Materials and Structures Group
School of Civil Engineering
Faculty of Engineering

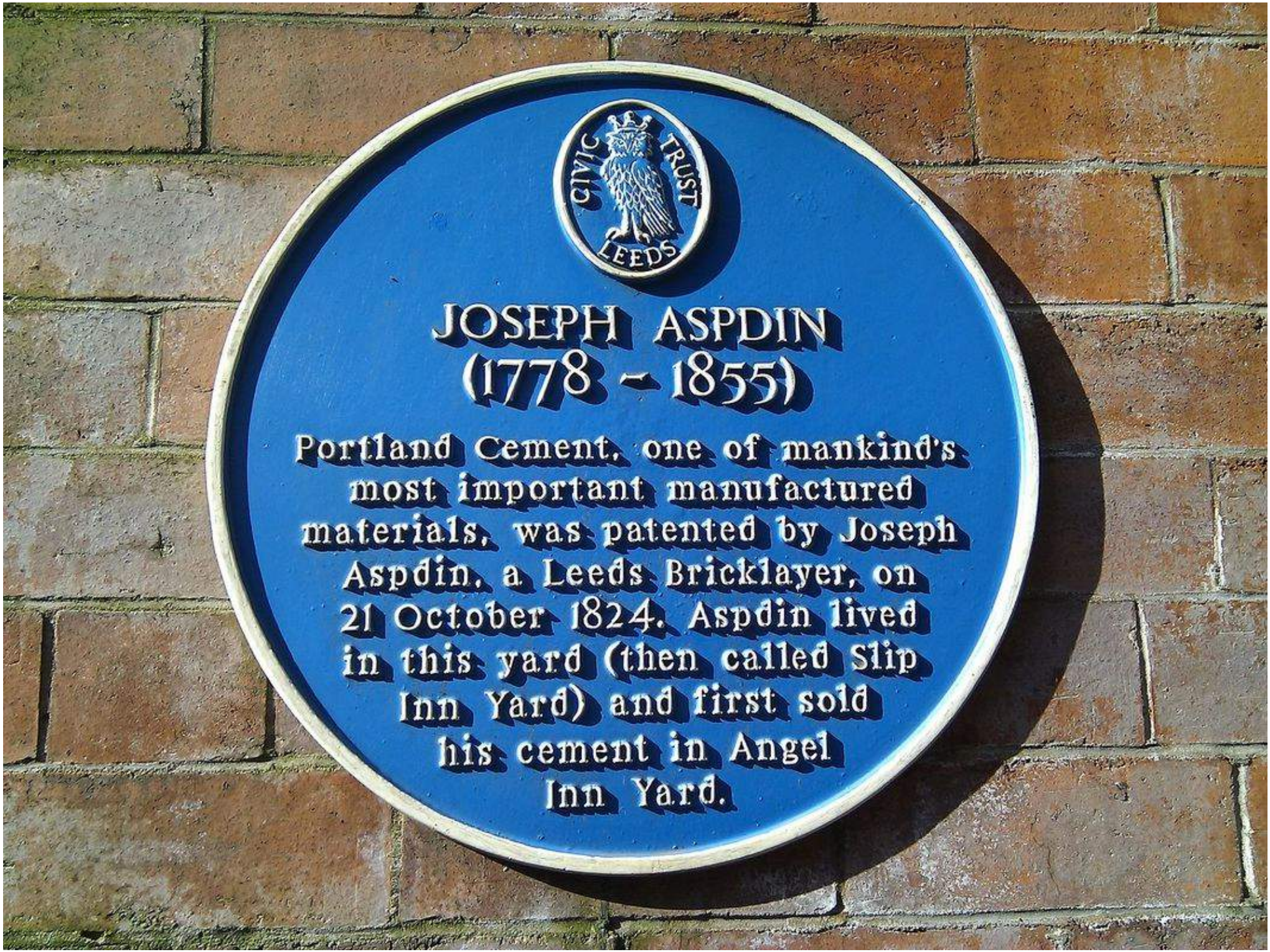
UNIVERSITY OF LEEDS

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, MIStructE, 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


CIVIC TRUST
LEEDS
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)

UNIVERSITY OF LEEDS

Neville Centre of Excellence in Concrete and Cement Engineering

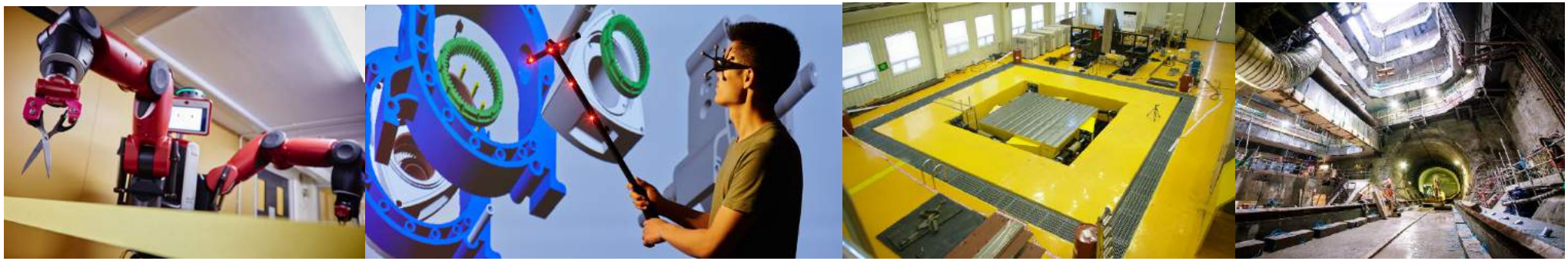
Sir William Henry Bragg Centre

Facilities

UNIVERSITY OF LEEDS

NEXUS

LETeC and CIM (UKCRIC) – off campus



Who we are

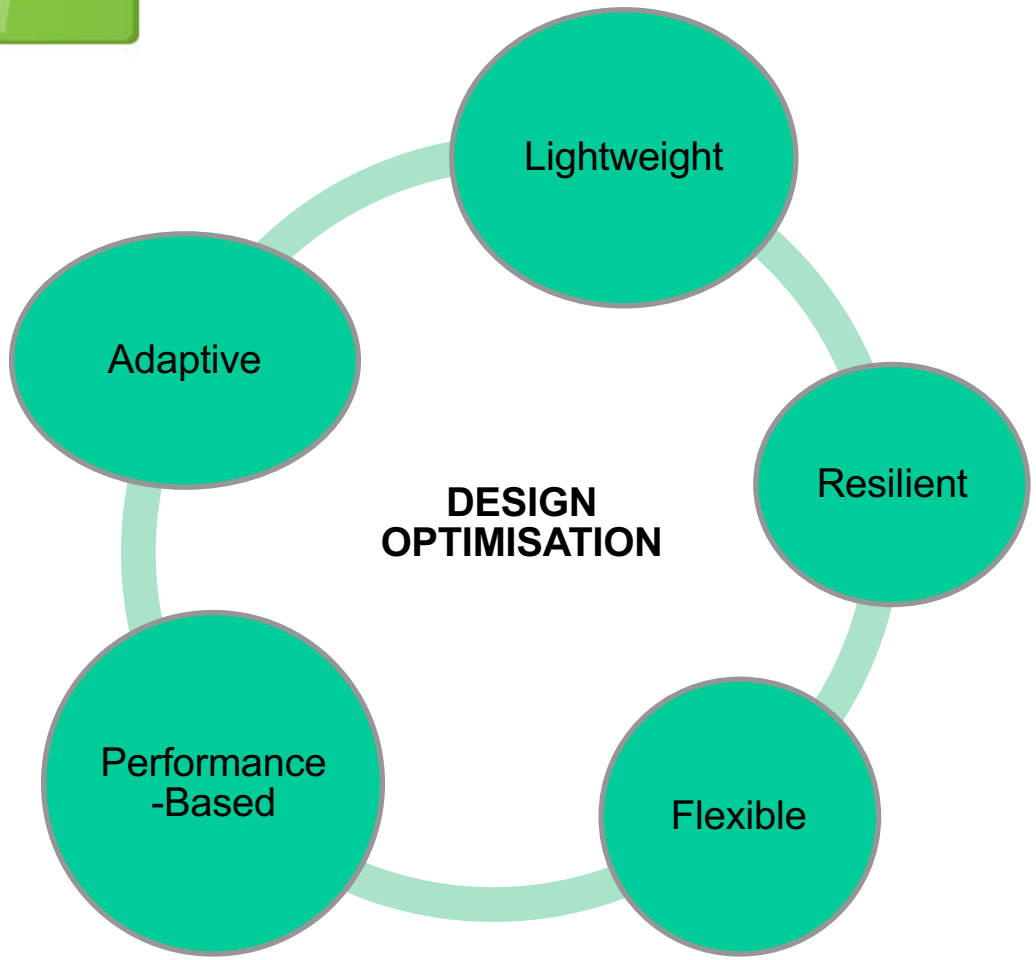
UNIVERSITY OF LEEDS

- 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

UNIVERSITY OF LEEDS



Multi-dimensional design

UNIVERSITY OF LEEDS

In Civil Engineering innate conservatism and stereotypes driven from standardisation…

