Effective Use of Q690 Steel Materials in Building Structures – Effective structural steel design to EN 1993-1

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Scope

- Adopting Structural Eurocodes in Asia
- Technical Guides
  - Effective use of equivalent steel materials
  - Design to Eurocodes using Chinese steel materials
- Design of Q690 steel materials using EN 1993-1
- Design of member buckling to EN 1993-1
- Structural behaviour of Q690 steel welded H-sections
  - Tensile tests 6 tests
  - Compression tests on Q690 stocky H-sections 9 tests
  - Compression tests on Q690 slender H-sections
    - Concentrically loaded columns 7 tests
    - Eccentrically loaded columns 8 tests
- Conclusions
Adopting Structural Eurocodes in Asia

- The Eurocodes are a new set of European structural design codes for building and civil engineering works. Conceived and developed over the past 40 years with the combined expertise of the member states of the European Union, they are arguably the most advanced structural codes in the world.

- The Eurocodes are intended to be mandatory for European public works and likely to become the de-facto standard for the private sector – both in Europe and world-wide.

- The structural Eurocodes had been available as European pre-standards (ENVs) for several years, and all of them had been published as full European Standards (ENs) in 2007.
Adopting Structural Eurocodes in Asia

Organization of the Eurocodes

The Structural Eurocodes are a new set of European structural design codes for building and civil engineering works. A total of 58 parts of the Eurocodes are published under 10 area heading:

- Eurocode 0 — EN1990: Basis of Structural Design
- Eurocode 1 — EN1991: Actions on Structures
- Eurocode 2 — EN1992: Design of Concrete Structures
- Eurocode 3 — EN1993: Design of Steel Structures
- Eurocode 4 — EN1994: Design of Composite Steel and Concrete Structures
- Eurocode 5 — EN1995: Design of Timber Structures
- Eurocode 6 — EN1996: Design of Masonry Structures
- Eurocode 7 — EN1997: Geotechnical Design
- Eurocode 8 — EN1998: Design of Structures for Earthquake Resistance
- Eurocode 9 — EN1999: Design of Aluminium Structures
Adopting Structural Eurocodes in Asia

Organization of the Eurocodes

EN 1990
Basis of design

EN 1991
Actions
Dead Imposed Wind

EN 1992
Concrete structures

EN 1993
Steel structures

EN 1994
Composite structures
Adopting Structural Eurocodes in Asia

Asia context

- Owing to the withdrawal of various British structural design standards in March 2010, the Works Department of the Government of the Hong Kong SAR have been migrating to Eurocodes in stages for the design of public works civil engineering structures while mandatory adoption of Eurocodes will commence in 2015.

- Moreover, as many countries, in particular, Asian countries, have already adopted the structural Eurocodes for design and construction of building structures, there is a growing need for design and construction engineers in Asia to acquire the new skills.

- EN 1993 -1 was developed in the 2000s, and the majority of the knowledge and engineering experience is based on S235 and S350 steel materials in many European countries. Some studies on S460 to S690 steel materials have also been conducted which give conservative design rules.
Effective use of equivalent steel materials

Equivalent Steel Materials to European Steel Materials Specifications

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• Civil Engineering Laboratory, Macau SAR
Effective use of equivalent steel materials

Equivalent Steel Materials to European Steel Materials Specifications

To provide a technical platform to allow effective use of steel materials manufactured to the following national specifications:

*Australia / New Zealand, China, EC, Japan, U.S.A.*

Specific requirements on material performance and quality assurance have been clearly identified to establish equivalency of steel materials to EN specifications.

The requirements follow closely to:

- *Code of Practice for the Structural Use of Steel*
  Buildings Department, Hong Kong SAR

- *Design Guide on Use of Alternative Structural Steel to BS5950 and Eurocode 3*
  Building and Construction Authority, Singapore.

