Carbon Footprint of Steel-Composite and Reinforced Concrete Buildings

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Outline

1. Background
2. Carbon Labelling Scheme for Construction Products
3. Low-carbon Design of Building Structures
4. The Way Forward
## National Reduction Targets

<table>
<thead>
<tr>
<th>Country</th>
<th>2020 CO₂ Reduction Target</th>
<th>Base year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>5-15%</td>
<td>2000</td>
</tr>
<tr>
<td>Canada</td>
<td>17%</td>
<td>2005</td>
</tr>
<tr>
<td>EU &amp; Members States</td>
<td>20%-30%</td>
<td>1990</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>19-33%</td>
<td>2005</td>
</tr>
<tr>
<td></td>
<td>50-60% (in terms of carbon intensity)</td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>25%</td>
<td>1990</td>
</tr>
<tr>
<td>Norway</td>
<td>30-40%</td>
<td>1990</td>
</tr>
<tr>
<td>US</td>
<td>17%</td>
<td>2005</td>
</tr>
<tr>
<td>IPCC recommendation</td>
<td>25-40%</td>
<td>1990</td>
</tr>
</tbody>
</table>

Buildings and Construction Contribution to GHG Emissions

#1. Building and Construction (>40%)

#2. Transportation (~20%)

#3. Industry (~20%)

Buildings in Hong Kong accounted for 60% of total local GHG emissions

Building’s Carbon Footprint

Embodied Carbon of construction materials

The greenhouse gases (GHGs) emissions from the extraction of raw materials, manufacturing, and transporting the construction materials to the border of construction site.

Source: RICS (2012), Methodology to Calculate Embodied Carbon of Materials, 1st edition, information paper, UK
Embodied carbon emissions of materials account for 15-20% life-cycle carbon emissions.

Why we pursue low-carbon materials?

- Selecting low-carbon materials helps reduce building carbon footprint.
Development of the CIC Carbon Labelling Scheme

CIC Carbon Labelling Scheme for Construction Products

Inspiration of Carbon Labelling for construction products 2009

HKU developed the carbon labelling framework for 6 types of construction products 2012

CIC Carbon Labelling Scheme Launched and open for applications Jan 2014

Research Phase II commences (covering 10 additional product types incl. concrete, stainless steel, asphalt, etc.) Mar 2014

Implementation & Development
- Promote the application and the use of low carbon materials
- Low-carbon design/construction
- Carbon tendering
- Export service on carbon certification

Launched in January 2014
Aim & Scope

- **Aim**: Provide verifiable and accurate information on the carbon footprint of construction materials for users to make informed decision thereby to combat the climate change

- A voluntary eco-labelling programme with independent third-party verification

- Focuses on a single impact category: Global Warming Potential

- System boundary: cradle to site

- Stimulate the demand for and supply of low carbon construction materials
Research on development of frameworks for additional 12 carbon-intensive product categories:

- Stainless steel
- Galvanized steel
- Cast iron
- Asphalt pavement
- Precast concrete
- Construction aggregate
- Brick
- Timber products / composite wood
- Gypsum board
- Tiles
- Glass
- Aluminium
Based on the carbon footprint of the assessed product, CIC shall issue the carbon label with corresponding class for a validity period of two years.
Involved Stakeholders / Organisations

- Development Bureau
- MTR
- HKPC
- Yau Lee Holdings Limited
- Alliance
- BSI
- Gammon
- Siam Yamato Steel Co., Ltd.
- Chun Wo Development Holdings Limited
- HKQAA
- Emirates Steel
- Wo Lee Steel Co. Ltd.
- Environmental Science Technology
Implementation Strategies

Integrating the Scheme into BEAM Plus

Liaison with HKGBC

Listing Labelled Products

Liaison with DevB, MTRC, HKHA,

Launching an Online Listing Service

Specifying the Use of Low Carbon Materials in Public Works
Implementation Strategies

Integrating the Scheme into BEAM Plus

BEAM Plus Existing Buildings Version 2.0: Comprehensive Scheme & Selective Scheme
Launched on 24 March 2016

Liaison with HKGBC

Listing Labelled Products

Launching an Online Listing Service

Specification of Low-carbon Building Materials & Products
Outline

1. Background
2. Carbon Labelling Scheme for Construction Products
3. Low-carbon Design of Building Structures
4. The Way Forward
What about the embodied carbon of a building structure?