"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

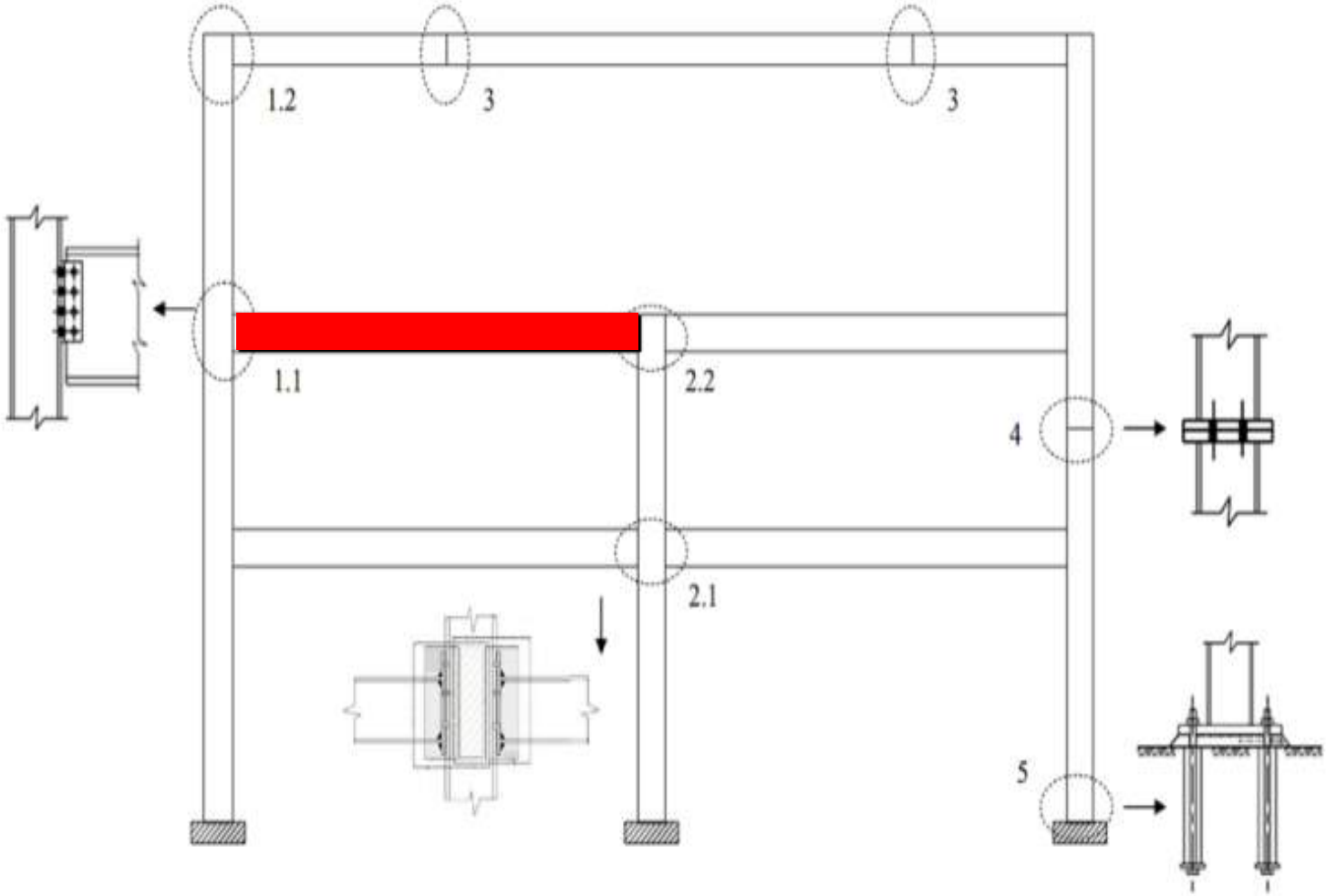
UNIVERSITY OF LEEDS

- 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
- **T**aller structures
- **C**ontrollable structures
- **R**epairable structures
- **R**eusable structures

Contents

UNIVERSITY OF LEEDS

Beams

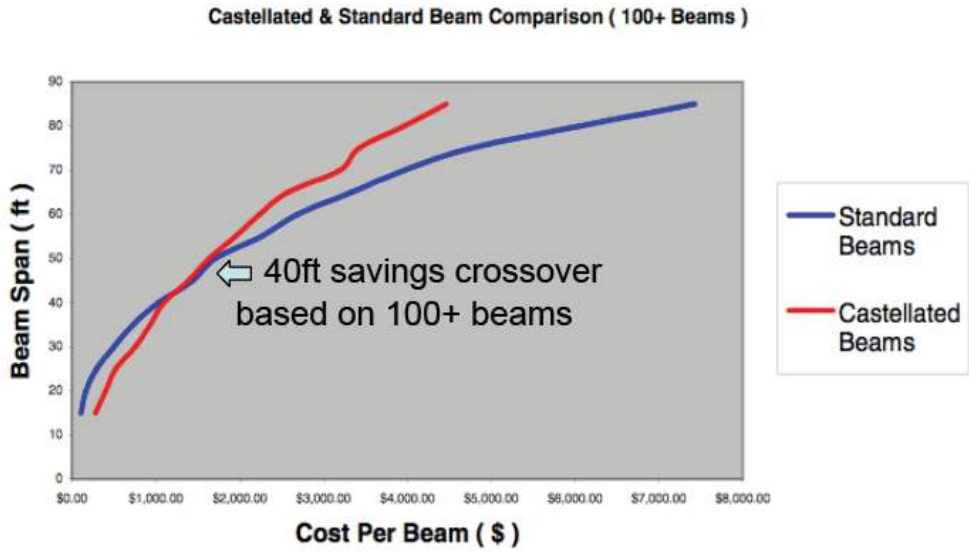


Perforated Beams

UNIVERSITY OF LEEDS

*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.*



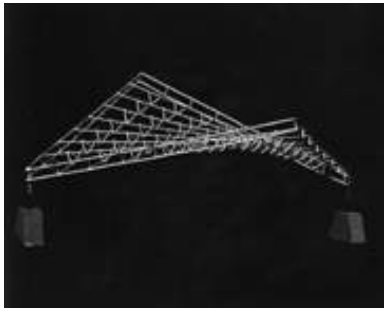
E.g., When a project requires over a hundred beams that are in excess of 12m, the savings can mount into several hundred thousand dollars.

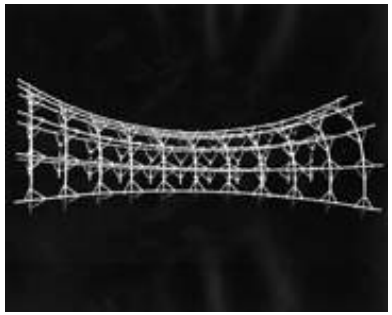
"Cellular beams have increased from 40% to 92% during the last 10 years in the UK!"

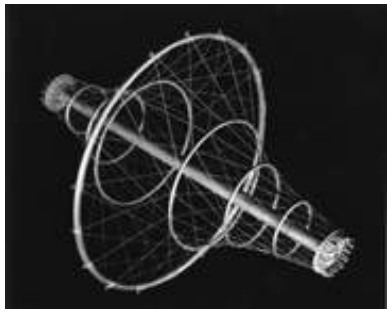
Inspiration

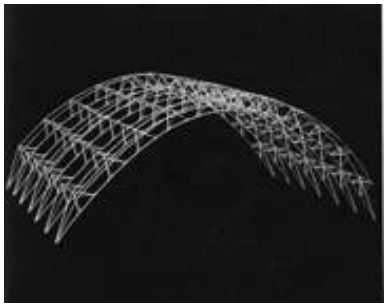
UNIVERSITY OF LEEDS

"The art of structure is where to put the holes…"









Robert le Ricolais (1894-1977)

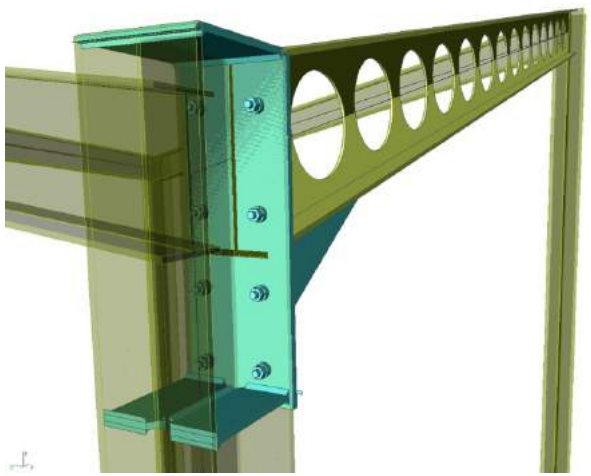
Medal of the French Society of Civil Engineers

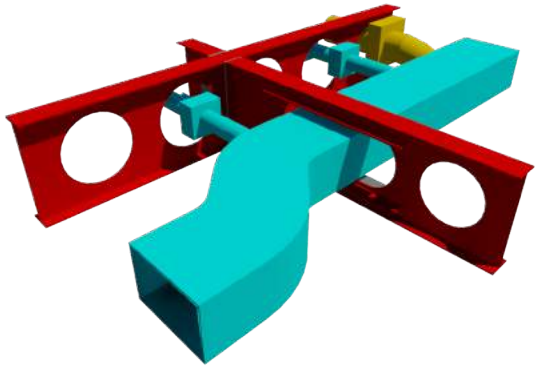
"experiments in structure" workshops at Illinois-Urbana, North Carolina, Harvard, Penn and Michigan.