The Professional Guide allows Chinese steel materials to compete directly with others based on technical considerations.
Effective use of equivalent steel materials

Various product forms of steel materials

<table>
<thead>
<tr>
<th>Steel Materials</th>
<th>Product Forms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural steels</td>
<td>• plates</td>
</tr>
<tr>
<td></td>
<td>• sections</td>
</tr>
<tr>
<td></td>
<td>• hollow sections</td>
</tr>
<tr>
<td></td>
<td>• sheet piles</td>
</tr>
<tr>
<td></td>
<td>• solid bars</td>
</tr>
<tr>
<td></td>
<td>• strips for cold formed open sections</td>
</tr>
<tr>
<td>Thin gauge strips</td>
<td>• strips for cold formed profiled sheetings</td>
</tr>
<tr>
<td>Connection materials</td>
<td>• stud connectors</td>
</tr>
<tr>
<td></td>
<td>• non-preloaded bolted assemblies</td>
</tr>
<tr>
<td></td>
<td>• preloaded bolted assemblies</td>
</tr>
<tr>
<td></td>
<td>• welding consumables</td>
</tr>
</tbody>
</table>
Effective use of equivalent steel materials

Equivalence of steel materials and their selection principles

Both minimum acceptable standards of *material performance* and quality assurance are considered to be essential requirements for steel materials to be accepted as “equivalent”.

Key selection principles have been identified as follows:

- **Material performance**
  - *mechanical strength* for structural adequacy,
  - *ductility* for sustained resistances at large deformations,
  - *toughness* in terms of energy absorption against impact, and
  - *chemical compositions* and *weldability* for minimized risks of crack formation in welds.
Effective use of equivalent steel materials
Equivalence of steel materials and their selection principles

Both minimum acceptable standards of material performance and quality assurance are considered to be essential requirements for steel materials to be accepted as “equivalent”.

Key selection principles have been identified as follows:
• Quality assurance systems
  a) demonstrated compliance with acceptable reference standards,
  b) demonstrated compliance with material tests with sufficient sampling on both chemical compositions and mechanical properties, and
  c) effective implementation of certificated quality assurance systems.
# Effective use of equivalent steel materials

## Classification of steel materials

<table>
<thead>
<tr>
<th>Nominal yield strength (N/mm²)</th>
<th>Class</th>
<th>Compliance with material performance requirements</th>
<th>Compliance with quality assurance requirements</th>
<th>Additional material Tests</th>
<th>Material class factor, $\gamma_{MC}$ for $R_{eH}$</th>
<th>Ultimate tensile strength, $R_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥ 235 and ≤ 690</td>
<td><strong>E1</strong></td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td><strong>E2</strong></td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td><strong>E3</strong></td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>
Effective use of equivalent steel materials

Classification of steel materials

A newly defined factor, namely, the material class factor, $\gamma_{MC}$, is adopted as a result of the classification.

- Nominal value of yield strength
  \[ f_y = \frac{R_{eH}}{\gamma_{MC}} \]

- Nominal value of ultimate tensile strength
  \[ f_u = \frac{R_m}{\gamma_{MC}} \]

where
- $R_{eH}$ is the minimum yield strength to product standards;
- $R_m$ is the ultimate tensile strength to product standards; and
- $\gamma_{MC}$ is the material class factor.
Effective use of equivalent steel materials
Quality assurance requirements to European steel materials specifications

- In general, a steel manufacturer will have already established a form of quality assurance.

- However, in order to demonstrate compliance with the quality assurance requirements for steel materials equivalent to European steel materials specifications, a steel manufacturer should further establish a Factory Production Control (FPC) System which is essential for demonstrating conformity of the steel material performance with European steel materials specifications.

- Moreover, in order to demonstrate effective implementation, the FPC System must be certified by an independent qualified Certification Body. For further information on a FPC Scheme, refer to Appendix B.4 of EN 10025-1.
A proposal to the Fund was submitted by the Hong Kong Polytechnic University with the support of the Hong Kong Constructional Metal Structures Association in September 2012:

**Adopting Eurocodes by Hong Kong Construction Industry:**
Technical Guide on Effective Design & Construction to European Steel Code

- To provide technical guidance to Hong Kong design and construction engineers to perform structural steel design to EN 1993-1-1.

- The project was approved in January 2013 for the project period from June 2013 to August 2014.
Design to Eurocodes using Chinese steel materials

Technical Guide on Effective Design & Construction to European Steel Code

Authored by

Ir Prof. K. F. Chung,
Ir Dr. Michael C.H. Yam, and
Dr. H.C. Ho

Supported by

• The Hong Kong Polytechnic University
• The Hong Kong Constructional Metal Structures Association
• The Chinese National Engineering Research Centre for Steel Construction
• The Chinese Confederation of Roll Forming Industry
Design to Eurocodes using Chinese steel materials

Basic considerations in selecting steel materials

- In Hong Kong context, the most important difference is the use of non-British or non-European steel materials!

