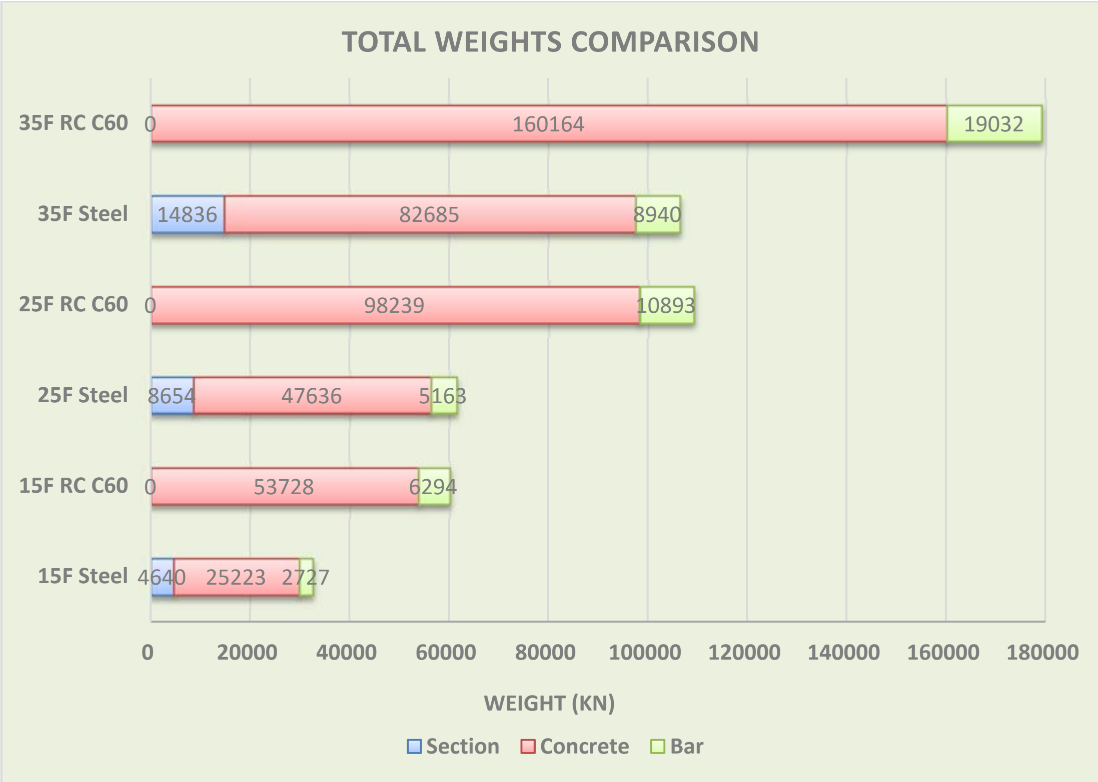


Figure 7. 3 Superstructure (Sup) Total Weights for Steel and RC Buildings in C60 Concrete for Models in 15F, 25F and 35F Respectively

7.4.2. Total Embodied Carbon

Based on the CFPs in Table 7.1 & 7.2, total carbon footprints of the Steel Building and the RC Building encompassing only superstructures have been calculated for all material combinations according to ICE database and the results are listed in the following Table 7.5, in the unit of $10^6 kgCO_2e$.

Steel Building	15F UL	15F Avg	15F LL	25F UL	25F Avg	25F LL	35F UL	35F Avg	35F LL
	Unit: 10^6kgCO_2e								
Virgin	2.73	2.65	2.53	5.13	4.97	4.75	8.83	8.56	8.18
39%R	2.00	1.92	1.81	3.76	3.61	3.39	6.49	6.22	5.84
59%R	1.64	1.56	1.44	3.08	2.92	2.71	5.32	5.04	4.67
RC Building	15F UL	15F Avg	15F LL	25F UL	25F Avg	25F LL	35F UL	35F Avg	35F LL
	Unit: 10^6kgCO_2e								
Virgin	2.90	2.72	2.48	5.13	4.80	4.35	8.72	8.19	7.46
39%R	2.31	2.14	1.89	4.12	3.79	3.34	6.95	6.42	5.69
59%R	2.02	1.84	1.60	3.60	3.28	2.83	6.06	5.53	4.80

Table 7. 5 Total EC of Buildings in Different Heights Associated with Different Materials (Sup Only)

7.4.3. Variable: Concrete Carbon Footprint Value

Sorting the total EC values for comparisons, in this section, data were plotted into bar charts according to the building heights and concrete carbon footprint values in order to examine the effects of varying concrete carbon footprint data for both Steel Building and RC Building in different heights with the same steel recycled contents included. Totally nine combinations could be summarized under this category, according to the building storeys and steel recycled level.

Concrete Grade C60		Steel Recycled Level		
		Virgin	39% R	59% R
Building Storeys	35F	A	D	G
	25F	B	E	H
	15F	C	F	I

Table 7. 6 Total EC Values Comparison Combinations for Steel/RC Buildings in C60 Concrete for Models in 15F, 25F and 35F

Examining Combinations A, B and C for comparison firstly, the following Figure 7.4 A, B & C show the total EC values in virgin steel with varying building storeys, as well as different carbon footprint data level applied under concrete grade C60.

As the building height increases, observations could be made that,

Combinations A, B & C:

i. From the trend of decrease of bar lengths according to the sequence of Combination A to B and then to C, total Embodied Carbon values of both the Steel Building and RC Building would decrease proportionally to the building heights

ii. The relative difference in terms of the total embodied carbon values of the entire building systems achieved by using Steel Building Scheme compared with the corresponding RC Building Scheme have been presented in the following Figure 7.4 as well. The differences are labelled in red, orange and green bars for concrete grade carbon footprint values according to the upper limit, average and lower limit values.

iii. In the same building height combination, the total EC values difference between steel and RC buildings decrease as the carbon footprint value level increases within the C60 concrete grade range. As for the same set of building height comparison, the different levels of concrete carbon footprint values apply to the same set of designs for Steel and RC buildings. The contribution of concrete to the total EC value of the Steel Building is very minor compared to steel and is as little as incomparable to the contribution of concrete to the total EC value of the RC Building. Therefore, as the concrete carbon footprint value level decreases, the accumulation of the total embodied carbon would decrease apparently, resulting in the increase in the total EC values difference.

iv. The above summarized results i ~ iii apply not only to the Steel Building and the RC Building models using ICE virgin steel carbon footprint values, i.e.

Combinations A, B & C, but also to the models using ICE carbon footprint values with different levels of recycled steel scrap, i.e. Combinations D, E & F for steel with 39% recycled scrap, as well as, Combinations G, H & I for steel with 59% recycled scrap. The results are listed in the following Figure 7.5 and Figure 7.6 where the above mentioned trends could be thereafter examined accordingly.

v. In terms of the total EC values in different building height combinations, it is observed that as the building height increases, the total EC values of RC Buildings are lower than those of the Steel Buildings correspondingly, which implicates that the RC Building Design Scheme would be more environmental friendly, generating lower environmental burdens to the global atmosphere when virgin steel is utilised as the major steel material. On the other hand, the Steel Building Design Scheme would be more environmental friendly when the building height is reduced to 15F using virgin steel as well.

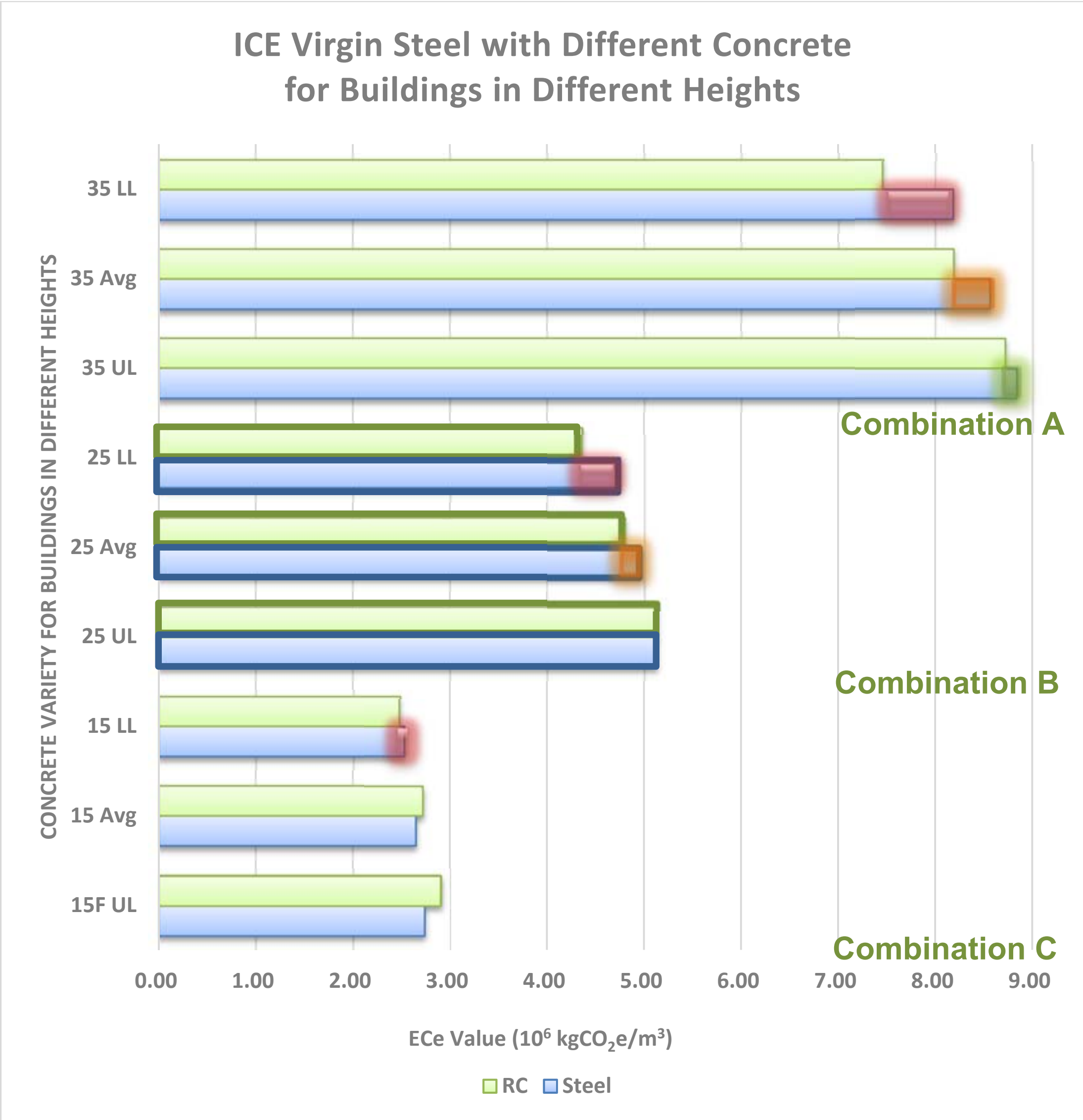


Figure 7. 4 Total Embodied Carbon Values Comparison of Steel and RC Buildings in Virgin Steel with C60 Concrete for Models in Different Heights: Combinations A, B & C.

Combinations D, E & F and Combinations G, H & I

vi. When the steel recycled level increases from virgin to 39%, it is noticed that the advantage of RC Building in terms of lower total embodied carbon emissions become less convincing due to the large percentage of recycled materials in use, even for relatively high level of building models in 35F. Furthermore, as the steel recycled level continues to increase from 39% to 59%, Steel Building models generate absolute environmental efficiency for buildings in all heights, implying the importance of recycled materials application, which would be detailed in the following part of discussion in section 7.4.4.

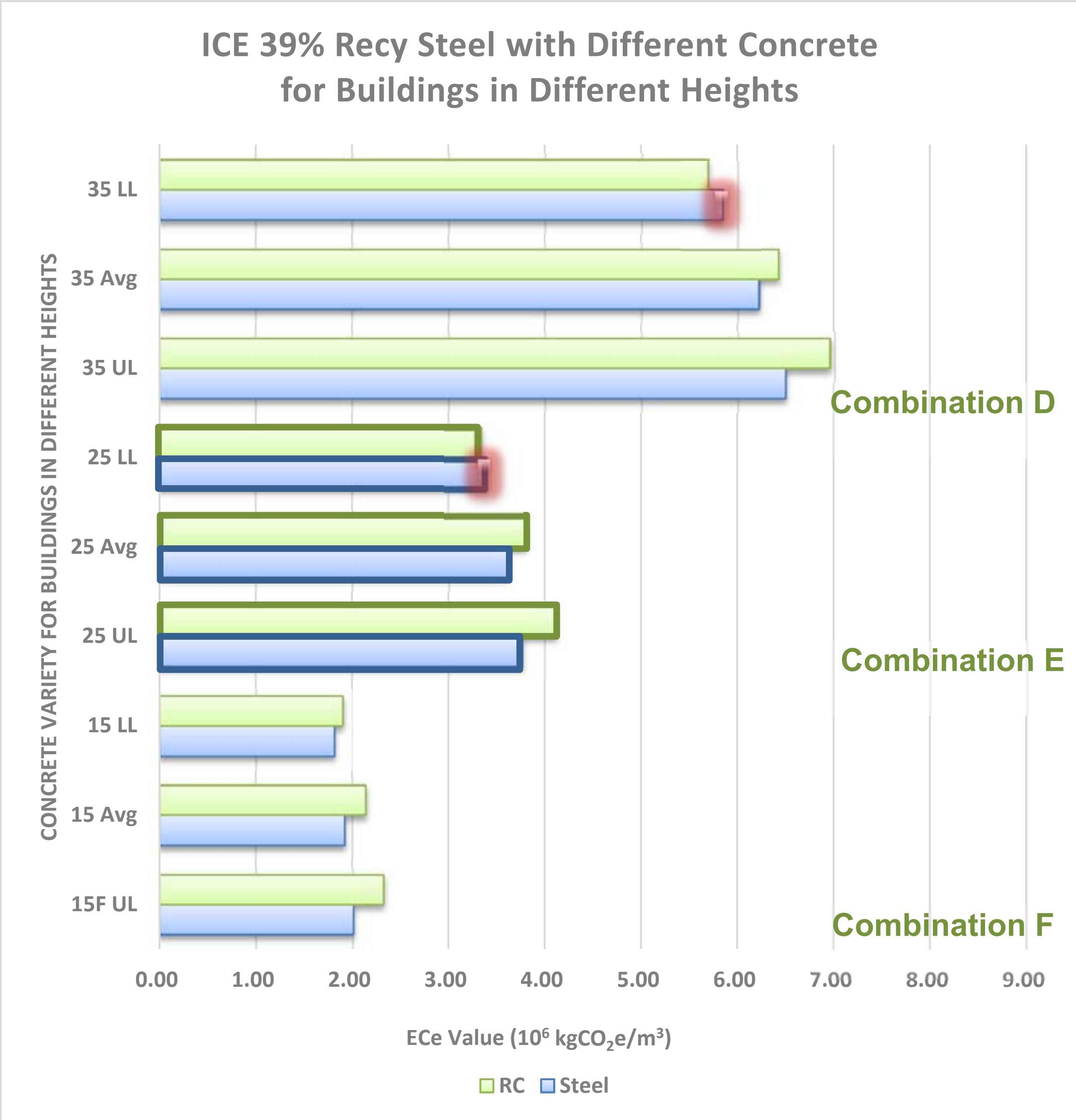


Figure 7. 5 Total Embodied Carbon Values Comparison of Steel and RC Buildings in 39% Recycled Steel (ICE) with C60 Concrete for Models in Different Heights: Combinations D, E & F.

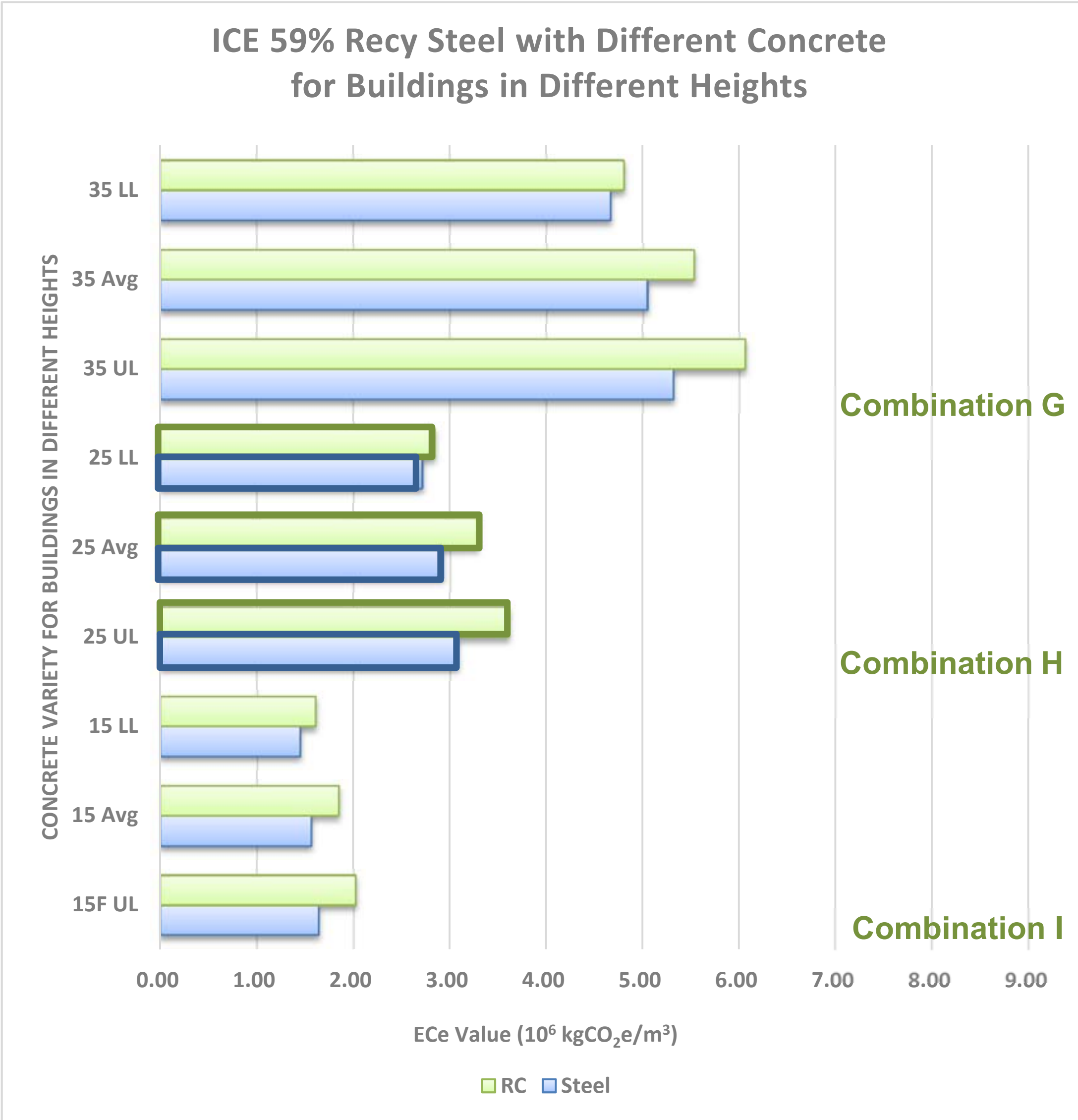


Figure 7. 6 Total Embodied Carbon Values Comparison of Steel and RC Buildings in 59% Recycled Steel (ICE) with C60 Concrete for Models in Different Heights: Combinations G, H& I.

7.4.4. Variable: Steel Carbon Footprint Value

Sorting the total EC values for comparisons, in this section, data were plotted into bar charts along columns in Table 7.5 in order to examine the effects of varying steel carbon footprint data for both Steel Building and RC Building with the same level of carbon footprint value applied to the associated concrete for buildings in different storeys. Totally nine combinations could be summarized under this category.

Combination names could follow the concrete carbon footprint levels and vary according to building levels, such as 15 storeys building in C60 Upper Limit concrete with Different Steel could be labelled as C60_UL, the following combinations are as following, 15F_C60_UL, 15F_C60_Avg, 15F_C60_LL, 35F_C60_UL, 35F_C60_Avg and 35F_C60_LL.

Combination Names		Building Levels		
		15F_C60	25F_C60	35F_C60
Carbon Footprint Level/Range	UL	15F_C60_UL	25F_C60_UL	35F_C60_UL
	Avg	15F_C60_Avg	25F_C60_Avg	35F_C60_Avg
	LL	15F_C60_LL	25F_C60_LL	35F_C60_LL

Table 7. 7 Total EC Values Comparison Combinations for Steel/RC Buildings in C60 Concrete and in Different Steel Recycled Levels for Models in 15F, 25F and 35F

The 25F_C60 series are identical to the C60 series in section 4.4.4.

Compare the 15F_C60, 25F_C60 and 35F_C60 series simultaneously. Figure 7.7, 7.8 & 7.9 show the total EC values with varying levels of recycled steel scrap inclusion, with different CF values applied to the different steel materials combined with each building level series.

As the Recycled Content of Scrap in Steel Products Increases from 0 (virgin) to 39% and then to 59%, it could be apparently noticed from Table 2 that the carbon footprint values of the recycled steel products could be reduced as much as only half of the virgin ones. Therefore, as the recycled content of scrap in steel products increases, observations could be made that,

i. In each of the three Combination Series, the total Embodied Carbon values of both Steel Building system and RC Building System decrease in every concrete carbon footprint level combination. Due to the large decrease of the CF values for the applied steel material with more recycled content of scrap included, the contribution of the carbon footprint due to the steel material obtained a great reduction and therefore further affect the total CF values of both building system in a large scale, thereafter, resulting in the same trend applied to the total Embodied Carbon values of both Steel Building and RC Building systems in all three Series. Especially for 35F series, the total carbon footprint reduction appears to be more significant.

ii. Though the concrete material makes up the majority weights of both the Steel and RC Buildings as shown in Figure 7.3 of the total weight comparison at the beginning of this chapter of content, as the CF values for steel could be as large as 20-30 times of those for concrete, depending on the percentage of recycled steel scrap inclusion, the contribution of the steel material to the total CF values could not be underestimated.

iii. In all the following combinations in the Figure 7.7, 7.8 & 7.9, lengths of arrows indicate the difference between Steel Building and RC Building systems in terms of total EC values adopting the same set of concrete and steel CF values for comparisons. Red arrows mean the total CF value of Steel Building is lower than that of the corresponding RC Building, while yellow arrows mean the total CF value of the RC Building is lower than that of the corresponding Steel Building. The one with the arrow means more environmental friendly in terms of total Embodied Carbons.

iv. In each of the nine combinations, as the recycled content of scrap in steel products increases, which is from virgin to 39% and then to 59%, it could be observed that a) the lengths of red arrows increase as in Combination 15F_C60_UL, 15F_C60_Avg and 25F_C60_UL, or b) the lengths of yellow arrows decrease firstly and then the arrows are switched to red with increasing lengths such as in Combination 15F_C60_LL, 25F_C60_Avg, 25F_C60_LL and the whole 35F series. These observations could provide a conclusion that the advantage of steel building in terms of total EC increases especially with increasing recycled content of scrap in the steel products, especially for low rise buildings so as the Steel Building Design would be more environmental friendly.

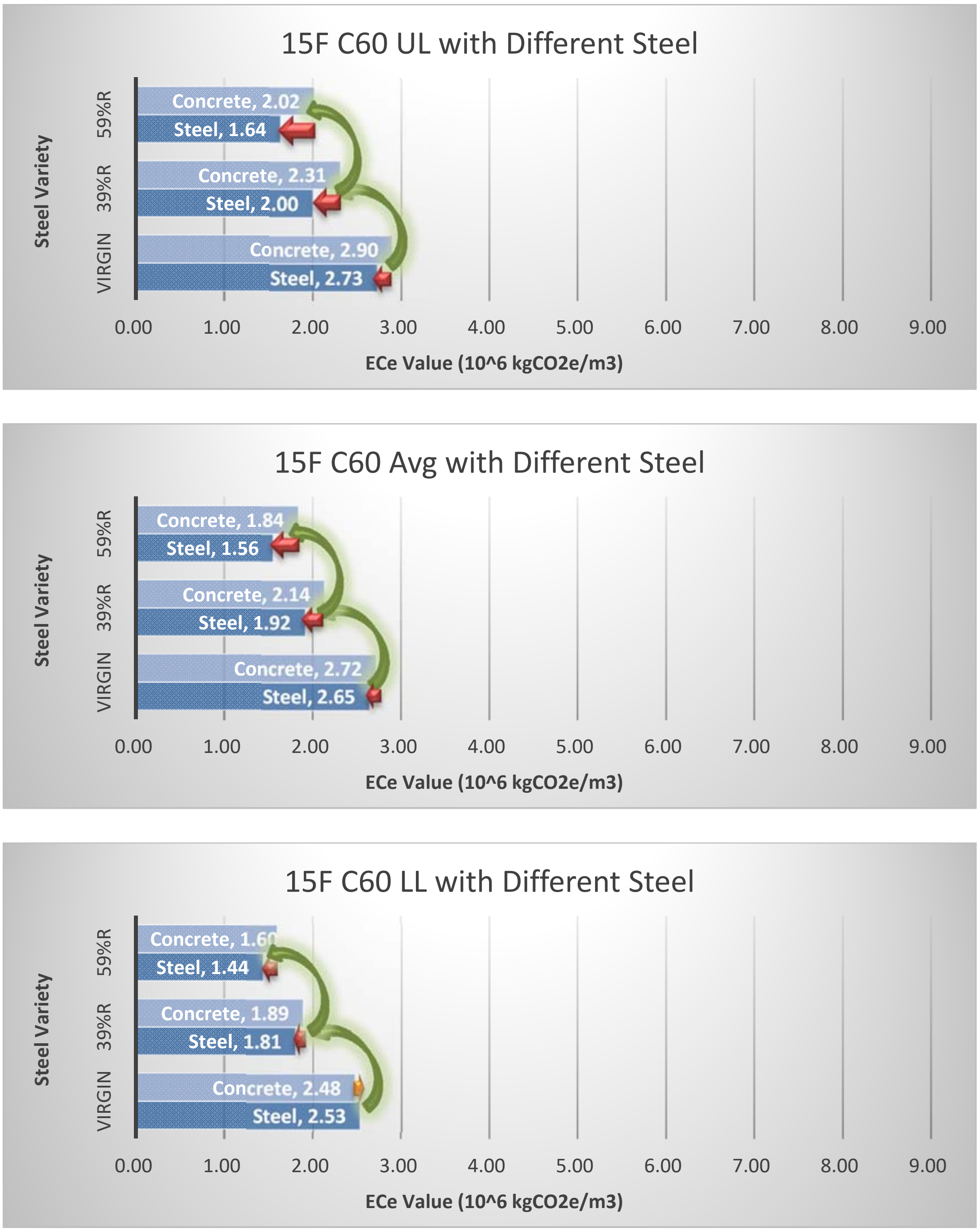


Figure 7. 7 Total Embodied Carbon Values Comparison of Steel and RC Buildings in C60 with Steel in Different Recycled Level for 15F Building Models: Combinations 15F_C60_UL, 15F_C60_Avg & 15F_C60_LL

