Research and Development in Design of Steel and Composite Structures

“strength through shape and material use”

Dr Konstantinos Daniel Tsavdaridis  MEng, MSc, DIC, PhD, EUR ING, CEng, MInstCE, FICE
Associate Professor of Structural Engineering
Leader of ‘Materials and Structures’ Theme

k.tsavdaridis@leeds.ac.uk
http://kostasdaniel.blogspot.co.uk/2015/04/research.html
JOSEPH ASPDIN
(1778 - 1855)

Portland Cement, one of mankind's most important manufactured materials, was patented by Joseph Aspdin, a Leeds Bricklayer, on 21 October 1824. Aspdin lived in this yard (then called Slip Inn Yard) and first sold his cement in Angel Inn Yard.
Facilities (new developments)

Neville Centre of Excellence in Concrete and Cement Engineering

Sir William Henry Bragg Centre
Facilities

NEXUS

LETeC and CIM (UKCRIC) – off campus
Who we are

- Institute for Resilient Infrastructure → Materials and Structures group
  - Extending infrastructure life
  - Manufacturing technologies
  - Sensors and instrumentation
  - Digital optimisation design and 3D printing
  - Computational modelling of complex structures

Our research is driven by the need to provide safe, sustainable, durable and resilient infrastructure now and in the future. This includes considering the energy and carbon impact of infrastructure, the means of fabrication and its physical performance when subject to environmental and human stresses.
Design optimisation

WHAT IS SUSTAINABILITY?

DESIGN OPTIMISATION

- Lightweight
- Adaptive
- Performance-Based
- Resilient
- Flexible
In the era of sustainable and resilient buildings, where the concept of redundancy plays a significant role, we should consider optimising every single structural element to the best of its efficiency and as a system.
Challenges in steel structures

- Increase span limits
- Decrease weight/stiffness ratio for large spans
- Reduce slab thickness and vibrations
- Bespoke beam design to accommodate architects needs and services
- Interaction of materials (hybrid elements)
- Cheaper manufacturing and fabrication techniques
- Taller structures
- Controllable structures
- Repairable structures
- Reusable structures
Beams
Perforated Beams

In 2006, the American Society of Civil Engineers publishes a study that identified the cost savings of the castellated beam compared to traditional wide flange steel beams. The research found that when a project required more than 5 beams, and beam length exceeded 18m, the castellated beam is more economical than the standard wide flange beam. (Note that this chart was based on 2006 dollars. Dollar values are higher today.)

In 2015, it is estimated that more than 35% of steel-framed buildings incorporate long spans in excess of 12m. In the late 1990s, cellular beams replaced castellated beams and gained prominence. Cellular beams are now estimated to have increased from 40% to 92% share of the steel beams in the UK market during the last decade according to the New Steel Construction (NSC) magazine.

E.g., When a project requires over a hundred beams that are in excess of 12m, the savings can mount into several hundred thousand dollars.

“Cellular beams have increased from 40% to 92% during the last 10 years in the UK!”
Inspiration

“The art of structure is where to put the holes…”

Robert le Ricolais (1894-1977)

Medal of the French Society of Civil Engineers

"experiments in structure" workshops at Illinois-Urbana, North Carolina, Harvard, Penn and Michigan.
Perforations in the webs of steel beams are widely used nowadays in **building construction** due to their ability to provide *lighter structural members, reduced material costs, in addition to the provision for greater flexibility in structural layouts particularly in the floor-to-ceiling height.*
Advantages

- Service integration
- Long, column free spans
- Flexibility and more usable floor area
- Less foundations
- Faster-easier erection
- Higher load bearing capacity at same beam weight
- Weld access holes
- Up to 10% lower installation cost
- Cheaper than pre-stressed concrete design (span)
Research on Perforated Beams
What is the Research on Perforated Beams?

Critical opening length \((c, l_o)\)

Position of PH is not ideal
Performance-Based Design

- Morphing Technology → ANSA (BETA CAE Systems S.A.)
- Topology Optimisation → HyperMesh/Optistruct (Altair Engineering)
Optimised Beams

- Structural Performance
- Manufacturability
- Cost

CASTELLATED BEAMS ALLOW DUCTS AND PIPING TO PASS THROUGH STRUCTURE
CONVENTIONAL BEAMS REQUIRE DUCTS AND PIPING TO PASS BELOW STRUCTURE INCREASING CEILING SPACE REQUIREMENT

Control opening length and ductility

Steel & Composite Structures – University of Leeds  Dr Konstantinos Daniel TSAVDARIDIS
Connections

YESTERDAY
- Pinned connections
- Rigid connections

TODAY
- Semi-rigid connections with rotational springs
# Northridge 1994 / Kobe 1995 Earthquakes

<table>
<thead>
<tr>
<th>Date</th>
<th>January 17, 1994</th>
</tr>
</thead>
<tbody>
<tr>
<td>Origin time</td>
<td>4:30:56 a.m. PST</td>
</tr>
<tr>
<td>Duration</td>
<td>10–20 seconds</td>
</tr>
<tr>
<td>Magnitude</td>
<td>$6.7 \text{ M}_w$</td>
</tr>
<tr>
<td>Depth</td>
<td>11.4 mi (18.3 km)</td>
</tr>
<tr>
<td>Epicenter</td>
<td>34.213°N 118.537°W</td>
</tr>
<tr>
<td>Type</td>
<td>Blind thrust</td>
</tr>
<tr>
<td>Areas affected</td>
<td>Greater Los Angeles Area, Southern California, United States</td>
</tr>
<tr>
<td>Total damage</td>
<td>$13–$44 billion</td>
</tr>
<tr>
<td>Max. intensity</td>
<td>IX (Violent)</td>
</tr>
<tr>
<td>Peak acceleration</td>
<td>1.82g horizontal</td>
</tr>
<tr>
<td>Casualties</td>
<td>57 killed</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Date</th>
<th>January 17, 1995</th>
</tr>
</thead>
<tbody>
<tr>
<td>Origin time</td>
<td>05:46:53</td>
</tr>
<tr>
<td>Magnitude</td>
<td>$6.9 \text{ M}_w$</td>
</tr>
<tr>
<td>Depth</td>
<td>17.8 km (10.9 mi)</td>
</tr>
<tr>
<td>Epicenter</td>
<td>34.59°N 135.07°E</td>
</tr>
<tr>
<td>Type</td>
<td>Strike-slip</td>
</tr>
<tr>
<td>Areas affected</td>
<td>Japan</td>
</tr>
<tr>
<td>Total damage</td>
<td>$200 billion USD</td>
</tr>
<tr>
<td>Max. intensity</td>
<td>Shindo 7</td>
</tr>
<tr>
<td>Peak acceleration</td>
<td>0.8 g</td>
</tr>
<tr>
<td>Casualties</td>
<td>5,502–6,434 killed</td>
</tr>
<tr>
<td></td>
<td>36,896–43,792 injured</td>
</tr>
<tr>
<td></td>
<td>251,301–310,000 displaced</td>
</tr>
</tbody>
</table>

[1] Northridge Earthquake
[2] Kobe Earthquake
The SAC Steel Project is funded by FEMA to solve the problem of brittle behavior of welded steel frame structures that surfaced in the January 17, 1994 Northridge, California (Los Angeles) Earthquake.

Before Northridge
- Steel buildings considered to be “invulnerable”
- Best earthquake resisting system

After Northridge
- “Pre-qualified” connections withdrawn
- Interim Guidelines, workshops/conferences
- New connections to be validated by testing

After 2000
- Improved prescriptive connections
- FEMA 350: Recommendations

The SAC joint venture is a joint venture of:

- Structural Engineers Association of California (SEAOC)
- Applied Technology Council (ATC)
- California Universities for Research in Earthquake engineering (CUREe)
Connection Failures
Connection Failures
Plastic Hinge Position

Column (Flexural & Axial Yielding)
Story mechanism

Panel Zone (Shear Yielding)
Secondary stress

Beam (Flexural Yielding)
Desirable location

Beam (Face of the column)
High inelastic strain demand lead to brittle failure
Strengthening Techniques - FEMA 350

- Bolted Flange Plate (BFP)
- Bolted Unstiffened End-Plate (BUEEP)
- Stiffened Extended End-Plate (BSEEP)
- CONXTECH CONX and KAISER Bolted Bracket (KBB)
Rehabilitation Methods

**Strengthening of the connection**
The most expensive method in terms of time-consuming, required material, and inspection.