- The following mechanical properties of the steel materials are considered to be very important:
  - strength,
  - ductility,
  - toughness,
  - through thickness properties,
  - strength, stiffness and thermal expansion at elevated temperatures.

- In addition, the steel materials should have a required service life which suits the expected environmental conditions, and hence, corrosion resistance is also important.
In general, all the key design rules given in EN1993-1-1 are described in the Technical Guide, and they are supplemented with explanatory notes in the same sequence as found in the Eurocode:

- General
- Basis of design
- Materials -
  - yield strengths
- Durability
- Structural analysis
- Ultimate limit states
  - resistances of cross-sections & members
- Serviceability limit states
Design to Eurocodes using Chinese steel materials

Overview of Technical Guide

Worked examples on cross-section properties & resistances

• Section analysis
• Resistances of cross-sections under single actions
• Resistances of cross-sections under multiple actions

Worked examples on member resistances

• A restrained beam
• An unrestrained beam
• A slender column under compression
• A slender column under co-existing compression and bending
• A column under simple construction

Detailed design information and parameters are also presented in a tabulated format for easy reference.
Design to Eurocodes using Chinese steel materials

Deliverables of Technical Guide

To provide technical guidance to design and construction engineers to work with Structural Eurocodes, including:

• EN 1990  Basis of Structural Design
• EN 1991  Actions on Structures
• EN 1993  Design of Steel Structures
• Various U.K. National Annexes

The Technical Guide is also compiled in accordance with prevailing local practice:

• The Code of Practice for the Structural Use of Steel (2011)
• Various documents issued by government departments
Design to Eurocodes using Chinese steel materials

Deliverables of Technical Guide

• To enable design and construction engineers to work with:
  • Rolled sections to BS / EN materials specifications
  • Welded sections to GB materials specifications

• To formalize the use of Chinese steel materials (as equivalent steel materials) on construction projects designed to Structural Eurocodes.
Design to Eurocodes using Chinese steel materials

Rolled sections

- I- and H-sections to:
  - EN 10025 on materials
  - BS4-1 on dimensions

- CHS, RHS and SHS to:
  - EN 10210-1 on materials
  - EN 10210-2 on dimensions
Design to Eurocodes using Chinese steel materials

Welded sections

EWIS and EWHS to:
- GB/T 700 & GB/T 1591 on materials

EWCHS, EWRHS and EWSHS to:
- GB/T 6725 & GB/T 8162 on materials
## Design to Eurocodes using Chinese steel materials

Data range of rolled and welded sections

<table>
<thead>
<tr>
<th>Rolled sections</th>
<th>Equivalent welded sections</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>S275</strong> and <strong>S355</strong></td>
<td><strong>Q235, Q275, Q345 and Q460</strong></td>
</tr>
<tr>
<td><strong>Rolled I-section:</strong> I-section</td>
<td>Welded I-section: <strong>EWI-section</strong></td>
</tr>
<tr>
<td><strong>Rolled H-section:</strong> H-section</td>
<td>Welded H-section: <strong>EWH-section</strong></td>
</tr>
<tr>
<td><strong>Hot-finished circular hollow section:</strong> CHS</td>
<td>Cold-formed circular hollow section: <strong>EWCHS</strong></td>
</tr>
<tr>
<td><strong>Hot-finished rectangular hollow section:</strong> RHS</td>
<td>Cold-formed rectangular hollow section: <strong>EWRHS</strong></td>
</tr>
<tr>
<td><strong>Hot-finished square hollow section:</strong> SHS</td>
<td>Cold-formed square hollow section: <strong>EWSHS</strong></td>
</tr>
</tbody>
</table>

234 sections

- Design Tables for dimensions & properties, and
- Design Tables for section resistances.
Design to Eurocodes using Chinese steel materials

Designing with rolled and welded sections

- Both the Professional Guide on the use of equivalent steel materials and the Technical Guide on advanced structural steel design are compiled to facilitate design and construction engineers to work effectively to EN 1993-1-1: Design of Steel Structures using Chinese steel materials and structural steelwork.

- Design and construction engineers are encouraged to take full advantages offered by these two documents for construction projects in Hong Kong and Singapore as well as neighbouring cities and countries in the Region.