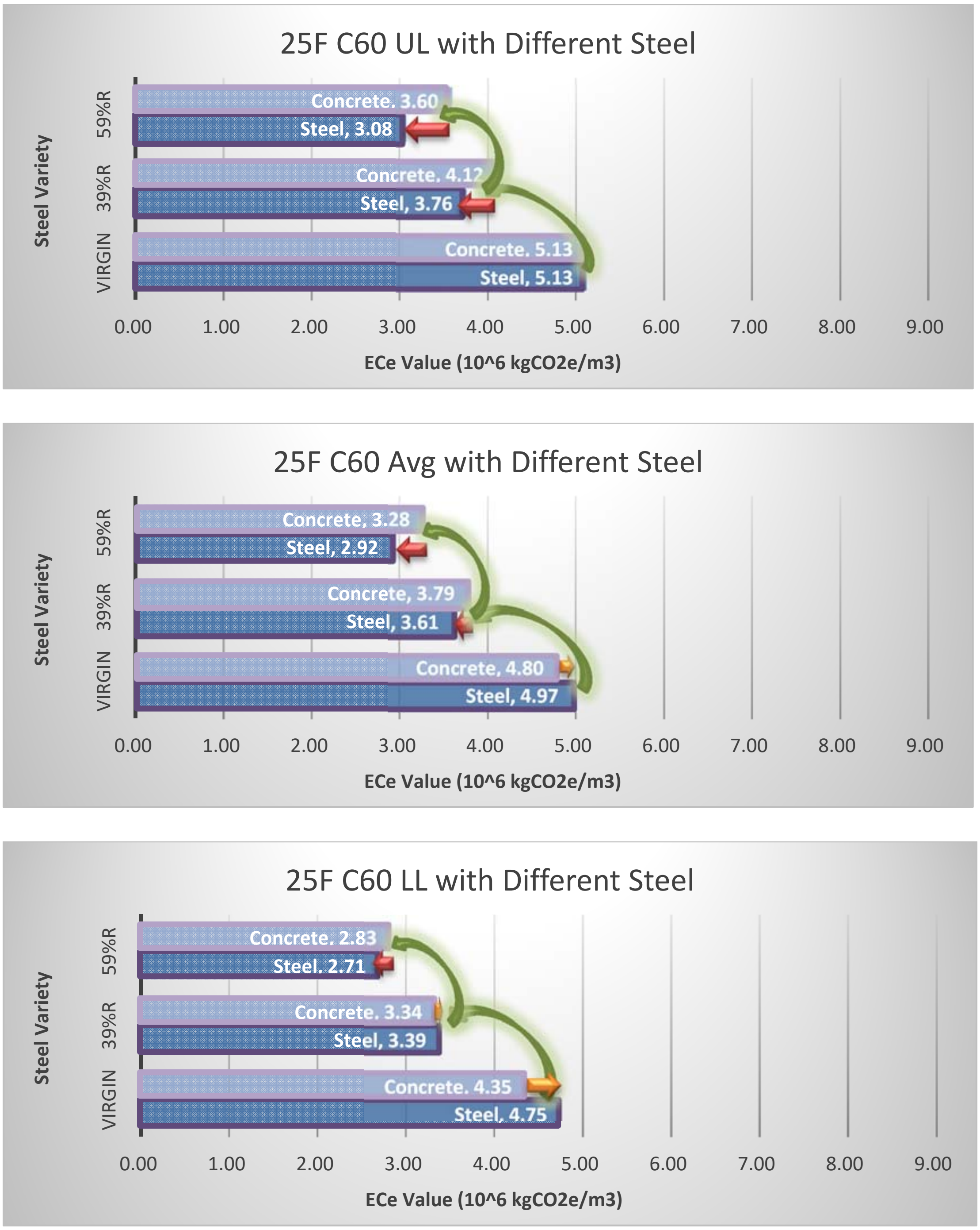


Figure 7. 8 Total Embodied Carbon Values Comparison of Steel and RC Buildings in C60 with Steel in Different Recycled Level for 25F Building Models: Combinations 25F_C60_UL, 25F_C60_Avg & 25F_C60_LL

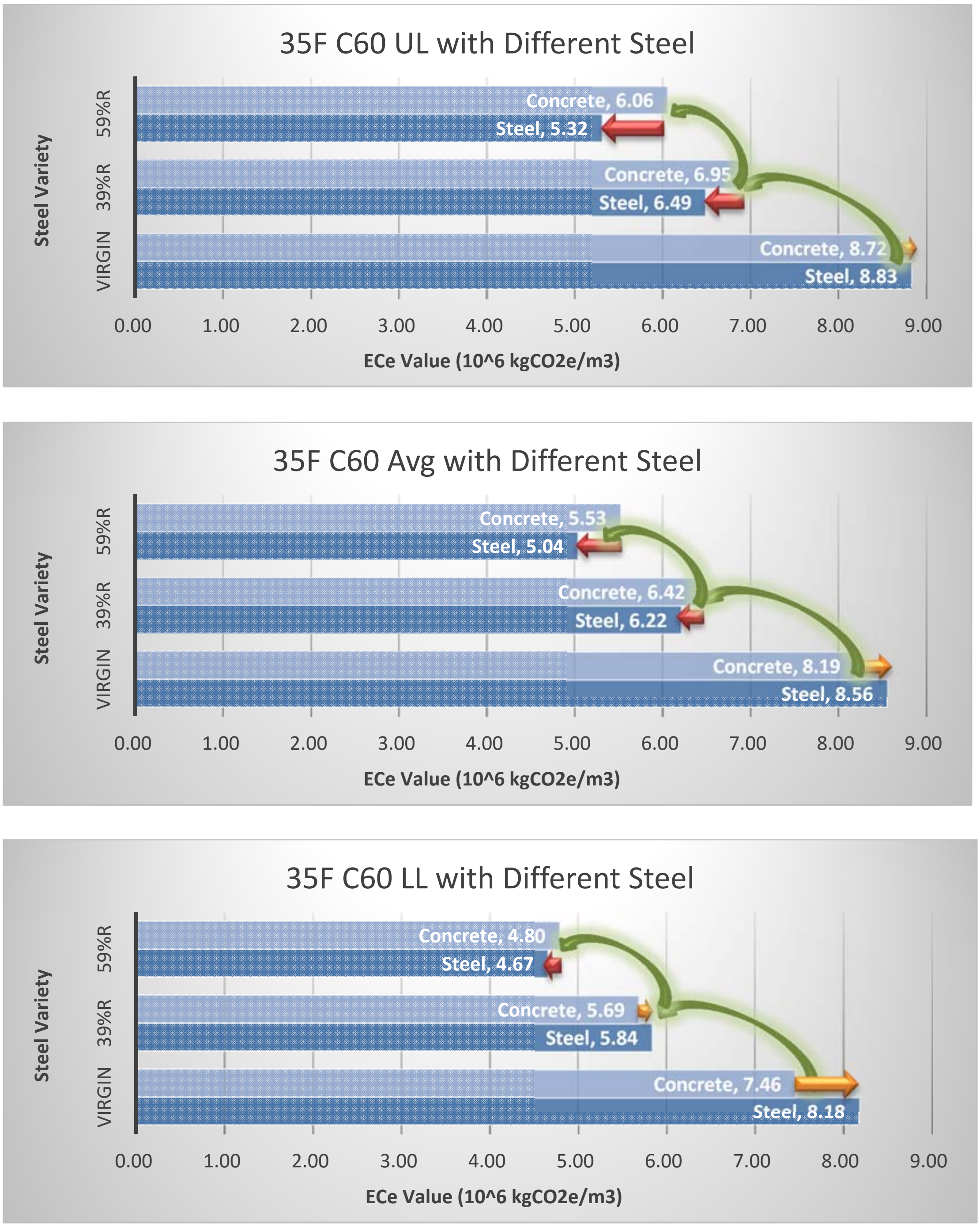


Figure 7. 9 Total Embodied Carbon Values Comparison of Steel and RC Buildings in C60 with Steel in Different Recycled Level for 35F Building Models: Combinations 35F_C60_UL, 35F_C60_Avg & 35F_C60_LL

7.4.5. Effect of Recycled Steel Content Inclusion

The combinations of different steel materials with various recycled rates have been shown in the effects evaluation in the previous section 4.4.6 and section 5.4.5. Such combinations include not only absolute virgin, absolute 39% recycled steel and absolute 59% recycled steel, but also partly virgin and partly recycled steel for steel sections accompanied by virgin rebars or recycled rebars due to the size limitation of recycled steel sections available in Hong Kong construction market.

The steel products adopted in the three building systems include steel sections and steel rebars, so the different combinations can be referred from the following illustrations:

15F Sup Combinations	Steel Section > 305	Steel Section ≤ 305	Steel Rebar	Total Recycled Steel Inclusion
VS59S&59B	Virgin	59%	59%	30%
VS59S&VB	Virgin	59%	Virgin	8%
VS39S&39B	Virgin	39%	39%	19%
VS39S&VB	Virgin	39%	Virgin	5%

Table 7. 8 Total Recycled Steel Inclusion Rates for Different Steel Material Combinations of Building Model in 15F.

25F Sup Combinations	Steel Section > 305	Steel Section ≤ 305	Steel Rebar	Total Recycled Steel Inclusion
VS59S&59B	Virgin	59%	59%	33%
VS59S&VB	Virgin	59%	Virgin	11%
VS39S&39B	Virgin	39%	39%	22%
VS39S&VB	Virgin	39%	Virgin	7%

Table 7. 9 Total Recycled Steel Inclusion Rates for Different Steel Material Combinations of Building Model in 25F.

35F Sup Combinations	Steel Section > 305	Steel Section ≤ 305	Steel Rebar	Total Recycled Steel Inclusion
VS59S&59B	Virgin	59%	59%	24%
VS59S&VB	Virgin	59%	Virgin	1.4%
VS39S&39B	Virgin	39%	39%	16%
VS39S&VB	Virgin	39%	Virgin	1%

Table 7. 10 Total Recycled Steel Inclusion Rates for Different Steel Material Combinations of Building Model in 35F.

The resulting bar charts in Figure 7.10, 7.11 & 7.12 below clearly summarized the comparisons of the total EC of all buildings with the same concrete carbon footprint, as the recycled content of scrap in steel products increases, the total EC value decreases in a similar manner.

Figure 7. 10 Total Embodied Carbon Values Comparison of 15F Steel and RC Buildings in C60 with Steel Materials in Various Recycled Steel Inclusion Scale

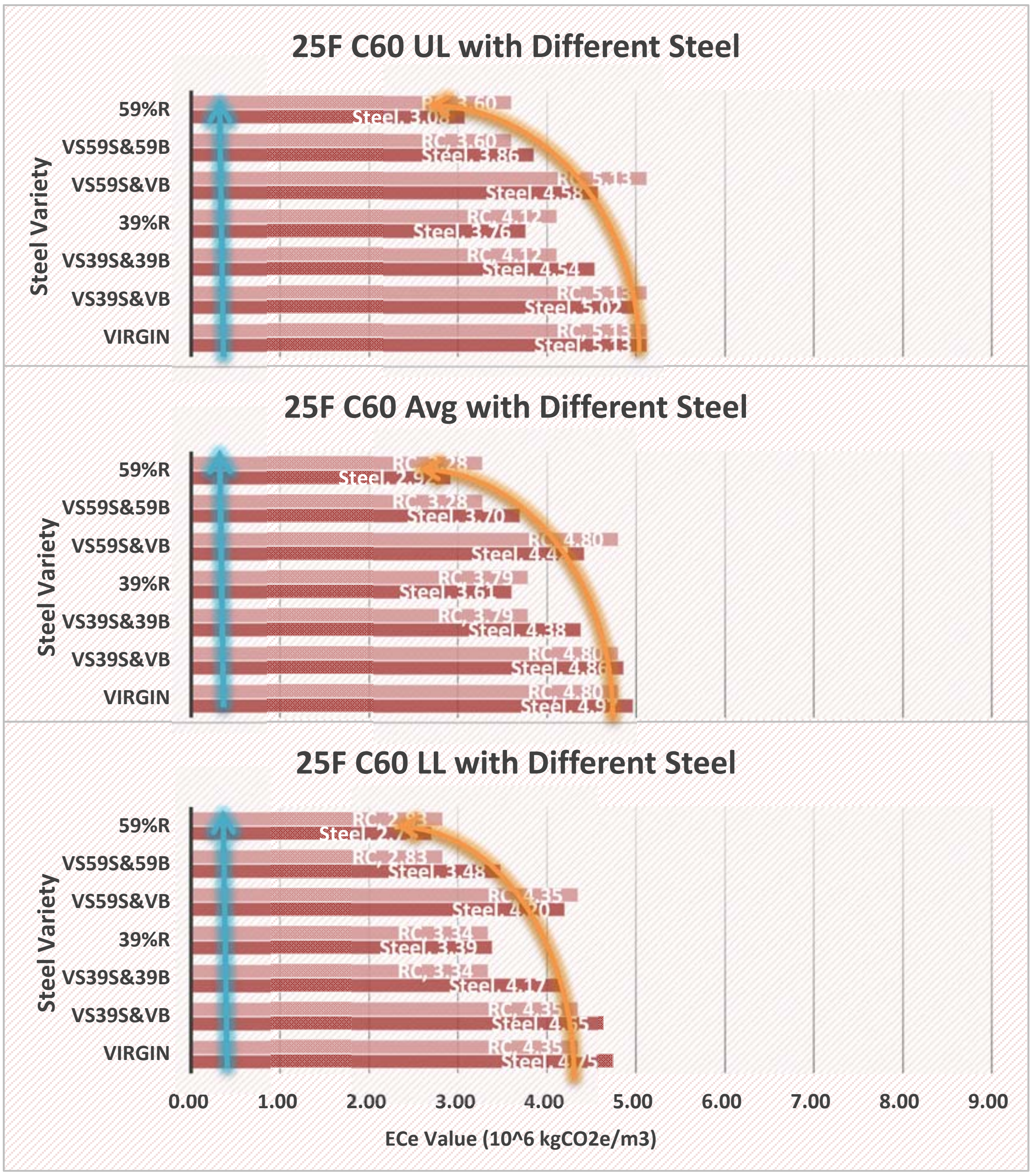


Figure 7. 11 Total Embodied Carbon Values Comparison of 25F Steel and RC Buildings in C60 with Steel Materials in Various Recycled Steel Inclusion Scale

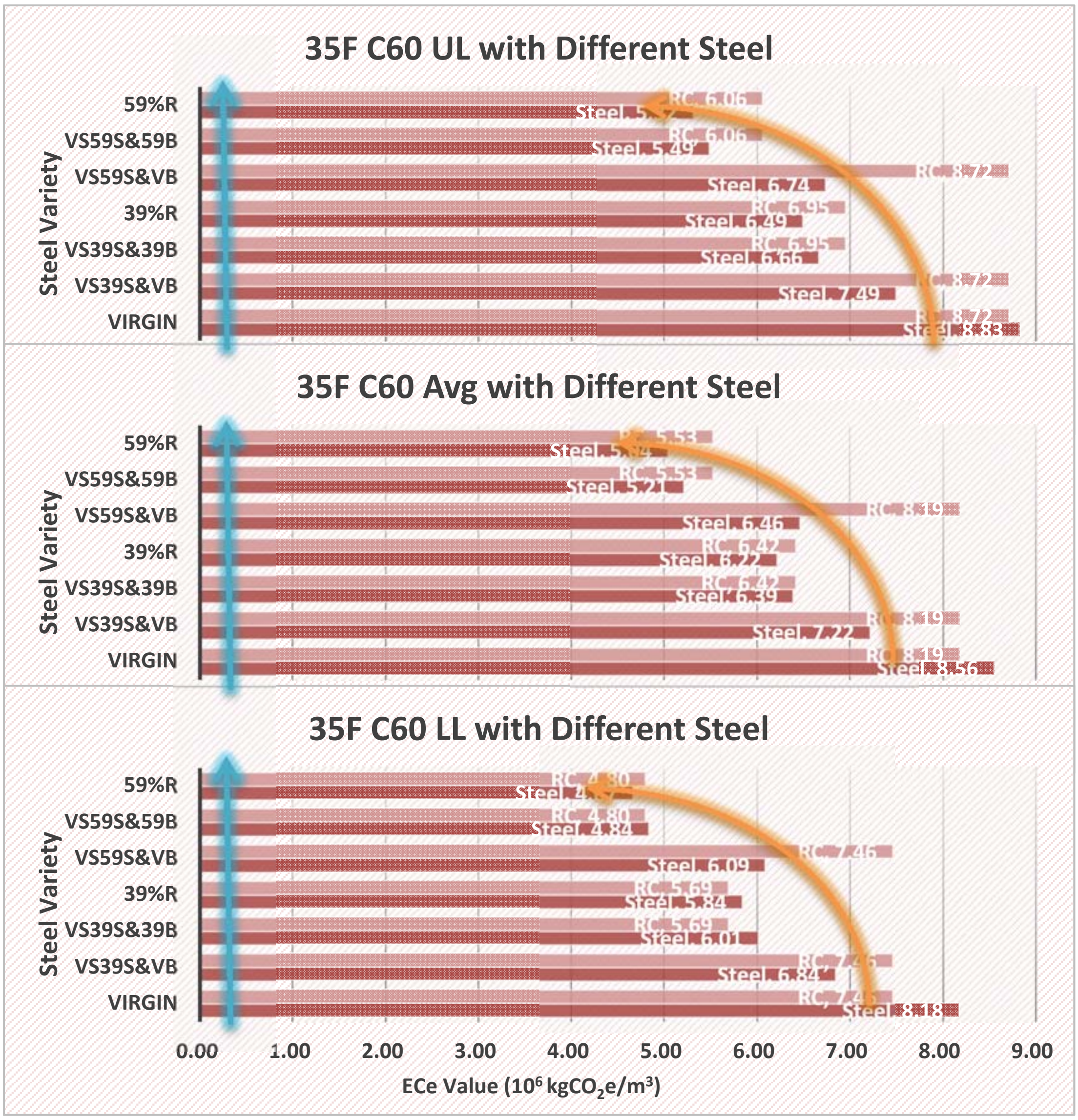


Figure 7. 12 Total Embodied Carbon Values Comparison of 35F Steel and RC Buildings in C60 with Steel Materials in Various Recycled Steel Inclusion Scale

Plot the above mentioned total ECe values in the following Figure 7.13 (a) ~ (d).

For building systems in different levels, the average carbon footprint value for C60 was selected to provide an overview of this set of comparison.

As concluded in the previous comparison studies in Chapter 4 and Chapter 5, the more recycled material used, the more environmental friendly the design would be. However, due to the product availability and size limitation in the certain construction material market, it is not practical to have all the products in application to be composed of fully recycled materials for the whole building system. Therefore, in this section, the relative environmental advantage of either the Steel Building Scheme or the RC Building Scheme in terms of lower total carbon emissions is also well deserved to be explored for building systems in lower rise 15 storeys and higher rise 35 storeys.

Figure 7.13 (a) provides a summary of all the total ECe values of both building schemes in different heights. The associated steel products adopted, recycled steel component percentage and the corresponding total ECe values for both Steel and RC Building systems in 15F, 25F and 35F could be referred in the following Table 7.11.

Building Levels	Steel Components	Recycled Steel Inclusion	Total ECe of Steel Building	Total ECe of RC Building
15F	Virgin	0%	2.65	2.72
	VS39S&VB	5%	2.47	2.72
	VS59S&VB	8%	2.23	2.72
	VS39S&39B	19%	2.22	2.14
	VS59S&59B	30%	1.85	1.84
	39%R	39%	1.92	2.14
	59%R	59%	1.56	1.84
25F	Virgin	0%	4.97	4.80
	VS39S&VB	7%	4.86	4.80
	VS59S&VB	11%	4.42	4.80
	VS39S&39B	22%	4.38	3.79
	VS59S&59B	33%	3.70	3.28
	39%R	39%	3.61	3.79
	59%R	59%	2.92	3.28
35F	Virgin	0%	8.56	8.19
	VS39S&VB	1%	7.22	8.19
	VS59S&VB	1.4%	6.46	8.19
	VS39S&39B	16%	6.39	6.42
	VS59S&59B	24%	5.21	5.53
	39%R	39%	6.22	6.42
	59%R	59%	5.04	5.53

Table 7. 11 List of Superstructure Total Carbon Emission Equivalent Values for Building Models in 15F, 25F & 35F

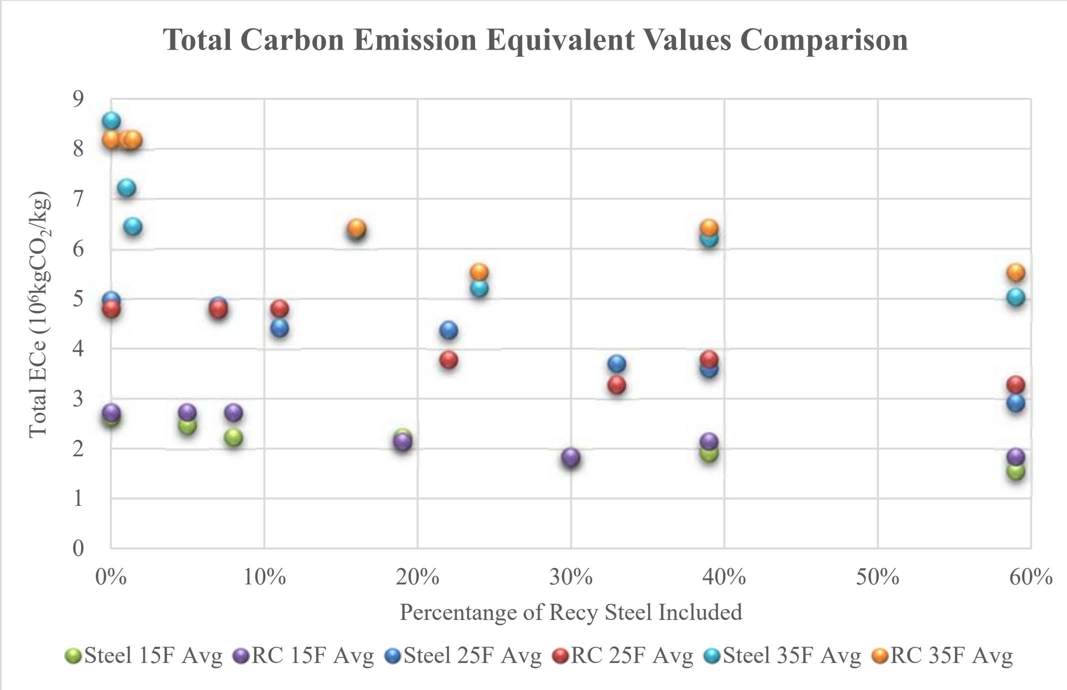


Figure 7. 13 Superstructure Total Carbon Emission Equivalent Values Comparison for Building Models in 15F, 25F & 35F: (a) Summary

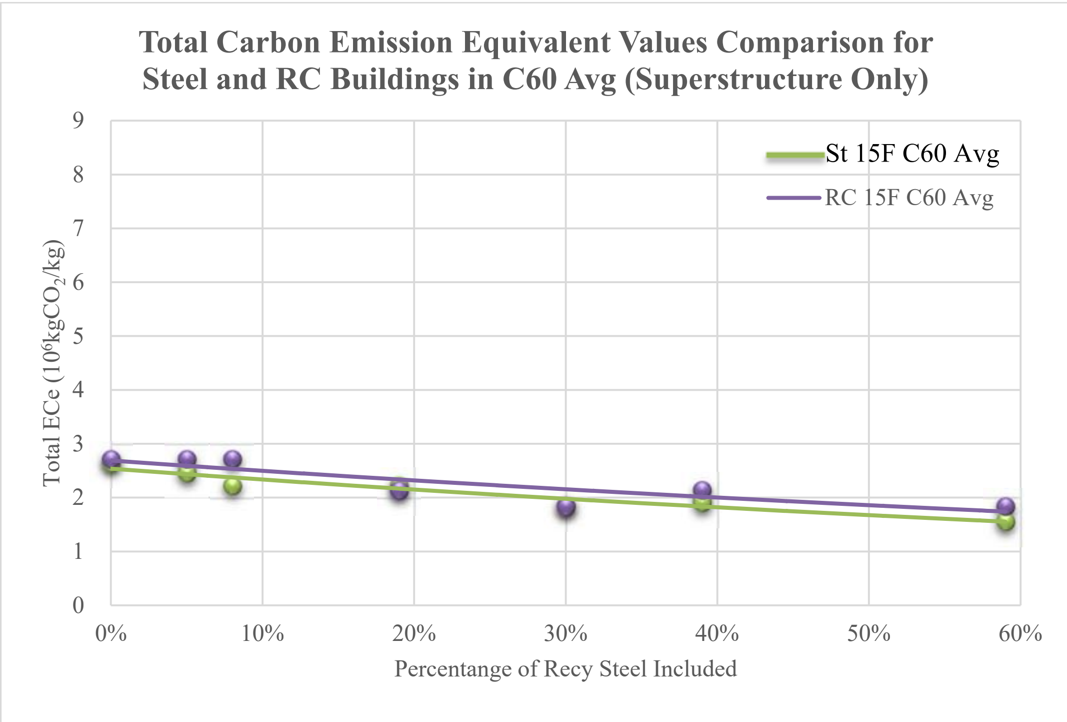


Figure 7. 13 (b) Comparison for 15F Building Models

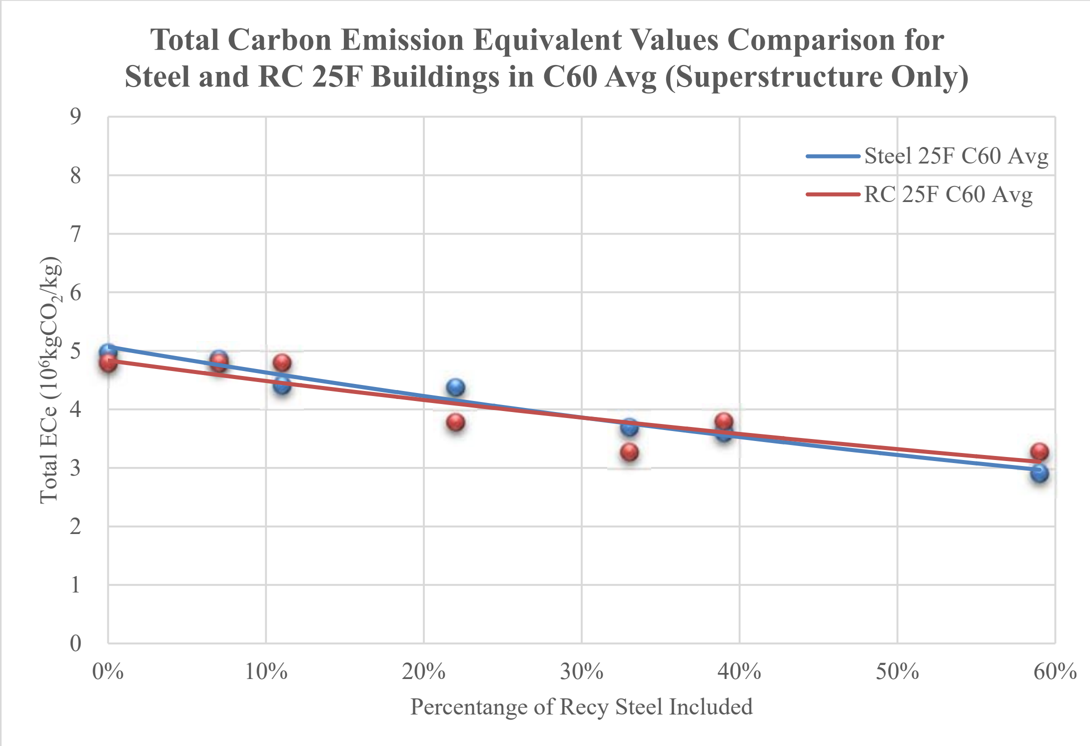


Figure 7. 13 (c) Comparison for 25F Building Models

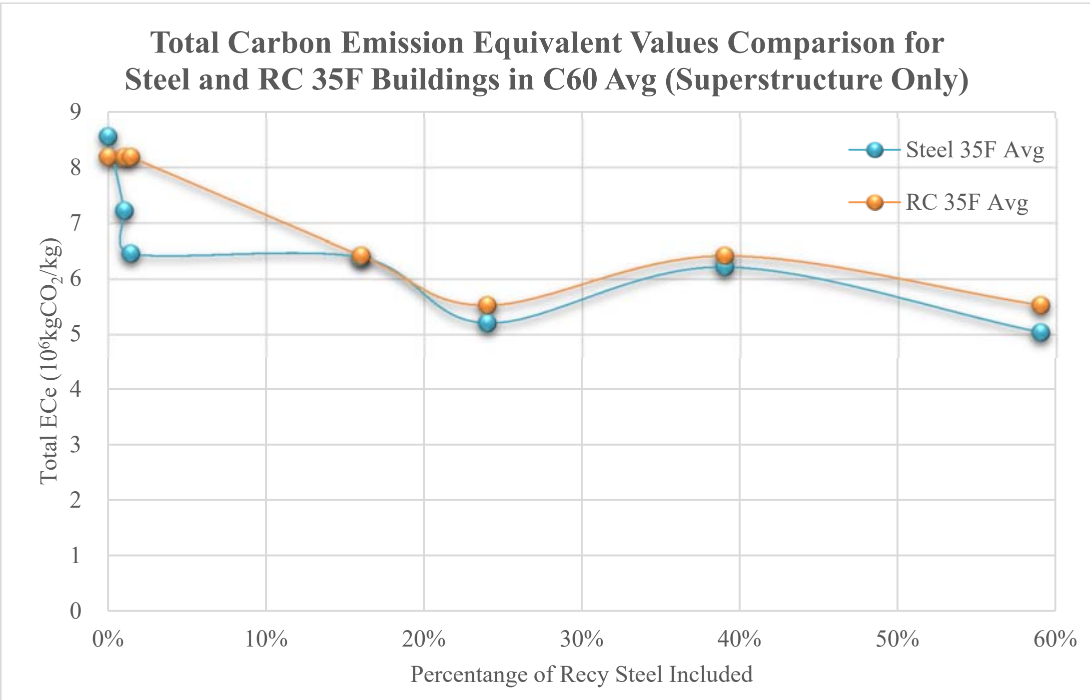


Figure 7. 13 (d) Comparison for 35F Building Models

In Figure 7.13 (b) ~ (d), trendlines were added to each set of total ECe results for both building schemes.

