SELECTION OF STEEL MATERIALS & COMPLIANCE WITH STRUCTURAL EUROCODES

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Chronology of events leading to the sinking of The Titanic…

- Titanic began its maiden voyage to New York at 12 noon on 10 April 1912 from Southampton, England.

- On the night of 14 April, at 11.40 pm, crew sighted an iceberg immediately ahead of ship.

- In about 40 seconds it collided with an iceberg estimated to weigh 200,000 tonnes.

- Iceberg struck the Titanic near bow and raked side of the ship’s hull damaging hull plates and popping rivets.

- At 2.20 am 15 April 1912, Titanic sank within 2 hrs and 40 mins with the loss of more than 1,500 lives.
the major cause of the Titanic sinking was attributed to **low impact toughness** of the steel used in its hull structure.
Charpy Impact tester - for determination of the Charpy Impact energy according to ASTM E-23, ISO, DIN, BN, JIS standards.
Why we need Toughness...

RMS Titanic, 14 April 1912

SS Schenectady T2 Oil Tanker, Jan 1943

Modern steel

Titanic steel

Source: Gannon 1995
Material, Design & Execution

- **Design**: BS5950
- **Material**: BS only
- **Execution**:
Material, Design & Execution

- **Design**: BS EN1993
- **Material**: BS ENs only
- **Execution**: BS EN1090
Uniquely Singapore!

Design
BS 5950
BS EN1993

Material
BS ENs & Non-BS ENs
(ASTM/JIS/AS/NZS/GB)

Execution
BS EN 1090
Construction Industry in Singapore

• Sustainability, productivity & resiliency in the industry:
  – Disruption in sand & granite supply
  – Increase productivity / Reduce migrant workers
• BS5950/EC3 design codes
  – Only covers BS/EN materials by default
• BS5950/EC3 + Chinese GB materials = ???
‘Alternative’ in Singapore’s context…

• not manufactured to BS/EN
• not covered in BS5950/EC3 by default
• easily available (GB, JIS, ASTM, AS/NZS)
• use to BS5950/EC3 ⇒ design guide needed
Singapore Steel Market (2013)

• Import of structural steel sections (plates, H & I sections, channels, angles, hollow sections)
  - China  588K Tonnes
  - Ukraine 488K Tonnes
  - Japan  472K Tonnes
  - Others  371K Tonnes
    (Korea, Thailand, Taiwan, Malaysia)

• Export (Indonesia) 639K Tonnes

TOTAL STRUCTURAL STEEL = 1.28M Tonnes
TOTAL REINFORCING STEEL = 1.50M Tonnes
Imported Prefabricated Steelwork (2013)

• Singapore imports fabricated structural steelwork from the following countries in 2013:
  – China, S$313M
  – Japan, S$284M
  – Malaysia, S$156M – subsidiaries of Singapore companies operating in Malaysia
  – Germany, S$53M
  – Korea, S$50M
Some Material Issues?

- Steel material production standards are substantial documents covering mechanical, chemical, physical and other delivery conditions
- One piece of steel is not necessarily the same as another although they may look the same
- **We are not the only ones using steel**
- We never buy steel by weight
- Testing a batch of steel from different ‘parents’ is meaningless
- Material failure can be sudden and disastrous
Performance Requirements for Structural Applications

- **Strength** – ability to carry load
- **Ductility** – ability to sustain permanent deformation without loss of strength
- **Toughness** – ability to absorb damage without fracture
- **Weldability** – ability to transfer load
Grand Challenge – Balance Performance!

Strength

Ductility
Toughness
Weldability
The performance of structural steel can be enhanced through three basic mechanisms, i.e.

- the introduction of interstitial and substitutional atoms \(\text{(micro alloying)}\)
- the generation and concentration of dislocations at the grain boundaries \(\text{(work or strain hardening)}\)
- the formation of additional grain boundaries \(\text{(heat treatment)}\).
Many Types of Steel Materials

- Carbon (non-alloy) steel
- Alloy (fine-grain) steel
- Cold-worked steel
- Heat-treated steel
Material Selection & Compliance

BC 1: 2008 - Design Guide on use of Alternative Steel Materials to BS5950

(Approved Document under Singapore’s Building Regulations and enforced by BCA of Singapore)

Material Selection & Compliance

BC 1: 2012 - Design Guide on use of Alternative Structural Steel to BS5950 and Eurocode 3

(Approved Document under Singapore’s Building Regulations and enforced by BCA of Singapore)
Selection of Equivalent Steel Materials – Hong Kong & Macau

(Industrial Guide for Best Construction Practice in Hong Kong and Macau)
Reinforcing Steel & Structural Steel

Trend is towards use of higher grade but more stringent higher performance steel are required.

