Investigation into structural behaviour of high strength S690 steels and their welded sections

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CNERC for Steel Construction (Hong Kong Branch)

Promoting sustainable infrastructure development in Hong Kong

Promoting export of Hong Kong and Chinese Steel Construction Industry

Promoting advanced structural engineering technology in modern steel construction

Development Bureau of Government of Hong Kong SAR
Construction Industry Council
Chinese Iron and Steel Association
Chinese Steel Construction Society
Chinese Constructional Metal Structures Association

Collaborators
Imperial College London, Institution of Structural Engineers, the Steel Construction Institute, Tsinghua University, Tongji University, University of Science and Technology Beijing.
Development of Hong Kong Construction Industry

Hong Kong Construction Industry

Development Bureau

Construction Industry Council

Chinese Steel Construction Industry

International Design Centre for Infrastructure Development

International Construction Centre for Infrastructure Development
Structural efficiency of building structures - Effective design and construction using high performance steel

High performance steel: Q690 ~ Q960

Normal grade steel: Q235 ~ Q345
Developing high-rise buildings is a global trend.
Demand of structural steel in international construction markets.
Investigation into structural behaviour of high strength S690 steels and their welded sections

- Mechanical properties of S690 steels
- Residual stresses of S690 welded H- and I-sections
- **Stocky columns of welded S690 H-sections**
- Slender columns of welded S690 H-sections
- Steel beams of welded S690 I-sections
- Strength reduction and softening of S690 welded joints
- Effects of welding onto microstructures of S690 welded joints
- Stocky columns of S690 welded H-sections with splices (butt-welded joints)
Stocky columns of S690 steel welded sections

Under compression

Structural behaviour of stocky welded H-sections under different loading and boundary conditions:

- Stocky columns under compression  
  - 12 tests.
- Stocky columns under combined compression and bending  
  - 8 tests.

Plate thickness: 6, 10 and 16 mm

Section C1  
(Class 1)

Section C2  
(Class 3)

Section C3  
(Class 2)

Section C4  
(Class 3)
**Stocky columns of S690 steel welded sections**

*Under compression*

<table>
<thead>
<tr>
<th>Test Series</th>
<th>C1S</th>
<th>C2S</th>
<th>C3S</th>
<th>C4S</th>
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<tbody>
<tr>
<td><strong>Typical failure mode</strong></td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
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<tr>
<td><strong>Quantity</strong></td>
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<td>3</td>
<td>3</td>
<td>3</td>
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<tr>
<td><strong>Member length</strong></td>
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<td>460 mm</td>
<td>610 mm</td>
<td>760 mm</td>
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<tr>
<td><strong>Section classification</strong></td>
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<td>Class 3</td>
<td>Class 2</td>
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</tr>
<tr>
<td><strong>Welding methods</strong></td>
<td>GMAW</td>
<td>GMAW</td>
<td>SAW</td>
<td>SAW</td>
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</table>
Stocky columns of S690 steel welded sections
Under compression

Design values and comparison against test data

<table>
<thead>
<tr>
<th>Specimens</th>
<th>$N_{Rd}$ (kN)</th>
<th>$N_{test}$ (kN)</th>
<th>$\frac{N_{Test}}{N_{Rd}}$</th>
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<tbody>
<tr>
<td>C1S</td>
<td>2344</td>
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<td>1.07</td>
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<td>2932</td>
<td>3006</td>
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<td>C3S</td>
<td>6614</td>
<td>7067</td>
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<td>C4S</td>
<td>8277</td>
<td>8364</td>
<td>1.01</td>
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</table>

Load shortening curves
Investigation into structural behaviour of high strength S690 steels and their welded sections

- Mechanical properties of S690 steels
- Residual stresses of S690 welded H- and I-sections
- Stocky columns of welded S690 H-sections
- **Slender columns of welded S690 H-sections**
- Steel beams of welded S690 I-sections
- Strength reduction and softening in S690 welded joints
- Effects of welding onto microstructures of S690 welded joints
- Stocky columns of S690 welded H-sections with splices (butt-welded joints)
Slender Columns of S690 Welded H-Sections

Under compression

- Slender welded H-sections under compression – 7 tests.
- Slender welded H-sections under combined compression and bending – 8 tests.