Figure 7.13 (c) is actually identical to Figure 4.13 (b) in section 4.4.6 for the superstructure Steel and RC Building designs in 25 storeys. an interception was noticed at around 28% at x-axis, which means that RC Building generates lower environmental impacts than Steel Building when low carbon footprint (low grade) concrete is used with recycled scrap rate of steel under 28%, otherwise, Steel Building generates lower environmental impacts when low carbon footprint (low grade) concrete is used with more than 28% recycled steel applied in the design.

Figure 7.13 (b) exhibits the total ECe results with different recycled steel inclusion for the Steel and RC Building Schemes in 15 storeys. The trendlines' showed no interception within the given recycled steel inclusion rate range, which indicates the absolute environmental advantage of Steel Design for the lower rise 15F building in terms of lower carbon emissions.

In Figure 7.13(d), the trendlines added was a little different from the rest due to the extremely low percentage of recycled steel product included, but these trendlines could also be considered to meet the purpose of comparison reasonably. When building height increases, more elements would be in need of size increase, resulting in fewer elements would be eligible to fall below the 305 limitation for recycled steel products application. As a matter of that, the recycled steel inclusion rate would be farely low for recycled steel products and virgin steel products adopted in the same building and it could be observed from the figure that the total ECe results for both building schemes in 35 storeys are very closed given the recycled steel inclusion rate under 16%. Obvious advantage appears only when the recycled steel inclusion percentage exceeds 16, i.e. the 35F Steel Building is more environmental friendly than the 35F RC Building if more than 16% of steel adopted in the whole Steel Building system was recycled steel.

As a conclusion of the above observations, for such lower rise commercial buildings in Hong Kong construction market, Steel Nonlinear analysis provides a structural and environmental efficient design option while for higher rise commercial buildings, certain recycled steel rates should be reached for Steel Building option achieving the most strutural and environmental efficiency. The certain percentage of recycled steel inclusion required would be subjected to building systems design schemes and should then be analysed case by case for a more environmental design option to be scientifically conducted.

CHAPTER 8

ENVIRONMENTAL IMPACTS COMPARISON OF A COMPOSITE AND A STEEL BUILDING WITH THE APPLICATION OF LOW-CARBON MATERIALS

Results from previous studies have been collated through the quantification and mitigation of total embodied carbon (EC) in a system level for steel and reinforced concrete (RC) design buildings at different heights with the scientific integration of low carbon materials and Nonlinear Structural optimisation. This section aims to further explore the environmental impacts of a steel building specifically designed with composite floor systems compared with a nonlinear steel design solution. As composite designed buildings have their exceptional advantages in material saving, cost saving and time saving, thereafter, this part of research serves as a supplementary study based on the environmental impacts evaluation methods conducted in the previous contents. The advantage of composite buildings' environmental sustainability would be able to be illustrated in a quantitative way. More low carbon building design options will be provided for the future reference of developers and engineers.

8.1. Summary of Building Models

A twelve-storey building modified from a real design project in Hong Kong has been selected as the analysis model for this comparative study. Two design schemes were carried out for this building to satisfy the design requirements in Hong Kong at the same time with their performance, i.e. serviceability limit states, under the same loading condition as closed as possible to make these two design schemes comparable.

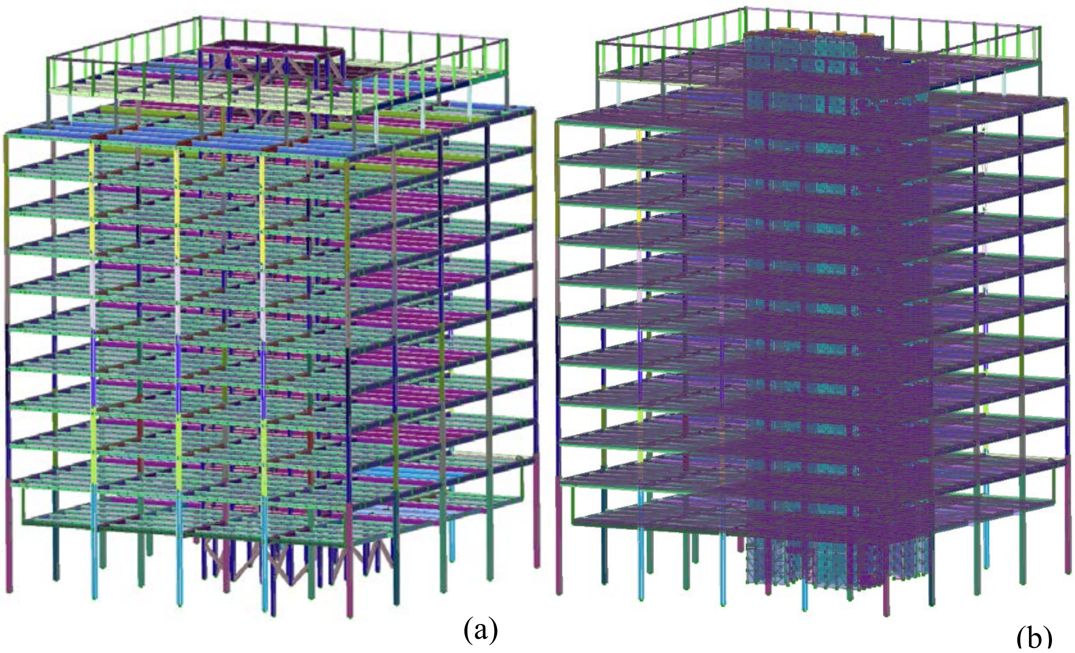


Figure 8. 1 Composite Building Models' Configurations of
(a) Steel Building and (b) Composite Building.

The building model was firstly designed in a steel structural frame ("Steel Building") consisting of steel beams, steel columns, steel bracing system all in steel grade of S355 with no RC structural walls and structural floors. Lateral stiffness is provided by steel lateral bracings to resist wind actions. Vertical actions including self-weight, super-imposed dead load, live load, etc., are resisted by steel beams through which are further transferred to the steel columns down to the ground. The structural configuration is illustrated in Figure 8.1(a).

On the other hand, in the second scheme, the building model was designed to be a hybrid steel and concrete structure ("Comp Building") consisting of steel columns, steel beams in steel grade of S355 with composite floor systems (including steel I-shape cellular beams to increase the structural efficiency acting together with composite floors), concrete grade C32 RC core-walls, RC beams. Lateral stiffness is provided by RC core-walls to resist wind actions. Vertical actions including self-weight, super-imposed dead load, live load, etc., are resisted by the composite floor system supported by steel cellular beams and through which are further transferred to the steel columns and RC walls and downward to the ground. The structural configuration is illustrated in Figure 8.1(b).

This preliminary appraisal assesses the structural behaviour of the building under dead, imposed and wind actions, as well as the effects due to temperature variation by direct analysis approach. All relevant loadings are considered to be applied either in individual or in such realistic combinations as to comprise the most critical effects on all the structural elements and the structure as a whole. The ultimate limit safety state and serviceability limit state cases are analysed to capture the fundamental requirements for the reliability of construction works.

8.2 Analysis Method

The second-order direct analysis suggested by the Hong Kong Steel Code 2011 was performed in this design on the deformed structures. Both P-Δ sway and P-δ bow nonlinear effects were included for determination of stresses in equilibrium with the defined actions for a global analysis dependent on geometrical, structural and material properties. NAF series – Non-linear Integrated Design and Analysis (NAF-NIDA) version 9.0 was employed for the second-order elastic analysis conducted in this study, which was an already approved approach for the non-linear analysis and design to Code of Practice for the Structural Use of Steel 2011 [38] and Eurocode-3 [26], with a number of application in the UK, Singapore, Hong Kong, China, Macau, Taiwan, India, and Myanmar, etc, in the past decade. With a conventional linear analysis, it is difficult to determine and visualise the real action effects especially in terms of the steel-composite floor system actions in which the simple effective length assumption is no longer reliable without taking consideration of secondary stresses and buckling effects.

8.3 Embodied Carbon Footprint

8.3.1 Data

The quantification of the construction buildings' total carbon footprint (CFP) was calculated by the accumulation of all the construction materials' carbon footprints. The CFP calculated under this Scheme was based on a "cradle-to-site" approach, covering all GHG emissions and removals of the product arising from raw material acquisition, transportation, production process, storing/packaging and finally transporting to the border of Hong Kong.

Currently, the Scheme database includes rebars and structural steel products as well as concrete products ranging from C30 to C60 grade concrete. The lowest carbon footprint values are 0.55 and 2.08 $kgCO_2e/kg$ for rebar and structural steel section available in Hong Kong construction material market respectively. However, due to the limitation of the product varieties and availability of the particular recycled rates of products provided in the Scheme database, a more consistent and systematic database, Bath Inventory of Carbon & Energy (ICE) Version 2.0 [35], was referred regarding the carbon footprint values for ready-mixed concrete in various grades, as well as steel rebars and sections with different recycled contents. The CFPs applied in this study are listed in the following Table 8.1 & 8.2:

Database	ICE			HKCIC
Concrete	Upper Limit (UL)	Average (Avg)	Lower Limit (LL)	
C32	337	276	197	~250

Table 8. 1 The Carbon footprint data of concrete applied in Composite Building Models (Unit: kg CO_2e/m^3)

Database	ICE			HKCIC
Steel	100% Virgin	39% Recycled	59% Recycled	Unknown
Section	3.03	2.03	1.53	2.08
Bar	2.77	1.86	1.40	0.55
Stainless Steel	6.15	N/A	N/A	Unknown

Table 8. 2 The Carbon footprint data of Steel Products applied in Composite Building Models (Unit: kg CO_2e/m^3)

8.3.2 Total EC Accumulation Methods.

Two series of results were collected, interpreted and compared in terms of both design schemes. As noted in the previous section, total carbon footprint is contributed by the accumulation of all the construction materials' carbon footprints. In the Steel Building, all the loadings are supported by steel members with no structural walls and slabs taking action. However, in the Comp Building, the steel composite floor systems consist of steel beams with composite decking system acting together with stainless steel deck sheet, concrete fill and shear studs. From a structural point of view, the total carbon footprints should include all the structural elements of the building system. Therefore, to make the two design schemes comparable, the range of structural elements included will fall into two categories, i.e. with or without slabs.

Comparison	**Steel Building**	**Comp Building**
8.1	**steel beams** **steel columns** **steel bracings**	**steel beams** **steel columns** **RC core-walls** **RC beams**
8.2	**steel beams** **steel columns** **steel bracings** **flat slabs**	**steel beams** **steel columns** **RC core-walls** **RC beams** **composite slabs**

Table 8. 3 Structural Elements Included in Calculation for Composite Building Models

8.4 Results Discussion

From Comparison 8.1, the advantages of Comp Building are to be examined by comparing the environmental effects of the accumulation of all structural elements supporting the horizontal loadings and vertical loadings. Therefore, it is expected to see how much could be saved in material used and total embodied carbon (EC) due to the bonding action provided by the composite floor system compared with flat slabs.

From Comparison 8.2, the slabs were taken into account in calculating the total EC. In the Comp Building, the total carbon footprint should include the slabs consist of concrete, steel sheet, sheer studs and reinforcements, while in the Steel Building, only concrete slabs with reinforcements in the same depths were included serving as comparable purpose between the two schemes. Thereafter, effects of the inclusion of the stainless steel deck sheet will be illustrated from the following comparison studies.

8.4.1 Total Weight.

In Comparison 8.1, the total weight of Steel Building frame is less than 1/3 of that of Comp Building. In Comparison 8.2, the total weight of Steel Building frame is around 2/3 of that of Comp Building. These two comparisons both showed a great level of decrease in material consumption in the nonlinear optimized Steel Building Scheme, which further infers that the underground construction could save even more material and cost under this scheme.

8.4.2 Total Embodied Carbon.

Based on the CFPs in Table 8.2 & 8.3, total carbon footprints of Steel Building and Comp Building have been calculated both in Comparison 8.1 & 8.2, in the unit of $10^6 kgCO_2e$. The steel sections and rebars were assumed to be made of uniform virgin steel, or steel material with 39% recycled scrap, or steel material with 59% recycled scrap according to ICE database. The total EC value with the adoption of the lowest values available from CIC Carbon Labelling System for steel sections and rebars were also included in Table 8.4.

Comparison	1 (C32, Unit: $10^6 kgCO_2e$)			2 (C32, Unit: $10^6 kgCO_2e$)		
Steel Building	**UL**	**Avg**	**LL**	**UL**	**Avg**	**LL**
Virgin	4.73	4.73	4.73	5.55	5.42	5.26
39%R	3.17	3.17	3.17	3.95	3.82	3.66
59%R	2.39	2.39	2.39	3.14	3.02	2.86
HKCIC	0.86	0.86	0.86	1.64	1.52	1.35
Comp Building	**UL**	**Avg**	**LL**	**UL**	**Avg**	**LL**
Virgin	4.24	4.15	4.03	6.27	6.04	5.75
39%R	3.01	2.92	2.80	4.99	4.77	4.48
59%R	2.39	2.30	2.18	4.35	4.13	3.84
HKCIC	1.81	1.72	1.60	3.80	3.58	3.29

Table 8. 4 Total Embodied Carbon Values Associated with Different Materials for Composite Building Models

8.4.3 Variable: Concrete Carbon Footprint Value.

The optimization reduction rates achieved by using Steel Building Scheme compared with Comp Building Scheme have been presented in the following Figure 8.1.

It could be observed that,

(a) From all the four rows of data for Steel Buildings in Comparison 8.1 as shown in Table 8.4, the same total EC values were observed for Steel Building made up of the same steel material. Since no concrete material of Steel Building was taken into account in Comparison 8.1, the total ECs of Steel Building depend only on the recycled contents of scrap in steel products, but not on the concrete carbon footprint values;

(b) From the rest three sets of four rows of data for Steel Buildings in Comparison 8.2, for Comp Building in Comparison 8.1 & 8.2 as shown in Table 8.4, the total EC of buildings with the same steel material adopted decreases as the carbon footprint value of the concrete adopted decreases;

According to Figure 8.2, relative total EC reduction of Steel Building with respect to Comp Building have been plotted for using C32 Avg concrete with various steel recycled rates (straight line for Comparison 8.2, dotted lines for Comparison 8.1).

(c) All the results from Comparison 8.1 are located below the x axis, i.e. in Comparison 8.1, Comp Buildings have lower total ECs than Steel Buildings;

(d) All results from Comparison 8.2 are located above the x axis, i.e. in Comparison 8.2, Comp Buildings have higher total ECs than Steel Buildings; since every line represents the total EC values of building models consisting of steel materials with the same recycled scrap level, therefore for every steel scrap recycled level, i.e. every line;

(e) In Comparison 8.1, as the carbon footprint value decreases for the concrete content of the two buildings, the advantage of Comp Building in terms of lower total EC increases;

(f) In Comparison 8.2, as the carbon footprint value decreases for the concrete content of the two buildings, the advantage of Steel Building in terms of lower total EC decreases, but even with the application of concrete material with the lowest carbon footprint value, the advantage of Steel Building still exists in a general level.

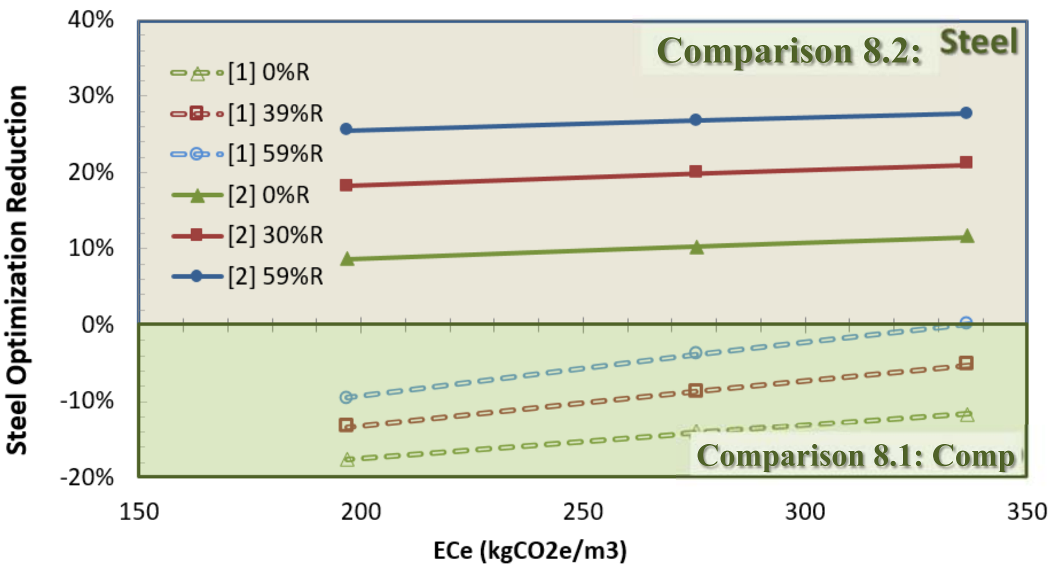


Figure 8. 2 The Steel Building Optimization Reduction Rates: Relative Total EC

8.4.4 Variable: Steel Carbon Footprint Value.

In real application, it is not practical to use recycled steel in the whole building structure due to size limitation of recycled steel products available and also as required in the Hong Kong local construction market. For example, in Hong Kong, the size limit of recycled steel section could be adopted is UKB305, so for steel beams and columns sized above UKB305, virgin steel sections should be applied strictly. The combinations of different steel materials with various recycled rates contribute to a steel recycled rates scale as shown along the y-axis in Figure 8.3 & 8.4.

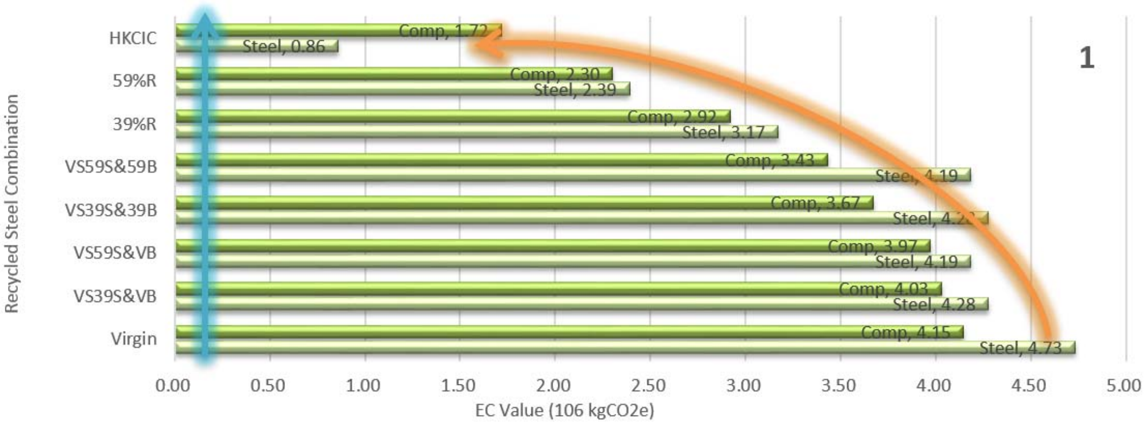


Figure 8. 3 Comparison 8.1: Total EC Values in C32 Avg CFP with Various Recycled Steel Material Inclusion Rates

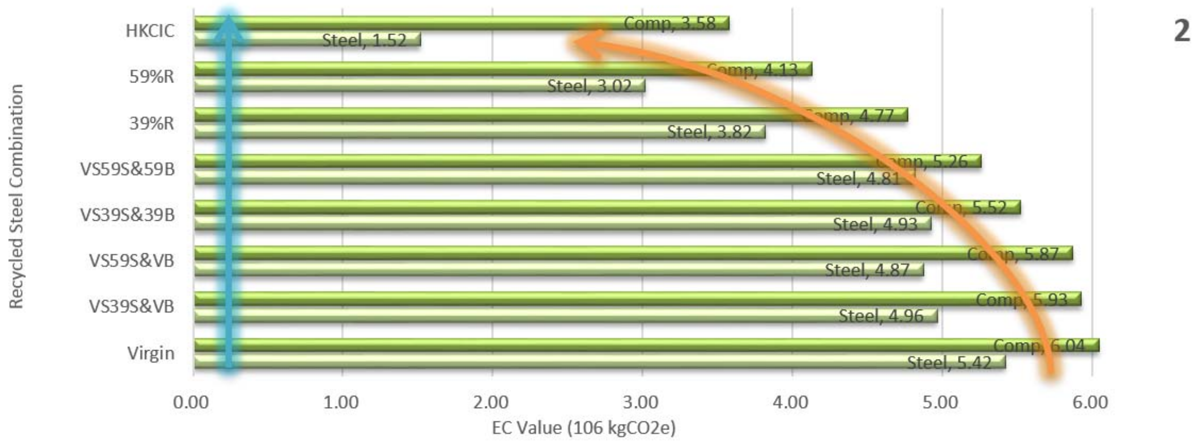


Figure 8. 4 Comparison 8.2: Total EC Values in C32 Avg CFP with Various Recycled Steel Material Inclusion Rates

(a) It could be apparently summarized from the comparisons of total EC of all buildings with the same concrete carbon footprint as shown in Figure 8.3 & 8.4, as the recycled content of scrap in steel products increases, the total EC value decreases. The same trends of total EC values' decrease apply to all Steel Buildings and Comp Buildings in Comparison 8.1 & 8.2 as shown in Figure 8.3 & 8.4.

In Comparison 8.1, (b) Figure 8.5 shows three sets of comparison lines of total EC values of both building schemes designed with different concrete carbon footprint values. The lines for Comp Buildings locate generally below those for Steel Buildings in Comparison 8.1, which represents the advantage of Comp Building in terms of lower total EC. Because of the little amount of section under UKB305 used in combinations from VS59S&59B to VS39S&VB as listed long Figure 8.3 & 8.4 y-axes, the inclusion of recycled steel is very limited, so the two lines are very closed when steel recycled rate is low in Figure 8.5 UL, Avg & LL. However, for upper limit and average carbon footprint values applied in both building schemes, interceptions were found at around 60% in x-axes, which means Comp Building generates lower environmental impacts than Steel Building when high carbon footprint concrete is used with recycled scrap rate of steel under 60%, otherwise, Steel Building generates lower environmental impacts when high carbon footprint concrete is used with more recycled steel applied in the design.

(c) As the carbon footprint value of concrete decreases, i.e. concrete with low carbon footprint is adopted, Steel Building could hardly win Comp Building in terms of environmental friendly since very high percentage of recycled steel is required for application, which can barely be satisfied given the practical market availability.

In Comparison 8.2, (b) Figure 8.6 shows three sets of comparison lines of total EC values of both building schemes designed with different concrete carbon footprint values. The lines for Steel Buildings locate wholly below those for Comp Buildings in Comparison 8.2, which represents the advantage of Steel Building in terms of lower total EC. This is totally opposite from the results obtained in Comparison 8.1.

(d) Whatever the carbon footprint value of concrete is, no interception could be observed or even deduced from the trend of the curves, which means Steel Building has the absolute environmental advantage over Comp Building independent of the concrete carbon footprints and steel recycled levels with the inclusion of concrete or composite slabs in the calculation of total EC. Though the total weight of the steel deck sheet is too small to be comparable to the total weight of the Comp Building, the CFP value of stainless steel as shown in Table 8.2 could indicate the large contribution of embodied carbon amount to the total EC value of Comp Building, there results in the absolute advantage of Steel Building in terms of environmental impacts over Comp Building design scheme.

