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STRAIGHT EVALUATION OF CARBON & STAINLESS STEEL PLATES WITH STAGGERED BOLTS SUBJECTED TO TENSION FORCES

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Outline:

• Introduction
• Eurocode 3 Provisions
• Experimental investigation
• Analysis of results
• Finite element numerical analysis
• Conclusions
Introduction

Eurocode 3 provisions

Investigation → stainless steel used → certain structural engineering applications like → joints under shear forces → current design criteria → based → deformation limits → re-evaluated → specially due → differences → yield to ultimate deformation & stress ratios
Current design provisions

Failurere modes $\rightarrow$ plate with holes under tension axial forces $\rightarrow$ 2 ultimate limit states: $\rightarrow$ gross area yield & $\rightarrow$ net area tension rupture

Characteristics of stainless-steel

- Rounded stress-strain behaviour
- Substantial strain hardening
- High ductility
- $f_u$ considerably above $f_y$
Eurocode 3

Provisions
\[ N_{pl,Rd} = \frac{A_g \cdot f_y}{\gamma_{M0}} \]

\[ N_{u,Rd} = \frac{k_r \cdot A_n \cdot f_u}{\gamma_{M2}} \]

\[ k_r = (1 + 3r(d_0/u - 0.3)) \]

\[ b_n = b - d_b + \frac{s^2}{4p} \]
Experiments

Following tests on bolt joint staggered plates were performed:

- Tensile coupon tests
- Bolt joint plates in tension tests → determine plastic collapse loads → staggered assemblages
# Summary of tensile coupons

<table>
<thead>
<tr>
<th></th>
<th>Carbon coupons</th>
<th>Stainless coupons</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>f_y (MPa)</td>
<td>f_u (MPa)</td>
<td>f_y (MPa)</td>
<td>f_u (MPa)</td>
</tr>
<tr>
<td>AC 1</td>
<td>388.97</td>
<td>485.97</td>
<td>I 1</td>
<td>352.30</td>
</tr>
<tr>
<td>AC 2</td>
<td>383.77</td>
<td>478.43</td>
<td>I 2</td>
<td>345.70</td>
</tr>
<tr>
<td>AC 3</td>
<td>348.29</td>
<td>450.55</td>
<td>I 3</td>
<td>352.20</td>
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<td>AC 4</td>
<td>404.39</td>
<td>495.91</td>
<td>I 4</td>
<td>347.80</td>
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<td>401.31</td>
<td>488.81</td>
<td>I 5</td>
<td>349.60</td>
</tr>
<tr>
<td>AC 6</td>
<td>394.01</td>
<td>472.43</td>
<td>I 6</td>
<td>356.10</td>
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<tr>
<td>Mean</td>
<td>386.79</td>
<td>478.68</td>
<td>Mean</td>
<td>350.62</td>
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### Standard Deviation

<table>
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<tr>
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<th>Standard Deviation</th>
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<td></td>
<td></td>
<td>20.34</td>
<td>16.02</td>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>Standard Deviation</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.70</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>15.11</td>
</tr>
</tbody>
</table>
Assess the mechanical behaviour & final capacity in determinate systems:

- 4 Carbon cover plate joint staggered bolts tests
- 3 Stainless cover plate joint staggered bolts tests
Continuous bolt joint tests

Assess tension capacity & collapse loads of determinate structures:

Load *versus* displacement - E3 CARBON S50 & E5 STAIN S50
Load *versus* displacement - E4_CARBON_S30 & E7_STAIN_S30
Stainless bolt joint results

Load versus displacement - E9_STAIN_S23
## Experimental Tests

### Comparison → design collapse & test resistance → cover staggered bolt joint tests

<table>
<thead>
<tr>
<th>ID</th>
<th>Experiment Failure Mode</th>
<th>Experiment Ultimate Load (kN)</th>
<th>EC3 Failure Mode</th>
<th>EC3 Ultimate Load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E3_CARB_S50</td>
<td>2H</td>
<td>310.0</td>
<td>3H</td>
<td>298.3</td>
</tr>
<tr>
<td>E4_CARB_S30</td>
<td>2H</td>
<td>296.0</td>
<td>3H</td>
<td>282.5</td>
</tr>
<tr>
<td>E5_INOX_S50</td>
<td>2H</td>
<td>480.0</td>
<td>AB</td>
<td>302.9</td>
</tr>
<tr>
<td>E6_CARB_S30_P10</td>
<td>3H</td>
<td>309.5</td>
<td>3H</td>
<td>282.5</td>
</tr>
<tr>
<td>E7_INOX_S30</td>
<td>2H</td>
<td>459.0</td>
<td>AB</td>
<td>302.9</td>
</tr>
<tr>
<td>E8_CARB_S50_P8</td>
<td>2H</td>
<td>326.0</td>
<td>2H</td>
<td>282.5</td>
</tr>
<tr>
<td>E9_INOX_S23</td>
<td>3H</td>
<td>436.0</td>
<td>AB</td>
<td>302.9</td>
</tr>
</tbody>
</table>

2H: two hole net rupture; 3H: three hole net rupture & AB: gross section yielding
Observations from comparisons with test results:

Influence → load application plate thickness, adopted initially equal to 15mm (E3_CARBS_50 & E4_CARBS_30).

2 other tests were performed, E6_CARBS_30_P10 (load plate thickness equal to 10 mm) & E8_CARBS_50_P8 (load plate thickness equal to 8 mm).