- Both minimum acceptable standards of *material performance* and *quality assurance* are considered to be essential requirements for steel materials to be accepted as “equivalent”.
Design of Q690 steel materials using EN 1993 -1

Design considerations

- High strength steel sections are efficient structural members owing to enhanced strength to self weight ratios.

- Cross-section resistances
  - Compression
  - Tension
  - Shear
  - Moment
  - Section classification

- Member resistances
  - Column bucking
  - Beam buckling
  - Beam-column buckling under combined compression and bending

- Connections
  - Bolted connections
  - Welded connections and welding
Design of member buckling to EN 1993 -1

Cross-section resistance

\[ N_{c,Rd} = A \cdot \frac{f_y}{\gamma_{MO}} \]

- No design strength is used at all.
- Instead, a yield strength and a material factor are used together in almost all equations.
Design of member buckling to EN 1993 -1

Member resistance

\[ N_{b,Rd} = \chi A \frac{f_y}{\gamma_{M1}} \]

\( \chi \) depends on the slenderness, \( \lambda \), of the member.
### Design of member buckling to EN 1993 -1

**Cross-section and member resistances**

<table>
<thead>
<tr>
<th>Resistances</th>
<th>BS 5950</th>
<th>EN 1993</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-section</td>
<td>( P = p_y A )</td>
<td>( N_{c,Rd} = A f_y / \gamma_{M0} )</td>
</tr>
<tr>
<td></td>
<td>( M = p_y S )</td>
<td>( M_{c,Rd} = W_{pl} f_y / \gamma_{M0} )</td>
</tr>
<tr>
<td>Member</td>
<td>( P = p_c A )</td>
<td>( N_{b,Rd} = \chi A f_y / \gamma_{M1} )</td>
</tr>
<tr>
<td></td>
<td>( M = p_b S )</td>
<td>( M_{b,Rd} = \chi_{LT} W_{pl} f_y / \gamma_{M1} )</td>
</tr>
</tbody>
</table>
# Design of member buckling to EN 1993 -1

## Slenderness

<table>
<thead>
<tr>
<th>Slenderness</th>
<th>BS 5950</th>
<th>EN 1993</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Geometric ratio</td>
<td>Force ratio</td>
</tr>
<tr>
<td><strong>Column</strong></td>
<td>( \lambda = \frac{L_E}{r} )</td>
<td>( \bar{\lambda} = \sqrt{\frac{A f_y}{N_{cr}}} )</td>
</tr>
<tr>
<td></td>
<td>where ( N_{cr} = \frac{\pi^2 EI}{L^2} )</td>
<td></td>
</tr>
<tr>
<td><strong>Beam</strong></td>
<td>( \lambda_{LT} = UV \lambda )</td>
<td>( \bar{\lambda}<em>{LT} = \sqrt{\frac{W_y f_y}{M</em>{cr}}} )</td>
</tr>
<tr>
<td></td>
<td>where ( M_{cr} = C_1 \frac{\pi^2 EI_z}{L^2} \sqrt{\frac{I_w}{I_z}} + \frac{L^2 GI_t}{\pi^2 EI_z} )</td>
<td></td>
</tr>
</tbody>
</table>
Design of member buckling to EN 1993 -1

Elastic critical force $N_{cr}$ and elastic critical moment $M_{cr}$

$N_{cr}$ and $M_{cr}$ are generic terms.

$N_{cr}$ and $M_{cr}$ may be readily determined using eigenvalue analysis through FEM.
Design of member buckling to EN 1993 -1

Member buckling design

**Compressive strength**, \( p_c \) (N/mm\(^2\))

**Slenderness**, \( \lambda = \frac{L_E}{r} \)

**BS 5950**

Interaction Perry-Robertson formula

Mathematical expression:

\[ p_E = \frac{\pi^2 E I}{L^2} \times \frac{1}{A} = \frac{\pi^2 E}{\lambda^2} \]

Material yielding

Elastic buckling
Design of member buckling to EN 1993 -1

Member buckling curves

An interactive curve for each steel grade / design yield strength:

\[ p_c = \frac{p_E p_y}{\phi + \sqrt{\phi^2 - p_E p_y}} \]

\[ \phi = \frac{p_y + (\eta + 1)p_E}{2} \]

One interactive curve for all steel grades. The material parameter \( \lambda_1 \) is used:

\[ \bar{\lambda} = \frac{\lambda}{\lambda_1} \]

\[ \lambda_1 = \pi \sqrt{\frac{E}{f_y}} \]

where E is the Young's modulus and \( f_y \) is the yield strength.
Same format of design formulae is adopted for all structural members which may buckle at both cold and hot states:

- Steel
- Steel-concrete composite
- Timber
- Aluminium

Equally applicable for structures at elevated temperatures when their temperature distribution histories are known.