What we know:-

- Material Use – Associated with Embodied Carbon & Energy
- Optimised Structural Design is Saving Material Consumption
- Carbon Labelling Scheme is Promoting Manufacture and Use of Low-carbon Materials

What is missing:-

- Optimised Structure Design ≠ Lowest Carbon Footprint of Building Structure
- Selection and Use of Low-carbon Material ≠ Lowest Carbon Footprint of Building Structure
Low-carbon Design of Building Structures

- Optimised Structure Design
- Select low-carbon Materials
- Lowest Carbon Footprint of Structure
Low-carbon Design of Building Structures

Low-carbon design of structure around the world

Concrete Centre & Arup, 2012

Comparison of embodied carbon (superstructure + substructure) for structural framing options across all the building types

Range in calculated embodied carbon for office buildings

(Sarah Kaethner and Jenny Burridge (2012), Embodied CO₂ of Structural Frames, The Structural Engineer)
Low-carbon design of structure around the world

Eaton & Amato, 1998

Embodied carbon of different building structures

(K J Eaton and A Amato (1998), A Comparative Environmental Life Cycle Assessment of Modern Office Buildings, SCI)
Low-carbon design of structure around the world

Other studies on low-carbon design of structure:

David Bennett (2010), Sustainable Concrete Architecture, RIBA Publishing


Embodied Carbon of Steel versus Concrete Buildings (2013), Cundall Johnston & Partners LLP
Research Aim and Objectives

Aims to examine the potential of embodied carbon reduction through optimising different RC and steel structural designs.

- **Nonlinear Optimization Method** - to optimise the structural design
- **Embodied carbon data of ready-mixed concrete and steel (overseas & local data)** - to calculate the overall carbon footprint of the optimised building structures
- **Comparison** - to investigate the impact of structure design and material usage on the building carbon footprint
Low-carbon Design of Building Structures

Methodology
Building Configurations & Requirements

25 floors
Height = 97.6m
Plan Area = 27.69m x 23.26m

Steel Building
• Steel Beam + Steel Columns
• Concrete Core Wall

Reinforced Concrete Building
• RC Beams + RC Columns
• Concrete Core Wall
Low-carbon Design of Building Structures

Methodology
Computer Analysis Method

- Steel Building
  - Second-order plastic (P-Δ-δ) analysis

- RC Building
  - Linear elastic analysis
Embodied Carbon Data

Inventory of Carbon and Energy (ICE), UK

The Carbon footprint data of concrete applied in this study (unit: kg CO₂e/m³):

<table>
<thead>
<tr>
<th>Concrete Grade</th>
<th>100% OPC</th>
<th>50% GGBS</th>
<th>Average Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C60</td>
<td>491</td>
<td>306</td>
<td>413</td>
</tr>
<tr>
<td>C80</td>
<td>598</td>
<td>381</td>
<td>507</td>
</tr>
<tr>
<td>C100 *</td>
<td>598</td>
<td>381</td>
<td>507</td>
</tr>
</tbody>
</table>

*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.*

The Carbon footprint data of steel applied in this study (unit: kg CO₂e/kg):

<table>
<thead>
<tr>
<th>Steel Type</th>
<th>Virgin steel</th>
<th>39% recycled scrap</th>
<th>59% recycled scrap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section</td>
<td>3.03</td>
<td>2.03</td>
<td>1.53</td>
</tr>
<tr>
<td>Bar</td>
<td>2.77</td>
<td>1.86</td>
<td>1.40</td>
</tr>
</tbody>
</table>
Low-carbon Design of Building Structures