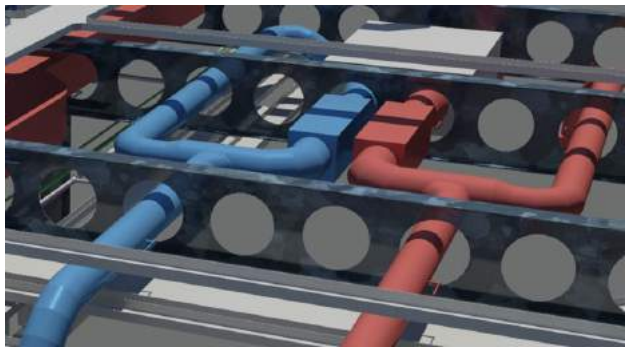
Weight over stiffness optimisation

UNIVERSITY OF LEEDS

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.*



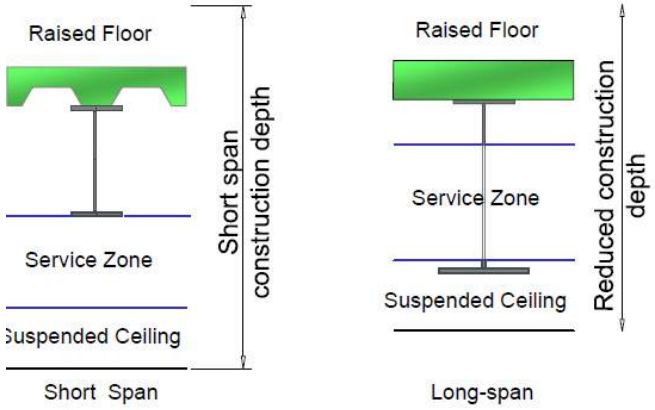




Advantages

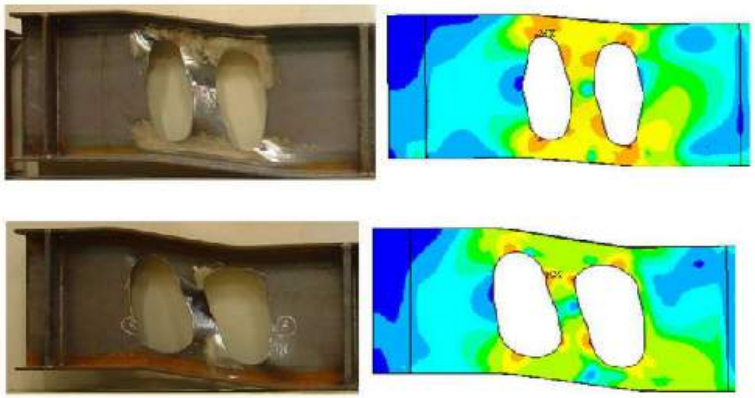
UNIVERSITY OF LEEDS

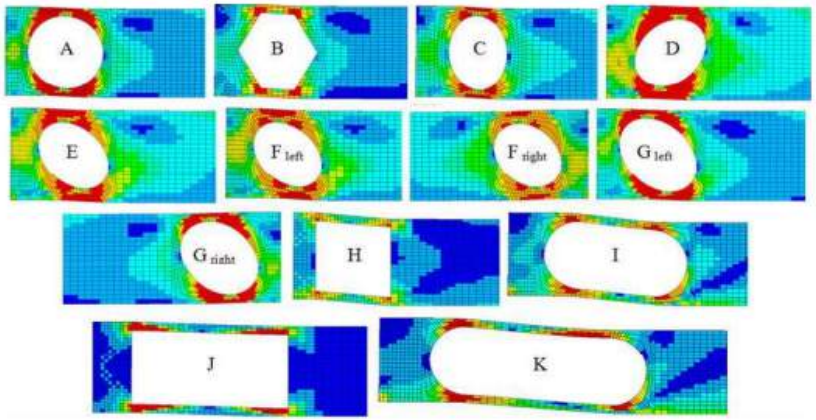
- ✓ Service integration
- ✓ Long, column free spans
- ✓ Flexibility and more usable floor area
- ✓ Less foundations
- ✓ Faster-easier erection
- ✓ Higher load bearing capacity at same beam weight
- ✓ Weld access holes
- ✓ Up to 10% lower installation cost
- ✓ Cheaper than pre-stressed concrete design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

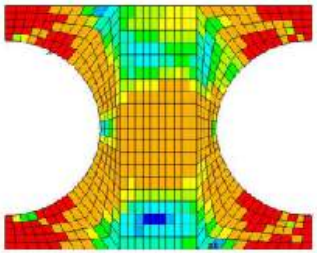


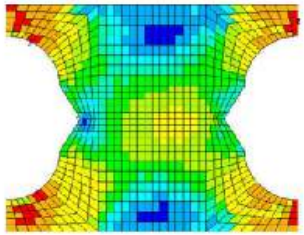
Research on Perforated Beams (2006~)