**Weakening - Reduced Beam Section**
Relatively costly. Required to break concrete parts at the location of cutting the flanges.

**Weakening - Reduced Web Section**
The cheapest method. No concrete break is required. First one in 2009!
Welds and heated zones of bottom flange may suffer high inelastic strain demand in case of the plastic hinge formed at the face of the column which can lead to brittle failure.
ANSI/AISC 358-10 and 358s1-11 & EC8
Beam weakening by reducing the cross-sectional area of the beam locally at a certain distance from the connection to shift the stresses away from the column’s face.
## RBS vs. RWS

<table>
<thead>
<tr>
<th></th>
<th>RBS</th>
<th>RWS</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Shear) Capacity</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>LTB</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Composite</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Time and Cost</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Flexibility</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Maintenance</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Services</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

---

### References

- Pachoumis et al., 2009. *Reduced Beam Section Moment Connections, Engineering Structures*
- Tsavdaridis et al., 2014. *Perforated Steel Beam-to-Column Connections, Journal of Earthquake Engineering*
Connections Types

Welded

WUF-B

Extended end plate

Steel & Composite Structures – University of Leeds

Dr Konstantinos Daniel TSAVDARIDIS
Welded Connections with isolated web opening
Test Apparatus

- 4-node Shell elements
- Manual (mapped) meshing
- Mesh convergence
- Eigen buckling employed

Pachoumis et al., 2009
Validation and Parametric Study

SAC protocol, FEMA 350/AISC

FE model vs. Experimental

Three digit number representing parameter $S$; (200mm, 300mm, 400mm)

Number indicating the opening depth ($d_o$); (1: $d_o=0.5h$, 2: $d_o=0.65h$, 3: $d_o=0.8h$)

Letter representing opening's category; (A, B, C)
Hysteretic Behaviours

Novel web opening shapes

Circular web openings

Steel & Composite Structures – University of Leeds
Dr Konstantinos Daniel TSAVDARIDIS
Hysteretic Behaviours

- ~ 50% lower load carrying capacity
- ~ +30% higher ductility capacity
Rotational Capacity

The higher the critical opening length - the higher is the strength degradation.
Vierendeel Mechanism
Effect of WOA on Ductility

(a) Rotational Ductility, $D_r$

(b) Rotational Ductility, $D_r$

(c) Rotational Ductility, $D_r$

- ● A-200
- ■ B-200
- ▲ C-200

- ● A-400
- ■ B-400
- ▲ C-400

Steel & Composite Structures – University of Leeds
Dr Konstantinos Daniel TSAVDARIDIS
### Results

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$M_x$ (kNm)</th>
<th>$M_u$ (kNm)</th>
<th>$\theta_y$ (rad)</th>
<th>$\theta_u$ (rad)</th>
<th>$\delta_B$</th>
<th>$\delta_K$ (kNm/rad)</th>
<th>$\delta_{WOA}$ (mm²)</th>
<th>$\delta_E$ (kNm/rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid</td>
<td>246</td>
<td>278.2</td>
<td>0.0072</td>
<td>0.0348</td>
<td>4.8</td>
<td>39109</td>
<td>-</td>
<td>80.0</td>
</tr>
<tr>
<td>RBS1</td>
<td>170</td>
<td>220</td>
<td>0.0070</td>
<td>0.0350</td>
<td>5.2</td>
<td>25000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>A1-200</td>
<td>188</td>
<td>232.7</td>
<td>0.0063</td>
<td>0.0399</td>
<td>6.5</td>
<td>35662</td>
<td>10387</td>
<td>88.3</td>
</tr>
<tr>
<td>A1-300</td>
<td>194</td>
<td>247.1</td>
<td>0.0066</td>
<td>0.0409</td>
<td>6.2</td>
<td>35709</td>
<td>10387</td>
<td>92.4</td>
</tr>
<tr>
<td>A1-400</td>
<td>238</td>
<td>292.2</td>
<td>0.0070</td>
<td>0.0419</td>
<td>7.0</td>
<td>35889</td>
<td>10387</td>
<td>94.7</td>
</tr>
<tr>
<td>A2-200</td>
<td>142</td>
<td>179.2</td>
<td>0.0059</td>
<td>0.0341</td>
<td>7.3</td>
<td>30844</td>
<td>17671</td>
<td>85.1</td>
</tr>
<tr>
<td>A2-300</td>
<td>145</td>
<td>187.9</td>
<td>0.0061</td>
<td>0.0390</td>
<td>7.0</td>
<td>31293</td>
<td>17671</td>
<td>87.1</td>
</tr>
<tr>
<td>A2-400</td>
<td>145.8</td>
<td>187.2</td>
<td>0.0063</td>
<td>0.0419</td>
<td>6.8</td>
<td>31312</td>
<td>17671</td>
<td>89.0</td>
</tr>
<tr>
<td>A3-200</td>
<td>103</td>
<td>135.6</td>
<td>0.0059</td>
<td>0.0458</td>
<td>7.8</td>
<td>21220</td>
<td>26590</td>
<td>70.4</td>
</tr>
<tr>
<td>A3-300</td>
<td>105.5</td>
<td>140.4</td>
<td>0.0062</td>
<td>0.0458</td>
<td>7.3</td>
<td>21360</td>
<td>26590</td>
<td>72.1</td>
</tr>
<tr>
<td>A3-400</td>
<td>109</td>
<td>146.1</td>
<td>0.0063</td>
<td>0.0459</td>
<td>7.2</td>
<td>21403</td>
<td>26590</td>
<td>73.3</td>
</tr>
<tr>
<td>B1-200</td>
<td>200</td>
<td>235.3</td>
<td>0.0064</td>
<td>0.0398</td>
<td>6.2</td>
<td>36825</td>
<td>7524</td>
<td>88.1</td>
</tr>
<tr>
<td>B1-300</td>
<td>206</td>
<td>254.0</td>
<td>0.0067</td>
<td>0.0399</td>
<td>6.0</td>
<td>36847</td>
<td>7524</td>
<td>90.4</td>
</tr>
<tr>
<td>B1-400</td>
<td>214</td>
<td>265.9</td>
<td>0.0071</td>
<td>0.0403</td>
<td>5.7</td>
<td>36900</td>
<td>7524</td>
<td>93.1</td>
</tr>
<tr>
<td>B2-200</td>
<td>159</td>
<td>197.8</td>
<td>0.0059</td>
<td>0.0416</td>
<td>7.1</td>
<td>33766</td>
<td>12801</td>
<td>87.5</td>
</tr>
<tr>
<td>B2-300</td>
<td>164</td>
<td>208.7</td>
<td>0.0062</td>
<td>0.0414</td>
<td>6.7</td>
<td>33832</td>
<td>12801</td>
<td>88.1</td>
</tr>
<tr>
<td>B2-400</td>
<td>171</td>
<td>220.8</td>
<td>0.0065</td>
<td>0.0412</td>
<td>6.3</td>
<td>33938</td>
<td>12801</td>
<td>89.5</td>
</tr>
<tr>
<td>B3-200</td>
<td>121</td>
<td>155.5</td>
<td>0.0058</td>
<td>0.0438</td>
<td>7.6</td>
<td>25941</td>
<td>19262</td>
<td>77.3</td>
</tr>
<tr>
<td>B3-300</td>
<td>125</td>
<td>163.0</td>
<td>0.0061</td>
<td>0.0437</td>
<td>7.2</td>
<td>26162</td>
<td>19262</td>
<td>78.6</td>
</tr>
<tr>
<td>B3-400</td>
<td>130</td>
<td>171.6</td>
<td>0.0062</td>
<td>0.0437</td>
<td>7.0</td>
<td>26240</td>
<td>19262</td>
<td>80.1</td>
</tr>
<tr>
<td>C1-200</td>
<td>209</td>
<td>245.7</td>
<td>0.0066</td>
<td>0.0383</td>
<td>5.8</td>
<td>37576</td>
<td>4283</td>
<td>85.9</td>
</tr>
<tr>
<td>C1-300</td>
<td>217</td>
<td>262.3</td>
<td>0.0069</td>
<td>0.0381</td>
<td>5.5</td>
<td>37588</td>
<td>4283</td>
<td>87.8</td>
</tr>
<tr>
<td>C1-400</td>
<td>227</td>
<td>275.7</td>
<td>0.0073</td>
<td>0.0362</td>
<td>4.9</td>
<td>38589</td>
<td>4283</td>
<td>88.0</td>
</tr>
<tr>
<td>C2-200</td>
<td>175</td>
<td>215.0</td>
<td>0.0062</td>
<td>0.0403</td>
<td>6.5</td>
<td>35678</td>
<td>7303</td>
<td>87.1</td>
</tr>
<tr>
<td>C2-300</td>
<td>186</td>
<td>228.3</td>
<td>0.0064</td>
<td>0.0400</td>
<td>6.3</td>
<td>35767</td>
<td>7303</td>
<td>88</td>
</tr>
<tr>
<td>C2-400</td>
<td>191.5</td>
<td>243.0</td>
<td>0.0068</td>
<td>0.0397</td>
<td>5.8</td>
<td>35874</td>
<td>7303</td>
<td>89</td>
</tr>
<tr>
<td>C3-200</td>
<td>142</td>
<td>179.8</td>
<td>0.0058</td>
<td>0.0419</td>
<td>7.2</td>
<td>30793</td>
<td>10965</td>
<td>82.5</td>
</tr>
<tr>
<td>C3-300</td>
<td>149.8</td>
<td>189.9</td>
<td>0.0062</td>
<td>0.0415</td>
<td>6.7</td>
<td>30871</td>
<td>10965</td>
<td>83.4</td>
</tr>
<tr>
<td>C3-400</td>
<td>157</td>
<td>201.2</td>
<td>0.0065</td>
<td>0.0412</td>
<td>6.3</td>
<td>30998</td>
<td>10965</td>
<td>84.6</td>
</tr>
</tbody>
</table>
Geometric Parameters