*Is the method effective for Q690 structural steelwork?*
Structural behaviour of Q690 steel welded H-sections

Member buckling of welded H-sections

Structural behaviour of welded H-sections with various effective lengths under different loading and boundary conditions:

- Tensile tests on steel plates of various thicknesses to examine their mechanical properties  – 6 tests.
- Compression tests on stocky H-sections to examine their section resistances  – 9 tests.
- Compression tests on slender H-sections under concentric axial loads to examine their member resistances  – 7 tests.
- Compression tests on slender H-sections under eccentric axial loads to examine their member resistances under combined compression and bending  – 8 tests.
Structural behaviour of Q690 steel welded H-sections

Four sections of rationalized dimensions

Plate thickness: 6, 10 and 16 mm
Tensile tests on Q690 steel materials

Full range stress – strain curves of steel plates with various thicknesses

σ (N/mm²)

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q690</td>
<td>6</td>
</tr>
<tr>
<td>Q690</td>
<td>10</td>
</tr>
<tr>
<td>Q690</td>
<td>16</td>
</tr>
<tr>
<td>S275</td>
<td>16</td>
</tr>
</tbody>
</table>

EN 1993-1-12: 2007 Clause 3.2.2(1)

i) For steel materials with $f_y$ between 460 and 700 N/mm²: $f_u/f_y \geq 1.05$

ii) Elongation at failure: $\geq 10\%$
## Tensile tests on Q690 steel materials

### Mechanical properties

<table>
<thead>
<tr>
<th>Nominal thickness (mm)</th>
<th>Measured thickness (mm)</th>
<th>$E$ (kN/mm$^2$)</th>
<th>$f_y$ (N/mm$^2$)</th>
<th>$f_u$ (N/mm$^2$)</th>
<th>$f_u / f_y$</th>
<th>Elongation at failure (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>5.68</td>
<td>210.4</td>
<td>781.2</td>
<td>821.8</td>
<td>1.05</td>
<td>13.6</td>
</tr>
<tr>
<td>10</td>
<td>9.85</td>
<td>207.7</td>
<td>754.4</td>
<td>807.0</td>
<td>1.07</td>
<td>16.3</td>
</tr>
<tr>
<td>16</td>
<td>15.86</td>
<td>208.4</td>
<td>799.8</td>
<td>858.7</td>
<td>1.07</td>
<td>19.7</td>
</tr>
</tbody>
</table>

Notes: $E$ is the elastic modulus; $f_y$ is the yield strength; $f_u$ is the tensile strength.

All the Q690 steel plates satisfy the mechanical requirements of EN 1993-1-12.
Compression tests on Q690 steel stocky H-sections

Test program

<table>
<thead>
<tr>
<th>Section Class ( f_y = 690\text{N/mm}^2 )</th>
<th>Test</th>
<th>( b_f ) (mm)</th>
<th>( t_f ) (mm)</th>
<th>( h_w ) (mm)</th>
<th>( t_w ) (mm)</th>
<th>( A ) (mm)</th>
<th>( L_s ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C1S</td>
<td>A/B/C</td>
<td>120</td>
<td>10</td>
<td>120</td>
<td>6</td>
<td>3120</td>
</tr>
<tr>
<td>3</td>
<td>C2S</td>
<td>A/B/C</td>
<td>150</td>
<td>10</td>
<td>150</td>
<td>6</td>
<td>3900</td>
</tr>
<tr>
<td>2</td>
<td>C3S</td>
<td>A/B/C</td>
<td>200</td>
<td>16</td>
<td>200</td>
<td>10</td>
<td>8400</td>
</tr>
</tbody>
</table>

Section C1 (Class 1)  
Section C2 (Class 3)  
Section C3 (Class 2)  
Section C4 (Class 3)
1000 tons hydraulic servo control testing system

The Structural Engineering Research Laboratory, PolyU
1000 tons hydraulic servo control testing system
The Structural Engineering Research Laboratory, PolyU

Technical specifications:
- Bi-directional loading;
- Vertical load can move horizontally to follow any lateral deflection of the test specimen;
- Testing space: 3.2 m (width) x 2.0 m (depth) x 3.5 m (height);
- Adjustable crosshead level: 850 to 3850 mm; and
- Load or displacement control.