UNIVERSITY OF LEEDS



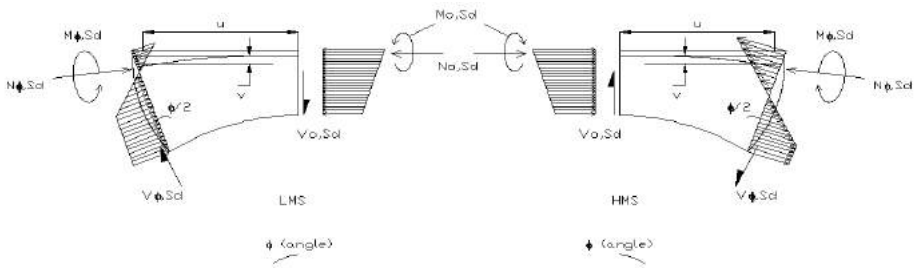


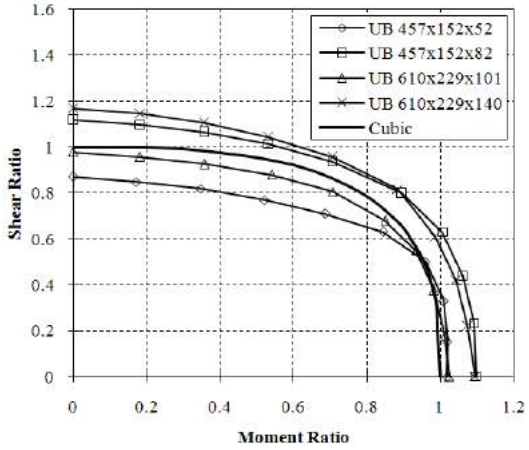


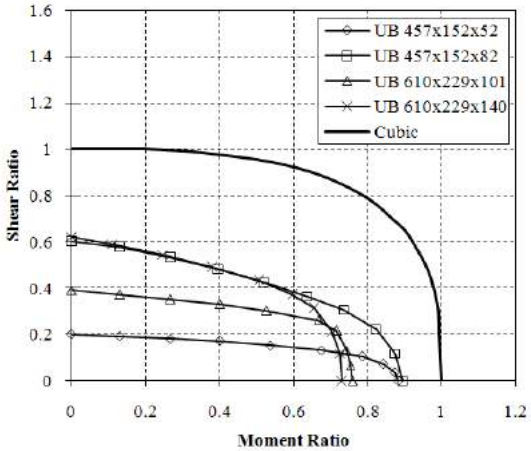


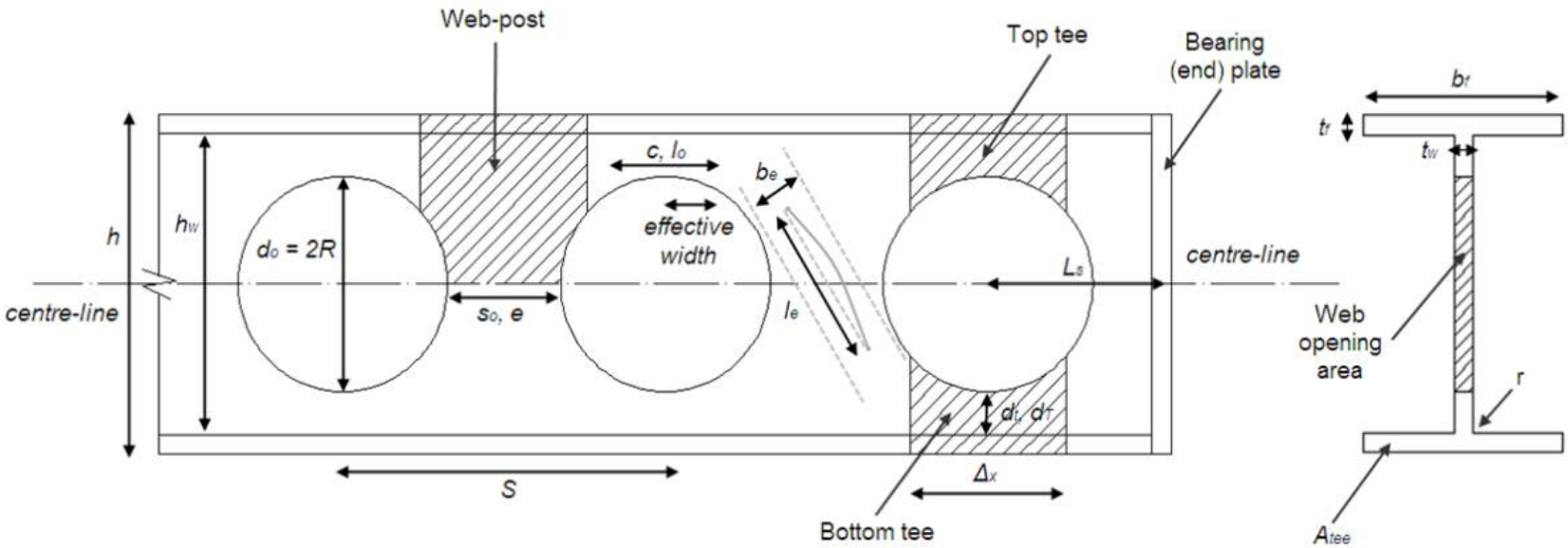
Research on Perforated Beams

UNIVERSITY OF LEEDS



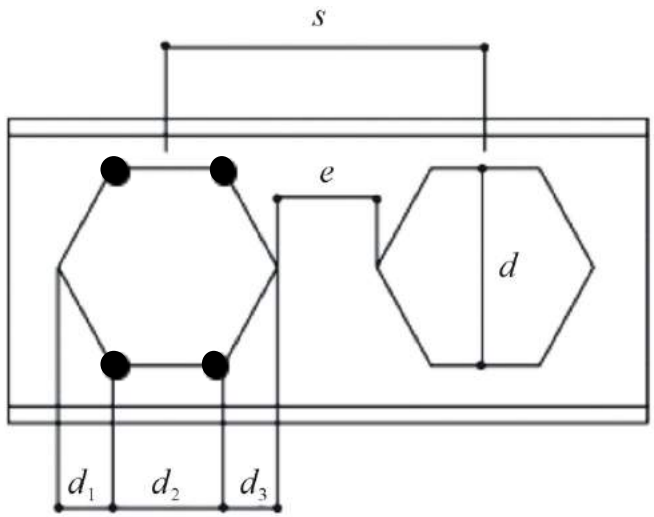






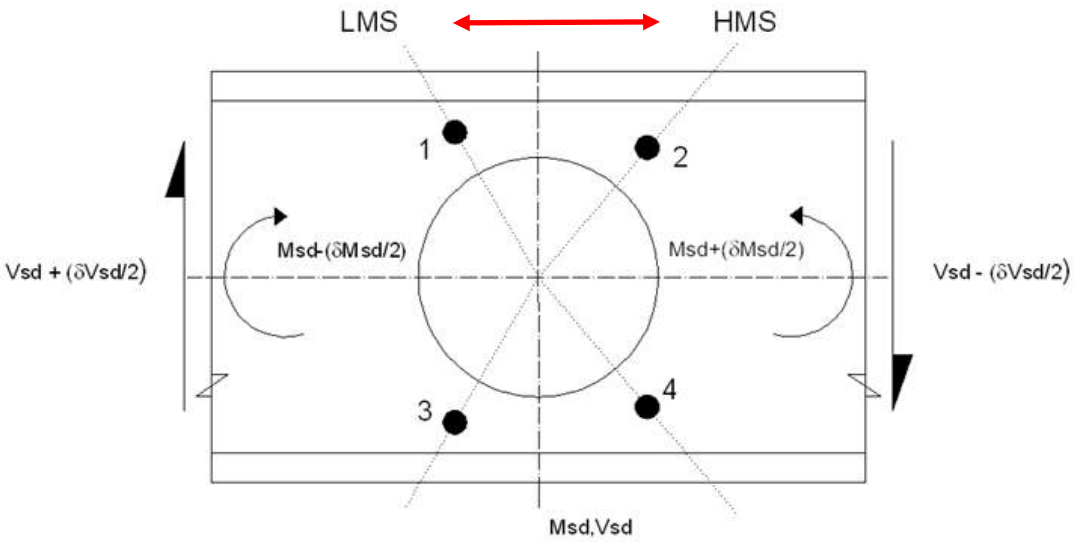
What is the Research on Perforated Beams?

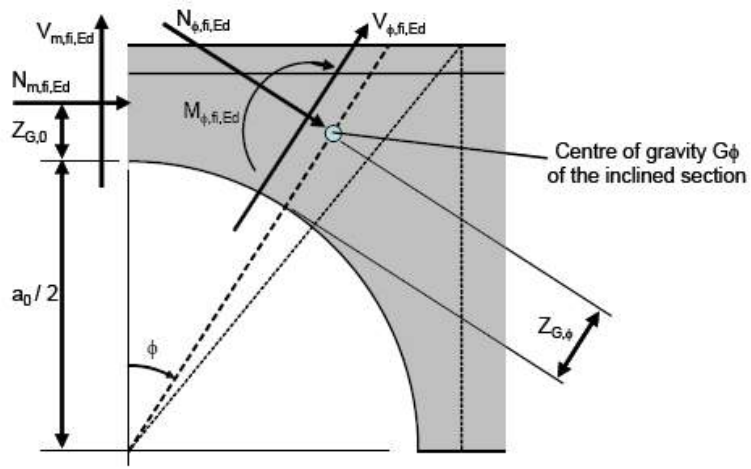
UNIVERSITY OF LEEDS



position of PH is not ideal

Critical opening length (c, l_o)