Parameter do
- Bigger
  - Vierendeel
  - Reducing stress from the connection

Parameter S
- Smaller
  - Vierendeel
  - Reducing stress from the connection

Opening Shape
- Large novel B, C or Medium circular A
  - Control Vierendeel
  - Control Plasticity via Shear Hinges

Balance
(Northridge) Welded Unreinforced Flange-Bolted (WUF-B) Connections with isolated web opening
Test Apparatus

<table>
<thead>
<tr>
<th>Member</th>
<th>Component</th>
<th>Yield Strength, $f_y$ [MPa]</th>
<th>Ultimate Strength, $f_u$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam</td>
<td>Flange</td>
<td>281</td>
<td>423</td>
</tr>
<tr>
<td></td>
<td>Web</td>
<td>332</td>
<td>438</td>
</tr>
<tr>
<td>Column</td>
<td>Flange</td>
<td>281</td>
<td>433</td>
</tr>
<tr>
<td></td>
<td>Web</td>
<td>304</td>
<td>450</td>
</tr>
</tbody>
</table>

Kim et al., 2012. Collapse resistance of unreinforced steel moment connections, The Struct. Design of Tall and Special Build., 21(10), 724-735
Validation and Parametric Study

Experimental vs FE Model - Rotation vs M/Mp

SAC protocol, FEMA/AISC

Parameter S:
- (350mm, 520mm, 700mm)

Opening Depth do:
- (1: 0.5h, 2: 0.65h, 3: 0.8h)

Opening Category:
- (A, B & C)
Vierendeel Mechanism

Von Mises stress for **Solid beam**
(at $M_p=468\text{kNm}$)

Equivalent Plastic Strain in top flange

Von Mises stress for **A2-700**
(at $M_p=455\text{kNm}$)

Equivalent Plastic Strain in top flange

Von Mises stress for **B3-700**
(at $M_p=401\text{kNm}$)

Equivalent Plastic Strain in top flange

Web buckling

Flange buckling

Von Mises stress for **B3-350**
(at $M_p=350\text{kNm}$)

Equivalent Plastic Strain in top flange
Rotational Capacity

Centre of rotation for solid and perforated beams.

The **higher** the critical opening length - the **higher** is the strength degradation.
Panel Zone Deformation

S increases

Medium and Large web openings placed near the connection.

Relative panel zone deformation from column centreline

Steel & Composite Structures – University of Leeds

Dr Konstantinos Daniel TSAVDARIDIS
### Results

<table>
<thead>
<tr>
<th>Connection type</th>
<th>Monotonic</th>
<th>Cyclic</th>
<th>Panel Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ultimate moment, Mu [kNm]</td>
<td>Ultimate rotation, $\phi_u$ [rad.]</td>
<td>Ultimate moment, Mu [kNm]</td>
</tr>
<tr>
<td>Solid</td>
<td>468.5</td>
<td>0.1290</td>
<td>391.7</td>
</tr>
<tr>
<td>A1-350</td>
<td>442.7</td>
<td>0.1163</td>
<td>390.4</td>
</tr>
<tr>
<td>A1-520</td>
<td>462.5</td>
<td>0.1262</td>
<td>390.5</td>
</tr>
<tr>
<td>A1-700</td>
<td>467.5</td>
<td>0.1279</td>
<td>390.7</td>
</tr>
<tr>
<td>A2-350</td>
<td>390.0</td>
<td>0.0775</td>
<td>385.5</td>
</tr>
<tr>
<td>A2-520</td>
<td>425.1</td>
<td>0.0943</td>
<td>389.7</td>
</tr>
<tr>
<td>A2-700</td>
<td>454.9</td>
<td>0.1180</td>
<td>389.5</td>
</tr>
<tr>
<td>A3-350</td>
<td>304.0</td>
<td>0.0231</td>
<td>331.7</td>
</tr>
<tr>
<td>A3-520</td>
<td>322.5</td>
<td>0.0293</td>
<td>320.8</td>
</tr>
<tr>
<td>A3-700</td>
<td>339.0</td>
<td>0.0368</td>
<td>335.8</td>
</tr>
<tr>
<td>B1-350</td>
<td>447.2</td>
<td>0.1112</td>
<td>390.6</td>
</tr>
<tr>
<td>B1-520</td>
<td>466.5</td>
<td>0.1277</td>
<td>390.5</td>
</tr>
<tr>
<td>B1-700</td>
<td>467.8</td>
<td>0.1292</td>
<td>390.4</td>
</tr>
<tr>
<td>B2-350</td>
<td>416.4</td>
<td>0.0940</td>
<td>389.2</td>
</tr>
<tr>
<td>B2-520</td>
<td>442.3</td>
<td>0.1082</td>
<td>390.1</td>
</tr>
<tr>
<td>B2-700</td>
<td>466.8</td>
<td>0.1280</td>
<td>390.0</td>
</tr>
<tr>
<td>B3-350</td>
<td>350.4</td>
<td>0.0386</td>
<td>347.4</td>
</tr>
<tr>
<td>B3-520</td>
<td>375.2</td>
<td>0.0542</td>
<td>371.5</td>
</tr>
<tr>
<td>B3-700</td>
<td>401.2</td>
<td>0.0743</td>
<td>384.9</td>
</tr>
<tr>
<td>C1-350</td>
<td>431.7</td>
<td>0.1087</td>
<td>382.0</td>
</tr>
<tr>
<td>C1-520</td>
<td>454.9</td>
<td>0.1234</td>
<td>382.7</td>
</tr>
<tr>
<td>C1-700</td>
<td>458.6</td>
<td>0.1254</td>
<td>389.7</td>
</tr>
<tr>
<td>C2-350</td>
<td>375.7</td>
<td>0.0537</td>
<td>369.5</td>
</tr>
<tr>
<td>C2-520</td>
<td>399.0</td>
<td>0.0710</td>
<td>380.9</td>
</tr>
<tr>
<td>C2-700</td>
<td>429.2</td>
<td>0.0951</td>
<td>384.8</td>
</tr>
<tr>
<td>C3-350</td>
<td>263.7</td>
<td>0.0184</td>
<td>260.8</td>
</tr>
<tr>
<td>C3-520</td>
<td>277.5</td>
<td>0.0220</td>
<td>275.5</td>
</tr>
<tr>
<td>C3-700</td>
<td>298.3</td>
<td>0.0257</td>
<td>295.1</td>
</tr>
</tbody>
</table>