Plate thickness: 6, 10 and 16 mm

Section C1 (Class 1)  
Section C2 (Class 3)  
Section C3 (Class 2)  
Section C4 (Class 3)
## Slender Columns of S690 Welded H-Sections
### Under compression

<table>
<thead>
<tr>
<th>Test samples</th>
<th>Specimen length $L_s$ (mm)</th>
<th>Effective length $L_{eff}$ (mm)</th>
<th>$\bar{\lambda}_z$</th>
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</thead>
<tbody>
<tr>
<td>C1PA</td>
<td></td>
<td></td>
<td>1.26</td>
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<tr>
<td>C2PA</td>
<td>1,610</td>
<td>1,990</td>
<td>1.01</td>
</tr>
<tr>
<td>C3PA</td>
<td></td>
<td></td>
<td>0.77</td>
</tr>
<tr>
<td>C4PA</td>
<td></td>
<td></td>
<td>0.62</td>
</tr>
<tr>
<td>C2QA</td>
<td></td>
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<td>1.41</td>
</tr>
<tr>
<td>C3QA</td>
<td>2,410</td>
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<td>1.09</td>
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<tr>
<td>C4QA</td>
<td></td>
<td></td>
<td>0.87</td>
</tr>
</tbody>
</table>

![Diagram of Slender Columns](image)
Slender Columns of S690 Welded H-sections
Under compression

- Material yielding against member buckling
- Reduced effect of residual stresses but similar effect of initial geometrical imperfections
- Confirmatory tests for use of current design rules
Slender Columns of S690 Welded H-sections

Under compression

Comparison with design curves in EN 1993-1

Buckling curve $a_0$

Buckling curve $c$
Slender Columns of S690 Welded H-sections

Under compression

• Four series of 88 numerical models:
  a) major- vs minor-axis buckling
  b) welding procedures with different heat energy input

• Predicted residual stress patterns are incorporated.

• Sections C1 to C8

![Buckling curve applied to slender columns of S460 welded H-sections (EN 1993-1-1)]

**Curve c**
Imperfection factor \( \alpha = 0.49 \)

**Curve b**
Imperfection factor \( \alpha = 0.34 \)

Proposed buckling curve for slender columns of S690 welded H-sections based on numerical data
Slender Columns of S690 Welded H-sections
Under combined compression and bending

Test programme

<table>
<thead>
<tr>
<th>Test</th>
<th>Specimen 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>1,610</td>
<td>1,990</td>
<td>1.29</td>
</tr>
<tr>
<td>C2PB</td>
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<td></td>
<td>1.03</td>
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<tr>
<td>C3PB</td>
<td></td>
<td></td>
<td>0.78</td>
</tr>
<tr>
<td>C4PB</td>
<td></td>
<td></td>
<td>0.62</td>
</tr>
<tr>
<td>C1QB</td>
<td>2,410</td>
<td>2,790</td>
<td>1.80</td>
</tr>
<tr>
<td>C2QB</td>
<td></td>
<td></td>
<td>1.44</td>
</tr>
<tr>
<td>C3QB</td>
<td></td>
<td></td>
<td>1.09</td>
</tr>
<tr>
<td>C4QB</td>
<td></td>
<td></td>
<td>0.87</td>
</tr>
</tbody>
</table>

Effective length $L_{eff}$
Specimen length $L_s$
Slender Columns of S690 Welded H-sections
Under combined compression and bending

- Axial buckling under end moments
- Reduced effect of residual stresses but similar effect of initial geometrical imperfections
- Confirmatory tests for use of current design rules
## Slender Columns of S690 Welded H-sections

### Under combined compression and bending

**Back analysis to EN 1993-1-1**

<table>
<thead>
<tr>
<th>Test</th>
<th>Effective length $L_{eff}$ (mm)</th>
<th>$\bar{\lambda}_z$</th>
<th>Buckling resistance under combined compression and bending (kN)</th>
<th>$\frac{N_{test}}{N_{Rd}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$N_{Rd}$ (Curve $a_0$)</td>
<td>$N_{test}$</td>
</tr>
<tr>
<td>C1PB</td>
<td>1,990</td>
<td>1.29</td>
<td>311</td>
<td>328</td>
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<tr>
<td>C2PB</td>
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<td>1,698</td>
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<td>C4PB</td>
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<td>0.62</td>
<td>2,609</td>
<td>2,660</td>
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<tr>
<td>C1QB</td>
<td>2,790</td>
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<tr>
<td>C2QB</td>
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<td>1.44</td>
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<td>418</td>
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<td>1,341</td>
<td>1,376</td>
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<td>0.87</td>
<td>2,203</td>
<td>2,276</td>
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</table>

e=100 mm

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**Notes:**

- Effective length $L_{eff}$ is the length at which the column is considered slender.
- $\bar{\lambda}_z$ is the slenderness ratio, which is used to calculate the buckling resistance.
- $N_{Rd}$ is the design buckling resistance.
- $N_{test}$ is the test buckling resistance.
- $\frac{N_{test}}{N_{Rd}}$ is the ratio of test to design buckling resistance.
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- Effects of welding onto microstructures of S690 welded joints
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Strength reduction and softening in S690 welded joints