Plate thickness → significantly alters → joint response → ultimate load & associated failure mode.
Experimental Tests

Load *versus* displacement – load plate thickness variation
Additional carbon steel results
## Additional carbon steel results

### Table 1: Second series of experiments geometry.

<table>
<thead>
<tr>
<th>Test</th>
<th>L (mm)</th>
<th>s (mm)</th>
<th>g (mm)</th>
<th>t (mm)</th>
<th>Load (kN)</th>
<th>Displacement (mm)</th>
<th>Test Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC_145_55_30</td>
<td>145</td>
<td>30</td>
<td>55</td>
<td>6</td>
<td>300.15</td>
<td>18.60</td>
<td>2H</td>
</tr>
<tr>
<td>AC_145_55_25</td>
<td>145</td>
<td>30</td>
<td>55</td>
<td>6</td>
<td>314.25</td>
<td>17.61</td>
<td>3H</td>
</tr>
<tr>
<td>AC_107_36_30</td>
<td>107</td>
<td>25</td>
<td>36</td>
<td>6</td>
<td>221.65</td>
<td>16.37</td>
<td>2H</td>
</tr>
<tr>
<td>AC_107_36_25</td>
<td>107</td>
<td>25</td>
<td>36</td>
<td>6</td>
<td>214.00</td>
<td>16.01</td>
<td>3H</td>
</tr>
<tr>
<td>AC_107_0_50</td>
<td>107</td>
<td>50</td>
<td>0</td>
<td>6</td>
<td>260.30</td>
<td>21.26</td>
<td>1H</td>
</tr>
</tbody>
</table>
Additional carbon steel results
Additional carbon steel results

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Additional carbon steel results

2nd test series → confirmed influence → internal plate thickness → plate failure mode → determine → limits → plate net rupture → passing through 2 or 3 holes → bolt horizontal spacing → 25 mm & 30 mm

Clear distinction of behaviour → observed → single bolt row layout & other tests

Test are continuing → s bolt horizontal spacing = 28 mm → further delimit → two failure modes
Numerical method

Basis of method:

- Tension capacity → cover plate joints → developed → Ansys 11 FE package.
- Numerical model → solid elements (SOLID45)
- Contact elements → (CONTA174 & TARGE170)
- Calibration → numerical model made → Kim & Kuwamura experiments → optimum mesh & element sizes → determined

Numerical Analysis

Finite element model & contact elements

UZ restrained region

contact elements

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Summary of comparisons

Comparison → test, design methods & numerical model:

INOX specimen
Summary of comparisons

Von Mises stress distribution (in MPa) → ultimate load in inox specimens:

a) Test – E5_INOX_S50
b) Test – E7_INOX_S30
c) Test – E9_INOX_S23
Summary of comparisons

Comparison → test & numerical model:

a) Strain gauges 2 & 4

b) Strain gauges 3 & 8
### Comparison → tests & numerical methods:

<table>
<thead>
<tr>
<th>Experimental tests</th>
<th>Experimental failure mode</th>
<th>Experimental ultimate load (kN)</th>
<th>Numerical failure mode</th>
<th>Numerical ultimate load (kN)</th>
<th>Difference Numerical x Experimental (%)</th>
<th>Difference Numerical x EC3 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E5-INOX-S50</td>
<td>2F</td>
<td>480.0</td>
<td>2F</td>
<td>389</td>
<td>19.0</td>
<td>28.8</td>
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<tr>
<td>E7-INOX-S30</td>
<td>2F</td>
<td>459.0</td>
<td>2F / 3F</td>
<td>389</td>
<td>15.2</td>
<td>28.8</td>
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<tr>
<td>E9-INOX-S23</td>
<td>3F</td>
<td>436.0</td>
<td>3F</td>
<td>385</td>
<td>11.6</td>
<td>27.5</td>
</tr>
</tbody>
</table>
Conclusions

- Investigation → experimental & numerical programme → structural response → carbon steel & stainless steel plates with staggered bolts under tension
Conclusions

- Initially experimental results → compared to theoretical results according to Eurocode 3 provisions → for carbon steel tests → good agreement → reached between → design equation & experiments → not corroborated in → stainless steel tests → large difference observed, mainly → ultimate load.
Conclusions

• Finite element numerical model developed with → Ansys 11.0 program → considered material & geometrical nonlinearities → Von Mises yield criterion & updated Lagrangian formulation → 28% Differences → Eurocode 3 & numerical models → compared.
Conclusions

- Numerical ultimate loads → less than → experimental counterparts → all investigated specimens → explained → developed numerical models represent → joints → idealized form → without imperfections or residual stresses → another reason → stainless steel stress vs. strain curve adopted in → finite element model → coupons → influenced → rolling direction
Conclusions

- Numerical & experimental assessment → stainless & carbon bolted tensioned members → more complicated → & influenced → several other design parameters → further research → currently being carried out → considering imperfections, residual stresses & coupons rolling directions
Conclusions

- Differences varying → 12% up to 19% → numerical & experimental compared → differences → partly due → natural conservatism present → most design standards → conservatism largely due → lack of experimental evidence → stainless steel structural response → present in literature.
Conclusions

• Authors would like to thank CAPES, CNPq & FAPERJ for the financial support to this research program. Thanks are also due to ACESITA & USIMINAS for donating the stainless & carbon steel plates used in the experiments
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