Vertical load actuator:
- Compression load: 10,000 kN
- Tension load: 3,000 kN
- Maximum displacement: +/- 250 mm
- Maximum speed: 1000 mm/min
- Load Accuracy: +/- 1.0 %
- Displacement precision: 0.04 %

Horizontal load actuator:
- Compression load: 3,000 kN
Compression tests on Q690 steel stocky H-sections

General test set-up of compression tests on stocky columns
Compression tests on Q690 steel stocky H-sections

Typical load – overall shortening curves

Test C3SC

\[ N_{Rt} = 7066 \text{ kN} \]
\[ N_{p\ell, Rd} = 6625 \text{ kN} \]

Graph showing the relationship between applied load and overall shortening.
Compression tests on Q690 steel stocky H-sections

Typical load – longitudinal strain curves

Test C3SC

\[ N_{R_t} = 7066 \text{ kN} \]
\[ N_{p_{f, rd}} = 6625 \text{ kN} \]
Compression tests on Q690 steel stocky H-sections
Section resistances – yielding and plastic plate buckling

- Test C1S : A/B/C
  \[ N_{Rt} = 2515 \text{ kN} \]
  \[ N_{Rt} = 2496 \text{ kN} \]
  \[ N_{Rt} = 2504 \text{ kN} \]

- Test C2S: A/B/C
  \[ N_{Rt} = 2515 \text{ kN} \]
  \[ N_{Rt} = 2496 \text{ kN} \]
  \[ N_{Rt} = 2504 \text{ kN} \]

- Test C3S: A/B/C
  \[ N_{Rt} = 7055 \text{ kN} \]
  \[ N_{Rt} = 7084 \text{ kN} \]
  \[ N_{Rt} = 7066 \text{ kN} \]
Compression tests on Q690 steel stocky H-sections
Section resistances – back analysis using EN 1993

<table>
<thead>
<tr>
<th>Test</th>
<th>Effective length $L_{\text{eff}}$ (mm)</th>
<th>$\bar{\lambda}_z$</th>
<th>$N_{\text{pl,Rd}}$ (kN)</th>
<th>$N_{\text{Rt}}$ (kN)</th>
<th>$\frac{N_{\text{Rt}}}{N_{\text{pl,Rd}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS1</td>
<td>A</td>
<td>280</td>
<td>0.18</td>
<td>2316</td>
<td>2515</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td></td>
<td></td>
<td>2311</td>
<td>2496</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td></td>
<td></td>
<td>2316</td>
<td>2504</td>
</tr>
<tr>
<td>C2S</td>
<td>A</td>
<td>280</td>
<td>0.14</td>
<td>2892</td>
<td>2998</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td></td>
<td></td>
<td>2904</td>
<td>3029</td>
</tr>
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<td>C</td>
<td></td>
<td></td>
<td>2921</td>
<td>2994</td>
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<tr>
<td>C3S</td>
<td>A</td>
<td>385</td>
<td>0.15</td>
<td>6581</td>
<td>7055</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td></td>
<td></td>
<td>6624</td>
<td>7084</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td></td>
<td></td>
<td>6625</td>
<td>7066</td>
</tr>
</tbody>
</table>

Notes:

- $\bar{\lambda}_z$ is the non-dimensional slenderness,
- $N_{\text{pl,Rd}}$ is the design section resistance based on measured yield strengths, and
- $N_{\text{Rt}}$ is the measured section resistance.
Compression tests on Q690 steel stocky H-sections

Normalized load – overall shortening curves

\[ \frac{N}{\sum (A_i f_{y,i})} \]

![Graph showing normalized load vs. overall shortening curves for different test series and classes.]