Metallurgical zones at different temperatures

SLB: solid-liquid boundary
CGHAZ: coarse grain heat affected zone
FGHAZ: fine grain heat affected zone
PRHAZ: partially recylized heat affected zone
UMB: unaffected base material
Robotic welding for Q690 steel sections

a) Infrared camera to record temperature history during welding

b) Infrared thermometer to monitor temperature

Electric blanket for pre-heating and post-heating
Robotic welding and monitoring
Strength reduction and softening in S690 welded joints
Pilot tests on strength reduction of welded sections
Strength reduction and softening in S690 welded joints

Pilot tests on strength reduction of welded sections

<table>
<thead>
<tr>
<th>Welding type</th>
<th>Expected Line heat input, q (kJ/mm)</th>
<th>Voltage, U (V)</th>
<th>Current, I (A)</th>
<th>Welding speed, v (mm/s)</th>
<th>Efficiency, η</th>
<th>No. of passes</th>
<th>Actual line heat input, q (kJ/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMAW</td>
<td>1.0</td>
<td>28.0</td>
<td>195</td>
<td>4.8</td>
<td></td>
<td>4</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>25.9</td>
<td>228</td>
<td>3.3</td>
<td>0.85</td>
<td>3</td>
<td>1.52</td>
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<tr>
<td></td>
<td>2.0</td>
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<td>230</td>
<td>2.5</td>
<td></td>
<td>2</td>
<td>2.03</td>
</tr>
<tr>
<td>SAW</td>
<td>5.0</td>
<td>33.0</td>
<td>630</td>
<td>4.0</td>
<td>0.95</td>
<td>1</td>
<td>4.94</td>
</tr>
</tbody>
</table>

(a) four passes, gap = 1 mm → q = 1.0 kJ/mm

(b) three passes, gap = 3 mm → q = 1.5 kJ/mm

(c) two passes, gap = 1 mm → q = 2.0 kJ/mm

(d) one pass, gap = 3 mm → q = 5.0 kJ/mm
Strength reduction and softening in S690 welded joints
Local deformations and necking prior to failure

(a) coupons from base plates
(b) coupons from weld metal

Stress (N/mm²)

1.0 kJ/mm  1.5 kJ/mm  2.0 kJ/mm  5.0 kJ/mm

Strain (%)
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Effects of welding onto microstructures of S690 welded joints

- **Simulation of various HAZs**

  - Different heat input energy: 1.0, 1.5, 2.0 kJ/mm
    - CGHAZ: $T_{\text{max}} = 1320 \, ^\circ\text{C}$
    - FGHAZ: $T_{\text{max}} = 1050 \, ^\circ\text{C}$
    - PRHAZ: $T_{\text{max}} = 800 \, ^\circ\text{C}$

  Sequential material tests to obtain constitutive model
  - Standard monotonic tests

  Uniform microstructures (unique HAZ guaranteed)
Effects of welding onto microstructures of S690 welded joints

- **Simulation of single-heated coupons**

<table>
<thead>
<tr>
<th>Coupons</th>
<th>Heat input energy, q (kJ/mm)</th>
<th>Simulated HAZ</th>
<th>Heating rate, R_{heating} (°C/s)</th>
<th>Max. temperature, T_{max} (°C)</th>
<th>Top time, t_{top} (s)</th>
<th>Cooling time from 800 to 500°C, t_{85} (s)</th>
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</thead>
<tbody>
<tr>
<td>1, 2</td>
<td>1.0</td>
<td>CGHAZ</td>
<td>100</td>
<td>1320</td>
<td>1</td>
<td>5.49</td>
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<tr>
<td>3, 4</td>
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<td>FGHAZ</td>
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<td>1050</td>
<td>1</td>
<td>5.49</td>
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<td>5, 6</td>
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<td>PRHAZ</td>
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<td>800</td>
<td>1</td>
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<td>7, 8</td>
<td>1.5</td>
<td>CGHAZ</td>
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<td>1320</td>
<td>1</td>
<td>12.36</td>
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<tr>
<td>9, 10</td>
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<td>FGHAZ</td>
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<td>1050</td>
<td>1</td>
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<td>11, 12</td>
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<td>13, 14</td>
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<td>CGHAZ</td>
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<td>21.97</td>
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<td>15, 16</td>
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<td>21.97</td>
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<tr>
<td>17, 18</td>
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<td>PRHAZ</td>
<td>100</td>
<td>800</td>
<td>1</td>
<td>21.97</td>
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</tbody>
</table>
Effects of welding onto microstructures of S690 welded joints