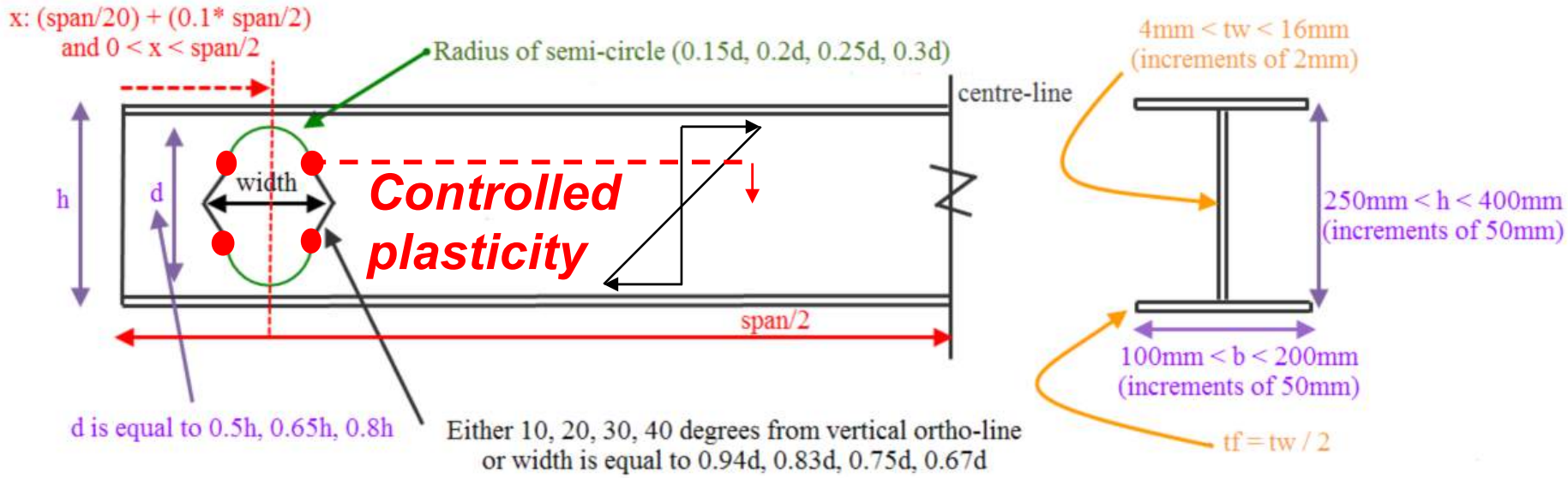




Performance-Based Design

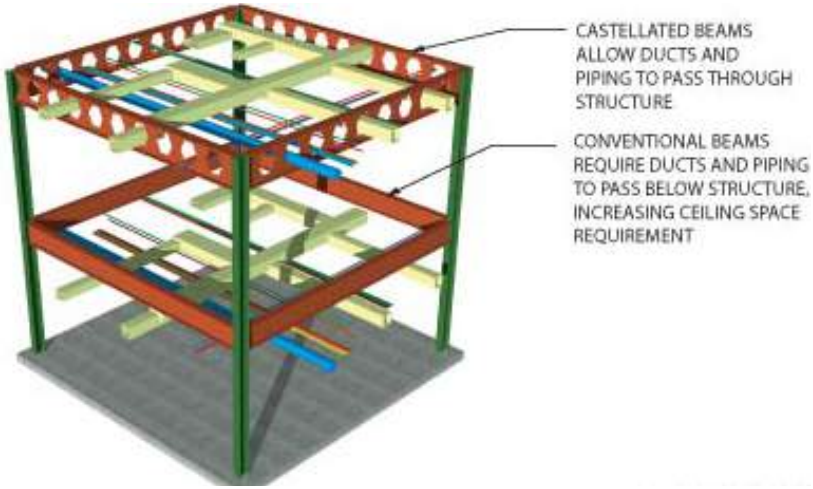
UNIVERSITY OF LEEDS

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

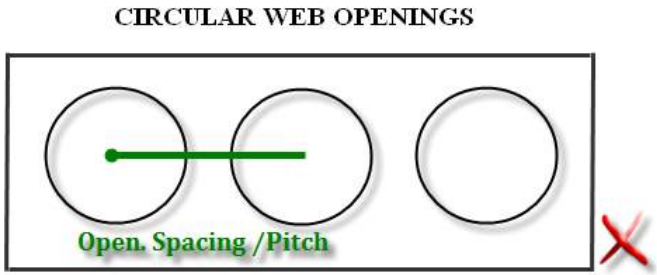


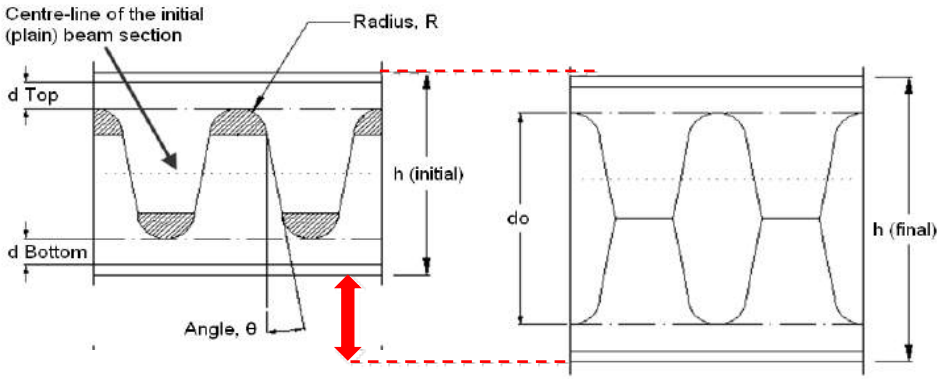
Optimised Beams

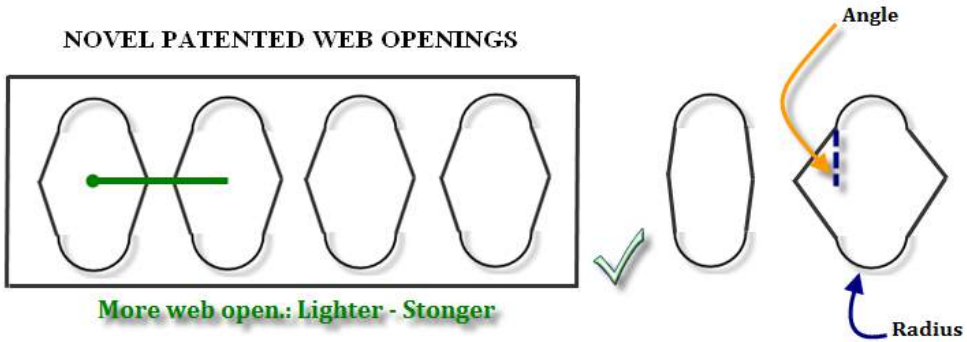
UNIVERSITY OF LEEDS



- ✓ **Structural Performance**
- ✓ **Manufacturability**
- ✓ **Cost**



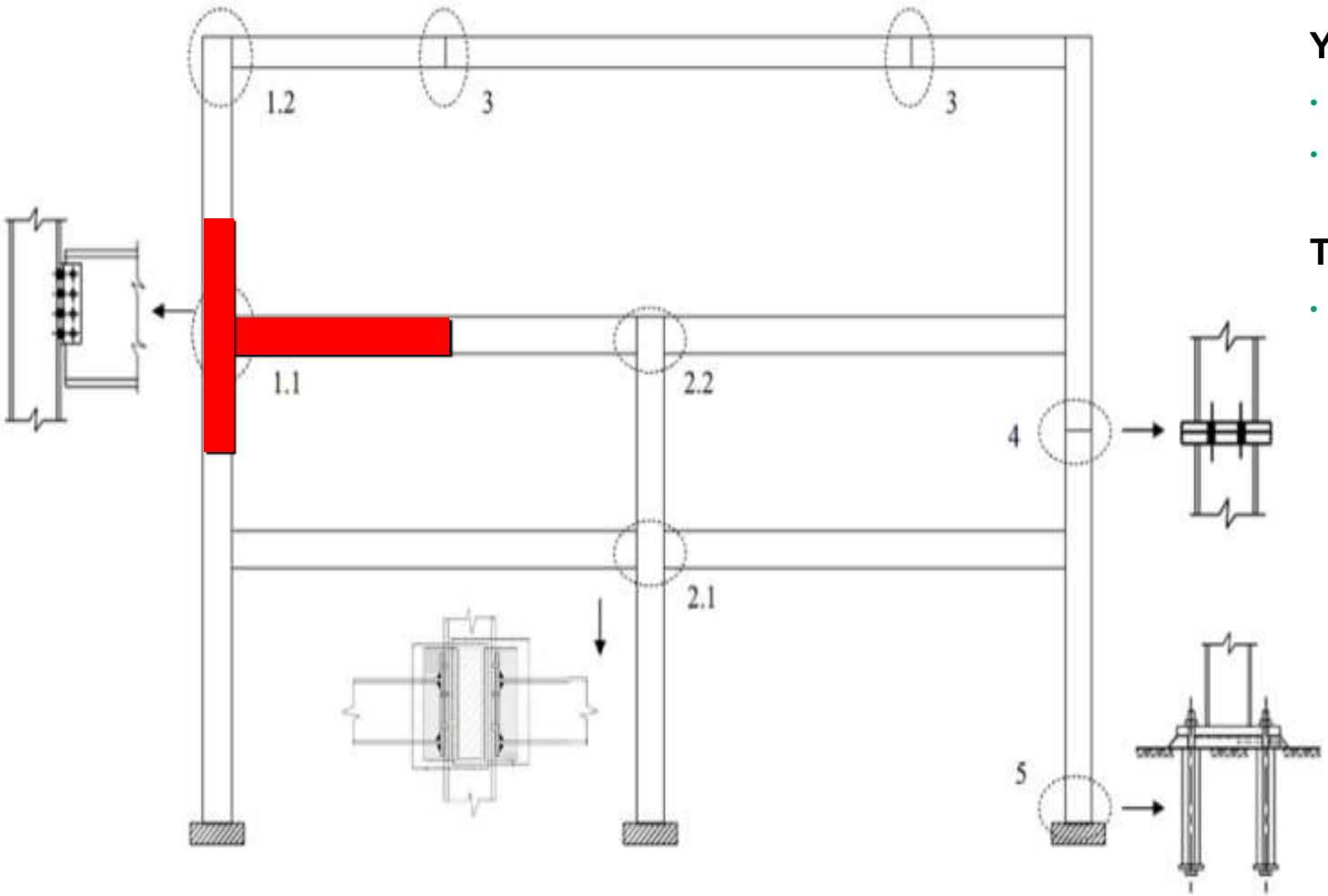




Control opening length and ductility

Connections

UNIVERSITY OF LEEDS



YESTERDAY

- **Pinned connections**
- **Rigid connections**

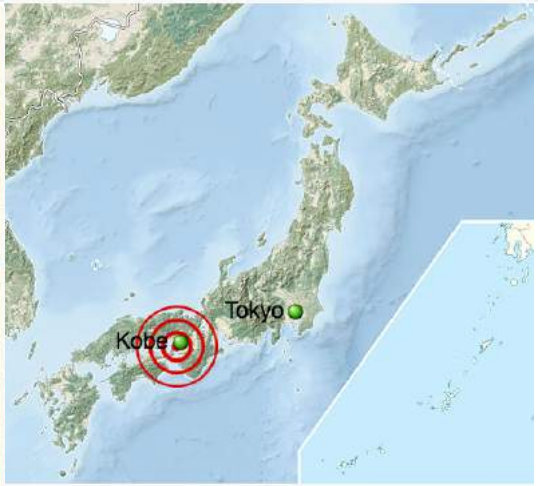
TODAY

- **Semi-rigid connections with rotational springs**

Northridge 1994 / Kobe 1995 Earthquakes

UNIVERSITY OF LEEDS

Date	January 17, 1994
Origin time	4:30:55 a.m. PST[1]
Duration	10–20 seconds[2]
Magnitude	6.7 M_w
Depth	11.4 mi (18.3 km)
Epicenter	34.213°N 118.537°W
Type	Blind thrust
Areas affected	Greater Los Angeles Area Southern California United States
Total damage	$13–$44 billion[3]
Max. intensity	IX (*Violent*)[1]
Peak acceleration	1.82*g* horizontal[4]
Casualties	57 killed > 8,700 injured



Date	January 17, 1995
Origin time	05:46:53 [1]
Magnitude	6.9 M_w [1]
Depth	17.6 km (10.9 mi) [1]
Epicenter	34.59°N 135.07°E [1]
Type	Strike-slip [2]
Areas affected	Japan
Total damage	$200 billion USD [3]
Max. intensity	Shindo 7
Peak acceleration	0.8 *g*
Casualties	5,502–6,434 killed [2] 36,896–43,792 injured [2] 251,301–310,000 displaced [2]

SAC joint venture

UNIVERSITY OF LEEDS

Structural Engineers Association of California (SEAOC)

Applied Technology Council (ATC)

California Universities for Research in Earthquake engineering (CUREe)

Before Northridge

- Steel buildings considered to be "invulnerable"
- Best earthquake resisting system

After Northridge

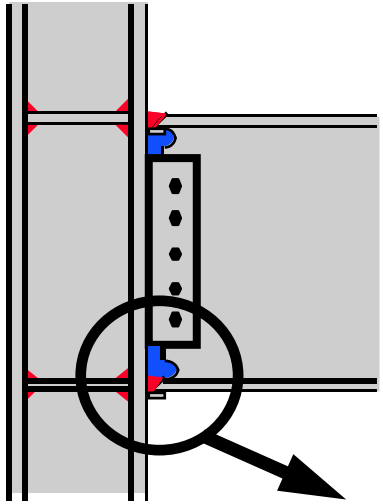
- "Pre-qualified" connections withdrawn
- Interim Guidelines, workshops/conferences
- New connections to be validated by testing

After 2000

- Improved prescriptive connections
- FEMA 350: Recommendations
- 2002 AISC Seismic Provisions