- Test C1S series – Class 1
- Test C2S series – Class 3
- Test C3S series – Class 2
Compression tests on Q690 steel slender H-sections
Concentrically loaded columns – General test set-up
Compression tests on Q690 steel slender H-sections
Concentrically loaded columns: Test program

<table>
<thead>
<tr>
<th>Test</th>
<th>System length $L_s$ (mm)</th>
<th>Effective length $L_{eff}$ (mm)</th>
<th>$\bar{\lambda}_z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1PA</td>
<td></td>
<td></td>
<td>1.26</td>
</tr>
<tr>
<td>C2PA</td>
<td></td>
<td>1610</td>
<td>1.01</td>
</tr>
<tr>
<td>C3PA</td>
<td></td>
<td>1990</td>
<td>0.77</td>
</tr>
<tr>
<td>C4PA</td>
<td></td>
<td>0.62</td>
<td></td>
</tr>
<tr>
<td>C2QA</td>
<td></td>
<td>2410</td>
<td>1.41</td>
</tr>
<tr>
<td>C3QA</td>
<td></td>
<td>2790</td>
<td>1.09</td>
</tr>
<tr>
<td>C4QA</td>
<td></td>
<td>0.87</td>
<td></td>
</tr>
</tbody>
</table>

Note: $\bar{\lambda}_z$ is the non-dimensional slenderness.
Compression tests on Q690 steel slender H-sections
Concentrically loaded columns

- Loading procedure
  - Pre-loading: up to 10% predicted resistance
  - Loading application

1. Initially, use load control:
   \[ \approx 10 \text{ N/mm}^2 \text{ per minute} \]

2. When approaching 80% of the predicted resistance, use displacement control:
   \[ \approx 0.2 \text{ mm per minute} \]
Compression tests on Q690 steel slender H-sections
Concentrically loaded columns

Test C2PA

Plate buckling

Overall buckling

Test C2QA

Plate buckling

Overall buckling
Compression tests on Q690 steel slender H-sections
Concentrically loaded columns: Load – deformation curves

Load – axial deformation curve

Test C2QA

Load – displacement curve

Test C2QA

Axial deformation $\Delta x$ (mm)

Lateral displacement $\Delta y$ (mm)
Compression tests on Q690 steel slender H-sections
Concentrically loaded columns: Load – strain curves

Test C2QA

Mid-height section
Compression tests on Q690 steel slender H-sections
Concentrically loaded columns
### Compression tests on Q690 steel slender H-sections

**Concentrically loaded columns: Back analysis to EN 1993-1**

<table>
<thead>
<tr>
<th>Test</th>
<th>Effective length $L_{\text{eff}}$ (mm)</th>
<th>$\bar{\lambda}_z$</th>
<th>Buckling resistance (kN)</th>
<th>$\frac{N_{b,\text{Rt}}}{N_{b,\text{Rd}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$N_{b,\text{Rd}}$ (Curve $a_0$)</td>
<td>$N_{b,\text{Rt}}$</td>
</tr>
<tr>
<td>C1PA</td>
<td>1990</td>
<td>1.26</td>
<td>1,232</td>
<td>1,284</td>
</tr>
<tr>
<td>C2PA</td>
<td></td>
<td>1.01</td>
<td>2,071</td>
<td>2,714</td>
</tr>
<tr>
<td>C3PA</td>
<td></td>
<td>0.77</td>
<td>5,738</td>
<td>5,924</td>
</tr>
<tr>
<td>C4PA</td>
<td></td>
<td>0.62</td>
<td>7,621</td>
<td>7,739</td>
</tr>
<tr>
<td>C2QA</td>
<td>2790</td>
<td>1.41</td>
<td>1,279</td>
<td>1,510</td>
</tr>
<tr>
<td>C3QA</td>
<td></td>
<td>1.09</td>
<td>4,361</td>
<td>4,464</td>
</tr>
<tr>
<td>C4QA</td>
<td></td>
<td>0.87</td>
<td>6,741</td>
<td>7,284</td>
</tr>
</tbody>
</table>

**Notes:**
- $\bar{\lambda}_z$ is the non-dimensional slenderness;
- $N_{b,\text{Rd}}$ is the design resistance based on measured yield strengths;
- $N_{b,\text{Rt}}$ is the measured section resistance against compression.
Compression tests on Q690 steel slender H-sections
Concentrically loaded columns: Back analysis to EN 1993-1

Use “Curve c” according to EN 1993-1-1 and -1-12.

Welded H-section buckling about minor axis
Compression tests on Q690 steel slender H-sections
Concentrically loaded columns: Back analysis to EN 1993-1

Use "Curve $a_0$" according to test results.