Superstructure Total Weight - Optimised Design

<table>
<thead>
<tr>
<th>Structure Total Weight</th>
<th>Weight (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RC Bldg. C100</td>
<td>76668 9640</td>
</tr>
<tr>
<td>RC Bldg. C80</td>
<td>86560 10001</td>
</tr>
<tr>
<td>RC Bldg. C60</td>
<td>98239 10893</td>
</tr>
<tr>
<td>Steel Bldg.</td>
<td>47636 5163</td>
</tr>
</tbody>
</table>

Sections include:
- RC Bldg. C100: 8654
- RC Bldg. C80: 86560
- RC Bldg. C60: 98239
- Steel Bldg.: 47636
Materials –

• **Rebar** – *virgin steel* (2.77 kg CO$_2$e/kg)
• Concrete – C60
• Concrete – **50% GGBS**, **Average**, **100% OPC**
  
  (306 kg CO$_2$e/m$^3$, 413 kg CO$_2$e/m$^3$, 491 kg CO$_2$e/m$^3$)

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Embodied Carbon ($10^6$ kg CO$_2$e/m$^3$)

- **50% GGBS**
- **Avg.**
- **100% OPC**

Use of Low-carbon Concrete = Total Embodied Carbon decreases
Low-carbon Design of Building Structures

RC Superstructure In Different Concrete Grade

Materials –

- **Rebar** – virgin steel (2.77) (kgCO₂e/kg)
- **Concrete** – average emissions factors (OPC + green concrete)
- **Concrete** – C60, C80, C100 (413) (507) (507) (kgCO₂e/m³)

Embodied Carbon (10^6 kgCO₂e/m³)

Concrete Grade Increases = Total Embodied Carbon decreases
Steel Superstructure In Different Green Steel

Materials –

- **Structural steel** – virgin, 39% recycled, 59% recycled
  
  (3.03) (2.03) (1.53) (kgCO₂e/kg)

- **Rebar** – virgin, 39% recycled, 59% recycled
  
  (2.77) (1.86) (1.40) (kgCO₂e/kg)

- **Concrete** – C60 average emissions factors (OPC + green concrete)
  
  (413) (kgCO₂e/m³)

Embodied Carbon (10^6 kgCO₂e/m³)

Use of Low-carbon Steel

= Total Embodied Carbon decreases
## What if we used the construction materials available in Hong Kong?

### HK Local Embodied Carbon Data:

<table>
<thead>
<tr>
<th>Applicant from</th>
<th>Product Category</th>
<th>Carbon Footprint Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rebar and Structural Steel</td>
<td>Unit: kgCO$_2$e/kg</td>
</tr>
<tr>
<td>Thailand</td>
<td>Section</td>
<td>0.55</td>
</tr>
<tr>
<td>Mainland China</td>
<td>Pipe</td>
<td>2.95</td>
</tr>
<tr>
<td>Taiwan</td>
<td>Section</td>
<td>1.37</td>
</tr>
<tr>
<td>Middle East</td>
<td>Rebar</td>
<td>2.08</td>
</tr>
<tr>
<td>Middle East</td>
<td>Section</td>
<td>2.36</td>
</tr>
<tr>
<td></td>
<td><strong>Ready-mixed Concrete</strong></td>
<td>Unit: kg CO$_2$e/m$^3$ concrete</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>C60 (OPC)</td>
<td>530</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>C60 (25% PFA)</td>
<td>413</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>C60 (40% GGBS)</td>
<td>355</td>
</tr>
</tbody>
</table>
### RC Superstructure ICE Data VS Local Data

<table>
<thead>
<tr>
<th>Material</th>
<th>Hong Kong Data</th>
<th>ICE Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>530 kg CO₂e/m³ (C60 OPC)</td>
<td>491 kg CO₂e/m³ (C60 OPC)</td>
</tr>
<tr>
<td>Rebar</td>
<td>2.08 kgCO₂e/kg</td>
<td>59% Recycled 39% Recycled Virgin</td>
</tr>
<tr>
<td>Structural Steel</td>
<td>0.55 kgCO₂e/kg</td>
<td>59% Recycled 39% Recycled Virgin</td>
</tr>
</tbody>
</table>