Comparison 8.1

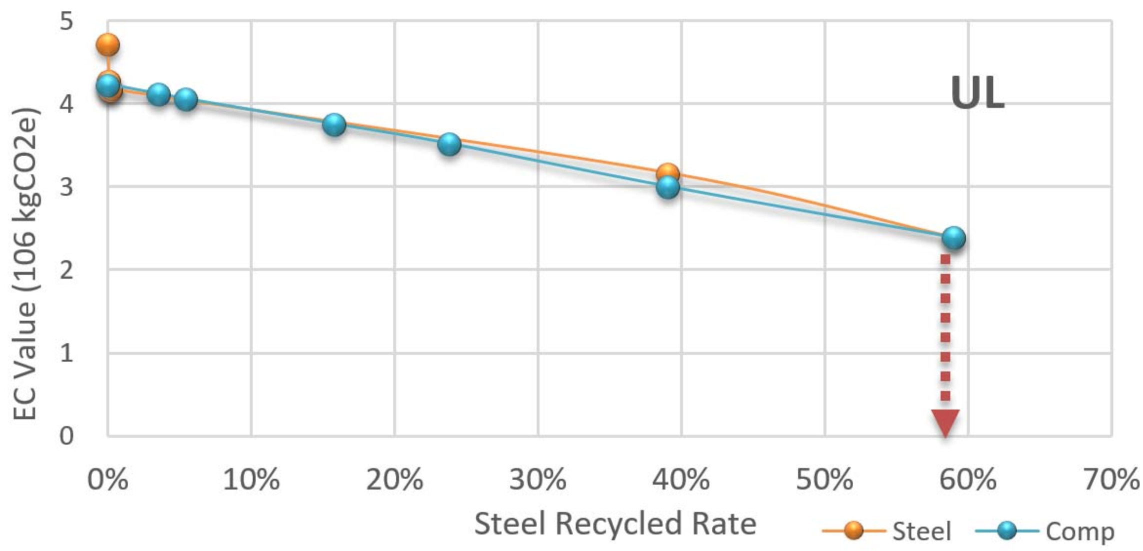


Figure 8. 5 Comparison 8.1: Total EC Values of Both Building Schemes Designed with Different Concrete/Steel Carbon Footprint Values: (a) Comparison 8.1 Composite Building Models in C32 UL

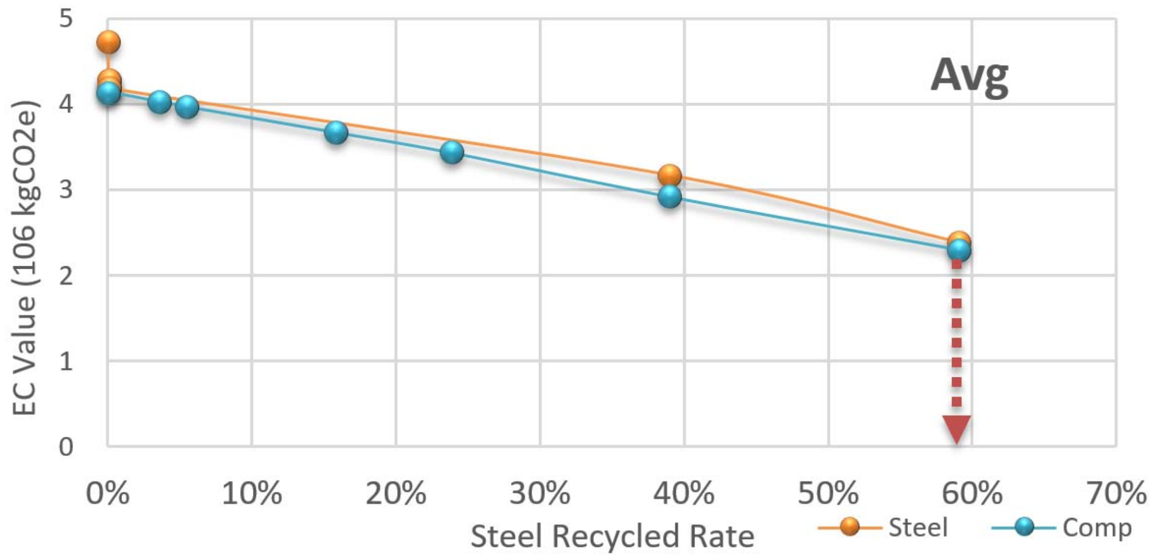


Figure 8. 6 (b) Comparison 8.1 Composite Building Models in C32 Avg

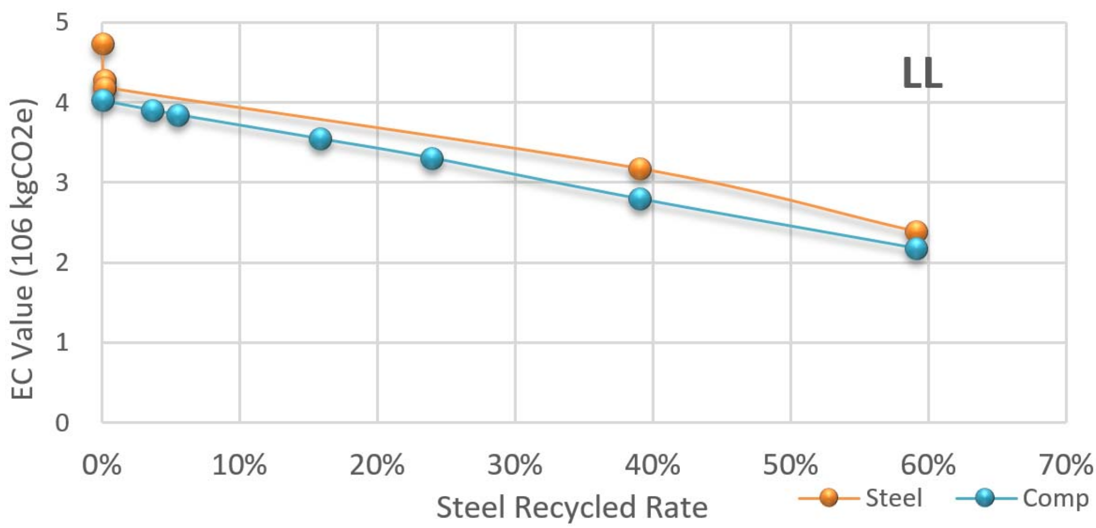


Figure 8. 7 (c) Comparison 8.1 Composite Building Models in C32 LL

Comparison 8.2

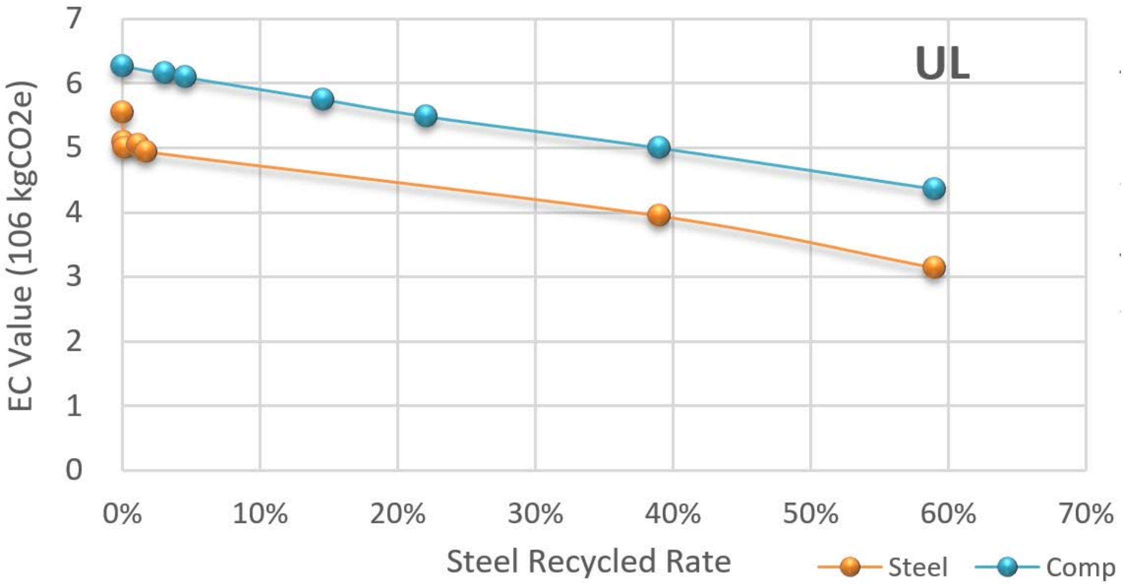


Figure 8. 8 Comparison 8.2: Total EC Values of Both Building Schemes Designed with Different Concrete/Steel Carbon Footprint Values: (a) Composite Building Models in C32 UL

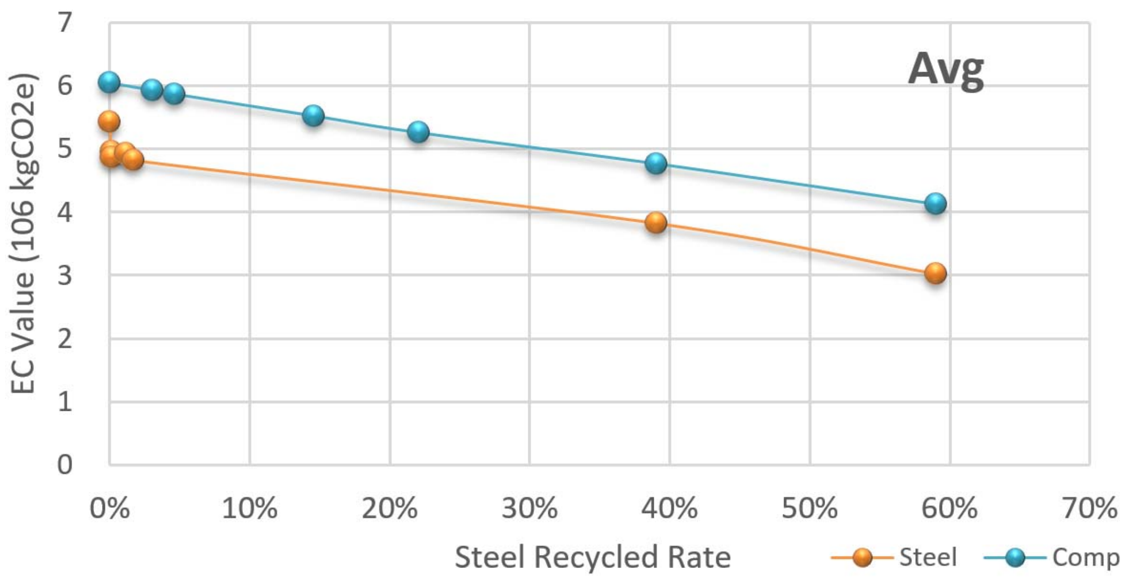


Figure 8. 9 (b) Comparison 8.2 Composite Building Models in C32 Avg

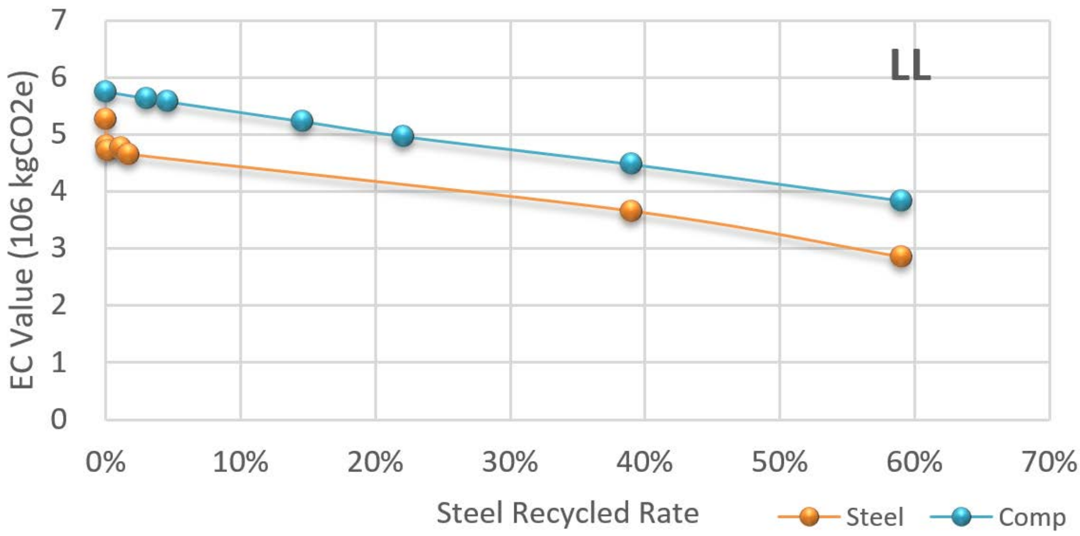


Figure 8. 10 (c) Comparison 8.2 Composite Building Models in C32 Avg

8.5 Conclusion Remarks

To summarize these two series of comparisons, for this twelve-storey building, similar observations could be drawn as those from previous comparisons of Steel and RC designed buildings that the building's total carbon footprint could be reasonably decreased with the application of low carbon footprint construction materials.

When only the supporting structural frames without slabs were considered in Comparison 8.1, which could be regarded as the normal practice in real application when such composite buildings are in need of being compared with others since the steel decking system could be considered to be comparable with other floor systems, though designed as forming part of the supporting structure. The sizes of steel members under slabs could be largely reduced due to the composite action within the composite floor system, therefore even taken into account of the concrete core walls, Comp Building exhibit better environmental sustainability than Steel Building except for the condition with very high carbon footprint concrete applied with highly recycled (generally over 60%) steel.

Comparison 8.2 included slabs for Steel Building and composite floor systems for Comp Building on top of the supporting structural frames taken into the calculation. Though the total weight of the steel deck sheet is too small to be comparable to the total weight of the Comp Building, the stainless steel deck sheets' contribution to the total EC value of Comp Building is very large, which resulted in the absolute advantage of Steel Building in terms of environmental impacts over Comp Building design scheme independent of the concrete carbon footprints and steel recycled levels.

The ICE database formed a source of reference in the early stage of the establishment of Hong Kong CIC carbon labelling system which adopts similar cradle-to-gate boundaries but based on UK or worldsteel construction industry market. Though there might result in many possible variations for application in Hong Kong, the study would still lead to a similar trend in the results, creating a reliable reference for structural engineers' environmental decisions.

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

In this chapter, the findings of this thesis are summarized and presented, and the recommendations for the future work are also given.

9.1 Conclusions

A PhD research project has been conducted under the cooperation between the Hong Kong Polytechnic University and the Hong Kong Construction Industry Council. The whole research process, including the research background, purpose, methodology, results comparisons and analysis, has been presented in this thesis, aiming to establish a new era for the green house gas environmental effects reduction contributed by the structural engineers from a structural way. A systematic integration method has been established and verified so as to incorporate the nonlinear structural optimisation with certain carbon footprint labelling system, in which way the building's total embodied carbon emissions would be evaluated from a system level. Based on this theory foundation, comparisons would be conducted in terms of the total embodied carbon emission values between several sets of models designed in different concrete strength, with different percentages of recycled steel scrap included, in different configurations and different heights. It is determined to figure out what kind of material combinations should be applied to the corresponding reinforced concrete, steel or steel-composite commercial buildings designed under the current Hong Kong construction industry and material supply situation, so as to make their energy consumption and greenhouse gas emissions reduction more compative for the benefit of long term environmental sustainability, providing more environmental friendly design options for future reference of developers and engineers.

The research findings and contributions of this work are summarized as follows:

1) Chapter 3 takes the material factor into consideration and examines the environmental performance of different forms of steel and reinforced concrete structures designed by both nonlinear structural optimisation and conventional linear analysis in terms of the total embodied carbon and energy values. The advantage of the well-known accurate and efficient nonlinear analysis applied in the design process has been proved in terms of the environmental impacts evaluation by comparing the total embodied carbon values of every couple of models under consideration, which would also form a basis and providing a theory foundation for the following comparisons of building models integrating the environmental parameters with different configurations and design methods.

2) A systematic integration of the above verified optimised structural design method with the UK based ICE Carbon Footprint Database has been

illustrated using a pair of 25-storey commercial buildings designed in steel or reinforced concrete with only superstructure part taken into account for analysis. Comparisons have been conducted in terms of the total embodied carbon emission values between this set of models designed in different concrete strength and with different percentages of recycled steel scrap included. It was determined to figure out what kind of material combinations should be applied to this kind of mid-rise commercial building designed in Hong Kong so as to make their environmental impacts more compative. Conclusion therefore drawn from the observations, the higher the concrete strength in use in the RC structural design, the more recycled steel scrap is required in the steel design option to make their environmental impacts competitive for these kind of mid-rise commercial buildings designed in Hong Kong construction market, with only superstructure part taken into account for analysis or for buildings built upon existing underground foundation.

3) Based on the same pair of 25-storey commercial buildings designed in steel or reinforced concrete, but not only the superstructure, also the underground parts were taken into account together for analysis. Same sets of comparisons revealed that with all the superstructure and underground elements taken into account, the higher the concrete strength in use in the RC structural design, the more recycled steel scrap is required in the steel design option to make their environmental impacts compatitive for these kinds of mid-rise commercial buildings designed in Hong Kong construction market. However,

for low grade concrete RC Building design to be carried out and compared with Steel Building option correspondingly, as for C60 concrete in use, 5% of recycled steel scrap material is required, while for C80 concrete in use, 32% of recycled steel scrap material is required, so that the Steel Building design option would achieve the best structural and environmental efficiency simultaneously given the absolute material weight reduction for Steel Building models. Therefore, it would be suggested to conduct a nonlinear steel building design scheme for these similar mid-rise commercial buildings in terms of their advantages in material save and eco-friendliness.

4) Chapter 6 applied the same structural design method and comparison analysis method to the same pair of building models considering the superstructure part or including the underground design as well, however, integrated with a set of Hong Kong based carbon labelling scheme. Comparisons would be carried out for different sets of carbon footprint values applied to the same set of building models. These observations could provide a conclusion that the advantage of steel building in terms of total EC increases especially with increasing recycled content of scrap in the steel products as available in Hong Kong construction materials market, so that the Steel Building Design would be more environmental friendly, while the lower the materials' CF values adopted, the more environmental friendly the design would be. Thereafter, the potential of the Hong Kong local construction industry has been proved in

terms of the environmental effects reduction with more and more Carbon Labelling System Certified Materials put into future design and construction.

5) Chapter 7 examined the environmental performance of building models again in different construction materials, designed with different methods, but in different heights or levels to make the whole study more consistent and complete, with the UK based ICE Carbon Footprint Database applied for evaluation. The relative material advantage of either steel or concrete for buildings in different heights has been explored on the basis of the previously established scientific relationship between material consumption, structural design optimization, selection and use of low carbon material, together with the associated building's total carbon footprint. Conclusions could be summarized for models in different height separately. For such lower rise commercial buildings in Hong Kong construction market, Steel Nonlinear analysis provides a structural and environmental efficient design option while for higher rise commercial buildings, certain recycled steel rates should be reached for Steel Building option achieving the most structural and environmental efficiency. The certain percentage of recycled steel inclusion required would be subjected to building systems design schemes and should then be analysed case by case for a more environmental design option to be scientifically conducted.

6) Chapter 8 extended the comparisons in terms of the total embodied carbon values in a system level to a different set of building models, which is to be a steel building designed specifically with composite floor systems included compared with a nonlinear steel design solution, applying the same integration method of low carbon materials and nonlinear structural optimisation. The results varied absolutely different depending on the comparison protocol included in the total embodied carbon values calculation. If the steel decking system was not included, the composite building design scheme would generally exhibit better environmental sustainability, so that the advantages of composite designed buildings in application have been extended to environmental sustainability, in the hope of providing an additional environmental friendly design option for future reference of developers and engineers.

To summarize these six series of comparisons, for all kinds of building models to be designed, a common observation could be drawn from previous comparison results that for all the Steel, RC and composite designed buildings that the building's total carbon footprint could be reasonably decreased with the application of nonlinear structural optimisation, as well as using low carbon footprint construction materials.

The ICE database formed a source of reference in the early stage of the establishment of Hong Kong CIC carbon labelling system which adopts similar cradle-to-gate boundaries but based on UK or worldsteel construction industry market.

Though there might result in many possible variations for application in Hong Kong, the study would still lead to a similar trend in the results, creating a reliable reference for structural engineers' environmental decisions.

9.2 Recommendations

This PhD research project has been conducted in collaboration with the Hong Kong Construction Industry Council, examined the environmental effects evaluation method through the scientific integration of low carbon materials and nonlinear structural optimisation and proved Hong Kong's potential in energy saving and greenhouse gas emissions reduction. A variety of building models have been included for study. Future comparison applications could be carried out in the same way with the aid of nonlinear structural analysis method. The current nonlinear design tool relies mostly on the computer programme NIDA which was developed by Professor S. L. Chan and his research team, which was already approved by the Buildings Department for nonlinear and second-order analysis to Code of Practice to Structural Uses of Steel, Hong Kong 2005 and 2011. Suggestion would be made for the further development of the computer programme. If the embodied carbon footprint values of elements in different sections and materials could be included as inputs of the material properties, the quantification of certain structures' total carbon footprint values would be realized directly through the programme, which would produce one more valuable output of the nonlinear or conventional linear structural analysis, providing a direct environmental impacts evaluation result for the concerned comparison. Though the final design decision of a project scheme might depend on all kinds of reasons including architectural aesthetics, social image and purpose, structural design methods, code of practice in use, geographic location and climate, construction time, labour resources, economic concerns and financial benefits, the important role environmental impacts would take worth more attention to realize a real life sustainable development.

For most comparison studies conducted in this research, carbon footprint values adopted for calculation were mostly referred according to the ICE database based on UK or world steel construction industry market, but few to the Hong Kong local database. The CFP therefore calculated was based on a “cradle-to-site” approach, covering all GHG emissions and removals of the product arising from raw material acquisition, transportation, production process, storing/packaging and finally transporting to the construction region. Hong Kong started the development of such carbon labelling scheme only in a few years history. The product varieties and availability of particular recycled rates of products provided in the Hong Kong CIC Carbon Labelling Scheme are currently very limited. Given a more consistent and systematic database established in Hong Kong construction industry, such environmental evaluation and comparison studies would be able to provide more complete and convincing results which would direct the future of environmental friendly structural design on a right path.

Since all of the models in use were modified from real buildings designed in Hong Kong three years ago, the most commonly adopted steel grade was S355 at that time.

In the current market, higher grade steel materials are available and widely adopted in the modern design based in the Hong Kong construction market, e.g. S460 and even S690. However, due to the limitation of the original slender design configration of all the models, the slenderness ratios for the majority of the beam members and the stiffness of most of the plates were very marginal already as required according to the Hong Kong code of practice 2011. Therefore, the application of steel materials in grade S355 was the most optimum choice at the previous design stage. According to the ICE database based on UK or world steel construction industry market, the embodied carbon factors for steel are identical independent of the steel grade, which implies that the total emobided carbon values for the whole building would decrease definitely when higher grade of steel material is adopted due to the decrease of the total weight of steel members, further enhancing the environmental advantage and prospect of steel design options with relatively lower percentage of recycled steel scrap inclusion to make steel design compatible to the RC ones.

Change of climate or environment situation is slow, while the process cannot be witnessed obviously in a short period. Every bit of contribution of energy save, GHG reductions and environmental improvement actions is small compared to the huge climate change, however, the long term accumulation of their effects could contribute significantly to the long term sustainability development. Responsibility to protect the earth as well as our surrounding living environment lies in every human being who shares the same resources given by the nature. Hopefully, our little step through advanced structural design and analysis would push the environment evolution forward and make our home more sustainable for future generations.

APPENDIX A

TOTAL CARBON FOOTPRINTS OF 25/F STEEL & C60 RC BUILDINGS (SUPERSTRUCTURE ONLY)

	Steel	RC C60
Category	Weight (kN)	Weight (kN)
Steel	**8654**	**0**
Concrete	49214.13	101486
Conc without R	**47635.74**	**98239**
Reinforcement	**5163**	**10893**

ICE

Steel-Primary (Virgin)					Concrete-C60 Upper Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	3.03	2.67E+06	0	0	3.03	0.00E+00
Concrete	47636	4857	0.205	9.94E+05	98239	10017	0.2045833	2.05E+06
Bar	5163	526	2.77	1.46E+06	10893	1111	2.77	3.08E+06
Total	**61452**	6266		5.13E+06	**109132**	11128		5.13E+06
			0%				-0.01%	

Steel-World Typical (39% Recy)					Concrete-C60 UL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	2.03	1.79E+06	0	0	2.03	0.00E+00
Concrete	47636	4857	0.205	9.94E+05	98239	10017	0.2045833	2.05E+06
Bar	5163	526	1.86	9.79E+05	10893	1111	1.86	2.07E+06
Total	61452	6266		3.76E+06	109132	11128		4.12E+06
Reduction to Concrete			**9%**				-9.33%	

Steel-Virgin&World Typical (39% Recy)					Concrete-C60 UL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)

Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00
Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	47636	4857	0.205	9.94E+05	98239	10017	0.2045833	2.05E+06
Bar Virgin	5163	526	2.77	1.46E+06	10893	1111	2.77	3.08E+06
Total	61452	6266		5.02E+06	109132	11128		5.13E+06
Reduction to Concrete				2%				-2.12%

Steel-Virgin&World Typical (39% Recy)					Concrete-C60 UL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00
Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	47636	4857	0.205	9.94E+05	98239	10017	0.2045833	2.05E+06
Bar 39% Re	5163	526	1.86	9.79E+05	10893	1111	1.86	2.07E+06
Total	61452	6266		4.54E+06	109132	11128		4.12E+06
Reduction to Concrete				-10%				9.37%

Steel-UK Typical (EC 59% Recy)					Concrete-C60 UL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	1.53	1.35E+06	0	0	1.53	0.00E+00
Concrete	47636	4857	0.205	9.94E+05	98239	10017	0.2045833	2.05E+06
Bar	5163	526	1.40	7.37E+05	10893	1111	1.4	1.56E+06
Total	61452	6266		3.08E+06	109132	11128		3.60E+06
Reduction to Concrete				15%				-16.99%

Steel-Virgin&World Typical (59% Recy)					Concrete-C60 UL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	47636	4857	0.205	9.94E+05	98239	10017	0.2045833	2.05E+06
Bar Virgin	5163	526	2.77	1.46E+06	10893	1111	2.77	3.08E+06

Total	61452	6266		4.58E+06	109132	11128		5.13E+06
Reduction to Concrete				11%				-11.96%

Steel-Virgin&World Typical (59% Recy)					Concrete-C60 UL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	47636	4857	0.205	9.94E+05	98239	10017	0.2045833	2.05E+06
Bar 59% Re	5163	526	1.40	7.37E+05	10893	1111	1.4	1.56E+06
Total	61452	6266		3.86E+06	109132	11128		3.60E+06
Reduction to Concrete				-7%				6.56%

ICE

Steel-Primary (Virgin)					Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	3.03	2.67E+06	0	0	3.03	0.00E+00
Concrete	47635.7428	4857	0.172	8.36E+05	98239	10017	0.1720833	1.72E+06
Bar	5162.64158	526	2.77	1.46E+06	10893	1111	2.77	3.08E+06
Total	**61452**	6266		4.97E+06	**109132**	11128		4.80E+06
				-3%				3.37%

Steel-World Typical (39% Recy)					Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	2.03	1.79E+06	0	0	2.03	0.00E+00
Concrete	47636	4857	0.172	8.36E+05	98239	10017	0.1720833	1.72E+06
Bar	5163	526	1.86	9.79E+05	10893	1111	1.86	2.07E+06
Total	61452	6266		3.61E+06	109132	11128		3.79E+06
Reduction to Concrete				5%				-5.09%

Steel-Virgin&World Typical (39% Recy)					Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00

Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	47636	4857	0.172	8.36E+05	98239	10017	0.1720833	1.72E+06
Bar Virgin	5163	526	2.77	1.46E+06	10893	1111	2.77	3.08E+06
Total	61452	6266		4.86E+06	109132	11128		4.80E+06
Reduction to Concrete				**-1%**				1.26%

Steel-Virgin&World Typical (39% Recy)					Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00
Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	47636	4857	0.172	8.36E+05	98239	10017	0.1720833	1.72E+06
Bar 39% Re	5163	526	1.86	9.79E+05	10893	1111	1.86	2.07E+06
Total	61452	6266		4.38E+06	109132	11128		3.79E+06
Reduction to Concrete				**-16%**				13.53%

Steel-UK Typical (EC 59% Recy)					Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	1.53	1.35E+06	0	0	1.53	0.00E+00
Concrete	47636	4857	0.172	8.36E+05	98239	10017	0.1720833	1.72E+06
Bar	5163	526	1.40	7.37E+05	10893	1111	1.4	1.56E+06
Total	61452	6266		2.92E+06	109132	11128		3.28E+06
Reduction to Concrete				**11%**				-12.18%

Steel-Virgin&World Typical (59% Recy)					Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	47636	4857	0.172	8.36E+05	98239	10017	0.1720833	1.72E+06
Bar Virgin	5163	526	2.77	1.46E+06	10893	1111	2.77	3.08E+06
Total	61452	6266		4.42E+06	109132	11128		4.80E+06
Reduction to Concrete				**8%**				-8.59%

Steel-Virgin&World Typical (59% Recy)					Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	47636	4857	0.172	8.36E+05	98239	10017	0.1720833	1.72E+06
Bar 59% Re	5163	526	1.40	7.37E+05	10893	1111	1.4	1.56E+06
Total	61452	6266		3.70E+06	109132	11128		3.28E+06
Reduction to Concrete				**-13%**				11.37%

ICE								
Steel-Primary (Virgin)					Concrete-C60 Lower Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	3.03	2.67E+06	0	0	3.03	0.00E+00
Concrete	47635.7428	4857	0.128	6.19E+05	98239	10017	0.1275	1.28E+06
Bar	5162.64158	526	2.77	1.46E+06	10893	1111	2.77	3.08E+06
Total	**61452**	6266		4.75E+06	**109132**	11128		4.35E+06
				-9%				8.36%

Steel-World Typical (39% Recy)					Concrete-C60 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	2.03	1.79E+06	0	0	2.03	0.00E+00
Concrete	47636	4857	0.128	6.19E+05	98239	10017	0.1275	1.28E+06
Bar	5163	526	1.86	9.79E+05	10893	1111	1.86	2.07E+06
Total	61452	6266		3.39E+06	109132	11128		3.34E+06
Reduction to Concrete				**-1%**				1.37%

Steel-Virgin&World Typical (39% Recy)					Concrete-C60 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00
Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	47636	4857	0.128	6.19E+05	98239	10017	0.1275	1.28E+06
Bar Virgin	5163	526	2.77	1.46E+06	10893	1111	2.77	3.08E+06

Total	61452	6266		4.65E+06	109132	11128		4.35E+06
Reduction to Concrete				-7%				6.27%