Welded H-section buckling about minor axis
Compression tests on Q690 steel slender H-sections

Eccentrically loaded columns: General test set-up
## Compression tests on Q690 steel slender H-sections

### Eccentrically loaded columns: Test program

<table>
<thead>
<tr>
<th>Test</th>
<th>System Length $L_s$ (mm)</th>
<th>Effective Length $L_{eff}$ (mm)</th>
<th>$\bar{\lambda}_z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1PB</td>
<td>1610</td>
<td>1990</td>
<td>1.29</td>
</tr>
<tr>
<td>C2PB</td>
<td>1.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C3PB</td>
<td>0.78</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C4PB</td>
<td>0.62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C1QB</td>
<td>2410</td>
<td>2790</td>
<td>1.80</td>
</tr>
<tr>
<td>C2QB</td>
<td>1.44</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C3QB</td>
<td>1.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C4QB</td>
<td>0.87</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: $\bar{\lambda}_z$ is the non-dimensional slenderness.

![Diagram of eccentrically loaded columns with LVDT and strain gauge](image)

- $e=100 \text{ mm}$
- Effective length $L_{eff}$
- Specimen length $L_s$
Compression tests on Q690 steel slender H-sections

Eccentrically loaded columns

Test C3PB

Plate buckling

Overall buckling

Test C3QB

Plate buckling

Overall buckling
Compression tests on Q690 steel slender H-sections

Eccentrically loaded columns
## Compression tests on Q690 steel slender H-sections

Eccentrically loaded columns – EN 1993-1: Cl. 6-3-3 & Method A

<table>
<thead>
<tr>
<th>Test</th>
<th>Effective length ( L_{\text{eff}} ) (mm)</th>
<th>( \bar{\lambda}_z )</th>
<th>Buckling resistance under combined compression and bending (kN)</th>
<th>( \frac{N_{\text{Rt}}}{N_{\text{Rd}}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1PB</td>
<td>1990</td>
<td>1.29</td>
<td>[231, 311]</td>
<td>[255, 328]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( N_{\text{Rd}} ) (Curve ( a_0 ))</td>
<td>( N_{\text{Rt}} )</td>
</tr>
<tr>
<td>C2PB</td>
<td></td>
<td>1.03</td>
<td>[504, 515]</td>
<td>[525, 527]</td>
</tr>
<tr>
<td>C3PB</td>
<td></td>
<td>0.78</td>
<td>[1641, 1650]</td>
<td>[1698, 1698]</td>
</tr>
<tr>
<td>C4PB</td>
<td></td>
<td>0.62</td>
<td>[2535, 2609]</td>
<td>[2660, 2660]</td>
</tr>
<tr>
<td>C1QB</td>
<td>2790</td>
<td>1.80</td>
<td>[233, 239]</td>
<td>[249, 250]</td>
</tr>
<tr>
<td>C2QB</td>
<td></td>
<td>1.44</td>
<td>[403, 403]</td>
<td>[418, 418]</td>
</tr>
<tr>
<td>C3QB</td>
<td></td>
<td>1.09</td>
<td>[1351, 1341]</td>
<td>[1376, 1376]</td>
</tr>
<tr>
<td>C4QB</td>
<td></td>
<td>0.87</td>
<td>[2203, 2203]</td>
<td>[2276, 2276]</td>
</tr>
</tbody>
</table>

Notes: \( \bar{\lambda}_z \) is the non-dimensional slenderness; 
\( N_{\text{Rd}} \) is the design member resistance based on measured yield strengths; and 
\( N_{\text{Rt}} \) is the measured member resistance under combined compression and bending.
Conclusions

- Modern design methods such as EN 1993 are applicable to Q690 steel members, provided that design parameters have been calibrated.

- In general, the current design rules for cross-section resistances are considered to be applicable to Q690 steel members.

- Section classification for determination of cross-section resistances may be enhanced.

- Owing to the increased yield strengths, the effect of residual stresses in column buckling of welded H-sections is relatively decreased.

- Design of member buckling will be enhanced with an improved choice of buckling curves according to calibration against test results.

- Design rules for beam-column buckling under combined compression and bending are found to be satisfactorily.
Effective Use of Q690 Steel Materials in Building Structures – Effective structural steel design to EN 1993 -1

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