Minimization of Embodied Energy in Reinforced Concrete

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Motivation

- Residential & commercial building sectors – 30% of greenhouse gas emissions in OECD countries*

- Most efforts to reduce CO$_2$ emissions typically focus on operating energy

- However, processing & manufacture of building materials have significant off-site impacts
  - Embodied energy used as a measure of this “upstream” impact

*OECD (2003)
Embodied Energy – Definition

• The sum of the energy required to extract, process, manufacture, transport, and install building materials

• Quantification of embodied energy for any particular material is an inexact science
  – Requires "long view" look at entire manufacturing and utilization process (via, e.g., Life Cycle Assessment)
Embodied Energy – Types

• Initial Embodied Energy (~ 15%)
  – Direct energy: Transportation of building materials and eventual building construction
  – Indirect energy: Production of building materials and technical installation materials

• Recurring Embodied Energy (~ 10%)
  – Building maintenance and renovation

Total Embodied Energy = Initial Embodied Energy + Recurring Embodied Energy
Embodied Energy – Statistics

• 10% of total energy consumption by buildings in the UK is embodied in materials*

• Embodied energy’s share of total life cycle energy can be as low as 5% and as high as 40%**

• Percentage will increase as attempts to develop zero-net energy buildings (ZEB) progress

*Goggins et al (2010)
**Sartori & Hestnes (2007); 60 case studies in 9 countries; estimated embodied energy values can vary greatly among countries.
Embodied Energy – Concrete

• Contrary to lay opinion concrete has a relatively low embodied energy

• However, concrete is the most widely used construction material with exception of fresh water
  – Global production increased from 40 million m$^3$ in 1900 to 6.4 billion m$^3$ in 1997*
  – Associated high usage in construction results in higher total embodied energy than any other material

*Council on Tall Buildings and Urban Habitat (2010)
Objective

Development of set of tools for automatic sizing of structural elements in reinforced concrete (RC) buildings in such a way that embodied energy is minimized.
Example – RC Beam of Rectangular Cross-Section
## Design Parameters (1 of 2)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factored Moment</td>
<td>$M_u = 400$ kN m</td>
</tr>
<tr>
<td>Factored Shear Force</td>
<td>$V_u = 220$ kN</td>
</tr>
<tr>
<td>Concrete Compressive Strength</td>
<td>$f'_c = 34$ MPa</td>
</tr>
<tr>
<td>Longitudinal Reinf. Yield Strength</td>
<td>$f_y = 420$ MPa</td>
</tr>
<tr>
<td>Shear Reinf. Yield Strength</td>
<td>$f_{yt} = 300$ MPa</td>
</tr>
<tr>
<td>Shear Reinf. Longitudinal Spacing</td>
<td>$s = 150$ mm</td>
</tr>
<tr>
<td>Section Length</td>
<td>$L = 7$ m</td>
</tr>
<tr>
<td>Concrete Cover + Radius of Bar</td>
<td>65 mm</td>
</tr>
</tbody>
</table>
## Design Parameters (2 of 2)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of Elasticity of Steel</td>
<td>$E = 2 \times 10^5$ MPa</td>
</tr>
<tr>
<td>Specific Mass of Steel</td>
<td>$\rho_s = 7,850$ kg/m$^3$</td>
</tr>
<tr>
<td>Lightweight Concrete Factor</td>
<td>$\lambda = 1$ (normal weight)</td>
</tr>
</tbody>
</table>
# Structural Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Unit Embodied Energy* ((E))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete ((f'_c = 34 \text{ MPa}))</td>
<td>3,180 MJ/m(^3)</td>
</tr>
<tr>
<td>Steel Rebar (Virgin) ((f_y = 420 \text{ MPa}))</td>
<td>32 MJ/kg</td>
</tr>
<tr>
<td>Steel Rebar (Recycled) ((f_y = 420 \text{ MPa}))</td>
<td>8.9 MJ/kg</td>
</tr>
</tbody>
</table>

*www.canadianarchitect.com; see also www.victoria.ac.nz/cbpr/documents/pdfs/ee-coefficients.pdf
# Unit Cost Ratios