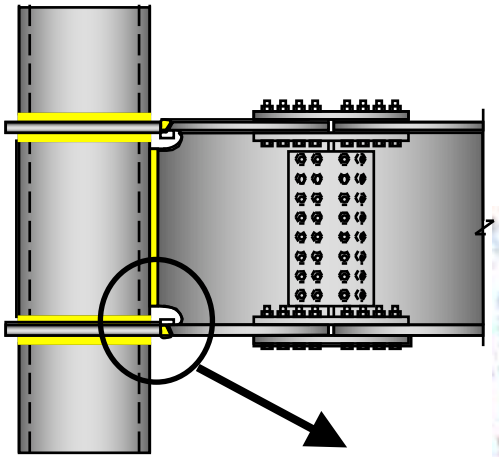
Connection Failures

UNIVERSITY OF LEEDS



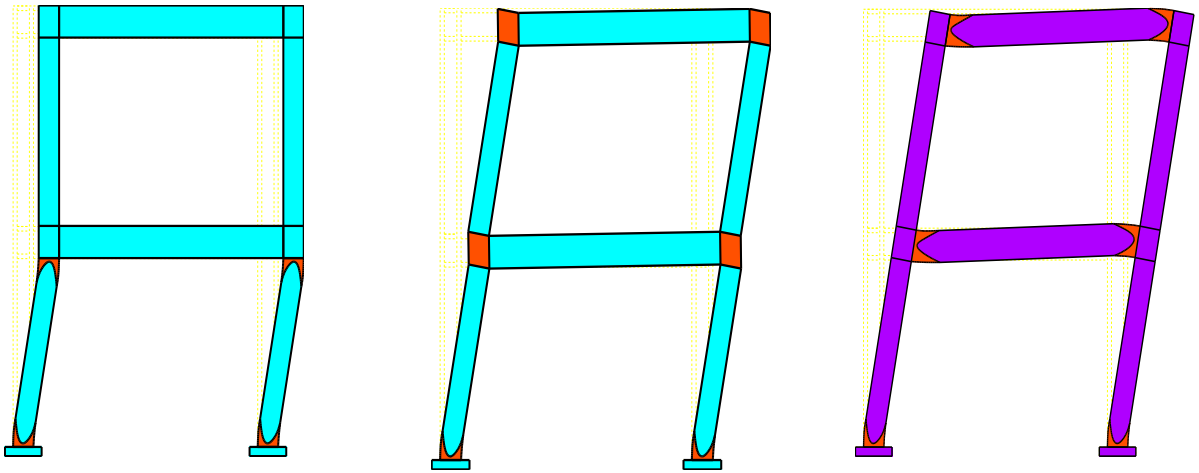
Connection Failures

UNIVERSITY OF LEEDS



Plastic Hinge Position

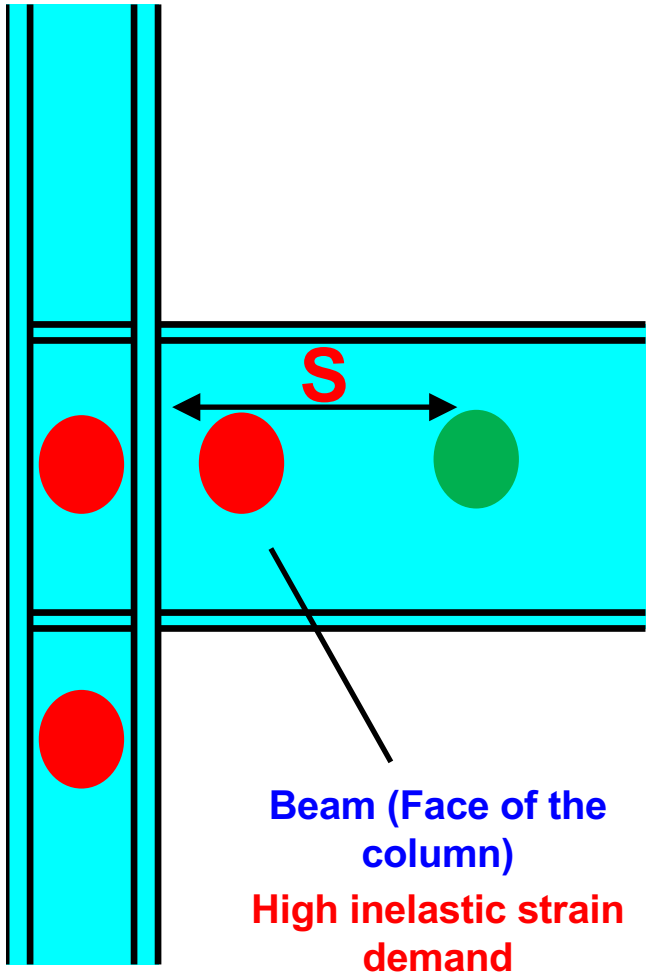
UNIVERSITY OF LEEDS



Column
(Flexural & Axial Yielding)
Story mechanism

Panel Zone
(Shear Yielding)
Secondary stress

Beam
(Flexural Yielding)
Desirable location

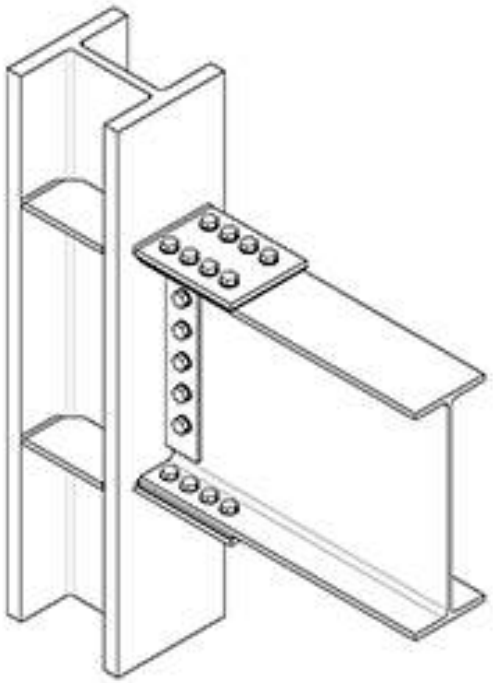


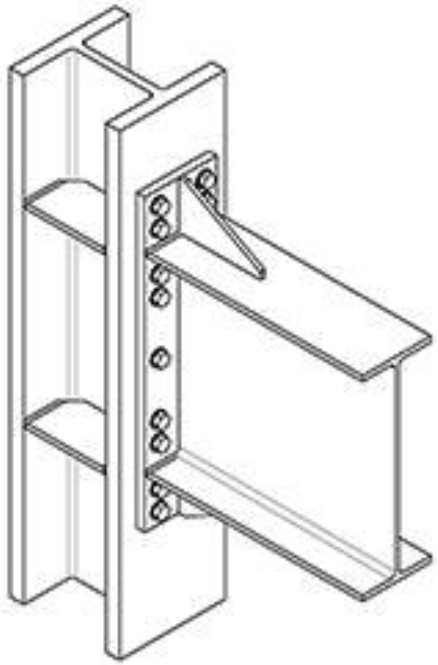
Beam (Face of the column)
High inelastic strain demand
lead to brittle failure

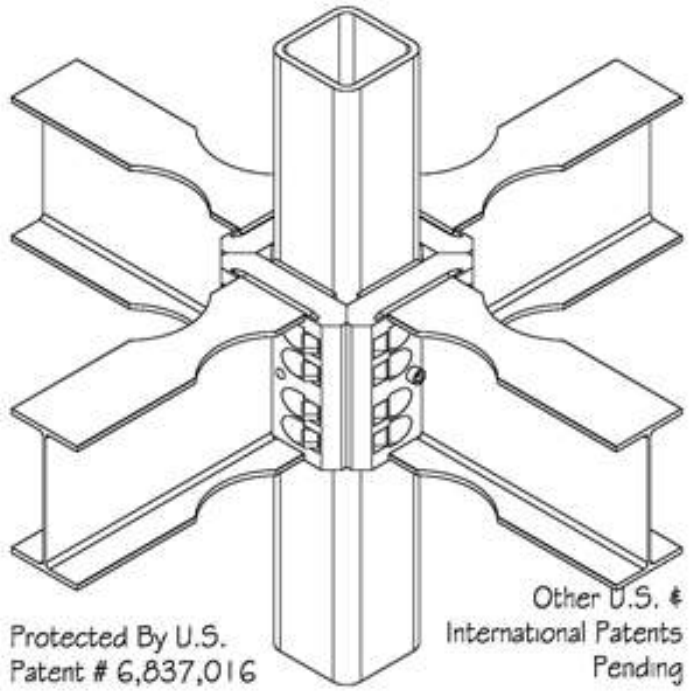