All connections with openings have effectively reduced the shear deformation of the panel zone.
Moment Capacity against WOA

S increases
## Results: Monotonic / Cyclic

<table>
<thead>
<tr>
<th>Connection Type</th>
<th>Ultimate Rotation, $\varphi_u$ [rad.]</th>
<th>Monotonic/Cyclic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cyclic Loading</td>
<td>Monotonic Loading</td>
</tr>
<tr>
<td>Solid</td>
<td>0.04970</td>
<td>0.1290</td>
</tr>
<tr>
<td>A1-350</td>
<td>0.04996</td>
<td>0.1163</td>
</tr>
<tr>
<td>A1-520</td>
<td>0.04996</td>
<td>0.1262</td>
</tr>
<tr>
<td>A1-700</td>
<td>0.05000</td>
<td>0.1279</td>
</tr>
<tr>
<td>A2-350</td>
<td>0.04969</td>
<td>0.0775</td>
</tr>
<tr>
<td>A2-520</td>
<td>0.04996</td>
<td>0.0943</td>
</tr>
<tr>
<td>A2-700</td>
<td>0.04996</td>
<td>0.1180</td>
</tr>
<tr>
<td>A3-350</td>
<td>0.04993</td>
<td>0.0231</td>
</tr>
<tr>
<td>A3-520</td>
<td>0.04996</td>
<td>0.0293</td>
</tr>
<tr>
<td>A3-700</td>
<td>0.04995</td>
<td>0.0368</td>
</tr>
<tr>
<td>B1-350</td>
<td>0.04986</td>
<td>0.1112</td>
</tr>
<tr>
<td>B1-520</td>
<td>0.04996</td>
<td>0.1277</td>
</tr>
<tr>
<td>B1-700</td>
<td>0.04996</td>
<td>0.1282</td>
</tr>
<tr>
<td>B2-350</td>
<td>0.04996</td>
<td>0.0940</td>
</tr>
<tr>
<td>B2-520</td>
<td>0.04991</td>
<td>0.1082</td>
</tr>
<tr>
<td>B2-700</td>
<td>0.04981</td>
<td>0.1280</td>
</tr>
<tr>
<td>B3-350</td>
<td>0.04996</td>
<td>0.0386</td>
</tr>
<tr>
<td>B3-520</td>
<td>0.04977</td>
<td>0.0542</td>
</tr>
<tr>
<td>B3-700</td>
<td>0.04996</td>
<td>0.0743</td>
</tr>
<tr>
<td>C1-350</td>
<td>0.04870</td>
<td>0.1087</td>
</tr>
<tr>
<td>C1-520</td>
<td>0.0493</td>
<td>0.1234</td>
</tr>
<tr>
<td>C1-700</td>
<td>0.0498</td>
<td>0.1254</td>
</tr>
<tr>
<td>C2-350</td>
<td>0.0495</td>
<td>0.0537</td>
</tr>
<tr>
<td>C2-520</td>
<td>0.0497</td>
<td>0.0710</td>
</tr>
<tr>
<td>C2-700</td>
<td>0.0479</td>
<td>0.0951</td>
</tr>
<tr>
<td>C3-350</td>
<td>0.0187</td>
<td>0.0184</td>
</tr>
<tr>
<td>C3-520</td>
<td>0.0198</td>
<td>0.0220</td>
</tr>
<tr>
<td>C3-700</td>
<td>0.0249</td>
<td>0.0257</td>
</tr>
</tbody>
</table>

In most cases, monotonic analyses overestimated the rotational behaviour (average of 1.78, median of 1.95).
Geometric Parameters

Parameter do
- Bigger
  - Vierendeel
    - Reducing stress from the connection

Parameter S
- Smaller
  - Vierendeel
    - Reducing stress from the connection

Opening Shape
- Large novel B or Medium other shape
  - Control Vierendeel
    - Control Plasticity via Shear Hinges
Let’s Baptise it!

RBS → Dog-Bone Connection

RWS → Inverted-Eye Connection
Bolted Connections with isolated web openings and perforated beams
Test Apparatus and Validation Study


Steel & Composite Structures – University of Leeds

Dr Konstantinos Daniel TSAVDARIDIS
FE Modelling

- Solid elements
- Contact elements
- Mapped meshing and manual refinements
- Mesh convergence
- Eigen buckling
Beam Failure Mode & RWS

- RWS $\rightarrow$ Vierendeel (Shear) mechanism
- RWS $\rightarrow$ Web-post Buckling mechanism
- RWS $\rightarrow$ LTB mechanism
Reduced Moment Capacity

Hysteretic Curve of Solid Beam Model

-10% to -15% extra

Hysteretic Curve of RWS 1 Model

Hysteretic Curve of RWS 2 Model

Hysteretic Curve of Fully Perforated Beam

Fully Perforated
Current Experimental Campaign

Steel & Composite Structures – University of Leeds

Dr Konstantinos Daniel TSAVDARIDIS
Current Experimental Campaign

Steel & Composite Structures – University of Leeds

Dr Konstantinos Daniel TSAVDARIDIS
Composite WUF-B Connections with isolated web openings
Test Apparatus

Lee et al., 2016
Validation Study

- Height of the column 3500mm
- Beam length 3597mm
- Column section H428x407x20x35
- Beam section H700x300x12x24
- Stud D19@300, height=120mm
- Wire mesh D6@100x100

Steel & Composite Structures – University of Leeds

Dr Konstantinos Daniel TSAVNDARIDIS
Validation Study

AISC cyclic seismic loading protocol

Hysteretic response

Normalized moment \( (\frac{M}{M_0}) \)

Rotation (rad)

Experimental test

FE model

Applied displacement at beam tip (mm)

Step

Surface tied to reference point

Applied displacement
Validation Study

Rupture of the bottom flange
Parametric Study

Representing the percentage of the edge distance to the \( h \).
For instance \( 150S \) means \( S=150\% h \)
Indicating the percentage of the opening depth to the \( h \).
For instance \( 75d \) means \( d_0=75\% h \)
Letter representing the connection type (\( R = \text{Bare}, P = \text{Composite connection} \)).
Failure Modes

- **P-NA-NA Flange rupture**
- **P-50d-150S Flange rupture**
- **P-50d-50S Flange buckling**
- **P-67d-125S Vierendeel mechanism**
- **P-75d-150S Vierendeel mechanism**
## Effect of Composite Action

<table>
<thead>
<tr>
<th>Web opening</th>
<th>0.5h</th>
<th>0.67h</th>
<th>0.75h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composite contribution % in positive direction</td>
<td>25%</td>
<td>43%</td>
<td>65%</td>
</tr>
<tr>
<td>Composite contribution % in negative direction</td>
<td>3%</td>
<td>16%</td>
<td>31%</td>
</tr>
</tbody>
</table>
Frame Analysis
(Incremental Dynamic Analysis - IDA)
Analysis Methodology