**Structure Embodied Carbon (10^6 kgCO₂e)**

- 59%R ICE Data: 3.6
- 39%R ICE Data: 4.12
- Virgin ICE Data: 5.13
Low-carbon Design of Building Structures

Steel Superstructure ICE Data VS Local Data

<table>
<thead>
<tr>
<th></th>
<th>Hong Kong Data</th>
<th>ICE Data</th>
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<td>59% Recycled</td>
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Structure Embodied Carbon (10^6 kgCO₂e)

- 59%R ICE Data: 3.08
- 39%R ICE Data: 3.76
- Virgin ICE Data: 5.13
Low-carbon Design of Building Structures

**RC vs. Steel Superstructure**

<table>
<thead>
<tr>
<th>Region</th>
<th>ICE Data</th>
<th>RC structure</th>
<th>Steel structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hong Kong Data</td>
<td>2.65</td>
<td>4.52</td>
<td></td>
</tr>
<tr>
<td>59%R ICE Data</td>
<td>3.08</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td>39%R ICE Data</td>
<td>3.76</td>
<td>4.12</td>
<td></td>
</tr>
<tr>
<td>Virgin ICE Data</td>
<td>5.13</td>
<td>5.13</td>
<td></td>
</tr>
</tbody>
</table>

Structure Embodied Carbon ($10^6$ kgCO$_2$e)
### What if we take foundation into consideration?

#### RC vs. Steel Superstructure + Foundation

<table>
<thead>
<tr>
<th>.Location</th>
<th>RC structure</th>
<th>Steel structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hong Kong Data</td>
<td>6.062</td>
<td>3.92</td>
</tr>
<tr>
<td>59%R ICE Data</td>
<td>3.786</td>
<td>3.49</td>
</tr>
<tr>
<td>39%R ICE Data</td>
<td>4.447</td>
<td>4.30</td>
</tr>
<tr>
<td>Virgin ICE Data</td>
<td>5.755</td>
<td>5.91</td>
</tr>
</tbody>
</table>

**Embodied Carbon (10^6 kgCO₂e)**
Conclusions

• RC Building vs. Steel Building (Which one is lower carbon?)
  
  ➢ *Material properties and compositions* (concrete grade, recycled contents, concrete with SCM such as PFA or GGBS, etc.)
  
  ➢ *Structural design* (performance requirement, local factor, approach of optimisation)
  
  ➢ *Geotechnical* (foundation) condition

• Composite Structure Building? *To be further investigated*
<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Background</td>
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<tr>
<td>2</td>
<td>Carbon Labelling Scheme for Construction Products</td>
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<td>Low-carbon Design of Building Structures</td>
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<tr>
<td>4</td>
<td>The Way Forward</td>
</tr>
</tbody>
</table>
Situations in Hong Kong

What hinder achieving lower carbon footprint of local concrete?

- Clients’ requirements & local specifications
  - Durability requirement
  - Minimum cementitious / recycled aggregate content

- Hong Kong’s climate - exposure to marine condition

- Construction cycles requirements

Source of Picture: https://en.wikipedia.org/wiki/Concrete_degradation
ECC (Engineered Cementitious Composites)
As known as “Bendable Concrete”

High-performance Concrete

- High tensile ductility
- Self-consolidating
- Minimum maintenance
- Highly tolerant to impact load
- Self-healing
- High durability
- High strength
“Smart” Concrete

Imagine a new concrete that...

- high strength
- high durability
- high tensile ductility
- minimum maintenance
- self-consolidating
- self-healing
- highly tolerant to impact load
- low environmental impacts
- minimum manpower demand
- low cost
Green moving towards a low-carbon city

Green Materials
Green Structural Design
Green Building

sources of photos:
http://widedscreen.com/3d-architecture-wallpaper-2/
http://blog.iqsdirectory.com/green-ideas-for-industry/construction-going-green-and-growing-green/
Thank You

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