Strengthening Techniques - FEMA 350

UNIVERSITY OF LEEDS

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

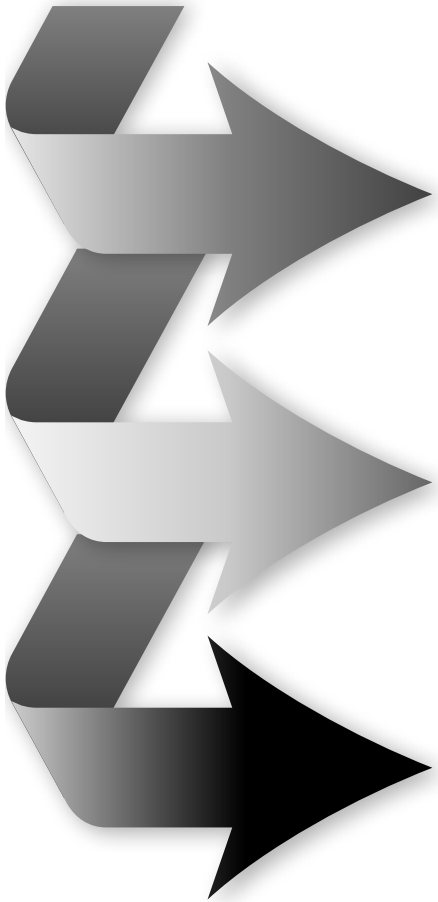






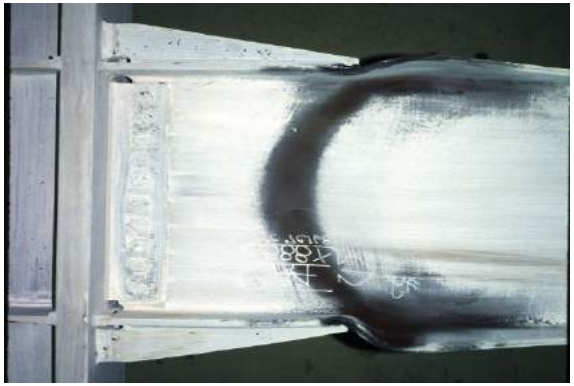
Rehabilitation Methods

UNIVERSITY OF LEEDS



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.

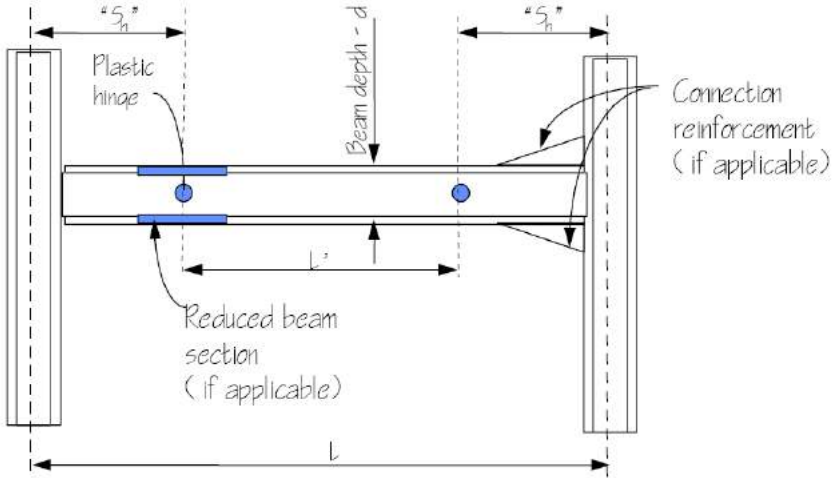
Weakening - Reduced Web Section

The cheapest method. No concrete break is required. First one in 2009!

Challenge RBS System!

UNIVERSITY OF LEEDS

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.



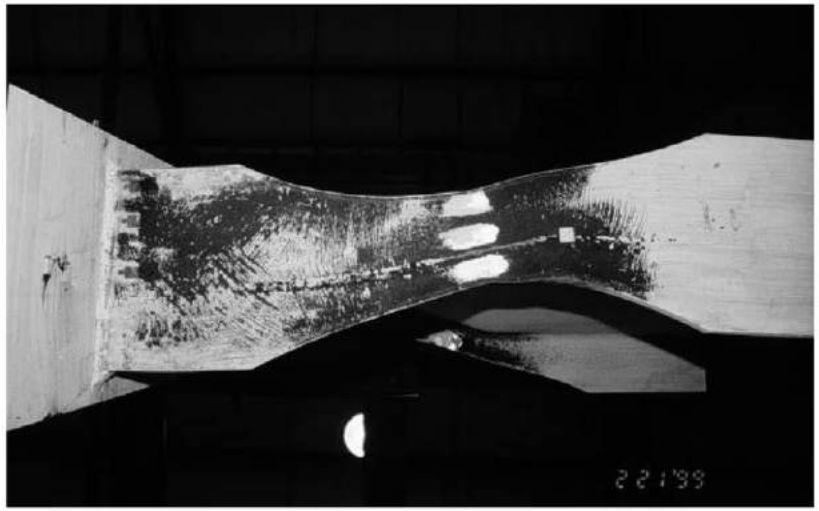
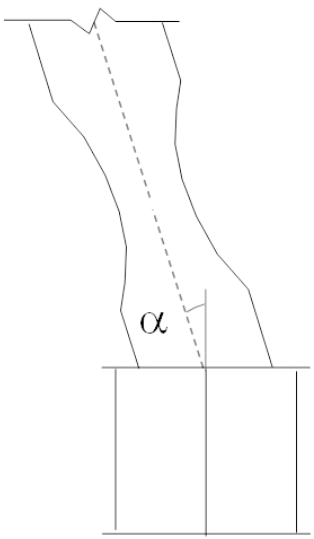