- Soft storey
- RBS/RWS systems
- FEA

- Weak beam – Strong Column
- Spring elements

Steel & Composite Structures – University of Leeds
Dr Konstantinos Daniel TSAVDARIDIS
Connection Properties

Monotonic Model

Hysteretic Model

Push-Over Curves

UNIVERSITY OF LEEDS

Steel & Composite Structures – University of Leeds

Dr Konstantinos Daniel TSAVDARIDIS
## Ground Motion Records

<table>
<thead>
<tr>
<th>EQ Index</th>
<th>Mag</th>
<th>Year</th>
<th>Earthquake Name</th>
<th>Fault Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.5</td>
<td>1979</td>
<td>Imperial Valley</td>
<td>Strike-slip</td>
</tr>
<tr>
<td>2</td>
<td>6.5</td>
<td>1979</td>
<td>Imperial Valley</td>
<td>Strike-slip</td>
</tr>
<tr>
<td>3</td>
<td>7.5</td>
<td>1999</td>
<td>Kocaeli, Turkey</td>
<td>Strike-slip</td>
</tr>
<tr>
<td>4</td>
<td>7.3</td>
<td>1992</td>
<td>Landers</td>
<td>Strike-slip</td>
</tr>
<tr>
<td>5</td>
<td>6.9</td>
<td>1989</td>
<td>Loma Prieta</td>
<td>Strike-slip</td>
</tr>
<tr>
<td>6</td>
<td>6.9</td>
<td>1995</td>
<td>Kobe, Japan</td>
<td>Strike-slip</td>
</tr>
<tr>
<td>7</td>
<td>6.9</td>
<td>1989</td>
<td>Loma Prieta</td>
<td>Strike-slip</td>
</tr>
<tr>
<td>8</td>
<td>7</td>
<td>1992</td>
<td>Cape Mendocino</td>
<td>Thrust</td>
</tr>
<tr>
<td>9</td>
<td>6.9</td>
<td>1989</td>
<td>Loma Prieta</td>
<td>Strike-slip</td>
</tr>
<tr>
<td>10</td>
<td>6.9</td>
<td>1989</td>
<td>Loma Prieta</td>
<td>Strike-slip</td>
</tr>
<tr>
<td>11</td>
<td>6.9</td>
<td>1995</td>
<td>Kobe, Japan</td>
<td>Strike-slip</td>
</tr>
<tr>
<td>12</td>
<td>6.5</td>
<td>1979</td>
<td>Imperial Valley</td>
<td>Strike-slip</td>
</tr>
<tr>
<td>13</td>
<td>6.5</td>
<td>1976</td>
<td>Friuli, Italy</td>
<td>Thrust (part blind)</td>
</tr>
<tr>
<td>14</td>
<td>6.7</td>
<td>1994</td>
<td>Northridge</td>
<td>Blind thrust</td>
</tr>
<tr>
<td>15</td>
<td>7.1</td>
<td>1999</td>
<td>Duzce Turkey</td>
<td>Strike-slip</td>
</tr>
<tr>
<td>16</td>
<td>7.3</td>
<td>1992</td>
<td>Landers</td>
<td>Strike-slip</td>
</tr>
<tr>
<td>17</td>
<td>6.7</td>
<td>1994</td>
<td>Northridge</td>
<td>Blind thrust</td>
</tr>
<tr>
<td>18</td>
<td>7.5</td>
<td>1999</td>
<td>Kocaeli, Turkey</td>
<td>Strike-slip</td>
</tr>
<tr>
<td>19</td>
<td>6.5</td>
<td>1979</td>
<td>Imperial Valley</td>
<td>Strike-slip</td>
</tr>
<tr>
<td>20</td>
<td>6.5</td>
<td>1976</td>
<td>Friuli, Italy</td>
<td>Thrust (part blind)</td>
</tr>
</tbody>
</table>
IDA Curves

4-story 8-story 16-story
(Geometric) Median of IDA Curves
Fragility Curves

Probability of exceeding the limit state of IO for three considered buildings with two different connection types (i.e., the RBS and RWS connections)
Design Recommendations for non-composite RWS connections
Rotational Moment Capacity of RWS/WUF-B Connections

4. Yielding of fin plate in rotation
5. Vierendeel bending at reduced web section in rotation

Shear and moment interaction at reduced web section
Design Method for WUF-B Connections

1. Calculate the moment capacity of reduced web section (Section 7.1) [2]
   
   \[ M_{bl} = N_{bl} \frac{d}{2} + M_{col} + M_{web} \]

   OK

2. Calculate the shear in web opening due to applied load [1]
   
   \[ V_{col} = \frac{M_{col}}{d} + \frac{M_{web}}{L} \]

   OK

3. Calculate the required shear capacity of WUF-B connection [1]
   
   \[ V_{req} = \frac{2V_{bl}}{d} \]

   OK

4. Estimate the number of bolts required for shear and design the shear tab [19]

   OK

5. Check the edge distance and bolt spacing [19]

   OK

6. Check the shear capacity of column web shear panel zone (EC3, Part 1-3)**

   OK

7. Design the column web horizontal stiffeners

   OK

8. Check the rotational capacity of columns web shear panel zone (Chen and Douglas, 2004)**

   \[ \theta_{col} < 0.06 \]

   OK

9. Check any not section fractures of shear tab (i.e. Mode 1 and Mode 2) and beam web [10]

   OK

10. Calculate the rotational capacity due to yielding (Section 7.2) and bolt bearing in the shear tab [19] [10]

    \[ k = \frac{d}{L} \] and \[ i = \frac{M_{col}}{L} + 40 \]

    OK

11. Calculate the additional beam deflection due to web openings [EC2:1995, pp.71-72]**

    \[ w_{web,add} = k \left( \frac{d}{2} \right)^2 \left( 1 - \frac{1}{d} \right) \times v_0 \text{ for } d \leq 0.11 \]

    OK

12. Calculate the rotational capacity of reduced web section [EC2:1995, pp.71-73]**

    \[ \theta_{web,add} = \theta_0 \left( \frac{d}{2} \right)^2 \]

    OK

13. Calculate the entire rotational capacity of WUF-WFR-B connection by summing up the rotational capacities of column web panel, shear tab yielding, bolt bearing and reduced beam

    \[ \theta_{total} = \theta_{col} + \theta_{web,add} + \theta_{bl} + \theta_{bolt} + \theta_{web} \]

OK
Design Method for WUF-B Connections

Calculate the moment capacity of reduced web section (Section 7.1) [1]

\[ M_{pl} = N_{bt,Rd} \times z + M_{pl,tt} + M_{pl,bt} \]

OK

Calculate the shear at web opening due to applied load [1]

\[ V_p = \frac{M_{pl} + M_{pl} + \frac{PL'}{2} + \frac{WL'^2}{2}}{L'} \]
The moment capacity of the reduced web section is calculated by:

\[ M_{pl} = N_{bt,Rd} \times z + M_{t1} + M_{b1} \]

The tensile resistance of top or bottom tee-section are calculated by:

\[ N_{bt,Rd} = \frac{A_{bt}f_y}{\gamma_m0} \]

The lever arm \((z)\) is equal to:

\[ z = h_b - \bar{y}_{tee} \times 2 \]

The area of the top or bottom tee-section is equal to:

\[ A_{bt} = b_{fb}t_{fb} + \left(\frac{h_b - d_0}{2} - t_{fb}\right) \times t_{wb} \]
Design Method for WUF-B Connections

Check the rotational capacity of column web shear panel zone [Charney and Downs, 2004]*

\[ \theta_{p,k} < 0.3 \theta_b \]

OK

Check any net section fractures of shear tab (i.e. Mode 1 and Mode 2) and beam web [30]