<table>
<thead>
<tr>
<th>Source</th>
<th>$R = \frac{C^s}{C^c}$</th>
<th>Comments</th>
</tr>
</thead>
</table>
| Paya-Zaforteza et al. (2009) | 1.10 (86.3)          | $f'_c = 35$ MPa, $f_y = 400$ MPa  
2007 Material Costs Only |
| Sahab et al. (2005)     | 0.91 (71.4)           | $f'_c = 35$ MPa, $f_y = 460$ MPa, $f_{yt}$ 
= 250 MPa  
2001 Material & Placement Costs |
| Guerra et al. (2009)    | 0.80 (63.3)           | $f'_c = 28$ MPa, $f_y = 420$ MPa, Material & Placement Costs |

$C^s =$ cost of reinf. steel per 100 kg  
$C^c =$ cost of concrete per m³  

*Note: $R$ in ( ) is based on expressing $C^s$ per m³*
## Design Variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width of compression face of member ((b))</td>
<td>Prescribed – 300 mm (\leq b \leq 800 \text{ mm})</td>
</tr>
<tr>
<td>Height of member ((h))</td>
<td>Prescribed – 300 mm (\leq h \leq 800 \text{ mm})</td>
</tr>
<tr>
<td>Area of longitudinal tension reinforcement ((A_s))</td>
<td>Given (M_u) and ((b, h)), each value calculated as per ACI 318-08M</td>
</tr>
<tr>
<td>Area of shear reinforcement within distance (s) ((A_v))</td>
<td>Given (V_u), (s), and ((b, h)), each value calculated as per ACI 318-08M</td>
</tr>
</tbody>
</table>
Objective Functions

• Total Section Cost

\[ f(b, h, A_s, A_v) = C^c [\rho_s (A_s + A_v)R + (bh - A_s - A_v)] \]

• Total Section Embodied Energy

\[ g(b, h, A_s, A_v) = \rho_s (A_s + A_v)E^s + (bh - A_s - A_v)E^c \]
Methodology

Let \( G = \{ (h_i, b_j) : i = 1 \ldots m, j = 1 \ldots n \} \)

Compute \( f(h, b, A_v, A_s) \forall (h, b) \in G \)

Find \( (h^c, b^c) \in G \) such that \( f(h^c, b^c, A_s, A_v) \leq f(h, b, A_s, A_v) \forall (h, b) \in G \)

Find \( (h^e, b^e) \in G \) such that \( g(h^e, b^e, A_s, A_v) \leq g(h, b, A_s, A_v) \forall (h, b) \in G \)

Compare: \( f(h^c, b^c, A_s, A_v) \& f(h^e, b^e, A_s, A_v) \)
\( g(h^e, b^e, A_s, A_v) \& g(h^c, b^c, A_s, A_v) \)
Cost vs. Embodied Energy (1 of 2)

Cost

\[ \text{conc.} + \text{long. reinf.} + \text{shear reinf.} = \text{TOTAL} \]

Embodied Energy

\[ \text{conc.} + \text{long. reinf.} + \text{shear reinf.} = \text{TOTAL} \]

Lowest costs do not necessarily mean lowest embodied energy!
Cost vs. Embodied Energy (2 of 2)

Proportions:

% Cost

% Embodied Energy

Contribution of concrete to embodied energy $<<$ than contribution of concrete to the cost
Example: $b = 500 \text{ mm}; \ R = 0.8$

**Cost Optimization**

**Embodied Energy Optimization**

Volume of concrete for section optimized for embodied energy $<$ for section optimized for cost; vice-versa for steel
For fixed width and $R = 0.8$:

**Optimized height**

**Cost & Emb. energy**

**Difference [%]**

**Optimization for embodied energy vs. optimization for cost:**

10 % reduction in embodied energy, 5% increase in cost
Differences with relative costs \((R)\) \[ R = \frac{\text{Steel cost [100 kg]}}{\text{Conc cost [m}^3\text{]}} \]

Given width \(b = 400\) mm,

As relative cost of steel becomes larger, optimization with respect to embodied energy results in larger energy savings

Conclusions

• Beam case study was performed to illustrate potential benefit of structural optimization in RC buildings for embodied energy and cost

• For embodied energy values and costs assumed, results indicate on the order of $\approx 10\%$ savings in embodied energy for an additional $\approx 5\%$ cost

• Future research: whole structures; multi-objective optimization with respect to cost and embodied energy