Steel-Virgin&World Typical (39% Recy)					Concrete-C60 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00
Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	47636	4857	0.128	6.19E+05	98239	10017	0.1275	1.28E+06
Bar 39% Re	5163	526	1.86	9.79E+05	10893	1111	1.86	2.07E+06
Total	61452	6266		4.17E+06	109132	11128		3.34E+06
Reduction to Concrete				-25%				19.76%

Steel-UK Typical (EC 59% Recy)					Concrete-C60 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	1.53	1.35E+06	0	0	1.53	0.00E+00
Concrete	47636	4857	0.128	6.19E+05	98239	10017	0.1275	1.28E+06
Bar	5163	526	1.40	7.37E+05	10893	1111	1.4	1.56E+06
Total	61452	6266		2.71E+06	109132	11128		2.83E+06
Reduction to Concrete				4%				-4.65%

Steel-Virgin&World Typical (59% Recy)					Concrete-C60 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	47636	4857	0.128	6.19E+05	98239	10017	0.1275	1.28E+06
Bar Virgin	5163	526	2.77	1.46E+06	10893	1111	2.77	3.08E+06
Total	61452	6266		4.20E+06	109132	11128		4.35E+06
Reduction to Concrete				3%				-3.56%

Steel-Virgin&World Typical (59% Recy)					Concrete-C60 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)

Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	47636	4857	0.128	6.19E+05	98239	10017	0.1275	1.28E+06
Bar 59% Re	5163	526	1.40	7.37E+05	10893	1111	1.4	1.56E+06
Total	61452	6266		3.48E+06	109132	11128		2.83E+06
Reduction to Concrete				**-23%**				18.68%

HK

	Steel (HK avg-CIC)				Concrete-C60 (HK avg-CIC)			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Steel Section	8654	882	0.55	4.85E+05	0	0	0.55	0.00E+00
Concrete C60	47636	4857	0.129	6.27E+05	98239	10017	0.129	1.29E+06
Steel Rebar	5163	526	2.08	1.09E+06	10893	1111	2.08	2.31E+06
Total	61452	6266		2.21E+06	109132	11128		3.60E+06
Reduction to Concrete				**39%**				-63.26%

APPENDIX B

TOTAL CARBON FOOTPRINTS OF 25/F STEEL & C80 RC BUILDINGS (SUPERSTRUCTURE ONLY)

	Steel	RC C80
Category	Weight (kN)	Weight (kN)
Steel	**8654**	**0**
Concrete	49214.13	89422
Conc without R	**47635.74**	**86560**
Reinforcement	**5163**	**10001**

ICE

	Steel-Primary (Virgin)				Concrete-C80 Upper Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	3.03	2.67E+06	0	0	3.03	0.00E+00
Concrete	47636	4857	0.249	1.21E+06	86560	8826	0.2491667	2.20E+06
Bar	5163	526	2.77	1.46E+06	10001	1020	2.77	2.82E+06
Total	**61452**	6266		5.34E+06	**96561**	9846		5.02E+06
				-6%				5.96%

	Steel-World Typical (39% Recy)				Concrete-C80 Upper Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	2.03	1.79E+06	0	0	2.03	0.00E+00
Concrete	47636	4857	0.249	1.21E+06	86560	8826	0.2491667	2.20E+06
Bar	5163	526	1.86	9.79E+05	10001	1020	1.86	1.90E+06
Total	61452	6266		3.98E+06	96561	9846		4.10E+06
Reduction to Concrete				3%				-2.89%

	Steel-Virgin&World Typical (39% Recy)				Concrete-C80 Upper Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00

Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00
Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	47636	4857	0.249	1.21E+06	86560	8826	0.2491667	2.20E+06
Bar Virgin	5163	526	2.77	1.46E+06	10001	1020	2.77	2.82E+06
Total	61452	6266		5.24E+06	96561	9846		5.02E+06
Reduction to Concrete				**-4%**				4.06%

Steel-Virgin&World Typical (39% Recy)					Concrete-C80 Upper Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00
Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	47636	4857	0.249	1.21E+06	86560	8826	0.2491667	2.20E+06
Bar 39% Re	5163	526	1.86	9.79E+05	10001	1020	1.86	1.90E+06
Total	61452	6266		4.76E+06	96561	9846		4.10E+06
Reduction to Concrete				**-16%**				13.90%

Steel-UK Typical (EC 59% Recy)					Concrete-C80 Upper Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	1.53	1.35E+06	0	0	1.53	0.00E+00
Concrete	47636	4857	0.249	1.21E+06	86560	8826	0.2491667	2.20E+06
Bar	5163	526	1.40	7.37E+05	10001	1020	1.4	1.43E+06
Total	61452	6266		3.30E+06	96561	9846		3.63E+06
Reduction to Concrete				**9%**				-9.99%

Steel-Virgin&World Typical (59% Recy)					Concrete-C80 Upper Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	47636	4857	0.249	1.21E+06	86560	8826	0.2491667	2.20E+06
Bar Virgin	5163	526	2.77	1.46E+06	10001	1020	2.77	2.82E+06
Total	61452	6266		4.80E+06	96561	9846		5.02E+06
Reduction to Concrete				**5%**				-4.77%

Steel-Virgin&World Typical (59% Recy)					Concrete-C80 Upper Limit			

	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	47636	4857	0.249	1.21E+06	86560	8826	0.2491667	2.20E+06
Bar 59% Re	5163	526	1.40	7.37E+05	10001	1020	1.4	1.43E+06
Total	61452	6266		4.07E+06	96561	9846		3.63E+06
Reduction to Concrete				**-12%**				10.97%

ICE

Steel-Primary (Virgin)					Concrete-C80 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	3.03	2.67E+06	0	0	3.03	0.00E+00
Concrete	47635.7428	4857	0.211	1.03E+06	86560	8826	0.21125	1.86E+06
Bar	5162.64158	526	2.77	1.46E+06	10001	1020	2.77	2.82E+06
Total	**61452**	6266		5.16E+06	**96561**	9846		4.69E+06
				-10%				9.09%

Steel-World Typical (39% Recy)					Concrete-C80 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	2.03	1.79E+06	0	0	2.03	0.00E+00
Concrete	47636	4857	0.211	1.03E+06	86560	8826	0.21125	1.86E+06
Bar	5163	526	1.86	9.79E+05	10001	1020	1.86	1.90E+06
Total	61452	6266		3.80E+06	96561	9846		3.76E+06
Reduction to Concrete				**-1%**				0.93%

Steel-Virgin&World Typical (39% Recy)					Concrete-C80 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00
Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	47636	4857	0.211	1.03E+06	86560	8826	0.21125	1.86E+06
Bar Virgin	5163	526	2.77	1.46E+06	10001	1020	2.77	2.82E+06
Total	61452	6266		5.05E+06	96561	9846		4.69E+06
Reduction to Concrete				**-8%**				7.18%

Steel-Virgin&World Typical (39% Recy)					Concrete-C80 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00
Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	47636	4857	0.211	1.03E+06	86560	8826	0.21125	1.86E+06
Bar 39% Re	5163	526	1.86	9.79E+05	10001	1020	1.86	1.90E+06
Total	61452	6266		4.57E+06	96561	9846		3.76E+06
Reduction to Concrete				**-22%**				17.75%

Steel-UK Typical (EC 59% Recy)					Concrete-C80 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	1.53	1.35E+06	0	0	1.53	0.00E+00
Concrete	47636	4857	0.211	1.03E+06	86560	8826	0.21125	1.86E+06
Bar	5163	526	1.40	7.37E+05	10001	1020	1.4	1.43E+06
Total	61452	6266		3.11E+06	96561	9846		3.29E+06
Reduction to Concrete				**5%**				-5.75%

Steel-Virgin&World Typical (59% Recy)					Concrete-C80 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	47636	4857	0.211	1.03E+06	86560	8826	0.21125	1.86E+06
Bar Virgin	5163	526	2.77	1.46E+06	10001	1020	2.77	2.82E+06
Total	61452	6266		4.61E+06	96561	9846		4.69E+06
Reduction to Concrete				**2%**				-1.70%

Steel-Virgin&World Typical (59% Recy)					Concrete-C80 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	47636	4857	0.211	1.03E+06	86560	8826	0.21125	1.86E+06
Bar 59% Re	5163	526	1.40	7.37E+05	10001	1020	1.4	1.43E+06

Total	61452	6266		3.89E+06	96561	9846		3.29E+06
Reduction to Concrete				-18%				15.36%

ICE								
	Steel-Primary (Virgin)				Concrete-C80 Lower Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	3.03	2.67E+06	0	0	3.03	0.00E+00
Concrete	47635.7428	4857	0.159	7.71E+05	86560	8826	0.15875	1.40E+06
Bar	5162.64158	526	2.77	1.46E+06	10001	1020	2.77	2.82E+06
Total	**61452**	6266		4.90E+06	**96561**	9846		4.23E+06
				-16%				13.81%

Steel-World Typical (39% Recy)					Concrete-C80 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	2.03	1.79E+06	0	0	2.03	0.00E+00
Concrete	47636	4857	0.159	7.71E+05	86560	8826	0.15875	1.40E+06
Bar	5163	526	1.86	9.79E+05	10001	1020	1.86	1.90E+06
Total	61452	6266		3.54E+06	96561	9846		3.30E+06
Reduction to Concrete				-7%				6.88%

Steel-Virgin&World Typical (39% Recy)					Concrete-C80 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00
Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	47636	4857	0.159	7.71E+05	86560	8826	0.15875	1.40E+06
Bar Virgin	5163	526	2.77	1.46E+06	10001	1020	2.77	2.82E+06
Total	61452	6266		4.80E+06	96561	9846		4.23E+06
Reduction to Concrete				-14%				11.91%

Steel-Virgin&World Typical (39% Recy)					Concrete-C80 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00
Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	47636	4857	0.159	7.71E+05	86560	8826	0.15875	1.40E+06

Bar 39% Re	5163	526	1.86	9.79E+05	10001	1020	1.86	1.90E+06
Total	61452	6266		4.32E+06	96561	9846		3.30E+06
Reduction to Concrete				-31%				23.63%

Steel-UK Typical (EC 59% Recy)					Concrete-C80 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	1.53	1.35E+06	0	0	1.53	0.00E+00
Concrete	47636	4857	0.159	7.71E+05	86560	8826	0.15875	1.40E+06
Bar	5163	526	1.40	7.37E+05	10001	1020	1.4	1.43E+06
Total	61452	6266		2.86E+06	96561	9846		2.83E+06
Reduction to Concrete				-1%				1.03%

Steel-Virgin&World Typical (59% Recy)					Concrete-C80 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	47636	4857	0.159	7.71E+05	86560	8826	0.15875	1.40E+06
Bar Virgin	5163	526	2.77	1.46E+06	10001	1020	2.77	2.82E+06
Total	61452	6266		4.36E+06	96561	9846		4.23E+06
Reduction to Concrete				-3%				2.98%

Steel-Virgin&World Typical (59% Recy)					Concrete-C80 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	47636	4857	0.159	7.71E+05	86560	8826	0.15875	1.40E+06
Bar 59% Re	5163	526	1.40	7.37E+05	10001	1020	1.4	1.43E+06
Total	61452	6266		3.63E+06	96561	9846		2.83E+06
Reduction to Concrete				-28%				22.17%

HK

Steel (HK avg-CIC)					Concrete-C80 (HK avg-CIC)			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Steel Section	8654	882	2.28	2.01E+06	0	0	2.28	0.00E+00
Concrete	47636	4857	0.204	9.92E+05	86560	8826	0.204	1.80E+06

Steel Rebar	5163	526	2.09	1.10E+06	10001	1020	2.09	2.13E+06
Total	61452	6266		4.10E+06	96561	9846		3.93E+06
Reduction to Concrete				-4%				4.15%

Steel (HK App)					Concrete-C80 (HK avg-CIC)			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Steel Section	8654	882	0.55	4.85E+05	0	0	0.55	0.00E+00
Concrete	47636	4857	0.204	9.92E+05	86560	8826	0.204	1.80E+06
Steel Rebar	5163	526	2.20	1.16E+06	10001	1020	2.2	2.24E+06
Total	61452	6266		2.64E+06	96561	9846		4.05E+06
Reduction to Concrete				**35%**				-53.52%

Steel-(HK avg & App)					Concrete-C80 (HK avg-CIC)			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Avg	6141	626	2.28	5.84E+05			2.28	0.00E+00
Section App	2513.4	256	0.55	4.85E+05			0.55	0.00E+00
Section Total	8654	882		1.07E+06	0	0		0.00E+00
Concrete	47636	4857	0.204	9.92E+05	86560	8826	0.2041667	1.80E+06
Bar Avg	5163	526	2.09	1.10E+06	10001	1020	2.09	2.13E+06
Total	61452	6266		3.16E+06	96561	9846		3.93E+06
Reduction to Concrete				**20%**				-24.41%

Steel-(HK avg & App)					Concrete-C80 (HK avg-CIC)			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Avg	6141	626	2.28	5.84E+05			2.28	0.00E+00
Section App	2513.4	256	0.55	4.85E+05			0.55	0.00E+00
Section Total	8654	882		1.07E+06	0	0		0.00E+00
Concrete	47636	4857	0.204	9.92E+05	86560	8826	0.2041667	1.80E+06
Bar App	5163	526	2.20	1.16E+06	10001	1020	2.2	2.24E+06
Total	61452	6266		3.22E+06	96561	9846		4.05E+06
Reduction to Concrete				**20%**				-25.66%

APPENDIX C

TOTAL CARBON FOOTPRINTS OF 25/F STEEL & C100 RC BUILDINGS (SUPERSTRUCTURE ONLY)

	Steel	RC C100
Category	Weight (kN)	Weight (kN)
Steel	**8654**	**0**
Concrete	49214.13	79202
Conc without R	**47635.74**	**76668**
Reinforcement	**5163**	**9640**

ICE								
Steel-Primary (Virgin)					Concrete-C100 Upper Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	3.03	2.67E+06	0	0	3.03	0.00E+00
Concrete	47636	4857	0.249	1.21E+06	76668	7818	0.2491667	1.95E+06
Bar	5163	526	2.77	1.46E+06	9640	983	2.77	2.72E+06
Total	**61452**	6266		5.34E+06	**86308**	8801		4.67E+06
				-14%				12.57%

Steel-World Typical (39% Recy)					Concrete-C100 Upper Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	2.03	1.79E+06	0	0	2.03	0.00E+00
Concrete	47636	4857	0.249	1.21E+06	76668	7818	0.2491667	1.95E+06
Bar	5163	526	1.86	9.79E+05	9640	983	1.86	1.83E+06
Total	61452	6266		3.98E+06	86308	8801		3.78E+06
Reduction to Concrete				**-5%**				5.14%

Steel-Virgin&World Typical (39% Recy)					Concrete-C100 Upper Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)

Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00
Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	47636	4857	0.249	1.21E+06	76668	7818	0.2491667	1.95E+06
Bar Virgin	5163	526	2.77	1.46E+06	9640	983	2.77	2.72E+06
Total	61452	6266		5.24E+06	86308	8801		4.67E+06
Reduction to Concrete				-12%				10.80%

Steel-Virgin&World Typical (39% Recy)					Concrete-C100 Upper Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00
Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	47636	4857	0.249	1.21E+06	76668	7818	0.2491667	1.95E+06
Bar 39% Re	5163	526	1.86	9.79E+05	9640	983	1.86	1.83E+06
Total	61452	6266		4.76E+06	86308	8801		3.78E+06
Reduction to Concrete				-26%				20.62%

Steel-UK Typical (EC 59% Recy)					Concrete-C100 Upper Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	1.53	1.35E+06	0	0	1.53	0.00E+00
Concrete	47636	4857	0.249	1.21E+06	76668	7818	0.2491667	1.95E+06
Bar	5163	526	1.40	7.37E+05	9640	983	1.4	1.38E+06
Total	61452	6266		3.30E+06	86308	8801		3.32E+06
Reduction to Concrete				1%				-0.81%

Steel-Virgin&World Typical (59% Recy)					Concrete-C100 Upper Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	47636	4857	0.249	1.21E+06	76668	7818	0.2491667	1.95E+06
Bar Virgin	5163	526	2.77	1.46E+06	9640	983	2.77	2.72E+06
Total	61452	6266		4.80E+06	86308	8801		4.67E+06
Reduction to Concrete				-3%				2.59%

Steel-Virgin&World Typical (59% Recy)					Concrete-C100 Upper Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	47636	4857	0.249	1.21E+06	76668	7818	0.2491667	1.95E+06
Bar 59% Re	5163	526	1.40	7.37E+05	9640	983	1.4	1.38E+06
Total	61452	6266		4.07E+06	86308	8801		3.32E+06
Reduction to Concrete				**-23%**				18.41%

ICE

Steel-Primary (Virgin)					Concrete-C100 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	3.03	2.67E+06	0	0	3.03	0.00E+00
Concrete	47635.7428	4857	0.211	1.03E+06	76668	7818	0.21125	1.65E+06
Bar	5162.64158	526	2.77	1.46E+06	9640.3	983	2.77	2.72E+06
Total	**61452**	6266		5.16E+06	**86308**	8801		4.37E+06
				-18%				15.19%

Steel-World Typical (39% Recy)					Concrete-C100 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	2.03	1.79E+06	0	0	2.03	0.00E+00
Concrete	47636	4857	0.211	1.03E+06	76668	7818	0.21125	1.65E+06
Bar	5163	526	1.86	9.79E+05	9640	983	1.86	1.83E+06
Total	61452	6266		3.80E+06	86308	8801		3.48E+06
Reduction to Concrete				**-9%**				8.34%

Steel-Virgin&World Typical (39% Recy)					Concrete-C100 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00
Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	47636	4857	0.211	1.03E+06	76668	7818	0.21125	1.65E+06
Bar Virgin	5163	526	2.77	1.46E+06	9640	983	2.77	2.72E+06
Total	61452	6266		5.05E+06	86308	8801		4.37E+06
Reduction to Concrete				**-15%**				13.42%

Steel-Virgin&World Typical (39% Recy)					Concrete-C100 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00
Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	47636	4857	0.211	1.03E+06	76668	7818	0.21125	1.65E+06
Bar 39% Re	5163	526	1.86	9.79E+05	9640	983	1.86	1.83E+06
Total	61452	6266		4.57E+06	86308	8801		3.48E+06
Reduction to Concrete				**-31%**				23.91%

Steel-UK Typical (EC 59% Recy)					Concrete-C100 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	1.53	1.35E+06	0	0	1.53	0.00E+00
Concrete	47636	4857	0.211	1.03E+06	76668	7818	0.21125	1.65E+06
Bar	5163	526	1.40	7.37E+05	9640	983	1.4	1.38E+06
Total	61452	6266		3.11E+06	86308	8801		3.03E+06
Reduction to Concrete				**-3%**				2.75%

Steel-Virgin&World Typical (59% Recy)					Concrete-C100 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	47636	4857	0.211	1.03E+06	76668	7818	0.21125	1.65E+06
Bar Virgin	5163	526	2.77	1.46E+06	9640	983	2.77	2.72E+06
Total	61452	6266		4.61E+06	86308	8801		4.37E+06
Reduction to Concrete				**-5%**				5.13%

Steel-Virgin&World Typical (59% Recy)					Concrete-C100 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00

Concrete	47636	4857	0.211	1.03E+06	76668	7818	0.21125	1.65E+06
Bar 59% Re	5163	526	1.40	7.37E+05	9640	983	1.4	1.38E+06
Total	61452	6266		3.89E+06	86308	8801		3.03E+06
Reduction to Concrete				-28%				22.16%
ICE								

Steel-Primary (Virgin)					Concrete-C100 Lower Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	3.03	2.67E+06	0	0	3.03	0.00E+00
Concrete	47635.7428	4857	0.159	7.71E+05	76668	7818	0.15875	1.24E+06
Bar	5162.64158	526	2.77	1.46E+06	9640.3	983	2.77	2.72E+06
Total	**61452**	6266		4.90E+06	**86308**	8801		3.96E+06
				-24%				19.15%

Steel-World Typical (39% Recy)					Concrete-C100 Lower Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	2.03	1.79E+06	0	0	2.03	0.00E+00
Concrete	47636	4857	0.159	7.71E+05	76668	7818	0.15875	1.24E+06
Bar	5163	526	1.86	9.79E+05	9640	983	1.86	1.83E+06
Total	61452	6266		3.54E+06	86308	8801		3.07E+06
Reduction to Concrete				**-15%**				13.33%

Steel-Virgin&World Typical (39% Recy)					Concrete-C100 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00
Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	47636	4857	0.159	7.71E+05	76668	7818	0.15875	1.24E+06
Bar Virgin	5163	526	2.77	1.46E+06	9640	983	2.77	2.72E+06
Total	61452	6266		4.80E+06	86308	8801		3.96E+06
Reduction to Concrete				**-21%**				17.37%

Steel-Virgin&World Typical (39% Recy)					Concrete-C100 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00

Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	47636	4857	0.159	7.71E+05	76668	7818	0.15875	1.24E+06
Bar 39% Re	5163	526	1.86	9.79E+05	9640	983	1.86	1.83E+06
Total	61452	6266		4.32E+06	86308	8801		3.07E+06
Reduction to Concrete				**-41%**				28.92%

Steel-UK Typical (EC 59% Recy)					Concrete-C100 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	1.53	1.35E+06	0	0	1.53	0.00E+00
Concrete	47636	4857	0.159	7.71E+05	76668	7818	0.15875	1.24E+06
Bar	5163	526	1.40	7.37E+05	9640	983	1.4	1.38E+06
Total	61452	6266		2.86E+06	86308	8801		2.62E+06
Reduction to Concrete				**-9%**				8.43%

Steel-Virgin&World Typical (59% Recy)					Concrete-C100 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	47636	4857	0.159	7.71E+05	76668	7818	0.15875	1.24E+06
Bar Virgin	5163	526	2.77	1.46E+06	9640	983	2.77	2.72E+06
Total	61452	6266		4.36E+06	86308	8801		3.96E+06
Reduction to Concrete				**-10%**				9.00%

Steel-Virgin&World Typical (59% Recy)					Concrete-C100 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	47636	4857	0.159	7.71E+05	76668	7818	0.15875	1.24E+06
Bar 59% Re	5163	526	1.40	7.37E+05	9640	983	1.4	1.38E+06
Total	61452	6266		3.63E+06	86308	8801		2.62E+06
Reduction to Concrete				**-39%**				27.99%

HK								
Steel (HK avg-CIC)					Concrete-C100 (HK avg-CIC)			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)

Steel Section	8654	882	2.28	2.01E+06	0	0	2.28	0.00E+00
Concrete	47636	4857	0.204	9.92E+05	76668	7818	0.204	1.60E+06
Steel Rebar	5163	526	2.09	1.10E+06	9640	983	2.09	2.05E+06
Total	61452	6266		4.10E+06	86308	8801		3.65E+06
Reduction to Concrete				**-12%**				11.05%

Steel (HK App)					Concrete-C100 (HK avg-CIC)			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Steel Section	8654	882	0.55	4.85E+05	0	0	0.55	0.00E+00
Concrete	47636	4857	0.204	9.92E+05	76668	7818	0.204	1.60E+06
Steel Rebar	5163	526	2.20	1.16E+06	9640	983	2.2	2.16E+06
Total	61452	6266		2.64E+06	86308	8801		3.76E+06
Reduction to Concrete				**30%**				-42.64%

Steel-(HK avg & App)					Concrete-C100 (HK avg-CIC)			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Avg	6141	626	2.28	5.84E+05			2.28	0.00E+00
Section App	2513.4	256	0.55	4.85E+05			0.55	0.00E+00
Section Total	8654	882		1.07E+06	0	0		0.00E+00
Concrete	47636	4857	0.204	9.92E+05	76668	7818	0.2041667	1.60E+06
Bar Avg	5163	526	2.09	1.10E+06	9640	983	2.09	2.05E+06
Total	61452	6266		3.16E+06	86308	8801		3.65E+06
Reduction to Concrete				**13%**				-15.47%

Steel-(HK avg & App)					Concrete-C100 (HK avg-CIC)			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Avg	6141	626	2.28	5.84E+05			2.28	0.00E+00
Section App	2513.4	256	0.55	4.85E+05			0.55	0.00E+00
Section Total	8654	882		1.07E+06	0	0		0.00E+00
Concrete	47636	4857	0.204	9.92E+05	76668	7818	0.2041667	1.60E+06
Bar App	5163	526	2.20	1.16E+06	9640	983	2.2	2.16E+06
Total	61452	6266		3.22E+06	86308	8801		3.76E+06
Reduction to Concrete				**14%**				-16.75%

APPENDIX D

TOTAL CARBON FOOTPRINTS OF 25/F STEEL & C60 RC BUILDINGS (SUPERSTRUCTURE & FOUNDATION)

	Steel	RC C60
Category	Weight (kN)	Weight (kN)
Steel	**8654**	**0**
Concrete		0
Conc without R	**79177.53**	**136431**
Reinforcement	**7808**	**14096**

ICE								
Steel-Primary (Virgin)					Concrete-C60 Upper Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	3.03	2.67E+06	0	0	3.03	0.00E+00
Concrete	79178	8074	0.205	1.65E+06	136431	13912	0.2045833	2.85E+06
Bar	7808	796	2.77	2.21E+06	14096	1437	2.77	3.98E+06
Total	**95640**	9752		6.53E+06	**150527**	15349		6.83E+06
				4%				-4.54%

Steel-World Typical (39% Recy)					Concrete-C60 UL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	2.03	1.79E+06	0	0	2.03	0.00E+00
Concrete	79178	8074	0.205	1.65E+06	136431	13912	0.2045833	2.85E+06
Bar	7808	796	1.86	1.48E+06	14096	1437	1.86	2.67E+06
Total	95640	9752		4.92E+06	150527	15349		5.52E+06
Reduction to Concrete				**11%**				-12.10%

Steel-Virgin&World Typical (39% Recy)					Concrete-C60 UL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)

Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00
Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	79178	8074	0.205	1.65E+06	136431	13912	0.2045833	2.85E+06
Bar Virgin	7808	796	2.77	2.21E+06	14096	1437	2.77	3.98E+06
Total	95640	9752		6.42E+06	150527	15349		6.83E+06
Reduction to Concrete				6%				-6.27%

Steel-Virgin&World Typical (39% Recy)					Concrete-C60 UL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00
Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	79178	8074	0.205	1.65E+06	136431	13912	0.2045833	2.85E+06
Bar 39% Re	7808	796	1.86	1.48E+06	14096	1437	1.86	2.67E+06
Total	95640	9752		5.70E+06	150527	15349		5.52E+06
Reduction to Concrete				-3%				3.17%

Steel-UK Typical (EC 59% Recy)					Concrete-C60 UL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	1.53	1.35E+06	0	0	1.53	0.00E+00
Concrete	79178	8074	0.205	1.65E+06	136431	13912	0.2045833	2.85E+06
Bar	7808	796	1.40	1.11E+06	14096	1437	1.4	2.01E+06
Total	95640	9752		4.12E+06	150527	15349		4.86E+06
Reduction to Concrete				15%				-18.02%

Steel-Virgin&World Typical (59% Recy)					Concrete-C60 UL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	79178	8074	0.205	1.65E+06	136431	13912	0.2045833	2.85E+06
Bar Virgin	7808	796	2.77	2.21E+06	14096	1437	2.77	3.98E+06
Total	95640	9752		5.98E+06	150527	15349		6.83E+06
Reduction to Concrete				12%				-14.10%

Steel-Virgin&World Typical (59% Recy)					Concrete-C60 UL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	79178	8074	0.205	1.65E+06	136431	13912	0.2045833	2.85E+06
Bar 59% Re	7808	796	1.40	1.11E+06	14096	1437	1.4	2.01E+06
Total	95640	9752		4.89E+06	150527	15349		4.86E+06
Reduction to Concrete				**-1%**				0.71%
ICE								

Steel-Primary (Virgin)					Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	3.03	2.67E+06	0	0	3.03	0.00E+00
Concrete	79177.5294	8074	0.172	1.39E+06	136431	13912	0.1720833	2.39E+06
Bar	7807.97304	796	2.77	2.21E+06	14096	1437	2.77	3.98E+06
Total	**95640**	9752		6.27E+06	**150527**	15349		6.38E+06
				2%				-1.71%