OK

Calculate the rotational capacity due to yielding (Section 7.2) and bolt bearing in the shear tab [29][30]

\[ k = \frac{EI}{L} = \frac{M}{\theta_{bolt\ bearing}} \quad and \quad I = \sum \frac{bd^3}{12} + Ay^2 \]
Design Method for WUF-B Connections

Calculate the additional beam deflection due to web openings [SCI P355, pp.71-73]*

\[ w_{b,add} = k_0 \left( \frac{l_0}{L} \right) \left( \frac{h_0}{h} \right) \left( 1 - \frac{x}{L} \right) \times w_b \quad \text{for } x \leq 0.5L \]

OK

Calculate the rotational capacity of reduced web section [SCI P355, pp.71-73]*

\[ w_{b,add} = \theta_b \left( \frac{x}{2} \right) \]

OK

Calculate the entire rotational capacity of RWS/WUF-B connection by summing up the rotational capacities of column web panel, shear tab yielding, bolt bearing and reduced beam

(i.e. \( \theta_{RWS/WUF-B} = \theta_{p,k} + \theta_{shear\ tab\ yielding} + \theta_{bolt\ bearing} + \theta_b \))
Standardisation

SCI P-100 (1994) \(\rightarrow\) SCI P-355 (2011) \(\rightarrow\) Eurocodes

EC3 Task SC3.T4 / Sub-task 9: Development of Advanced Design Rules for Extended Girder Applications (Girders with Openings)

\&

EC8 WG2/TC13 (Earthquake Engineering: Strengthening of Existing Structures)
Slabs
Slabs Design Impact

10 Story Building

- Column Contribution
- Slab Contribution

SMQ Gross (kg/m^2)

Column Spacing (m)

[Diagram showing the relationship between SMQ Gross and Column Spacing for a 10 Story Building.]
Slabs Design Impact
Slabs Design Impact
Development of Flooring Systems

Steel & Composite Structures

University of Leeds

Dr Konstantinos Daniel TSAVDARIDIS

Composite Slim-Floor Beam (CoSFB) System

Farringdon Road, London

Concrete infill (with or without steel reinforcement)

0.5h to 0.75h

Concrete slab (prefabricated)

Steel beam

Concrete dowels

Milliners Wharf, Manchester

Steel stiffener
Improves the shear capacity at holes close to support

Concrete infill
(without steel reinforcement)

Steel un-perforated (solid)section
State-of-the-art

CoSFB – Composite Slim-Floor Beam

Composite floor system with standing beam

Slim-floor beam (SFB) system – non composite

Composite Slim-Floor Beam (CoSFB) System

Steel beam

Concrete slab (prefabricated)

Concrete dowels

2 existing systems → 1 Innovative system

Major benefits without adding to the complexity of the fabrication or compromising of the cost

COUPE TYPE surCOFRADAL PAC 260 PAC
Sustainable Materials Matrix

[The Structural Engineer, Feb 2018]
The ultra-light and ultra-shallow flooring system consists of two main structural components, which are lightweight concrete floor and lightweight steel beams.

The concrete floor, which is in the form of T-ribbed slab sections, has been constructed using reinforced lightweight foamed concrete.

The lightweight steel edge beams encapsulate the floor slab in the middle and provide clean and straight finish edges.

This flooring system will be fully prefabricated in the shop.
Proposed Formulae for LCA

- **Production Stage:**
  \[
  \begin{align*}
  EE_{-P} &= \sum_{i=1}^{n} (W_i \times EE_{(i)-LCI}) \\
  EC_{-P} &= \sum_{i=1}^{n} (W_i \times EC_{(i)-LCI})
  \end{align*}
  \] (1)

- **Transportation Stage:**
  \[
  \begin{align*}
  EE_{-T} &= \sum_{i=1}^{n} (W_i \times D_i \times EE_{(i)-LCI(\text{TR})}) \\
  EC_{-T} &= \sum_{i=1}^{n} (W_i \times D_i \times EC_{(i)-LCI(\text{TR})})
  \end{align*}
  \] (2)

- **End of life Stage:**

  **Steel recycling according to substitution method (Hammond et al., 2008)**
  \[
  \begin{align*}
  EE_{-ST-EOL} &= \sum_{i=1}^{n} (W_i \times EE_{(i)-LCI(\text{EOL})}) + \sum_{i=1}^{n} (W_i \times D_i \times EE_{(i)-LCI(\text{TR})}) \tag{5 & 6}
  \end{align*}
  \]

  **Concrete demolition (Hammond et al., 2008)**
  \[
  \begin{align*}
  EE_{-CON-EOL} &= \sum_{i=1}^{n} (W_i \times EE_{(i)-LCI(\text{EOL})}) + \sum_{i=1}^{n} (W_i \times D_i \times EE_{(i)-LCI(\text{TR})}) \tag{7 & 8}
  \end{align*}
  \]
# Life Cycle Inventory (LCI)

## Embodied carbon and embodied energy coefficients for the production of materials (Hammond et al., 2008)

<table>
<thead>
<tr>
<th>Material</th>
<th>Embodied Energy Coefficient (MJ/kg)</th>
<th>Embodied Carbon Coefficient (kgCO$_2$e/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>5.5</td>
<td>0.93</td>
</tr>
<tr>
<td>Sand</td>
<td>0.081</td>
<td>0.0048</td>
</tr>
<tr>
<td>Gravel</td>
<td>0.083</td>
<td>0.0052</td>
</tr>
<tr>
<td>Water</td>
<td>0.01</td>
<td>0.001</td>
</tr>
<tr>
<td>Fly ash</td>
<td>0.1</td>
<td>0.008</td>
</tr>
<tr>
<td>Silica fume</td>
<td>0.1</td>
<td>0.014</td>
</tr>
<tr>
<td>Super-plasticizer</td>
<td>9.0</td>
<td>0.25</td>
</tr>
<tr>
<td>Reinforcing steel bar</td>
<td>17.4</td>
<td>1.31</td>
</tr>
<tr>
<td>Metal Deck</td>
<td>22.6</td>
<td>1.54</td>
</tr>
<tr>
<td>Steel Section</td>
<td>21.50</td>
<td>1.42</td>
</tr>
<tr>
<td>Rock wool Insulation</td>
<td>16.8</td>
<td>1.12</td>
</tr>
<tr>
<td>Expanded Polystyrene</td>
<td>88.6</td>
<td>3.29</td>
</tr>
</tbody>
</table>

## Embodied carbon and embodied energy coefficients for the end of life of materials (Hammond et al., 2008)

<table>
<thead>
<tr>
<th>Material</th>
<th>Embodied Energy Coefficient (MJ/kg)</th>
<th>Embodied Carbon Coefficient (kgCO$_2$e/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel recycling</td>
<td>13.1</td>
<td>0.75</td>
</tr>
<tr>
<td>Reinforcing steel bar recycling</td>
<td>11</td>
<td>0.74</td>
</tr>
<tr>
<td>Concrete demolition</td>
<td>0.007</td>
<td>0.00054</td>
</tr>
<tr>
<td>Rock wool Insulation</td>
<td>N.D.A</td>
<td>N.D.A</td>
</tr>
<tr>
<td>Expanded Polystyrene</td>
<td>N.D.A</td>
<td>N.D.A</td>
</tr>
</tbody>
</table>

## Embodied carbon and embodied energy coefficients for the transportation of materials (Hammond et al., 2008)

<table>
<thead>
<tr>
<th>Transportation</th>
<th>Embodied Energy Coefficient (MJ/tkm)</th>
<th>Embodied Carbon Coefficient (kgCO$_2$e/tkm)</th>
<th>Distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle</td>
<td>2.4</td>
<td>0.15</td>
<td>100</td>
</tr>
</tbody>
</table>
## LCA Results