<table>
<thead>
<tr>
<th></th>
<th>Reinforcing Steel</th>
<th>Structural Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td><strong>Yield strength (MPa)</strong></td>
<td>400 to 600</td>
<td></td>
</tr>
<tr>
<td><strong>Modulus of elasticity (GPa)</strong></td>
<td>200</td>
<td></td>
</tr>
<tr>
<td><strong>$f_t/f_y$ or $f_u/f_y$</strong></td>
<td>≥ 1.05</td>
<td>≥ 1.08</td>
</tr>
<tr>
<td><strong>Elongation (%)</strong></td>
<td>≥ 2.5</td>
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<tr>
<td><strong>Ultimate strain</strong></td>
<td></td>
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</table>
Reinforcing Steel

Strength

Yield strength $f_{yk}$ or $f_{0.2k}$ and tensile strength $f_t$.

Ductility

Ratio of tensile strength to yield strength $f_t/f_{yk}$

Elongation at maximum force $\varepsilon_{uk}$.

Stress-strain relations for reinforcing steel
Many Types of Reinforcing Steel

- Reinforcing bars
- Coils
- Welded fabric
- Lattice girders
Cold-Reduced Steel Wires

Hot-rolled Wire Rod
Dia. 5.5mm to 14mm
YS : 300 N/mm²

Finished Wire Coils
Dia. 5mm to 13mm,
YS : 500 N/mm²

Profiling Rollers
- Dia. Reduction
e.g. 8mm > 7mm
Cold-Worked Steel Welded Fabric

Wires in coil / pre-cut form

Welded Fabric

Computerised Machine
Material requirement for ’primary seismic members’

<table>
<thead>
<tr>
<th>Ductility Class</th>
<th>DCL (Low)</th>
<th>DCM (Medium)</th>
<th>DCH (High)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete grade</td>
<td>No limit</td>
<td>≥ C16/20</td>
<td>≥ C20/25</td>
</tr>
<tr>
<td>Steel Class (EC2, Table C1)</td>
<td>B or C</td>
<td>B or C</td>
<td>Only C</td>
</tr>
<tr>
<td>Longitudinal bars</td>
<td>only ribbed</td>
<td>only ribbed</td>
<td>only ribbed</td>
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</tbody>
</table>

DCL - ductility class ‘low’
DCM - ductility class ‘medium’
DCH - ductility class ‘high’

For ‘secondary seismic members’, they do not need to conform to these requirements.
In addition, for seismic detailing, there are stringent requirements for reinforcing steel mainly focusing on:

- Bar diameter
- Bar spacing
- Minimum bar numbers
- Minimum reinforcement area
- Maximum reinforcement area
Detailing of Primary Seismic Beams

For DCL following EC2
For DCM&DCH critical regions (detailing to EC8)
out of critical regions (detailing to EC2)

Critical region \( l_{cr} = h_w \) (depth of beam) for DCM
\[ l_{cr} = 1.5h_w \] for DCH
Detailing of Primary Seismic Columns

For DCL
detailing to EC2

For DCM&DCH
critical regions (detailing to EC8)
out of critical regions (detailing to EC2)

Critical region

\[ l_{cr} = \max \left\{ h_c; \frac{l_{cl}}{6}; 0.45 \right\} \]

\[ l_{cr} = \max \left\{ 1.5h_c; \frac{l_{cl}}{6}; 0.6 \right\} \]

for DCM
for DCH

\( h_c \) is the largest cross-sectional dimension of column
\( l_{cl} \) is the clear length of the column

Beam-column joint “special” confinement to clause 5.4.3.3 (EC8)
Trend is towards use of higher grade but more stringent higher performance steel are required…

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Some product standards have requirements on nominal yield and tensile strength, or their minimum values only. The stress ratio calculated according to these nominal values cannot comply with EC3, for e.g. profiled sheet sheeting.

<table>
<thead>
<tr>
<th>Standard</th>
<th>Grade</th>
<th>Nominal yield strength (MPa)</th>
<th>Nominal tensile strength (MPa)</th>
<th>Stress ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS 1397</td>
<td>G450</td>
<td>450</td>
<td>480</td>
<td>1.07</td>
</tr>
<tr>
<td></td>
<td>G500</td>
<td>500</td>
<td>520</td>
<td>1.04</td>
</tr>
<tr>
<td></td>
<td>G550</td>
<td>550</td>
<td>550</td>
<td>1.00</td>
</tr>
<tr>
<td>AS 1595</td>
<td>CA 500</td>
<td>500</td>
<td>510</td>
<td>1.02</td>
</tr>
<tr>
<td>EN 10149</td>
<td>S 550MC</td>
<td>550</td>
<td>600</td>
<td>1.09</td>
</tr>
<tr>
<td></td>
<td>S 600MC</td>
<td>600</td>
<td>650</td>
<td>1.08</td>
</tr>
<tr>
<td></td>
<td>S 650MC</td>
<td>650</td>
<td>700</td>
<td>1.08</td>
</tr>
<tr>
<td></td>
<td>S 700MC</td>
<td>700</td>
<td>750</td>
<td>1.07</td>
</tr>
<tr>
<td>EN 10326</td>
<td>S550GD</td>
<td>550</td>
<td>560</td>
<td>1.02</td>
</tr>
<tr>
<td>ISO 4997</td>
<td>CH550</td>
<td>550</td>
<td>550</td>
<td>1.00</td>
</tr>
</tbody>
</table>
High Strength Steel (HSS)

Normal strength steel: Steel grades S235 to S460
High strength steel: Steel grades greater than S460 up to S690

Compared to normal strength steel, high strength steel has lower ductility.
High Performance Structural Steel

Effects of Welding
- Strength (Hardness)
- Ductility
- Toughness
- Residual stress
- Distortion
High Heat Input for Construction Productivity

Low heat input welding
Shielded metal arc welding, Gas metal arc welding, etc.