Steel-World Typical (39% Recy)					Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	2.03	1.79E+06	0	0	2.03	0.00E+00
Concrete	79178	8074	0.172	1.39E+06	136431	13912	0.1720833	2.39E+06
Bar	7808	796	1.86	1.48E+06	14096	1437	1.86	2.67E+06
Total	95640	9752		4.66E+06	150527	15349		5.07E+06
Reduction to Concrete				**8%**				-8.71%

Steel-Virgin&World Typical (39% Recy)					Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00
Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	79178	8074	0.172	1.39E+06	136431	13912	0.1720833	2.39E+06
Bar Virgin	7808	796	2.77	2.21E+06	14096	1437	2.77	3.98E+06
Total	95640	9752		6.16E+06	150527	15349		6.38E+06
Reduction to Concrete				**3%**				-3.45%

	Steel-Virgin&World Typical (39% Recy)				Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00
Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	79178	8074	0.172	1.39E+06	136431	13912	0.1720833	2.39E+06
Bar 39% Re	7808	796	1.86	1.48E+06	14096	1437	1.86	2.67E+06
Total	95640	9752		5.44E+06	150527	15349		5.07E+06
Reduction to Concrete				-7%				6.82%

	Steel-UK Typical (EC 59% Recy)				Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	1.53	1.35E+06	0	0	1.53	0.00E+00
Concrete	79178	8074	0.172	1.39E+06	136431	13912	0.1720833	2.39E+06
Bar	7808	796	1.40	1.11E+06	14096	1437	1.4	2.01E+06
Total	95640	9752		3.85E+06	150527	15349		4.41E+06
Reduction to Concrete				13%				-14.33%

	Steel-Virgin&World Typical (59% Recy)				Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	79178	8074	0.172	1.39E+06	136431	13912	0.1720833	2.39E+06
Bar Virgin	7808	796	2.77	2.21E+06	14096	1437	2.77	3.98E+06
Total	95640	9752		5.72E+06	150527	15349		6.38E+06
Reduction to Concrete				10%				-11.43%

	Steel-Virgin&World Typical (59% Recy)				Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00

Concrete	79178	8074	0.172	1.39E+06	136431	13912	0.1720833	2.39E+06
Bar 59% Re	7808	796	1.40	1.11E+06	14096	1437	1.4	2.01E+06
Total	95640	9752		4.63E+06	150527	15349		4.41E+06
Reduction to Concrete				-5%				4.84%
ICE								

Steel-Primary (Virgin)					Concrete-C60 Lower Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	3.03	2.67E+06	0	0	3.03	0.00E+00
Concrete	79177.5294	8074	0.128	1.03E+06	136431	13912	0.1275	1.77E+06
Bar	7807.97304	796	2.77	2.21E+06	14096	1437	2.77	3.98E+06
Total	**95640**	9752		5.91E+06	**150527**	15349		5.76E+06
				-3%				2.59%

Steel-World Typical (39% Recy)					Concrete-C60 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	2.03	1.79E+06	0	0	2.03	0.00E+00
Concrete	79178	8074	0.128	1.03E+06	136431	13912	0.1275	1.77E+06
Bar	7808	796	1.86	1.48E+06	14096	1437	1.86	2.67E+06
Total	95640	9752		4.30E+06	150527	15349		4.45E+06
Reduction to Concrete				**3%**				-3.39%

Steel-Virgin&World Typical (39% Recy)					Concrete-C60 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00
Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	79178	8074	0.128	1.03E+06	136431	13912	0.1275	1.77E+06
Bar Virgin	7808	796	2.77	2.21E+06	14096	1437	2.77	3.98E+06
Total	95640	9752		5.80E+06	150527	15349		5.76E+06
Reduction to Concrete				**-1%**				0.82%

Steel-Virgin&World Typical (39% Recy)					Concrete-C60 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00

Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	79178	8074	0.128	1.03E+06	136431	13912	0.1275	1.77E+06
Bar 39% Re	7808	796	1.86	1.48E+06	14096	1437	1.86	2.67E+06
Total	95640	9752		5.08E+06	150527	15349		4.45E+06
Reduction to Concrete				**-14%**				12.42%

Steel-UK Typical (EC 59% Recy)					Concrete-C60 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	1.53	1.35E+06	0	0	1.53	0.00E+00
Concrete	79178	8074	0.128	1.03E+06	136431	13912	0.1275	1.77E+06
Bar	7808	796	1.40	1.11E+06	14096	1437	1.4	2.01E+06
Total	95640	9752		3.49E+06	150527	15349		3.79E+06
Reduction to Concrete				**8%**				-8.35%

Steel-Virgin&World Typical (59% Recy)					Concrete-C60 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	79178	8074	0.128	1.03E+06	136431	13912	0.1275	1.77E+06
Bar Virgin	7808	796	2.77	2.21E+06	14096	1437	2.77	3.98E+06
Total	95640	9752		5.36E+06	150527	15349		5.76E+06
Reduction to Concrete				**7%**				-7.35%

Steel-Virgin&World Typical (59% Recy)					Concrete-C60 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	79178	8074	0.128	1.03E+06	136431	13912	0.1275	1.77E+06
Bar 59% Re	7808	796	1.40	1.11E+06	14096	1437	1.4	2.01E+06
Total	95640	9752		4.27E+06	150527	15349		3.79E+06
Reduction to Concrete				**-13%**				11.35%

HK								
Steel (HK avg-CIC)					Concrete-C60 (HK avg-CIC)			

	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Steel Section	8654	882	0.55	4.85E+05	0	0	0.55	0.00E+00
Concrete C60	79178	8074	0.129167	1.04E+06	136431	13912	0.129	1.80E+06
Steel Rebar	7808	796	2.08	1.66E+06	14096	1437	2.08	2.99E+06
Total	95640	9752		3.18E+06	150527	15349		4.79E+06
Reduction to Concrete				**33%**				-50.33%

APPENDIX E

TOTAL CARBON FOOTPRINTS OF 25/F STEEL & C80 RC BUILDINGS (SUPERSTRUCTURE & FOUNDATION)

	Steel	RC C80
Category	Weight (kN)	Weight (kN)
Steel	**8654**	**0**
Concrete	0	0
Conc without R	**79177.53**	**123443**
Reinforcement	**7808**	**13094**

ICE

	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
					Concrete-C80 Upper Limit			
Section	8654	882	3.03	2.67E+06	0	0	3.03	0.00E+00
Concrete	79178	8074	0.249	2.01E+06	123443	12587	0.2491667	3.14E+06
Bar	7808	796	2.77	2.21E+06	13094	1335	2.77	3.70E+06
Total	**95640**	9752		6.89E+06	**136538**	13922		6.83E+06
				-1%				0.81%

	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
					Concrete-C80 Upper Limit			
Section	8654	882	2.03	1.79E+06	0	0	2.03	0.00E+00
Concrete	79178	8074	0.249	2.01E+06	123443	12587	0.2491667	3.14E+06
Bar	7808	796	1.86	1.48E+06	13094	1335	1.86	2.48E+06
Total	95640	9752		5.28E+06	136538	13922		5.62E+06
				6%				-6.36%

	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
					Concrete-C80 Upper Limit			
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00

Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	79178	8074	0.249	2.01E+06	123443	12587	0.2491667	3.14E+06
Bar Virgin	7808	796	2.77	2.21E+06	13094	1335	2.77	3.70E+06
Total	95640	9752		6.78E+06	136538	13922		6.83E+06
				1%				-0.73%

					Concrete-C80 Upper Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00
Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	79178	8074	0.249	2.01E+06	123443	12587	0.2491667	3.14E+06
Bar 39% Re	7808	796	1.86	1.48E+06	13094	1335	1.86	2.48E+06
Total	95640	9752		6.06E+06	136538	13922		5.62E+06
				-8%				7.27%

					Concrete-C80 Upper Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	1.53	1.35E+06	0	0	1.53	0.00E+00
Concrete	79178	8074	0.249	2.01E+06	123443	12587	0.2491667	3.14E+06
Bar	7808	796	1.40	1.11E+06	13094	1335	1.4	1.87E+06
Total	95640	9752		4.48E+06	136538	13922		5.01E+06
				11%				-11.82%

					Concrete-C80 Upper Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	79178	8074	0.249	2.01E+06	123443	12587	0.2491667	3.14E+06
Bar Virgin	7808	796	2.77	2.21E+06	13094	1335	2.77	3.70E+06
Total	95640	9752		6.34E+06	136538	13922		6.83E+06
				7%				-7.74%

					Concrete-C80 Upper Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)

Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	79178	8074	0.249	2.01E+06	123443	12587	0.2491667	3.14E+06
Bar 59% Re	7808	796	1.40	1.11E+06	13094	1335	1.4	1.87E+06
Total	95640	9752		5.25E+06	136538	13922		5.01E+06
				-5%				4.71%

ICE

					Concrete-C80 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	3.03	2.67E+06	0	0	3.03	0.00E+00
Concrete	79177.5 294	8074	0.211	1.71E+06	123443	12587	0.21125	2.66E+06
Bar	7807.97 304	796	2.77	2.21E+06	13094	1335	2.77	3.70E+06
Total	**95640**	9752		6.58E+06	**136538**	13922		6.36E+06
				-4%				3.45%

					Concrete-C80 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	2.03	1.79E+06	0	0	2.03	0.00E+00
Concrete	79178	8074	0.211	1.71E+06	123443	12587	0.21125	2.66E+06
Bar	7808	796	1.86	1.48E+06	13094	1335	1.86	2.48E+06
Total	95640	9752		4.98E+06	136538	13922		5.14E+06
				3%				-3.31%

					Concrete-C80 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00
Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	79178	8074	0.211	1.71E+06	123443	12587	0.21125	2.66E+06
Bar Virgin	7808	796	2.77	2.21E+06	13094	1335	2.77	3.70E+06
Total	95640	9752		6.48E+06	136538	13922		6.36E+06
				-2%				1.87%

	Concrete-C80 Avg

	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00
Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	79178	8074	0.211	1.71E+06	123443	12587	0.21125	2.66E+06
Bar 39% Re	7808	796	1.86	1.48E+06	13094	1335	1.86	2.48E+06
Total	95640	9752		5.75E+06	136538	13922		5.14E+06
				-12%				10.63%

					Concrete-C80 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	1.53	1.35E+06	0	0	1.53	0.00E+00
Concrete	79178	8074	0.211	1.71E+06	123443	12587	0.21125	2.66E+06
Bar	7808	796	1.40	1.11E+06	13094	1335	1.4	1.87E+06
Total	95640	9752		4.17E+06	136538	13922		4.53E+06
				8%				-8.59%

					Concrete-C80 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	79178	8074	0.211	1.71E+06	123443	12587	0.21125	2.66E+06
Bar Virgin	7808	796	2.77	2.21E+06	13094	1335	2.77	3.70E+06
Total	95640	9752		6.04E+06	136538	13922		6.36E+06
				5%				-5.30%

					Concrete-C80 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	79178	8074	0.211	1.71E+06	123443	12587	0.21125	2.66E+06
Bar 59% Re	7808	796	1.40	1.11E+06	13094	1335	1.4	1.87E+06
Total	95640	9752		4.95E+06	136538	13922		4.53E+06

				-9%				8.46%
ICE								
					Concrete-C80 Lower Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	3.03	2.67E+06	0	0	3.03	0.00E+00
Concrete	79177.5294	8074	0.159	1.28E+06	123443	12587	0.15875	2.00E+06
Bar	7807.97304	796	2.77	2.21E+06	13094	1335	2.77	3.70E+06
Total	**95640**	9752		6.16E+06	**136538**	13922		5.70E+06
				-8%				7.53%

					Concrete-C80 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	2.03	1.79E+06	0	0	2.03	0.00E+00
Concrete	79178	8074	0.159	1.28E+06	123443	12587	0.15875	2.00E+06
Bar	7808	796	1.86	1.48E+06	13094	1335	1.86	2.48E+06
Total	95640	9752		4.55E+06	136538	13922		4.48E+06
				-2%				1.59%

					Concrete-C80 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00
Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	79178	8074	0.159	1.28E+06	123443	12587	0.15875	2.00E+06
Bar Virgin	7808	796	2.77	2.21E+06	13094	1335	2.77	3.70E+06
Total	95640	9752		6.05E+06	136538	13922		5.70E+06
				-6%				5.92%

					Concrete-C80 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00
Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	79178	8074	0.159	1.28E+06	123443	12587	0.15875	2.00E+06
Bar 39% Re	7808	796	1.86	1.48E+06	13094	1335	1.86	2.48E+06

Total	95640	9752		5.33E+06	136538	13922		4.48E+06
				-19%				15.92%

					Concrete-C80 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	1.53	1.35E+06	0	0	1.53	0.00E+00
Concrete	79178	8074	0.159	1.28E+06	123443	12587	0.15875	2.00E+06
Bar	7808	796	1.40	1.11E+06	13094	1335	1.4	1.87E+06
Total	95640	9752		3.75E+06	136538	13922		3.87E+06
				3%				-3.23%

					Concrete-C80 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	79178	8074	0.159	1.28E+06	123443	12587	0.15875	2.00E+06
Bar Virgin	7808	796	2.77	2.21E+06	13094	1335	2.77	3.70E+06
Total	95640	9752		5.61E+06	136538	13922		5.70E+06
				1%				-1.48%

					Concrete-C80 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	79178	8074	0.159	1.28E+06	123443	12587	0.15875	2.00E+06
Bar 59% Re	7808	796	1.40	1.11E+06	13094	1335	1.4	1.87E+06
Total	95640	9752		4.52E+06	136538	13922		3.87E+06
				-17%				14.49%

HK

					Concrete-C80 (HK avg-CIC)			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Steel Section	8654	882	2.28	2.01E+06	0	0	2.28	0.00E+00
Concrete	79178	8074	0.204	1.65E+06	123443	12587	0.204	2.57E+06
Steel Rebar	7808	796	2.09	1.66E+06	13094	1335	2.09	2.79E+06

Total	95640	9752		5.32E+06	136538	13922		5.36E+06
				1%				-0.68%

					Concrete-C80 (HK avg-CIC)			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Steel Section	8654	882	0.55	4.85E+05	0	0	0.55	0.00E+00
Concrete	79178	8074	0.204	1.65E+06	123443	12587	0.204	2.57E+06
Steel Rebar	7808	796	2.20	1.75E+06	13094	1335	2.2	2.94E+06
Total	95640	9752		3.89E+06	136538	13922		5.51E+06
				29%				-41.75%

					Concrete-C80 (HK avg-CIC)			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Avg	6141	626	2.28	5.84E+05			2.28	0.00E+00
Section App	2513.4	256	0.55	4.85E+05			0.55	0.00E+00
Section Total	8654	882		1.07E+06	0	0		0.00E+00
Concrete	79178	8074	0.204	1.65E+06	123443	12587	0.2041667	2.57E+06
Bar Avg	7808	796	2.09	1.66E+06	13094	1335	2.09	2.79E+06
Total	95640	9752		4.38E+06	136538	13922		5.36E+06
				18%				-22.33%

					Concrete-C80 (HK avg-CIC)			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Avg	6141	626	2.28	5.84E+05			2.28	0.00E+00
Section App	2513.4	256	0.55	4.85E+05			0.55	0.00E+00
Section Total	8654	882		1.07E+06	0	0		0.00E+00
Concrete	79178	8074	0.204	1.65E+06	123443	12587	0.2041667	2.57E+06
Bar App	7808	796	2.20	1.75E+06	13094	1335	2.2	2.94E+06
Total	95640	9752		4.47E+06	136538	13922		5.51E+06
				19%				-23.22%

APPENDIX F

TOTAL CARBON FOOTPRINTS OF 25/F STEEL & C100 RC BUILDINGS (SUPERSTRUCTURE & FOUNDATION)

	Steel	RC C100
Category	Weight (kN)	Weight (kN)
Steel	**8654**	**0**
Concrete	0	0
Conc without R	**79177.53**	**112367**
Reinforcement	**7808**	**12634**

ICE								
Steel-Primary (Virgin)					Concrete-C100 Upper Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	3.03	2.67E+06	0	0	3.03	0.00E+00
Concrete	79178	8074	0.249	2.01E+06	112367	11458	0.2491667	2.85E+06
Bar	7808	796	2.77	2.21E+06	12634	1288	2.77	3.57E+06
Total	**95640**	9752		6.89E+06	**125002**	12746		6.42E+06
				-7%				6.78%

Steel-World Typical (39% Recy)					Concrete-C100 Upper Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	2.03	1.79E+06	0	0	2.03	0.00E+00
Concrete	79178	8074	0.249	2.01E+06	112367	11458	0.2491667	2.85E+06
Bar	7808	796	1.86	1.48E+06	12634	1288	1.86	2.40E+06
Total	95640	9752		5.28E+06	125002	12746		5.25E+06
Reduction to Concrete				**-1%**				0.62%

Steel-Virgin&World Typical (39% Recy)					Concrete-C100 Upper Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)

Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00
Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	79178	8074	0.249	2.01E+06	112367	11458	0.2491667	2.85E+06
Bar Virgin	7808	796	2.77	2.21E+06	12634	1288	2.77	3.57E+06
Total	95640	9752		6.78E+06	125002	12746		6.42E+06
Reduction to Concrete				**-6%**				5.33%

Steel-Virgin&World Typical (39% Recy)					Concrete-C100 Upper Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00
Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	79178	8074	0.249	2.01E+06	112367	11458	0.2491667	2.85E+06
Bar 39% Re	7808	796	1.86	1.48E+06	12634	1288	1.86	2.40E+06
Total	95640	9752		6.06E+06	125002	12746		5.25E+06
Reduction to Concrete				**-15%**				13.35%

Steel-UK Typical (EC 59% Recy)					Concrete-C100 Upper Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	1.53	1.35E+06	0	0	1.53	0.00E+00
Concrete	79178	8074	0.249	2.01E+06	112367	11458	0.2491667	2.85E+06
Bar	7808	796	1.40	1.11E+06	12634	1288	1.4	1.80E+06
Total	95640	9752		4.48E+06	125002	12746		4.66E+06
Reduction to Concrete				**4%**				-4.07%

Steel-Virgin&World Typical (59% Recy)					Concrete-C100 Upper Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	79178	8074	0.249	2.01E+06	112367	11458	0.2491667	2.85E+06
Bar Virgin	7808	796	2.77	2.21E+06	12634	1288	2.77	3.57E+06
Total	95640	9752		6.34E+06	125002	12746		6.42E+06
Reduction to Concrete				**1%**				-1.26%

Steel-Virgin&World Typical (59% Recy)					Concrete-C100 Upper Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	79178	8074	0.249	2.01E+06	112367	11458	0.2491667	2.85E+06
Bar 59% Re	7808	796	1.40	1.11E+06	12634	1288	1.4	1.80E+06
Total	95640	9752		5.25E+06	125002	12746		4.66E+06
Reduction to Concrete				-13%				11.32%
ICE								

Steel-Primary (Virgin)					Concrete-C100 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	3.03	2.67E+06	0	0	3.03	0.00E+00
Concrete	79177.5294	8074	0.211	1.71E+06	112367	11458	0.21125	2.42E+06
Bar	7807.97304	796	2.77	2.21E+06	12634	1288	2.77	3.57E+06
Total	**95640**	9752		6.58E+06	**125002**	12746		5.99E+06
				-10%				9.05%

Steel-World Typical (39% Recy)					Concrete-C100 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	2.03	1.79E+06	0	0	2.03	0.00E+00
Concrete	79178	8074	0.211	1.71E+06	112367	11458	0.21125	2.42E+06
Bar	7808	796	1.86	1.48E+06	12634	1288	1.86	2.40E+06
Total	95640	9752		4.98E+06	125002	12746		4.82E+06
Reduction to Concrete				-3%				3.23%

Steel-Virgin&World Typical (39% Recy)					Concrete-C100 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00
Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	79178	8074	0.211	1.71E+06	112367	11458	0.21125	2.42E+06
Bar Virgin	7808	796	2.77	2.21E+06	12634	1288	2.77	3.57E+06
Total	95640	9752		6.48E+06	125002	12746		5.99E+06
Reduction to Concrete				-8%				7.56%

	Steel-Virgin&World Typical (39% Recy)				Concrete-C100 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00
Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	79178	8074	0.211	1.71E+06	112367	11458	0.21125	2.42E+06
Bar 39% Re	7808	796	1.86	1.48E+06	12634	1288	1.86	2.40E+06
Total	95640	9752		5.75E+06	125002	12746		4.82E+06
Reduction to Concrete				-19%				16.29%

	Steel-UK Typical (EC 59% Recy)				Concrete-C100 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	1.53	1.35E+06	0	0	1.53	0.00E+00
Concrete	79178	8074	0.211	1.71E+06	112367	11458	0.21125	2.42E+06
Bar	7808	796	1.40	1.11E+06	12634	1288	1.4	1.80E+06
Total	95640	9752		4.17E+06	125002	12746		4.22E+06
Reduction to Concrete				1%				-1.29%

	Steel-Virgin&World Typical (59% Recy)				Concrete-C100 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	79178	8074	0.211	1.71E+06	112367	11458	0.21125	2.42E+06
Bar Virgin	7808	796	2.77	2.21E+06	12634	1288	2.77	3.57E+06
Total	95640	9752		6.04E+06	125002	12746		5.99E+06
Reduction to Concrete				-1%				0.80%

	Steel-Virgin&World Typical (59% Recy)				Concrete-C100 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00

Concrete	79178	8074	0.211	1.71E+06	112367	11458	0.21125	2.42E+06
Bar 59% Re	7808	796	1.40	1.11E+06	12634	1288	1.4	1.80E+06
Total	95640	9752		4.95E+06	125002	12746		4.22E+06
Reduction to Concrete				**-17%**				14.61%
ICE								

Steel-Primary (Virgin)					Concrete-C100 Lower Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	3.03	2.67E+06	0	0	3.03	0.00E+00
Concrete	79177.5 294	8074	0.159	1.28E+06	112367	11458	0.15875	1.82E+06
Bar	7807.97 304	796	2.77	2.21E+06	12634	1288	2.77	3.57E+06
Total	**95640**	9752		6.16E+06	**125002**	12746		5.39E+06
				-14%				12.55%

Steel-World Typical (39% Recy)					Concrete-C100 Lower Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	2.03	1.79E+06	0	0	2.03	0.00E+00
Concrete	79178	8074	0.159	1.28E+06	112367	11458	0.15875	1.82E+06
Bar	7808	796	1.86	1.48E+06	12634	1288	1.86	2.40E+06
Total	95640	9752		4.55E+06	125002	12746		4.22E+06
Reduction to Concrete				**-8%**				7.44%

Steel-Virgin&World Typical (39% Recy)					Concrete-C100 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00
Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	79178	8074	0.159	1.28E+06	112367	11458	0.15875	1.82E+06
Bar Virgin	7808	796	2.77	2.21E+06	12634	1288	2.77	3.57E+06
Total	95640	9752		6.05E+06	125002	12746		5.39E+06
Reduction to Concrete				**-12%**				11.02%

Steel-Virgin&World Typical (39% Recy)					Concrete-C100 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	1.79E+06			2.03	0.00E+00

Section Total	8654	882		2.57E+06	0	0		0.00E+00
Concrete	79178	8074	0.159	1.28E+06	112367	11458	0.15875	1.82E+06
Bar 39% Re	7808	796	1.86	1.48E+06	12634	1288	1.86	2.40E+06
Total	95640	9752		5.33E+06	125002	12746		4.22E+06
Reduction to Concrete				**-26%**				20.92%

Steel-UK Typical (EC 59% Recy)					Concrete-C100 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	8654	882	1.53	1.35E+06	0	0	1.53	0.00E+00
Concrete	79178	8074	0.159	1.28E+06	112367	11458	0.15875	1.82E+06
Bar	7808	796	1.40	1.11E+06	12634	1288	1.4	1.80E+06
Total	95640	9752		3.75E+06	125002	12746		3.62E+06
Reduction to Concrete				**-3%**				3.31%

Steel-Virgin&World Typical (59% Recy)					Concrete-C100 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	79178	8074	0.159	1.28E+06	112367	11458	0.15875	1.82E+06
Bar Virgin	7808	796	2.77	2.21E+06	12634	1288	2.77	3.57E+06
Total	95640	9752		5.61E+06	125002	12746		5.39E+06
Reduction to Concrete				**-4%**				4.03%

Steel-Virgin&World Typical (59% Recy)					Concrete-C100 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	1.35E+06			1.53	0.00E+00
Section Total	8654	882		2.13E+06	0	0		0.00E+00
Concrete	79178	8074	0.159	1.28E+06	112367	11458	0.15875	1.82E+06
Bar 59% Re	7808	796	1.40	1.11E+06	12634	1288	1.4	1.80E+06
Total	95640	9752		4.52E+06	125002	12746		3.62E+06
Reduction to Concrete				**-25%**				19.91%

HK

Steel (HK avg-CIC)					Concrete-C100 (HK avg-CIC)			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)

Steel Section	8654	882	2.28	2.01E+06	0	0	2.28	0.00E+00
Concrete	79178	8074	0.204	1.65E+06	112367	11458	0.204	2.34E+06
Steel Rebar	7808	796	2.09	1.66E+06	12634	1288	2.09	2.69E+06
Total	95640	9752		5.32E+06	125002	12746		5.03E+06
Reduction to Concrete			**-6%**				5.49%	

Steel (HK App)					Concrete-C100 (HK avg-CIC)			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Steel Section	8654	882	0.55	4.85E+05	0	0	0.55	0.00E+00
Concrete	79178	8074	0.204	1.65E+06	112367	11458	0.204	2.34E+06
Steel Rebar	7808	796	2.20	1.75E+06	12634	1288	2.2	2.83E+06
Total	95640	9752		3.89E+06	125002	12746		5.17E+06
Reduction to Concrete			**25%**				-33.16%	

Steel-(HK avg & App)					Concrete-C100 (HK avg-CIC)			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Avg	6141	626	2.28	5.84E+05			2.28	0.00E+00
Section App	2513.4	256	0.55	4.85E+05			0.55	0.00E+00
Section Total	8654	882		1.07E+06	0	0		0.00E+00
Concrete	79178	8074	0.204	1.65E+06	112367	11458	0.2041667	2.34E+06
Bar Avg	7808	796	2.09	1.66E+06	12634	1288	2.09	2.69E+06
Total	95640	9752		4.38E+06	125002	12746		5.03E+06
Reduction to Concrete			**13%**				-14.83%	

Steel-(HK avg & App)					Concrete-C100 (HK avg-CIC)			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Avg	6141	626	2.28	5.84E+05			2.28	0.00E+00
Section App	2513.4	256	0.55	4.85E+05			0.55	0.00E+00
Section Total	8654	882		1.07E+06	0	0		0.00E+00
Concrete	79178	8074	0.204	1.65E+06	112367	11458	0.2041667	2.34E+06
Bar App	7808	796	2.20	1.75E+06	12634	1288	2.2	2.83E+06
Total	95640	9752		4.47E+06	125002	12746		5.17E+06
Reduction to Concrete			**14%**				-15.75%	

APPENDIX G

TOTAL CARBON FOOTPRINTS OF 15/F STEEL & C60 RC BUILDINGS (SUPERSTRUCTURE ONLY)

Steel		15/F RC C60
Category	Weight (kN)	Weight (kN)
Steel	**4640.2**	**0**
Conc without R	**25222.62**	**53728**
Reinforcement	**2727**	**6294**

ICE								
	Steel-Primary (Virgin)				Concrete-C60 Upper Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	4640.2	473	3.03	1.43E+06	0	0	3.03	0.00E+00
Concrete	25223	2572	0.205	5.26E+05	53728	5479	0.2045833	1.12E+06
Bar	2727	278	2.77	7.70E+05	6294	642	2.77	1.78E+06
Total	**32590**	3323		2.73E+06	**60022**	6120		2.90E+06
				6%				-6.17%

	Steel-World Typical (39% Recy)				Concrete-C60 UL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	4640.2	473	2.03	9.60E+05	0	0	2.03	0.00E+00
Concrete	25223	2572	0.205	5.26E+05	53728	5479	0.2045833	1.12E+06
Bar	2727	278	1.86	5.17E+05	6294	642	1.86	1.19E+06
Total	32590	3323		2.00E+06	60022	6120		2.31E+06
Reduction to Concrete				**13%**				-15.50%