### Embodied Carbon and Embodied Energy Comparison of flooring systems

<table>
<thead>
<tr>
<th>Stage</th>
<th>Embodied Energy (GJ)</th>
<th>Embodied Carbon (tonne CO$_2$e)</th>
<th>Embodied Energy (GJ)</th>
<th>Embodied Carbon (tonne CO$_2$e)</th>
<th>% Reduction in Embodied Energy</th>
<th>% Reduction in Embodied Carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>CoSFB with Cofradal 260mm flooring system</td>
<td>Proposed System</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production</td>
<td>106.25</td>
<td>8.69</td>
<td>90.19</td>
<td>8.67</td>
<td>15</td>
<td>0.23</td>
</tr>
<tr>
<td>Transport</td>
<td>5.24</td>
<td>0.32</td>
<td>3.01</td>
<td>0.19</td>
<td>42</td>
<td>40</td>
</tr>
<tr>
<td>End of Life</td>
<td>46.63</td>
<td>3.10</td>
<td>36.54</td>
<td>2.12</td>
<td>21</td>
<td>31</td>
</tr>
</tbody>
</table>
Weight and Size Comparison of the Flooring Systems

Flooring System Types

- New Flooring System
- USFB with MD
- USFB with pcu
- CoSFB with MD
- CoSFB with pcu
- COSFB with Cofradal
Life Efficiency Comparison

Lower weight and larger prefabricated width unit size than other prefabricated/precast units which enhancing the lift efficiency by about 60%!
Structural Topology Optimisation & 3D Printing
Structural Topology Optimisation (STO)

“Achieving the most with the least…”
White Magnolia Plaza building in Shanghai demonstrates how topology optimisation can be used to inspire the structural engineer. The form of the tower was envisaged, by the architect, as being complexly curved. The project engineers, used topology optimisation to visualise the distribution of forces within the exterior envelope of the building.

Arata Isozaki envisaged a design that mimicked the Sidra tree for the structural support of a canopy to shelter the convention centre in Doha, Qatar. The form of the canopy structure was found using topology optimisation, specifically the BESO technique that mimics actual process by which trees grow.
Global and Local STO Studies

Optimisation of exoskeleton structures

Optimised perforated beams without (top) and with (bottom) symmetric constraints active
STO & Perforated Beams

Fig. 5. Extracting geometry from element density results of topology optimisation using EDFMesh: (a) element density plot, (b) geometrically defined surfaces.

Fig. 6. Beam models compared: (a) topology optimised beam web design, (b) cellular beam design.

Stress Analysis and Design of Perforated Beams

Steel & Composite Structures – University of Leeds

Dr Konstantinos Daniel TSAVDARIDIS
Aluminium Members

Non-structural members

(Randolph & Kissel, 2002)

Structural members

(Mazzolani, 2008)
RULE: Stiffer $\rightarrow$ Deeper $\rightarrow$ Increased inertia $\rightarrow$ More slender $\rightarrow$ Susceptible to buckling.

Aluminium + Low Modulus of Elasticity $\rightarrow$ Large Deflections and Local Instabilities

Optimum Material Distribution
Element Optimisation – Global Approach
Element Optimisation – Global Approach
2D Optimisation - Beams

Varying aspect ratios

Varying support conditions
2D Optimisation - Columns
Post-processing Beams (SOM)

Sectional Optimisation Method via X-rays

Overlaid results

Final interpretations
Post-processing Columns (SOM)

Sectional Optimisation Method via X-rays

Overlaid results

Final interpretations
Bi-axial with Bending
Two of the optimised beam cross-sections developed have been compared against a selection of three conventional and two additional novel sections. Due to the large mid-span deflections seen in the first set of models, the conventional sections marginally out-performing the optimised profiles. At the ultimate load, the conventional sections were unable to resist the maximum applied load of 2 MPa, however they show significant deflections. Novel cross-section F is quite significant, showing both the highest failure load and the lowest deflections.

Results - Beams.

All beams analysed have been subject to a uniformly distributed pressure to the top face. The critical buckling loads and their corresponding deflections were extracted for all cross-section models (shown in Table 4). The per-

<table>
<thead>
<tr>
<th>Section</th>
<th>Pressure Load (MPa)</th>
<th>Ultimate pressure [N/mm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.25</td>
<td>0.75</td>
</tr>
<tr>
<td>B</td>
<td>0.50</td>
<td>1.50</td>
</tr>
<tr>
<td>C</td>
<td>0.75</td>
<td>1.75</td>
</tr>
<tr>
<td>D</td>
<td>1.00</td>
<td>1.69</td>
</tr>
<tr>
<td>E</td>
<td>1.25</td>
<td>1.82</td>
</tr>
<tr>
<td>F</td>
<td>1.50</td>
<td>1.63</td>
</tr>
<tr>
<td>G</td>
<td>1.75</td>
<td>1.89</td>
</tr>
</tbody>
</table>

Table 4.

The results show a much clearer comparison when looking at the Load-deformation curves for 1 m pinned beams. The failure loads and corresponding deflections for each section are also presented in the Load-deformation curves in Fig. 11. The per-

Fig. 9. Load-deformation curves for 1 m pinned beams.
Columns

A clear separation between Sections 2 and 4, and the rest of the specimens is observed with Sections 2 and 4 indicating the worst performance. Despite the same load limit, Section 2 shows a worse response due to the largest magnitude of the lateral deflection.

Fig. 10. Column cross-sections employed in finite element analysis

Table 5. Analysis results for 2 m pinned columns

<table>
<thead>
<tr>
<th>Section</th>
<th>Ultimate load [N/mm²]</th>
<th>Deflection at mid-span [mm]</th>
<th>Max lateral deflection [mm]</th>
<th>Vertical deflection [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>154.09</td>
<td>0.67</td>
<td>0.72</td>
<td>4.43</td>
</tr>
<tr>
<td>2</td>
<td>144.94</td>
<td>1.66</td>
<td>1.80</td>
<td>4.29</td>
</tr>
<tr>
<td>3</td>
<td>151.01</td>
<td>0.53</td>
<td>0.58</td>
<td>4.38</td>
</tr>
<tr>
<td>4</td>
<td>144.94</td>
<td>1.43</td>
<td>1.58</td>
<td>4.27</td>
</tr>
<tr>
<td>5</td>
<td>155.44</td>
<td>0.59</td>
<td>0.64</td>
<td>4.47</td>
</tr>
<tr>
<td>6</td>
<td>151.01</td>
<td>0.72</td>
<td>0.78</td>
<td>4.40</td>
</tr>
</tbody>
</table>

Fig. 11. Load-deflection curves for 2 m pinned columns
Cross-Section Classification

- Outer Web
- Inner Web
- Central Pocket
- Outer Pocket
Morphogenesis

Section 1

Section 2

Section 3
Cross-section classification via EC9

Using properties of EN AC-43300 T64

Assumed straight parts

<table>
<thead>
<tr>
<th>Part</th>
<th>b (mm)</th>
<th>t (mm)</th>
<th>(\eta)</th>
<th>(\beta = \eta \frac{b}{t})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer web</td>
<td>25</td>
<td>4.1</td>
<td>0.7</td>
<td>4.3</td>
</tr>
<tr>
<td>Inner Web</td>
<td>30</td>
<td>5.5</td>
<td>0.7</td>
<td>3.8</td>
</tr>
<tr>
<td>Inner Flange</td>
<td>25</td>
<td>5.5</td>
<td>1</td>
<td>4.5</td>
</tr>
<tr>
<td>Outer Flange</td>
<td>12</td>
<td>2</td>
<td>1</td>
<td>6</td>
</tr>
</tbody>
</table>

6.1.4.4 Classification of cross-section parts

(1) The classification of parts of cross-sections is linked to the values of the slenderness parameter \(\beta\) as follows:

<table>
<thead>
<tr>
<th>Parts in beams</th>
<th>Parts in struts</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\beta &lt; \beta_1) : class 1</td>
<td>(\beta &lt; \beta_1) : class 1 or 2</td>
</tr>
<tr>
<td>(\beta_1 &lt; \beta &lt; \beta_2) : class 2</td>
<td>(\beta_1 &lt; \beta &lt; \beta_2) : class 3</td>
</tr>
<tr>
<td>(\beta_2 &lt; \beta &lt; \beta_3) : class 3</td>
<td>(\beta_2 &lt; \beta &lt; \beta_3) : class 4</td>
</tr>
<tr>
<td>(\beta_3 &lt; \beta) : class 4</td>
<td>(\beta_3 &lt; \beta) : class 4</td>
</tr>
</tbody>
</table>

**Internal Parts**

\(\beta_1 = 11 \times 1.41 = 15.51\)
\(\beta_2 = 16 \times 1.41 = 22.56\)
\(\beta_3 = 22 \times 1.41 = 31.02\)

**Outstands Parts**

\(\beta_1 = 3 \times 1.41 = 4.23\)
\(\beta_2 = 4.5 \times 1.41 = 6.345\)
\(\beta_3 = 6 \times 1.41 = 8.46\)

Table 6.2 - Slenderness parameters \(\beta_1/e\), \(\beta_2/e\) and \(\beta_3/e\)

<table>
<thead>
<tr>
<th>Material classification according to Table 3.2</th>
<th>Internal part</th>
<th>Outstand part</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class A, without welds</td>
<td>11</td>
<td>16</td>
</tr>
<tr>
<td>Class A, with welds</td>
<td>9</td>
<td>13</td>
</tr>
<tr>
<td>Class B, with welds</td>
<td>13</td>
<td>16.5</td>
</tr>
<tr>
<td>Class B, without welds</td>
<td>10</td>
<td>13.5</td>
</tr>
</tbody>
</table>

\(e = \sqrt{250/f_y}, f_y \text{ in N/mm}^2\)

Steel & Composite Structures – University of Leeds  Dr Konstantinos Daniel TSAVDARIDIS
The cost in influencing criteria as being very similar to those for rolled sections, however, specific costs may vary dramatically for bespoke die designs. In general, costs for hollow sections have been reported as being up to five times more expensive than solid or open profiles. Cheaper manufacture methods are available, such as shell casting rather than die casting, however, larger tolerances for imperfection may be expected.

On the other hand, recently, designers are pushing technologies to realise the full potential of 3D printing and overcome material quality, monitoring, and size limitations (Fig. 1—the biggest 3D printing for metallic members). This method of fabrication is a new process of making a 3D solid object directly from a digital model. It is an additive process where successive layers of material are laid down in a controlled way to achieve the desired (optimised) shape, replacing traditional machining techniques, dealing with material removal through cutting and splitting, sawing/drilling/rounding off, and CNC turning/milling. There are three 3D printing techniques such as:

(i) Extrusion type—Fuse Deposition Modelling (FDM) used for thermoplastics: PLA, ABS, nylon, alumide (a mix of nylon and aluminium);
(ii) Granular type—Selective Laser Sintering (SLS) used for thermoplastics, metal powders, and ceramic powders;
(iii) Liquid type—Multi Jet Modelling (MJM) used for acrylic plastic.

The cost of the 3D printing is comparable to the one of the extrusion process, but cannot be precisely evaluated since massive production is required while the industry is still experimenting. For this reason, this paper contributes to the effort demonstrating the need for larger scale 3D printers as well as focus on high production of structural elements through comprehensive comparisons between typical structural aluminium cross-section members that can be produced by extrusion process, and fully optimised structural aluminium members that can only be manufactured by 3D printers. Table 1 below, is the first attempt to compare the pros and cons of the two aforementioned manufacturing processes and draw the overall picture of the current state-of-the-art.

<table>
<thead>
<tr>
<th></th>
<th>Extrusion</th>
<th>3D Printing</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advantages</strong></td>
<td>• Length (long span, &lt;30 m)</td>
<td>• No supply chain is required</td>
</tr>
<tr>
<td></td>
<td>• Quick production (20–70 m/min)</td>
<td>• Achieve any optimised complex shape (decrease weight to stiffness ratio)</td>
</tr>
<tr>
<td></td>
<td>• Similar cost to cold forming</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• No trimming or milling is required</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Very few imperfections and residual stresses</td>
<td></td>
</tr>
<tr>
<td><strong>Disadvantages</strong></td>
<td>• Constant cross-section along the length of the member</td>
<td>• Size limitations (so far)</td>
</tr>
<tr>
<td></td>
<td>• Need pre-production of the die</td>
<td>• Brittle performance in certain occasions</td>
</tr>
<tr>
<td></td>
<td>• Can be five times more expensive than solid or open profile</td>
<td>• Cracking control is required</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Roughness control is required (direction dependent)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Time expensive process</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Certain models only suitable for limited temperature range</td>
</tr>
</tbody>
</table>
Sky is the Limit…

Aluminium is presently extracted exclusively from bauxite, however, it also exists in other minerals within the earth's crust to make it the third most abundant element. Combined with the high recyclability rate of the end product, this ensures that there is adequate material for continued sustainable construction for an almost indefinite period.

Once combined with its alloying elements, the new material is classed as being a casting or wrought alloy, dependent on whether it is to be melted before casting. As a result, most hot rolled and extruded applications utilise wrought alloys. The heat treatment process is then followed by quenching and ageing, during which the majority of hardening occurs.

The current state-of-the-art manufacturing process for aluminium member is the extrusion process Fig. 1 (a)-left. The extrusion process creates cross-sectional shapes by forcing hot metal, in the form of a billet, through an opening called a die (e.g., porthole and bridge dies). The corresponding cross-section then matches the profile of the die, regardless of its complexity. This enables designers to create specific sections to meet requirements, simply by producing the appropriate die; such as the complex shapes shown in Fig. 1 (a)-right. This method provides a relatively high quality result with national specifications allowing a deviation of approximately 5% from the nominal thickness.

Sciaky EBAM 300
Company: Sciaky Inc
Process: Metal Filament 3D Printing
Build Size: 5791 x 1219 x 1219 mm
Today is the Future...
Research Team (PhD students & Post-Docs)

MR. JALAL KIANI
MSc, PhD Candidate
Uni. of Memphis, USA

MISS INAS MAHMOOD
MSc, PhD Candidate
University of Leeds

MR. MOHAMED SHAHEEN
MSc in Structures
Uni. of Cairo, Egypt
Tokyo Institute of Techn., Japan

MR. ALEX WHITWORTH
MEng, PhD Candidate,
WSP Engineer
University of Leeds

DR. C. MARAVEAS
Research Fellow
University of Liege

DR. G. CAI
Research Fellow
University of Luxembourg

MR. ARNAB CHAKRABORTY
MEng, CEng, MStructE, PhD Candidate,
Network Rail Senior Engineer
University of Leeds

DR. M. ABAMBRES
Research Fellow
University of Lisbon

Steel & Composite Structures – University of Leeds

Dr Konstantinos Daniel TSAVDAIRIDIS
Research Team (MEng & MSc students)

Mr T. Papadopoulos
MEng in Civil Eng.
University of Leeds

Mr Chris Pilbin
MEng in Civil Eng.
University of Leeds

Mr Kavoos Bushehri
MSc in Structures
University of Leeds

Mr Daniel Naughton
MEng in Civil Eng.
University of Leeds

Mr Chris Winship
MSc in Structures
University of Leeds

Mr Chun Lau
MEng in Civil Eng.
University of Leeds

Mr Grekavicious
MEng in Civil Eng.
University of Leeds

Mr Jack Huges
MEng in Civil Eng.
University of Leeds

Mr J. Kingman
MEng in Civil Eng.
University of Leeds

Mr M. Abdelwahab
MEng in Civil Eng.
University of Leeds

Mr Alikem Adugu
MEng in Civil Eng.
University of Leeds

Mr Adam Pollard
MEng in Arch. Eng.
University of Leeds

Steel & Composite Structures – University of Leeds

Dr Konstantinos Daniel TSAVNDARIDIS
Aknowledgments
Thank you!

http://kostasdaniel.blogspot.co.uk