- Weld heat input: 10〜100kJ/cm
- Multi pass welding for heavy gauge plate
  > Low work efficiency
- Minor degradation of material properties in weld metal and heat affected zone

High heat input welding
Submerged arc welding, Electroslag welding, etc.

- Weld heat input: 150〜1000kJ/cm
- Single pass welding for heavy gauge plate
  > High work efficiency
- Significant degradation of material properties in weld metal and heat affected zone
Heat Input for Various Processes

20kJ/cm

HAZ

HAZ

GMAW
(Gas-shielded Metal-Arc Welding)
CO2 welding

500kJ/cm

HAZ

HAZ

SAW
(Submerged Arc Welding)

800kJ/cm

HAZ

HAZ

ESW
(ElectroSlag Welding)

skin plate

diaphragm

BOX column for high building
Example - Fabrication of Box Column
Submerged Arc Welding (SAW)

Welding direction of SAW: perpendicular to column longitudinal

- Feed the welding wire into the flux supplied ahead of welding wires.
- Large current, multiple electrodes > High work efficiency
Electro-Slag Welding (ESW)

- Welding direction of ESW: perpendicular to column longitudinal

- Feed the welding wire into molten slag
  - Welding wire and base metal melt due to resistance heating of slag
- Upward welding
Material Requirements for Eurocodes

<table>
<thead>
<tr>
<th></th>
<th>EC2</th>
<th>EC3</th>
<th>EC4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>C12/15- C90/105</td>
<td>–</td>
<td>C20/25 - C60/75</td>
</tr>
<tr>
<td>Light weight</td>
<td>LC12/13 – LC80/88</td>
<td>–</td>
<td>LC20/22 - LC60/66</td>
</tr>
<tr>
<td>Reinforcing steel</td>
<td>400 - 600 N/mm²</td>
<td>–</td>
<td>400 - 600 N/mm²</td>
</tr>
<tr>
<td>Structural steel</td>
<td>–</td>
<td>≤ 700 N/mm²</td>
<td>≤ 460 N/mm²</td>
</tr>
</tbody>
</table>

Same trend towards use of higher grade concrete, leading to greater construction productivity. However, the ranges in EC4 are more restricted than those in EC2 and EC3, **WHY?**
## Need for Material Compatibility

### Maximum Strength of Steel before Concrete Crushes

<table>
<thead>
<tr>
<th>Grade</th>
<th>S235</th>
<th>S275</th>
<th>S355</th>
<th>S420</th>
<th>S460</th>
<th>S500</th>
<th>S550</th>
<th>S620</th>
<th>S690</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ C50/60</td>
<td>235</td>
<td>275</td>
<td>355</td>
<td>420</td>
<td>420</td>
<td>420</td>
<td>420</td>
<td>420</td>
<td>420</td>
</tr>
<tr>
<td>C55/67</td>
<td>235</td>
<td>275</td>
<td>355</td>
<td>420</td>
<td>460</td>
<td>464</td>
<td>464</td>
<td>464</td>
<td>464</td>
</tr>
<tr>
<td>C60/75</td>
<td>235</td>
<td>275</td>
<td>355</td>
<td>420</td>
<td>460</td>
<td>483</td>
<td>483</td>
<td>483</td>
<td>483</td>
</tr>
<tr>
<td>C70/85</td>
<td>235</td>
<td>275</td>
<td>355</td>
<td>420</td>
<td>460</td>
<td>500</td>
<td>504</td>
<td>504</td>
<td>504</td>
</tr>
<tr>
<td>C80/95</td>
<td>235</td>
<td>275</td>
<td>355</td>
<td>420</td>
<td>460</td>
<td>500</td>
<td>525</td>
<td>525</td>
<td>525</td>
</tr>
<tr>
<td>C90/105</td>
<td>235</td>
<td>275</td>
<td>355</td>
<td>420</td>
<td>460</td>
<td>500</td>
<td>546</td>
<td>546</td>
<td>546</td>
</tr>
</tbody>
</table>

\[ f_y, \varepsilon_2 = E_a \varepsilon_{c2} \leq f_y \]

![Graph showing maximum strength of steel before concrete crushes](image)

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**Note:** The values represent the maximum strength of steel (in MPa) for different grades of steel before concrete crushes. The graph illustrates the stress-strain relationship for two different grades (C50/60 and S690).
Concrete Filled Tubular Members with High Strength Materials - An Extension of Eurocode 4 Method to C90/105 Concrete and S550 Steel

Took advantage of confinement provided by the outer steel tube and validated against a large test database!

Thank you !