	Steel-Virgin&World Typical (39% Recy)				Concrete-C60 UL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00

Section 39% Re	2513.4	256	2.03	9.60E+05			2.03	0.00E+00
Section Total	4640.2	473		1.74E+06	0	0		0.00E+00
Concrete	25223	2572	0.205	5.26E+05	53728	5479	0.2045833	1.12E+06
Bar Virgin	2727	278	2.77	7.70E+05	6294	642	2.77	1.78E+06
Total	32590	3323		3.03E+06	60022	6120		2.90E+06
Reduction to Concrete				-5%				4.45%

Steel-Virgin&World Typical (39% Recy)					Concrete-C60 UL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	9.60E+05			2.03	0.00E+00
Section Total	4640.2	473		1.74E+06	0	0		0.00E+00
Concrete	25223	2572	0.205	5.26E+05	53728	5479	0.2045833	1.12E+06
Bar 39% Re	2727	278	1.86	5.17E+05	6294	642	1.86	1.19E+06
Total	32590	3323		2.78E+06	60022	6120		2.31E+06
Reduction to Concrete				-20%				16.76%

Steel-UK Typical (EC 59% Recy)					Concrete-C60 UL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	4640.2	473	1.53	7.24E+05	0	0	1.53	0.00E+00
Concrete	25223	2572	0.205	5.26E+05	53728	5479	0.2045833	1.12E+06
Bar	2727	278	1.40	3.89E+05	6294	642	1.4	8.99E+05
Total	32590	3323		1.64E+06	60022	6120		2.02E+06
Reduction to Concrete				19%				-23.18%

Steel-Virgin&World Typical (59% Recy)					Concrete-C60 UL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	7.24E+05			1.53	0.00E+00
Section Total	4640.2	473		1.50E+06	0	0		0.00E+00
Concrete	25223	2572	0.205	5.26E+05	53728	5479	0.2045833	1.12E+06
Bar Virgin	2727	278	2.77	7.70E+05	6294	642	2.77	1.78E+06
Total	32590	3323		2.80E+06	60022	6120		2.90E+06
Reduction to Concrete				4%				-3.64%

Steel-Virgin&World Typical (59% Recy)					Concrete-C60 UL			

	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	7.24E+05			1.53	0.00E+00
Section Total	4640.2	473		1.50E+06	0	0		0.00E+00
Concrete	25223	2572	0.205	5.26E+05	53728	5479	0.2045833	1.12E+06
Bar 59% Re	2727	278	1.40	3.89E+05	6294	642	1.4	8.99E+05
Total	32590	3323		2.42E+06	60022	6120		2.02E+06
Reduction to Concrete				**-20%**				16.42%

ICE

Steel-Primary (Virgin)					Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	4640.2	473	3.03	1.43E+06	0	0	3.03	0.00E+00
Concrete	25222.62	2572	0.172	4.43E+05	53728	5479	0.1720833	9.43E+05
Bar	2727	278	2.77	7.70E+05	6294	642	2.77	1.78E+06
Total	**32590**	3323		2.65E+06	**60022**	6120		2.72E+06
				3%				-2.80%

Steel-World Typical (39% Recy)					Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	4640.2	473	2.03	9.60E+05	0	0	2.03	0.00E+00
Concrete	25223	2572	0.172	4.43E+05	53728	5479	0.1720833	9.43E+05
Bar	2727	278	1.86	5.17E+05	6294	642	1.86	1.19E+06
Total	32590	3323		1.92E+06	60022	6120		2.14E+06
Reduction to Concrete				**10%**				-11.26%

Steel-Virgin&World Typical (39% Recy)					Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	9.60E+05			2.03	0.00E+00
Section Total	4640.2	473		1.74E+06	0	0		0.00E+00
Concrete	25223	2572	0.172	4.43E+05	53728	5479	0.1720833	9.43E+05
Bar Virgin	2727	278	2.77	7.70E+05	6294	642	2.77	1.78E+06
Total	32590	3323		2.95E+06	60022	6120		2.72E+06
Reduction to Concrete				**-8%**				7.78%

Steel-Virgin&World Typical (39% Recy)					Concrete-C60 Avg			

	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	9.60E+05			2.03	0.00E+00
Section Total	4640.2	473		1.74E+06	0	0		0.00E+00
Concrete	25223	2572	0.172	4.43E+05	53728	5479	0.1720833	9.43E+05
Bar 39% Re	2727	278	1.86	5.17E+05	6294	642	1.86	1.19E+06
Total	32590	3323		2.70E+06	60022	6120		2.14E+06
Reduction to Concrete				**-26%**				20.78%

Steel-UK Typical (EC 59% Recy)					Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	4640.2	473	1.53	7.24E+05	0	0	1.53	0.00E+00
Concrete	25223	2572	0.172	4.43E+05	53728	5479	0.1720833	9.43E+05
Bar	2727	278	1.40	3.89E+05	6294	642	1.4	8.99E+05
Total	32590	3323		1.56E+06	60022	6120		1.84E+06
Reduction to Concrete				**16%**				-18.35%

Steel-Virgin&World Typical (59% Recy)					Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	7.24E+05			1.53	0.00E+00
Section Total	4640.2	473		1.50E+06	0	0		0.00E+00
Concrete	25223	2572	0.172	4.43E+05	53728	5479	0.1720833	9.43E+05
Bar Virgin	2727	278	2.77	7.70E+05	6294	642	2.77	1.78E+06
Total	32590	3323		2.71E+06	60022	6120		2.72E+06
Reduction to Concrete				**0%**				-0.27%

Steel-Virgin&World Typical (59% Recy)					Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	7.24E+05			1.53	0.00E+00
Section Total	4640.2	473		1.50E+06	0	0		0.00E+00
Concrete	25223	2572	0.172	4.43E+05	53728	5479	0.1720833	9.43E+05
Bar 59% Re	2727	278	1.40	3.89E+05	6294	642	1.4	8.99E+05
Total	32590	3323		2.33E+06	60022	6120		1.84E+06

Reduction to Concrete			-27%					21.06%
ICE								
Steel-Primary (Virgin)					Concrete-C60 Lower Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	4640.2	473	3.03	1.43E+06	0	0	3.03	0.00E+00
Concrete	25222.62	2572	0.128	3.28E+05	53728	5479	0.1275	6.99E+05
Bar	2727	278	2.77	7.70E+05	6294	642	2.77	1.78E+06
Total	**32590**	3323		2.53E+06	**60022**	6120		2.48E+06
			-2%					2.19%

Steel-World Typical (39% Recy)					Concrete-C60 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	4640.2	473	2.03	9.60E+05	0	0	2.03	0.00E+00
Concrete	25223	2572	0.128	3.28E+05	53728	5479	0.1275	6.99E+05
Bar	2727	278	1.86	5.17E+05	6294	642	1.86	1.19E+06
Total	32590	3323		1.81E+06	60022	6120		1.89E+06
Reduction to Concrete			5%					-4.80%

Steel-Virgin&World Typical (39% Recy)					Concrete-C60 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	9.60E+05			2.03	0.00E+00
Section Total	4640.2	473		1.74E+06	0	0		0.00E+00
Concrete	25223	2572	0.128	3.28E+05	53728	5479	0.1275	6.99E+05
Bar Virgin	2727	278	2.77	7.70E+05	6294	642	2.77	1.78E+06
Total	32590	3323		2.84E+06	60022	6120		2.48E+06
Reduction to Concrete			-14%					12.66%

Steel-Virgin&World Typical (39% Recy)					Concrete-C60 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	9.60E+05			2.03	0.00E+00
Section Total	4640.2	473		1.74E+06	0	0		0.00E+00
Concrete	25223	2572	0.128	3.28E+05	53728	5479	0.1275	6.99E+05
Bar 39% Re	2727	278	1.86	5.17E+05	6294	642	1.86	1.19E+06
Total	32590	3323		2.58E+06	60022	6120		1.89E+06

Reduction to Concrete			-36%			26.72%	

Steel-UK Typical (EC 59% Recy)					Concrete-C60 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	4640.2	473	1.53	7.24E+05	0	0	1.53	0.00E+00
Concrete	25223	2572	0.128	3.28E+05	53728	5479	0.1275	6.99E+05
Bar	2727	278	1.40	3.89E+05	6294	642	1.4	8.99E+05
Total	32590	3323		1.44E+06	60022	6120		1.60E+06
Reduction to Concrete				10%				-10.82%

Steel-Virgin&World Typical (59% Recy)					Concrete-C60 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	7.24E+05			1.53	0.00E+00
Section Total	4640.2	473		1.50E+06	0	0		0.00E+00
Concrete	25223	2572	0.128	3.28E+05	53728	5479	0.1275	6.99E+05
Bar Virgin	2727	278	2.77	7.70E+05	6294	642	2.77	1.78E+06
Total	32590	3323		2.60E+06	60022	6120		2.48E+06
Reduction to Concrete				-5%				4.71%

Steel-Virgin&World Typical (59% Recy)					Concrete-C60 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	7.24E+05			1.53	0.00E+00
Section Total	4640.2	473		1.50E+06	0	0		0.00E+00
Concrete	25223	2572	0.128	3.28E+05	53728	5479	0.1275	6.99E+05
Bar 59% Re	2727	278	1.40	3.89E+05	6294	642	1.4	8.99E+05
Total	32590	3323		2.22E+06	60022	6120		1.60E+06
Reduction to Concrete				-39%				27.99%

APPENDIX H

TOTAL CARBON FOOTPRINTS OF 35/F STEEL & C60 RC BUILDINGS (SUPERSTRUCTURE ONLY)

	Steel	35/F RC C60
Category	Weight (kN)	Weight (kN)
Steel	**14836**	**0**
Conc without R	**82685.14**	**160164**
Reinforcement	**8940**	**19032**

ICE

Steel-Primary (Virgin)					Concrete-C60 Upper Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	14836	1513	3.03	4.58E+06	0	0	3.03	0.00E+00
Concrete	82685	8431	0.205	1.72E+06	160164	16332	0.2045833	3.34E+06
Bar	8940	912	2.77	2.53E+06	19032	1941	2.77	5.38E+06
Total	**106461**	10856		8.83E+06	**179196**	18272		8.72E+06
				-1%				1.32%

Steel-World Typical (39% Recy)					Concrete-C60 UL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	14836	1513	2.03	3.07E+06	0	0	2.03	0.00E+00
Concrete	82685	8431	0.205	1.72E+06	160164	16332	0.2045833	3.34E+06
Bar	8940	912	1.86	1.70E+06	19032	1941	1.86	3.61E+06
Total	106461	10856		6.49E+06	179196	18272		6.95E+06
Reduction to Concrete				**7%**				-7.08%

Steel-Virgin&World Typical (39% Recy)					Concrete-C60 UL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00

Section 39% Re	2513.4	256	2.03	3.07E+06			2.03	0.00E+00
Section Total	14836	1513		3.85E+06	0	0		0.00E+00
Concrete	82685	8431	0.205	1.72E+06	160164	16332	0.2045833	3.34E+06
Bar Virgin	8940	912	2.77	2.53E+06	19032	1941	2.77	5.38E+06
Total	106461	10856		8.10E+06	179196	18272		8.72E+06
Reduction to Concrete				**7%**				-7.65%

Steel-Virgin&World Typical (39% Recy)					Concrete-C60 UL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	3.07E+06			2.03	0.00E+00
Section Total	14836	1513		3.85E+06	0	0		0.00E+00
Concrete	82685	8431	0.205	1.72E+06	160164	16332	0.2045833	3.34E+06
Bar 39% Re	8940	912	1.86	1.70E+06	19032	1941	1.86	3.61E+06
Total	106461	10856		7.27E+06	179196	18272		6.95E+06
Reduction to Concrete				**-5%**				4.36%

Steel-UK Typical (EC 59% Recy)					Concrete-C60 UL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	14836	1513	1.53	2.31E+06	0	0	1.53	0.00E+00
Concrete	82685	8431	0.205	1.72E+06	160164	16332	0.2045833	3.34E+06
Bar	8940	912	1.40	1.28E+06	19032	1941	1.4	2.72E+06
Total	106461	10856		5.32E+06	179196	18272		6.06E+06
Reduction to Concrete				**12%**				-13.97%

Steel-Virgin&World Typical (59% Recy)					Concrete-C60 UL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	2.31E+06			1.53	0.00E+00
Section Total	14836	1513		3.09E+06	0	0		0.00E+00
Concrete	82685	8431	0.205	1.72E+06	160164	16332	0.2045833	3.34E+06
Bar Virgin	8940	912	2.77	2.53E+06	19032	1941	2.77	5.38E+06
Total	106461	10856		7.34E+06	179196	18272		8.72E+06
Reduction to Concrete				**16%**				-18.74%

Steel-Virgin&World Typical (59% Recy)					Concrete-C60 UL			

	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	2.31E+06			1.53	0.00E+00
Section Total	14836	1513		3.09E+06	0	0		0.00E+00
Concrete	82685	8431	0.205	1.72E+06	160164	16332	0.2045833	3.34E+06
Bar 59% Re	8940	912	1.40	1.28E+06	19032	1941	1.4	2.72E+06
Total	106461	10856		6.09E+06	179196	18272		6.06E+06
Reduction to Concrete				-1%				0.56%

ICE

Steel-Primary (Virgin)					Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	14836	1513	3.03	4.58E+06	0	0	3.03	0.00E+00
Concrete	82685.14	8431	0.172	1.45E+06	160164	16332	0.1720833	2.81E+06
Bar	8940	912	2.77	2.53E+06	19032	1941	2.77	5.38E+06
Total	**106461**	10856		8.56E+06	**179196**	18272		8.19E+06
				-5%				4.37%

Steel-World Typical (39% Recy)					Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	14836	1513	2.03	3.07E+06	0	0	2.03	0.00E+00
Concrete	82685	8431	0.172	1.45E+06	160164	16332	0.1720833	2.81E+06
Bar	8940	912	1.86	1.70E+06	19032	1941	1.86	3.61E+06
Total	106461	10856		6.22E+06	179196	18272		6.42E+06
Reduction to Concrete				3%				-3.26%

Steel-Virgin&World Typical (39% Recy)					Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	3.07E+06			2.03	0.00E+00
Section Total	14836	1513		3.85E+06	0	0		0.00E+00
Concrete	82685	8431	0.172	1.45E+06	160164	16332	0.1720833	2.81E+06
Bar Virgin	8940	912	2.77	2.53E+06	19032	1941	2.77	5.38E+06
Total	106461	10856		7.82E+06	179196	18272		8.19E+06
Reduction to Concrete				4%				-4.63%

Steel-Virgin&World Typical (39% Recy)	Concrete-C60 Avg

	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	3.07E+06			2.03	0.00E+00
Section Total	14836	1513		3.85E+06	0	0		0.00E+00
Concrete	82685	8431	0.172	1.45E+06	160164	16332	0.1720833	2.81E+06
Bar 39% Re	8940	912	1.86	1.70E+06	19032	1941	1.86	3.61E+06
Total	106461	10856		6.99E+06	179196	18272		6.42E+06
Reduction to Concrete				-9%				8.21%

Steel-UK Typical (EC 59% Recy)					Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	14836	1513	1.53	2.31E+06	0	0	1.53	0.00E+00
Concrete	82685	8431	0.172	1.45E+06	160164	16332	0.1720833	2.81E+06
Bar	8940	912	1.40	1.28E+06	19032	1941	1.4	2.72E+06
Total	106461	10856		5.04E+06	179196	18272		5.53E+06
Reduction to Concrete				9%				-9.63%

Steel-Virgin&World Typical (59% Recy)					Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	2.31E+06			1.53	0.00E+00
Section Total	14836	1513		3.09E+06	0	0		0.00E+00
Concrete	82685	8431	0.172	1.45E+06	160164	16332	0.1720833	2.81E+06
Bar Virgin	8940	912	2.77	2.53E+06	19032	1941	2.77	5.38E+06
Total	106461	10856		7.07E+06	179196	18272		8.19E+06
Reduction to Concrete				14%				-15.83%

Steel-Virgin&World Typical (59% Recy)					Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	2.31E+06			1.53	0.00E+00
Section Total	14836	1513		3.09E+06	0	0		0.00E+00
Concrete	82685	8431	0.172	1.45E+06	160164	16332	0.1720833	2.81E+06
Bar 59% Re	8940	912	1.40	1.28E+06	19032	1941	1.4	2.72E+06
Total	106461	10856		5.82E+06	179196	18272		5.53E+06

Reduction to Concrete			-5%				5.00%
ICE							

Steel-Primary (Virgin)					Concrete-C60 Lower Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	14836	1513	3.03	4.58E+06	0	0	3.03	0.00E+00
Concrete	82685.14	8431	0.128	1.07E+06	160164	16332	0.1275	2.08E+06
Bar	8940	912	2.77	2.53E+06	19032	1941	2.77	5.38E+06
Total	**106461**	10856		8.18E+06	**179196**	18272		7.46E+06
				-10%				8.87%

Steel-World Typical (39% Recy)					Concrete-C60 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	14836	1513	2.03	3.07E+06	0	0	2.03	0.00E+00
Concrete	82685	8431	0.128	1.07E+06	160164	16332	0.1275	2.08E+06
Bar	8940	912	1.86	1.70E+06	19032	1941	1.86	3.61E+06
Total	106461	10856		5.84E+06	179196	18272		5.69E+06
Reduction to Concrete				**-3%**				2.56%

Steel-Virgin&World Typical (39% Recy)					Concrete-C60 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	3.07E+06			2.03	0.00E+00
Section Total	14836	1513		3.85E+06	0	0		0.00E+00
Concrete	82685	8431	0.128	1.07E+06	160164	16332	0.1275	2.08E+06
Bar Virgin	8940	912	2.77	2.53E+06	19032	1941	2.77	5.38E+06
Total	106461	10856		7.45E+06	179196	18272		7.46E+06
Reduction to Concrete				**0%**				-0.14%

Steel-Virgin&World Typical (39% Recy)					Concrete-C60 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	3.07E+06			2.03	0.00E+00
Section Total	14836	1513		3.85E+06	0	0		0.00E+00
Concrete	82685	8431	0.128	1.07E+06	160164	16332	0.1275	2.08E+06
Bar 39% Re	8940	912	1.86	1.70E+06	19032	1941	1.86	3.61E+06
Total	106461	10856		6.62E+06	179196	18272		5.69E+06

Reduction to Concrete	**-16%**			13.99%

Steel-UK Typical (EC 59% Recy)					Concrete-C60 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	14836	1513	1.53	2.31E+06	0	0	1.53	0.00E+00
Concrete	82685	8431	0.128	1.07E+06	160164	16332	0.1275	2.08E+06
Bar	8940	912	1.40	1.28E+06	19032	1941	1.4	2.72E+06
Total	106461	10856		4.67E+06	179196	18272		4.80E+06
Reduction to Concrete			**3%**					-2.86%

Steel-Virgin&World Typical (59% Recy)					Concrete-C60 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	2.31E+06			1.53	0.00E+00
Section Total	14836	1513		3.09E+06	0	0		0.00E+00
Concrete	82685	8431	0.128	1.07E+06	160164	16332	0.1275	2.08E+06
Bar Virgin	8940	912	2.77	2.53E+06	19032	1941	2.77	5.38E+06
Total	106461	10856		6.69E+06	179196	18272		7.46E+06
Reduction to Concrete			**10%**					-11.46%

Steel-Virgin&World Typical (59% Recy)					Concrete-C60 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	2.31E+06			1.53	0.00E+00
Section Total	14836	1513		3.09E+06	0	0		0.00E+00
Concrete	82685	8431	0.128	1.07E+06	160164	16332	0.1275	2.08E+06
Bar 59% Re	8940	912	1.40	1.28E+06	19032	1941	1.4	2.72E+06
Total	106461	10856		5.44E+06	179196	18272		4.80E+06
Reduction to Concrete			**-13%**					11.82%

APPENDIX I

TOTAL CARBON FOOTPRINTS OF 12/F STEEL & COMPOSITE BUILDINGS (SUPERSTRUCTURE ONLY+WITHOUT SLAB)

	Steel		RC Total	C50	C32
Category	Weight (kN)		Weight (kN)		
Steel	**15321.01**		**8536**		
Stainless Steel Sheet	**0**		**0**		
Concrete	0		45003	865.82	44137
Conc without R	**0.00**	C32	**43563**	**838.11**	**42724.62**
Reinforcement	**0**		**4710**	90.61	4619.673

ICE								
Steel-Primary (Virgin)					Concrete- Upper Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	15321.01	1562	3.03	4.73E+06	8536	870	3.03	2.64E+06
C50	*0*	*0*	*0.184*	*0.00E+00*	*838.11*	*85*	*0.18*	*1.57E+04*
C32	*0*	*0*	*0.140*	*0.00E+00*	*42725*	*4357*	*0.14*	*6.12E+05*
Concrete TOTAL	0	0		0.00E+00	43563	4442	0.00	6.27E+05
Bar	0	0	2.77	0.00E+00	4710	480	2.77	1.33E+06
Stainless	0	0	6.15	0.00E+00	0	0	6.15	0.00E+00
Total	**15321**	1562		4.73E+06	**56809**	5793		4.60E+06
				-3%				2.92%

Steel-World Typical (39% Recy)					Concrete- UL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	15321.01	1562	2.03	3.17E+06	8536	870	2.03	1.77E+06

C50	*0*	*0*	*0.184*	*0.00E+00*	*838.11*	*85*	*0.18*	*1.57E+04*
C32	*0*	*0*	*0.140*	*0.00E+00*	*42725*	*4357*	*0.14*	*6.12E+05*
Concrete TOTAL	0	0		0.00E+00	43563	4442	0.00	6.27E+05
Bar	0	0	1.86	0.00E+00	4710	480	1.86	8.93E+05
Stainless	0	0	6.15	0.00E+00	0	0	6.15	0.00E+00
Total	**15321**	1562		3.17E+06	**56809**	5793		3.29E+06
Reduction to Concrete				**4%**				-3.67%

Steel-Virgin&World Typical (39% Recy)					Concrete- UL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	3.17E+06			2.03	1.77E+06
Section Total	15321.01	1562		3.95E+06	8536	870		1.77E+06
C50	*0*	*0*	*0.184*	*0.00E+00*	*838.11*	*85*	*0.18*	*1.57E+04*
C32	*0*	*0*	*0.140*	*0.00E+00*	*42725*	*4357*	*0.14*	*6.12E+05*
Concrete TOTAL	0	0		0.00E+00	43563	4442	0.00	6.27E+05
Bar Virgin	0	0	2.77	0.00E+00	4710	480	2.77	1.33E+06
Stainless	0	0	6.15	0.00E+00	0	0	6.15	0.00E+00
Total	15321	1562		3947920	56809	5793		3724806
Reduction to Concrete				**-6%**				5.65%

Steel-Virgin&World Typical (39% Recy)					Concrete- UL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	3.17E+06			2.03	1.77E+06
Section Total	15321.01	1562		3.95E+06	8536	870		1.77E+06
C50	*0*	*0*	*0.184*	*0.00E+00*	*838.11*	*85*	*0.18*	*1.57E+04*
C32	*0*	*0*	*0.140*	*0.00E+00*	*42725*	*4357*	*0.14*	*6.12E+05*
Concrete TOTAL	0	0		0.00E+00	43563	4442	0.00	6.27E+05
Bar 39% Re	0	0	1.86	0.00E+00	4710	480	1.86	8.93E+05
Stainless	0	0	6.15	0.00E+00	0	0	6.15	0.00E+00
Total	15321	1562		4.E+06	56809	5793		3.E+06
Reduction to Concrete				**-20%**				16.72%

Steel-UK Typical (EC 59% Recy)					Concrete- UL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)

Section	15321.01	1562	1.53	2.39E+06	8536	870	1.53	1.33E+06
C50	*0*	*0*	*0.184*	*0.00E+00*	*838.11*	*85*	*0.18*	*1.57E+04*
C32	*0*	*0*	*0.140*	*0.00E+00*	*42725*	*4357*	*0.14*	*6.12E+05*
Concrete TOTAL	0	0		0.00E+00	43563	4442	0.00	6.27E+05
Bar	0	0	1.40	0.00E+00	4710	480	1.4	6.72E+05
Stainless	0	0	6.15	0.00E+00	0	0	6.15	0.00E+00
Total	15321	1562		2.E+06	56809	5793		3.E+06
Reduction to Concrete				**9%**				-10.10%

Steel-Virgin&World Typical (59% Recy)					Concrete- UL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	2.39E+06			1.53	1.33E+06
Section Total	15321.01	1562		3.17E+06	8536	870		1.33E+06
C50	*0*	*0*	*0.184*	*0.00E+00*	*838.11*	*85*	*0.18*	*1.57E+04*
C32	*0*	*0*	*0.140*	*0.00E+00*	*42725*	*4357*	*0.14*	*6.12E+05*
Concrete TOTAL	0	0		0.00E+00	43563	4442	0.00	6.27E+05
Bar Virgin	0	0	2.77	0.00E+00	4710	480	2.77	1.33E+06
Stainless	0	0	6.15	0.00E+00	0	0	6.15	0.00E+00
Total	15321	1562		3.17E+06	56809	5793		3.29E+06
Reduction to Concrete				**4%**				-3.88%

Steel-Virgin&World Typical (59% Recy)					Concrete- UL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	2.39E+06			1.53	1.33E+06
Section Total	15321.01	1562		3.17E+06	8536	870		1.33E+06
C50	*0*	*0*	*0.184*	*0.00E+00*	*838.11*	*85*	*0.18*	*1.57E+04*
C32	*0*	*0*	*0.140*	*0.00E+00*	*42725*	*4357*	*0.14*	*6.12E+05*
Concrete TOTAL	0	0		0.00E+00	43563	4442	0.00	6.27E+05
Bar 59% Re	0	0	1.40	0.00E+00	4710	480	1.4	6.72E+05
Stainless	0	0	6.15	0.00E+00	0	0	6.15	0.00E+00
Total	15321	1562		3.17E+06	56809	5793		2.63E+06
Reduction to Concrete				**-20%**				16.90%

ICE								
Steel-Primary (Virgin)					Concrete- Avg			

	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	15321.01	1562	3.03	4.73E+06	8536	870	3.03	2.64E+06
C50	*0*	*0*	*0.151*	*0.00E+00*	*838.11*	*85*	*0.15*	*1.29E+04*
C32	*0*	*0*	*0.115*	*0.00E+00*	*42725*	*4357*	*0.12*	*5.01E+05*
Concrete TOTAL	0	0		0.00E+00	43563	4442	0.00	5.14E+05
Bar	0	0	2.77	0.00E+00	4710.3	480	2.77	1.33E+06
Stainless	0	0	6.15	0.00E+00	0	0	6.15	0.00E+00
Total	**15321**	1562		4.73E+06	**56809**	5793		4.48E+06
				-6%				5.32%

Steel-World Typical (39% Recy)					Concrete- Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	15321.01	1562	2.03	3.17E+06	8536	870	2.03	1.77E+06
C50	*0*	*0*	*0.151*	*0.00E+00*	*838.11*	*85*	*0.15*	*1.29E+04*
C32	*0*	*0*	*0.115*	*0.00E+00*	*42725*	*4357*	*0.12*	*5.01E+05*
Concrete TOTAL	0	0		0.00E+00	43563	4442	0.00	5.14E+05
Bar	0	0	1.86	0.00E+00	4710	480	1.86	8.93E+05
Stainless	0	0	6.15	0.00E+00	0	0	6.15	0.00E+00
Total	**15321**	1562		3.17E+06	**56809**	5793		3.17E+06
Reduction to Concrete				**0%**				-0.09%