- Welding simulator and test set-up

Gleeble 2000 Thermal Simulation Testing Machine
Effects of welding onto microstructures of S690 welded joints

Temperature history of welded sections and microstructures of HAZ

Heat input energy = 1.0 kJ/mm

- **HAZ-A**
- **HAZ-B**
- **HAZ-C**

a) Temperature history at various locations within the welded sections.

b) Observed microstructures of S690 parent plate, weld metal and HAZs
Effects of welding onto microstructures of S690 welded joints

Test programme of thermal mechanical simulation

In order to simulate microstructures of HAZ in S690 steels, a total of 18 funnel-shaped coupons were heat treated according to the measured temperature history.

<table>
<thead>
<tr>
<th>Test coupon</th>
<th>Heat input energy, q (kJ/mm)</th>
<th>Simulated HAZ</th>
<th>Heating rate, $R_{\text{heating}}$ (°C/s)</th>
<th>Max temperature, $T_{\text{max}}$ (°C)</th>
<th>Top time, $t_{\text{top}}$ (s)</th>
<th>Cooling time, $t_{85}$ * (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>1.0</td>
<td>HAZ-A</td>
<td>100</td>
<td>1320</td>
<td>1</td>
<td>5.49</td>
</tr>
<tr>
<td>~ P6</td>
<td></td>
<td>HAZ-B</td>
<td>100</td>
<td>1050</td>
<td>1</td>
<td>5.49</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HAZ-C</td>
<td>100</td>
<td>800</td>
<td>1</td>
<td>5.49</td>
</tr>
<tr>
<td>Q1</td>
<td>1.5</td>
<td>HAZ-A</td>
<td>100</td>
<td>1320</td>
<td>1</td>
<td>12.36</td>
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<tr>
<td>~ Q6</td>
<td></td>
<td>HAZ-B</td>
<td>100</td>
<td>1050</td>
<td>1</td>
<td>12.36</td>
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<tr>
<td></td>
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<td>HAZ-C</td>
<td>100</td>
<td>800</td>
<td>1</td>
<td>12.36</td>
</tr>
<tr>
<td>R1</td>
<td>2.0</td>
<td>HAZ-A</td>
<td>100</td>
<td>1320</td>
<td>1</td>
<td>21.97</td>
</tr>
<tr>
<td>~ R6</td>
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<td>HAZ-B</td>
<td>100</td>
<td>1050</td>
<td>1</td>
<td>21.97</td>
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<tr>
<td></td>
<td></td>
<td>HAZ-C</td>
<td>100</td>
<td>800</td>
<td>1</td>
<td>21.97</td>
</tr>
</tbody>
</table>

Note: * $t_{85}$ denotes a time required for cooling from 800°C to 500°C.
Effects of welding onto microstructures of S690 welded joints

Monotonic tensile tests

2.0 kJ/mm – $T_{\text{max}} = 800 \, ^\circ\text{C}$

2.0 kJ/mm – $T_{\text{max}} = 1050 \, ^\circ\text{C}$

2.0 kJ/mm – $T_{\text{max}} = 1320 \, ^\circ\text{C}$

b) Typical HAZ coupons after thermal mechanical physical simulation

c) Standard tensile test
Effects of welding onto microstructures of S690 welded joints

Typical failure modes of HAZ coupons

- **1.0 kJ/mm**
- **1.5 kJ/mm**
- **2.0 kJ/mm**

![Failed HAZ coupons](image)

- **$T_{\text{max}} = 800^\circ\text{C}$**
- **$T_{\text{max}} = 1050^\circ\text{C}$**
- **$T_{\text{max}} = 1320^\circ\text{C}$**

- **Shear fracture around the circumference**
- **Tensile fracture in the central core**

![Typical cross section after fracture](image)

b) Typical cross section after fracture
Effects of welding onto microstructures of S690 welded joints