Steel-Virgin&World Typical (39% Recy)					Concrete- Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	3.17E+06			2.03	1.77E+06
Section Total	15321.01	1562		3.95E+06	8536	870		1.77E+06
C50	*0*	*0*	*0.151*	*0.00E+00*	*838.11*	*85*	*0.15*	*1.29E+04*
C32	*0*	*0*	*0.115*	*0.00E+00*	*42725*	*4357*	*0.12*	*5.01E+05*
Concrete TOTAL	0	0		0.00E+00	43563	4442	0.00	5.14E+05
Bar Virgin	0	0	2.77	0.00E+00	4710	480	2.77	1.33E+06
Stainless	0	0	6.15	0.00E+00	0	0	6.15	0.00E+00
Total	15321	1562		3.95E+06	56809	5793		3.61E+06
Reduction to Concrete				**-9%**				8.53%

Steel-Virgin&World Typical (39% Recy)					Concrete- Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)

Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	3.17E+06			2.03	1.77E+06
Section Total	15321.01	1562		3.95E+06	8536	870		1.77E+06
C50	*0*	*0*	*0.151*	*0.00E+00*	*838.11*	*85*	*0.15*	*1.29E+04*
C32	*0*	*0*	*0.115*	*0.00E+00*	*42725*	*4357*	*0.12*	*5.01E+05*
Concrete TOTAL	0	0		0.00E+00	43563	4442	0.00	5.14E+05
Bar 39% Re	0	0	1.86	0.00E+00	4710	480	1.86	8.93E+05
Stainless	0	0	6.15	0.00E+00	0	0	6.15	0.00E+00
Total	15321	1562		3.95E+06	56809	5793		3.17E+06
Reduction to Concrete				**-24%**				19.60%

Steel-UK Typical (EC 59% Recy)					Concrete-Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	15321.01	1562	1.53	2.39E+06	8536	870	1.53	1.33E+06
C50	*0*	*0*	*0.151*	*0.00E+00*	*838.11*	*85*	*0.15*	*1.29E+04*
C32	*0*	*0*	*0.115*	*0.00E+00*	*42725*	*4357*	*0.12*	*5.01E+05*
Concrete TOTAL	0	0		0.00E+00	43563	4442	0.00	5.14E+05
Bar	0	0	1.40	0.00E+00	4710	480	1.4	6.72E+05
Stainless	0	0	6.15	0.00E+00	0	0	6.15	0.00E+00
Total	15321	1562		2.39E+06	56809	5793		2.52E+06
Reduction to Concrete				**5%**				-5.35%

Steel-Virgin&World Typical (59% Recy)					Concrete- Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	2.39E+06			1.53	1.33E+06
Section Total	15321.01	1562		3.17E+06	8536	870		1.33E+06
C50	*0*	*0*	*0.151*	*0.00E+00*	*838.11*	*85*	*0.15*	*1.29E+04*
C32	*0*	*0*	*0.115*	*0.00E+00*	*42725*	*4357*	*0.12*	*5.01E+05*
Concrete TOTAL	0	0		0.00E+00	43563	4442	0.00	5.14E+05
Bar Virgin	0	0	2.77	0.00E+00	4710	480	2.77	1.33E+06
Stainless	0	0	6.15	0.00E+00	0	0	6.15	0.00E+00
Total	15321	1562		3.17E+06	56809	5793		3.18E+06
Reduction to Concrete				**0%**				-0.29%

Steel-Virgin&World Typical (59% Recy)	Concrete- Avg

	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	2.39E+06			1.53	1.33E+06
Section Total	15321.01	1562		3.17E+06	8536	870		1.33E+06
C50	*0*	*0*	*0.151*	*0.00E+00*	*838.11*	*85*	*0.15*	*1.29E+04*
C32	*0*	*0*	*0.115*	*0.00E+00*	*42725*	*4357*	*0.12*	*5.01E+05*
Concrete TOTAL	0	0		0.00E+00	43563	4442	0.00	5.14E+05
Bar 59% Re	0	0	1.40	0.00E+00	4710	480	1.4	6.72E+05
Stainless	0	0	6.15	0.00E+00	0	0	6.15	0.00E+00
Total	15321	1562		3.17E+06	56809	5793		2.52E+06
Reduction to Concrete				**-26%**				20.49%

ICE								
Steel-Primary (Virgin)					Concrete- Lower Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	15321.01	1562	3.03	4.73E+06	8536	870	3.03	2.64E+06
C50	*0*	*0*	*0.184*	*0.00E+00*	*838.11*	*85*	*0.18*	*1.57E+04*
C32	*0*	*0*	*0.140*	*0.00E+00*	*42725*	*4357*	*0.14*	*6.12E+05*
Concrete TOTAL	0	0		0.00E+00	43563	4442	0.00	6.27E+05
Bar	0	0	2.77	0.00E+00	4710.3	480	2.77	1.33E+06
Stainless	0	0	6.15	0.00E+00	0	0	6.15	0.00E+00
Total	**15321**	1562		4.73E+06	**56809**	5793		4.60E+06
				-3%				2.92%

Steel-World Typical (39% Recy)					Concrete- LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	15321.01	1562	2.03	3.17E+06	8536	870	2.03	1.77E+06
C50	*0*	*0*	*0.184*	*0.00E+00*	*838.11*	*85*	*0.18*	*1.57E+04*
C32	*0*	*0*	*0.140*	*0.00E+00*	*42725*	*4357*	*0.14*	*6.12E+05*
Concrete TOTAL	0	0		0.00E+00	43563	4442	0.00	6.27E+05
Bar	0	0	1.86	0.00E+00	4710	480	1.86	8.93E+05
Stainless	0	0	6.15	0.00E+00	0	0	6.15	0.00E+00
Total	**15321**	1562		3.17E+06	**56809**	5793		3.29E+06
Reduction to Concrete				**4%**				-3.67%

Steel-Virgin&World Typical (39% Recy)					Concrete- LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)

Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	3.17E+06			2.03	1.77E+06
Section Total	15321.01	1562		3.95E+06	8536	870		1.77E+06
C50	*0*	*0*	*0.184*	*0.00E+00*	*838.11*	*85*	*0.18*	*1.57E+04*
C32	*0*	*0*	*0.140*	*0.00E+00*	*42725*	*4357*	*0.14*	*6.12E+05*
Concrete TOTAL	0	0		0.00E+00	43563	4442	0.00	6.27E+05
Bar Virgin	0	0	2.77	0.00E+00	4710	480	2.77	1.33E+06
Stainless	0	0	6.15	0.00E+00	0	0	6.15	0.00E+00
Total	15321	1562		3.95E+06	56809	5793		3.72E+06
Reduction to Concrete				**-6%**				5.65%

Steel-Virgin&World Typical (39% Recy)					Concrete- LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	3.17E+06			2.03	1.77E+06
Section Total	15321.01	1562		3.95E+06	8536	870		1.77E+06
C50	*0*	*0*	*0.184*	*0.00E+00*	*838.11*	*85*	*0.18*	*1.57E+04*
C32	*0*	*0*	*0.140*	*0.00E+00*	*42725*	*4357*	*0.14*	*6.12E+05*
Concrete TOTAL	0	0		0.00E+00	43563	4442	0.00	6.27E+05
Bar 39% Re	0	0	1.86	0.00E+00	4710	480	1.86	8.93E+05
Stainless	0	0	6.15	0.00E+00	0	0	6.15	0.00E+00
Total	15321	1562		3.95E+06	56809	5793		3.29E+06
Reduction to Concrete				**-20%**				16.72%

Steel-UK Typical (EC 59% Recy)					Concrete- LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	15321.01	1562	1.53	2.39E+06	8536	870	1.53	1.33E+06
C50	*0*	*0*	*0.184*	*0.00E+00*	*838.11*	*85*	*0.18*	*1.57E+04*
C32	*0*	*0*	*0.140*	*0.00E+00*	*42725*	*4357*	*0.14*	*6.12E+05*
Concrete TOTAL	0	0		0.00E+00	43563	4442	0.00	6.27E+05
Bar	0	0	1.40	0.00E+00	4710	480	1.4	6.72E+05
Stainless	0	0	6.15	0.00E+00	0	0	6.15	0.00E+00
Total	15321	1562		2.39E+06	56809	5793		2.63E+06
Reduction to Concrete				**9%**				-10.10%

Steel-Virgin&World Typical (59% Recy)					Concrete- LL			

	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	2.39E+06			1.53	1.33E+06
Section Total	15321.01	1562		3.17E+06	8536	870		1.33E+06
C50	*0*	*0*	*0.184*	*0.00E+00*	*838.11*	*85*	*0.18*	*1.57E+04*
C32	*0*	*0*	*0.140*	*0.00E+00*	*42725*	*4357*	*0.14*	*6.12E+05*
Concrete TOTAL	0	0		0.00E+00	43563	4442	0.00	6.27E+05
Bar Virgin	0	0	2.77	0.00E+00	4710	480	2.77	1.33E+06
Stainless	0	0	6.15	0.00E+00	0	0	6.15	0.00E+00
Total	15321	1562		3.17E+06	56809	5793		3.29E+06
Reduction to Concrete				**4%**				-3.88%

Steel-Virgin&World Typical (59% Recy)					Concrete- LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	2.39E+06			1.53	1.33E+06
Section Total	15321.01	1562		3.17E+06	8536	870		1.33E+06
C50	*0*	*0*	*0.184*	*0.00E+00*	*838.11*	*85*	*0.18*	*1.57E+04*
C32	*0*	*0*	*0.140*	*0.00E+00*	*42725*	*4357*	*0.14*	*6.12E+05*
Concrete TOTAL	0	0		0.00E+00	43563	4442	0.00	6.27E+05
Bar 59% Re	0	0	1.40	0.00E+00	4710	480	1.4	6.72E+05
Stainless	0	0	6.15	0.00E+00	0	0	6.15	0.00E+00
Total	15321	1562		3.17E+06	56809	5793		2.63E+06
Reduction to Concrete				**-20%**				16.90%

APPENDIX J

TOTAL CARBON FOOTPRINTS OF 12/F STEEL & COMPOSITE BUILDINGS (SUPERSTRUCTURE ONLY+INCLUDING SLAB)

	Steel		RC Total		C50	C32
Category	Weight (kN)		Weight (kN)			
Steel	**15321.01**		**8536**			
Stainless	**1188.628**		**1185.3**			
Steel Sheet	**98**					
Conc without R	**56634.57**	C32	**110986**		**838.11**	**110148.2**
Reinforcement	**483**		**5285**		90.61	5194.548

ICE								
Steel-Primary (Virgin)					Concrete-C60 Upper Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	15321.01	1562	3.03	4.73E+06	8536	870	3.03	2.64E+06
C50	*0*	*0*	*0.184*	*0.00E+00*	*838.11*	*85*	*0.18*	*1.57E+04*
C32	*56635*	*5775*	*0.140*	*8.11E+05*	*110148*	*11232*	*0.14*	*1.58E+06*
Concrete TOTAL	56635	5775		8.11E+05	110986	11317	0.00	1.59E+06
Bar	483	49	2.77	1.36E+05	5285	539	2.77	1.49E+06
Stainless	1189	121	6.15	7.45E+05	1185	121	6.15	7.43E+05
Total	**73627**	7508		6.43E+06	**125993**	12847		6.47E+06
				1%				-0.62%

Steel-World Typical (39% Recy)					Concrete-C60 UL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)

Section	15321.01	1562	2.03	3.17E+06	8536	870	2.03	1.77E+06
C50	*0*	*0*	*0.184*	*0.00E+00*	*838.11*	*85*	*0.18*	*1.57E+04*
C32	*56635*	*5775*	*0.140*	*8.11E+05*	*110148*	*11232*	*0.14*	*1.58E+06*
Concrete TOTAL	56635	5775		8.11E+05	110986	11317	0.00	1.59E+06
Bar	483	49	1.86	9.16E+04	5285	539	1.86	1.00E+06
Stainless	1189	121	6.15	7.45E+05	1185	121	6.15	7.43E+05
Total	**73627**	7508		4.82E+06	**125993**	12847		5.11E+06
Reduction to Concrete				**6%**				-5.94%

Steel-Virgin&World Typical (39% Recy)					Concrete-C60 UL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	3.17E+06			2.03	1.77E+06
Section Total	15321.01	1562		3.95E+06	8536	870		1.77E+06
C50	*0*	*0*	*0.184*	*0.00E+00*	*838.11*	*85*	*0.18*	*1.57E+04*
C32	*56635*	*5775*	*0.140*	*8.11E+05*	*110148*	*11232*	*0.14*	*1.58E+06*
Concrete TOTAL	56635	5775		8.11E+05	110986	11317	0.00	1.59E+06
Bar Virgin	483	49	2.77	1.36E+05	5285	539	2.77	1.49E+06
Stainless	1189	121	6.15	7.45E+05	1185	121	6.15	7.43E+05
Total	73627	7508		5640599	125993	12847		5595867
Reduction to Concrete				**-1%**				0.79%

Steel-Virgin&World Typical (39% Recy)					Concrete-C60 UL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	3.17E+06			2.03	1.77E+06
Section Total	15321.01	1562		3.95E+06	8536	870		1.77E+06
C50	*0*	*0*	*0.184*	*0.00E+00*	*838.11*	*85*	*0.18*	*1.57E+04*
C32	*56635*	*5775*	*0.140*	*8.11E+05*	*110148*	*11232*	*0.14*	*1.58E+06*
Concrete TOTAL	56635	5775		8.11E+05	110986	11317	0.00	1.59E+06
Bar 39% Re	483	49	1.86	9.16E+04	5285	539	1.86	1.00E+06
Stainless	1189	121	6.15	7.45E+05	1185	121	6.15	7.43E+05
Total	73627	7508		6.E+06	125993	12847		5.E+06

Reduction to Concrete			**-10%**				8.76%

Steel-UK Typical (EC 59% Recy)					Concrete-C60 UL			
	Weight (kN)	Weight (tons)	ECe Coefficie nts	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficie nts	ECe (kgCO2)
Section	15321.01	1562	1.53	2.39E+06	8536	870	1.53	1.33E+06
C50	*0*	*0*	*0.184*	*0.00E+00*	*838.11*	*85*	*0.18*	*1.57E+04*
C32	*56635*	*5775*	*0.140*	*8.11E+05*	*110148*	*11232*	*0.14*	*1.58E+06*
Concrete TOTAL	56635	5775		8.11E+05	110986	11317	0.00	1.59E+06
Bar	483	49	1.40	6.89E+04	5285	539	1.4	7.54E+05
Stainless	1189	121	6.15	7.45E+05	1185	121	6.15	7.43E+05
Total	73627	7508		4.E+06	125993	12847		4.E+06
Reduction to Concrete				**9%**				-10.13%

Steel-Virgin&World Typical (59% Recy)					Concrete-C60 UL			
	Weight (kN)	Weight (tons)	ECe Coefficie nts	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficie nts	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	2.39E+06			1.53	1.33E+06
Section Total	15321.01	1562		3.17E+06	8536	870		1.33E+06
C50	*0*	*0*	*0.184*	*0.00E+00*	*838.11*	*85*	*0.18*	*1.57E+04*
C32	*56635*	*5775*	*0.140*	*8.11E+05*	*110148*	*11232*	*0.14*	*1.58E+06*
Concrete TOTAL	56635	5775		8.11E+05	110986	11317	0.00	1.59E+06
Bar Virgin	483	49	2.77	1.36E+05	5285	539	2.77	1.49E+06
Stainless	1189	121	6.15	7.45E+05	1185	121	6.15	7.43E+05
Total	73627	7508		4.86E+06	125993	12847		5.16E+06
Reduction to Concrete				**6%**				-6.20%

Steel-Virgin&World Typical (59% Recy)					Concrete-C60 UL			
	Weight (kN)	Weight (tons)	ECe Coefficie nts	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficie nts	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	2.39E+06			1.53	1.33E+06
Section Total	15321.01	1562		3.17E+06	8536	870		1.33E+06
C50	*0*	*0*	*0.184*	*0.00E+00*	*838.11*	*85*	*0.18*	*1.57E+04*

C32	*56635*	*5775*	*0.140*	*8.11E+05*	*110148*	*11232*	*0.14*	*1.58E+06*
Concrete TOTAL	56635	5775		8.11E+05	110986	11317	0.00	1.59E+06
Bar 59% Re	483	49	1.40	6.89E+04	5285	539	1.4	7.54E+05
Stainless	1189	121	6.15	7.45E+05	1185	121	6.15	7.43E+05
Total	73627	7508		4.79E+06	125993	12847		4.42E+06
Reduction to Concrete				**-8%**				7.71%

ICE								
Steel-Primary (Virgin)					Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	15321.01	1562	3.03	4.73E+06	8536	870	3.03	2.64E+06
C50	*0*	*0*	*0.151*	*0.00E+00*	*838.11*	*85*	*0.15*	*1.29E+04*
C32	*56635*	*5775*	*0.115*	*6.64E+05*	*110148*	*11232*	*0.12*	*1.29E+06*
Concrete TOTAL	56635	5775		6.64E+05	110986	11317	0.00	1.30E+06
Bar	482.885293	49	2.77	1.36E+05	5285.2	539	2.77	1.49E+06
Stainless	1189	121	6.15	7.45E+05	1185	121	6.15	7.43E+05
Total	**73627**	7508		6.28E+06	**125993**	12847		6.18E+06
				-2%				1.62%

Steel-World Typical (39% Recy)					Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	15321.01	1562	2.03	3.17E+06	8536	870	2.03	1.77E+06
C50	*0*	*0*	*0.151*	*0.00E+00*	*838.11*	*85*	*0.15*	*1.29E+04*
C32	*56635*	*5775*	*0.115*	*6.64E+05*	*110148*	*11232*	*0.12*	*1.29E+06*
Concrete TOTAL	56635	5775		6.64E+05	110986	11317	0.00	1.30E+06
Bar	483	49	1.86	9.16E+04	5285	539	1.86	1.00E+06
Stainless	1189	121	6.15	7.45E+05	1185	121	6.15	7.43E+05
Total	**73627**	7508		4.67E+06	**125993**	12847		4.82E+06
Reduction to Concrete				**3%**				-3.10%

Steel-Virgin&World Typical (39% Recy)					Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	3.17E+06			2.03	1.77E+06

Section Total	15321.01	1562		3.95E+06	8536	870		1.77E+06
C50	*0*	*0*	*0.151*	*0.00E+00*	*838.11*	*85*	*0.15*	*1.29E+04*
C32	*56635*	*5775*	*0.115*	*6.64E+05*	*110148*	*11232*	*0.12*	*1.29E+06*
Concrete TOTAL	56635	5775		6.64E+05	110986	11317	0.00	1.30E+06
Bar Virgin	483	49	2.77	1.36E+05	5285	539	2.77	1.49E+06
Stainless	1189	121	6.15	7.45E+05	1185	121	6.15	7.43E+05
Total	73627	7508		5.49E+06	125993	12847		5.31E+06
Reduction to Concrete				**-4%**				3.39%

Steel-Virgin&World Typical (39% Recy)					Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	3.17E+06			2.03	1.77E+06
Section Total	15321.01	1562		3.95E+06	8536	870		1.77E+06
C50	*0*	*0*	*0.151*	*0.00E+00*	*838.11*	*85*	*0.15*	*1.29E+04*
C32	*56635*	*5775*	*0.115*	*6.64E+05*	*110148*	*11232*	*0.12*	*1.29E+06*
Concrete TOTAL	56635	5775		6.64E+05	110986	11317	0.00	1.30E+06
Bar 39% Re	483	49	1.86	9.16E+04	5285	539	1.86	1.00E+06
Stainless	1189	121	6.15	7.45E+05	1185	121	6.15	7.43E+05
Total	73627	7508		5.45E+06	125993	12847		4.82E+06
Reduction to Concrete				**-13%**				11.60%

Steel-UK Typical (EC 59% Recy)					Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	15321.01	1562	1.53	2.39E+06	8536	870	1.53	1.33E+06
C50	*0*	*0*	*0.151*	*0.00E+00*	*838.11*	*85*	*0.15*	*1.29E+04*
C32	*56635*	*5775*	*0.115*	*6.64E+05*	*110148*	*11232*	*0.12*	*1.29E+06*
Concrete TOTAL	56635	5775		6.64E+05	110986	11317	0.00	1.30E+06
Bar	483	49	1.40	6.89E+04	5285	539	1.4	7.54E+05
Stainless	1189	121	6.15	7.45E+05	1185	121	6.15	7.43E+05
Total	73627	7508		3.87E+06	125993	12847		4.13E+06
Reduction to Concrete				**6%**				-6.86%

Steel-Virgin&World Typical (59% Recy)	Concrete-C60 Avg

	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	2.39E+06			1.53	1.33E+06
Section Total	15321.01	1562		3.17E+06	8536	870		1.33E+06
C50	*0*	*0*	*0.151*	*0.00E+00*	*838.11*	*85*	*0.15*	*1.29E+04*
C32	*56635*	*5775*	*0.115*	*6.64E+05*	*110148*	*11232*	*0.12*	*1.29E+06*
Concrete TOTAL	56635	5775		6.64E+05	110986	11317	0.00	1.30E+06
Bar Virgin	483	49	2.77	1.36E+05	5285	539	2.77	1.49E+06
Stainless	1189	121	6.15	7.45E+05	1185	121	6.15	7.43E+05
Total	73627	7508		4.71E+06	125993	12847		4.87E+06
Reduction to Concrete				**3%**				-3.39%

Steel-Virgin&World Typical (59% Recy)					Concrete-C60 Avg			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	2.39E+06			1.53	1.33E+06
Section Total	15321.01	1562		3.17E+06	8536	870		1.33E+06
C50	*0*	*0*	*0.151*	*0.00E+00*	*838.11*	*85*	*0.15*	*1.29E+04*
C32	*56635*	*5775*	*0.115*	*6.64E+05*	*110148*	*11232*	*0.12*	*1.29E+06*
Concrete TOTAL	56635	5775		6.64E+05	110986	11317	0.00	1.30E+06
Bar 59% Re	483	49	1.40	6.89E+04	5285	539	1.4	7.54E+05
Stainless	1189	121	6.15	7.45E+05	1185	121	6.15	7.43E+05
Total	73627	7508		4.65E+06	125993	12847		4.13E+06
Reduction to Concrete				**-12%**				11.00%
ICE								

Steel-Primary (Virgin)					Concrete-C60 Lower Limit			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	15321.01	1562	3.03	4.73E+06	8536	870	3.03	2.64E+06
C50	*0*	*0*	*0.184*	*0.00E+00*	*838.11*	*85*	*0.18*	*1.57E+04*
C32	*56635*	*5775*	*0.140*	*8.11E+05*	*110148*	*11232*	*0.14*	*1.58E+06*
Concrete TOTAL	56635	5775		8.11E+05	110986	11317	0.00	1.59E+06

Bar	482.885293	49	2.77	1.36E+05	5285.2	539	2.77	1.49E+06
Stainless	1189	121	6.15	7.45E+05	1185	121	6.15	7.43E+05
Total	**73627**	7508		6.43E+06	**125993**	12847		6.47E+06
				1%				-0.62%

Steel-World Typical (39% Recy)					Concrete-C60 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	15321.01	1562	2.03	3.17E+06	8536	870	2.03	1.77E+06
C50	*0*	*0*	*0.184*	*0.00E+00*	*838.11*	*85*	*0.18*	*1.57E+04*
C32	*56635*	*5775*	*0.140*	*8.11E+05*	*110148*	*11232*	*0.14*	*1.58E+06*
Concrete TOTAL	56635	5775		8.11E+05	110986	11317	0.00	1.59E+06
Bar	483	49	1.86	9.16E+04	5285	539	1.86	1.00E+06
Stainless	1189	121	6.15	7.45E+05	1185	121	6.15	7.43E+05
Total	**73627**	7508		4.82E+06	**125993**	12847		5.11E+06
Reduction to Concrete				**6%**				-5.94%

Steel-Virgin&World Typical (39% Recy)					Concrete-C60 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 39% Re	2513.4	256	2.03	3.17E+06			2.03	1.77E+06
Section Total	15321.01	1562		3.95E+06	8536	870		1.77E+06
C50	*0*	*0*	*0.184*	*0.00E+00*	*838.11*	*85*	*0.18*	*1.57E+04*
C32	*56635*	*5775*	*0.140*	*8.11E+05*	*110148*	*11232*	*0.14*	*1.58E+06*
Concrete TOTAL	56635	5775		8.11E+05	110986	11317	0.00	1.59E+06
Bar Virgin	483	49	2.77	1.36E+05	5285	539	2.77	1.49E+06
Stainless	1189	121	6.15	7.45E+05	1185	121	6.15	7.43E+05
Total	73627	7508		5.64E+06	125993	12847		5.60E+06
Reduction to Concrete				**-1%**				0.79%

Steel-Virgin&World Typical (39% Recy)					Concrete-C60 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00

Section 39% Re	2513.4	256	2.03	3.17E+06			2.03	1.77E+06
Section Total	15321.01	1562		3.95E+06	8536	870		1.77E+06
C50	*0*	*0*	*0.184*	*0.00E+00*	*838.11*	*85*	*0.18*	*1.57E+04*
C32	*56635*	*5775*	*0.140*	*8.11E+05*	*110148*	*11232*	*0.14*	*1.58E+06*
Concrete TOTAL	56635	5775		8.11E+05	110986	11317	0.00	1.59E+06
Bar 39% Re	483	49	1.86	9.16E+04	5285	539	1.86	1.00E+06
Stainless	1189	121	6.15	7.45E+05	1185	121	6.15	7.43E+05
Total	73627	7508		5.60E+06	125993	12847		5.11E+06
Reduction to Concrete				**-10%**				8.76%

Steel-UK Typical (EC 59% Recy)					Concrete-C60 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section	15321.01	1562	1.53	2.39E+06	8536	870	1.53	1.33E+06
C50	*0*	*0*	*0.184*	*0.00E+00*	*838.11*	*85*	*0.18*	*1.57E+04*
C32	*56635*	*5775*	*0.140*	*8.11E+05*	*110148*	*11232*	*0.14*	*1.58E+06*
Concrete TOTAL	56635	5775		8.11E+05	110986	11317	0.00	1.59E+06
Bar	483	49	1.40	6.89E+04	5285	539	1.4	7.54E+05
Stainless	1189	121	6.15	7.45E+05	1185	121	6.15	7.43E+05
Total	73627	7508		4.02E+06	125993	12847		4.42E+06
Reduction to Concrete				**9%**				-10.13%

Steel-Virgin&World Typical (59% Recy)					Concrete-C60 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	2.39E+06			1.53	1.33E+06
Section Total	15321.01	1562		3.17E+06	8536	870		1.33E+06
C50	*0*	*0*	*0.184*	*0.00E+00*	*838.11*	*85*	*0.18*	*1.57E+04*
C32	*56635*	*5775*	*0.140*	*8.11E+05*	*110148*	*11232*	*0.14*	*1.58E+06*
Concrete TOTAL	56635	5775		8.11E+05	110986	11317	0.00	1.59E+06
Bar Virgin	483	49	2.77	1.36E+05	5285	539	2.77	1.49E+06
Stainless	1189	121	6.15	7.45E+05	1185	121	6.15	7.43E+05
Total	73627	7508		4.86E+06	125993	12847		5.16E+06
Reduction to Concrete				**6%**				-6.20%

Steel-Virgin&World Typical (59% Recy)					Concrete-C60 LL			
	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)	Weight (kN)	Weight (tons)	ECe Coefficients	ECe (kgCO2)
Section Virgin	6141	626	3.03	7.77E+05			3.03	0.00E+00
Section 59% Re	2513.4	256	1.53	2.39E+06			1.53	1.33E+06
Section Total	15321.01	1562		3.17E+06	8536	870		1.33E+06
C50	*0*	*0*	*0.184*	*0.00E+00*	*838.11*	*85*	*0.18*	*1.57E+04*
C32	*56635*	*5775*	*0.140*	*8.11E+05*	*110148*	*11232*	*0.14*	*1.58E+06*
Concrete TOTAL	56635	5775		8.11E+05	110986	11317	0.00	1.59E+06
Bar 59% Re	483	49	1.40	6.89E+04	5285	539	1.4	7.54E+05
Stainless	1189	121	6.15	7.45E+05	1185	121	6.15	7.43E+05
Total	73627	7508		4.79E+06	125993	12847		4.42E+06
Reduction to Concrete				**-8%**				7.71%

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