Key findings from HAZ coupon tests

i) For test coupons of HAZ near the fusion zone, i.e. HAZ-A, their yield strengths were enhanced by 140%, 129% and 109%, whilst tensile strengths were enhanced by 145%, 132% and 114% with the heat input energy at 1.0, 1.5 and 2.0 kJ/mm respectively.

ii) For test coupons of HAZ in the middle of the welded zone, i.e. HAZ-B, their yield strengths were enhanced by 137%, 133% and 113%, whilst their tensile strengths were enhanced by 148%, 135% and 122% with the heat input energy at 1.0, 1.5 and 2.0 kJ/mm respectively.

iii) For test coupons of HAZ near the parent steel, i.e. HAZ-C, their yield strengths were reduced to 94%, 92% and 93%, whilst their tensile strengths were 107%, 100% and 97% with the heat input energy at 1.0, 1.5 and 2.0 kJ/mm respectively.

iv) Consequently, the weakest location of the welded sections in S690 steels is HAZ-C.
Effects of welding onto microstructures of S690 welded joints

- Through a rigorous welding exercise using a robotic welding system with precise control to heat input energy, temperature history of different locations of HAZ were directly measured for subsequent thermal mechanical physical simulation, and thus, test coupons of HAZ with consistent microstructures were readily obtained.

- S690 steels are sensitive to the heating / cooling cycles during welding. Heat input energy is recommended to be carefully controlled in order to attain their nominal strengths and ductility in the welded sections. Based on the test results, a heat input energy of 1.0 kJ/mm should be adopted in practical welding of S690 steels.

- A heat input energy of 1.0 kJ/mm should be adopted in practical welding of S690 steels when softening in the HAZ is not allowed. However, a heat input energy of 1.5 or even 2.0 kJ/mm may be adopted in practical welding of S690 steel if softening in the HAZ is allowed, and a small reduction ($\approx 3\%$) in the tensile strength of the welded sections is acceptable.
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- Mechanical properties of S690 steels
- Residual stresses of S690 welded H- and I-sections
- Stocky columns of welded S690 H-sections
- Slender columns of welded S690 H-sections
- Steel beams of welded S690 I-sections
- Strength reduction an softening of S690 welded joints after welding
- Effects of welding onto microstructures of S690 welded joints
- Stocky columns of S690 welded H-sections with splices (butt-welded joints)
Stocky columns of S690 welded H-sections with splices

Stocky column tests of butt-welded H-sections

a) Section C1
   Class 1

b) Section C2
   Class 3

c) Section C3
   Class 2

d) Section C4
   Class 3

Tests setup

Transducers (LVDT)

Bearing plate
Actuator

SG2
SG3
SG1
SG4
Stain gauges

butt welding
Stocky columns of S690 welded H-sections with splices

Typical failure modes

Heat input energy = 1.0 kJ/mm during welding
Stocky columns of S690 welded H-sections with splices

Load deformation curves

Axial Compression, \( P \) (kN)

Axial Shortening, \( \Delta \) (mm)

Class 1

Class 2

Class 3

\[ N_{c,Rd} = 8042 \text{ kN} \]

\[ N_{c,Rd} = 6393 \text{ kN} \]

\[ N_{c,Rd} = 3139 \text{ kN} \]

\[ N_{c,Rd} = 2515 \text{ kN} \]
Conclusions

- A number of experimental and numerical investigations into structural behavior of high strength S690 steels and their welded sections were conducted by CNERC.

- In general, structural behavior of high strength S690 welded sections are demonstrated to follow closely to that of welded sections of normal strength S355 steels.

- Modern design rules such as those given in EN 1993-1 are shown to be generally applicable to these S690 welded sections when suitable selected design data and parameters are employed:
  - Stocky columns
  - Slender columns
  - Partially restrained beams
Conclusions

- In order to examine the effects of welding onto strengths of welded joints and sections, both standard tensile tests on coupons of welded joints and compression tests on stocky columns with butt-welded splices have been conducted. It is shown that:
  - While the effects of welding onto yield strengths of cylindrical coupons of welded joints are significant, their effects on compression resistances of stocky columns are rather small.
  - Reduction in resistances of stocky columns is shown to be directly related to the heat input energy employed during welding. For heat input energy smaller than or equal to 2.0 kJ/mm, no reduction to their design resistances is found.

- Consequently, the effects of welding onto structural behavior of S690 welded sections are readily quantified, and this allows structural engineers to design S690 welded joints and sections rationally.