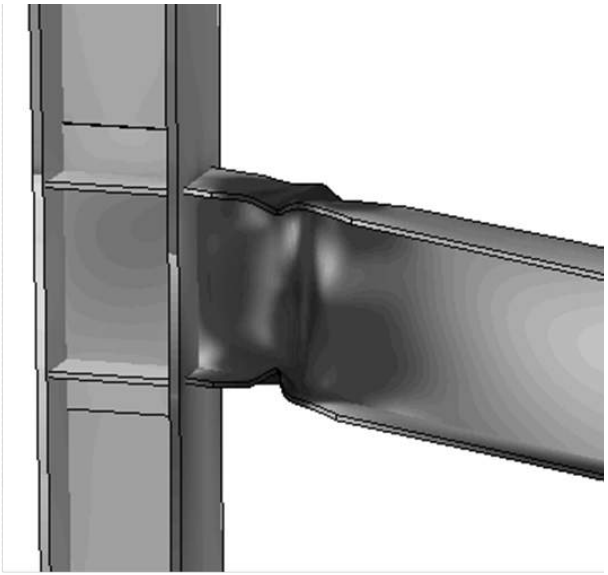
Fig. 8 - North Beam Bottom Flange RBS After Testing

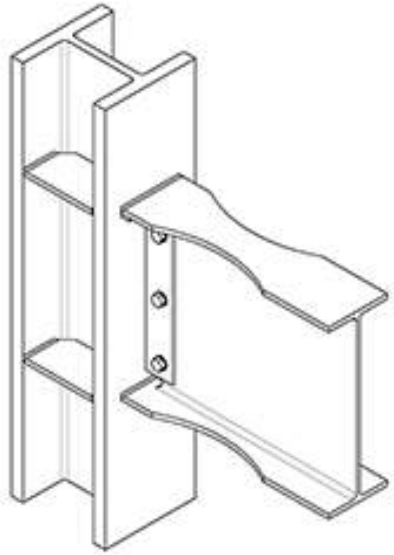
past **now**

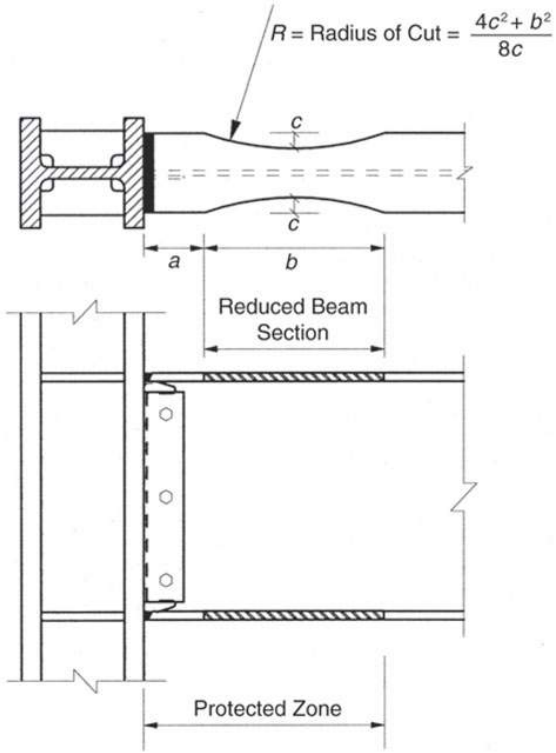
ANSI/AISC 358-10 and 358s1-11 & EC8

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.



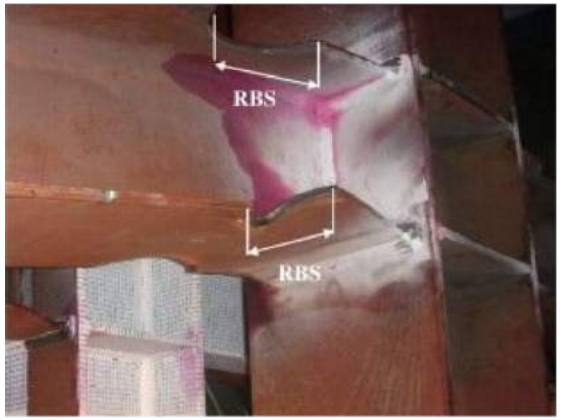




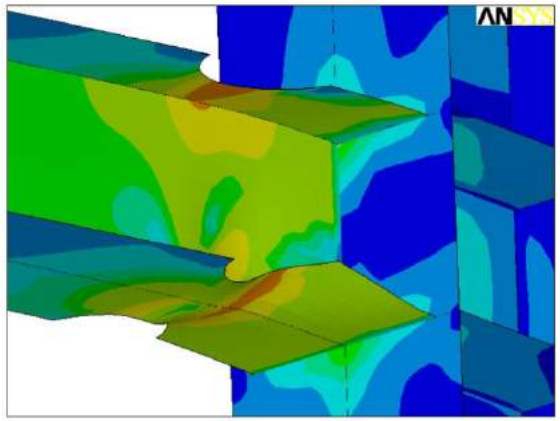


RBS vs. RWS

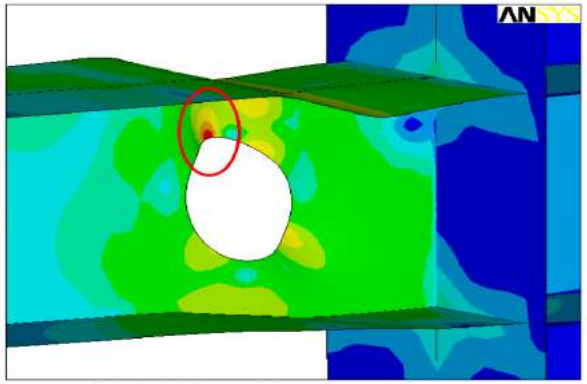
UNIVERSITY OF LEEDS



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



Tsavdaridis et al., 2014. Perforated Steel Beam-to-Column Connections, Journal of Earthquake Engineering

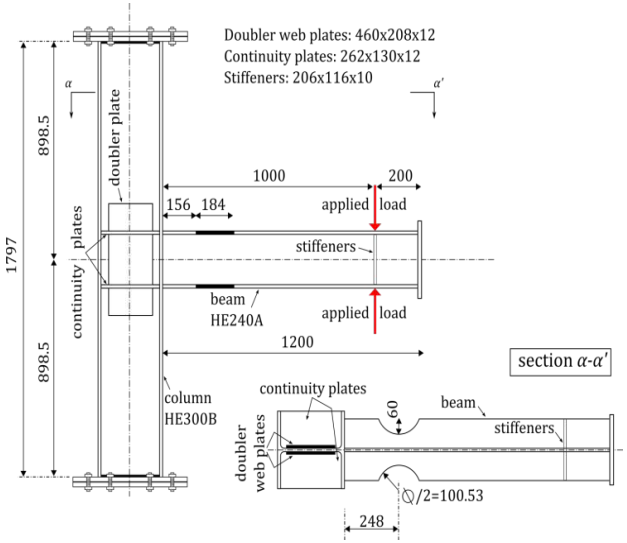
Yang et al., 2009. Aseismic behaviours of steel MRF with opening in beam web, J. Con. Steel. Res.

	RBS	RWS
(Shear) Capacity	✓	
LTB		✓
Composite		✓
Time and Cost		✓
Flexibility		✓
Maintenance		✓
Services		✓

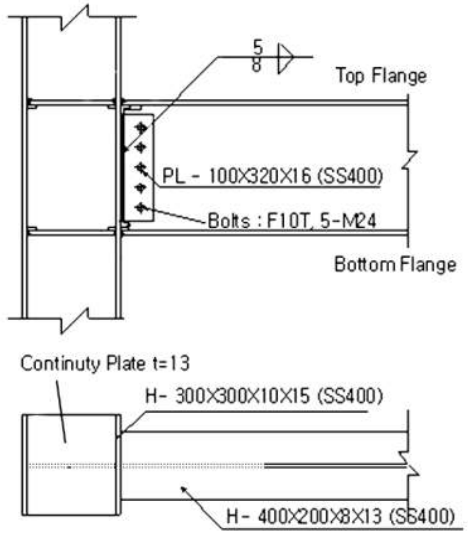
Connections Types

UNIVERSITY OF LEEDS

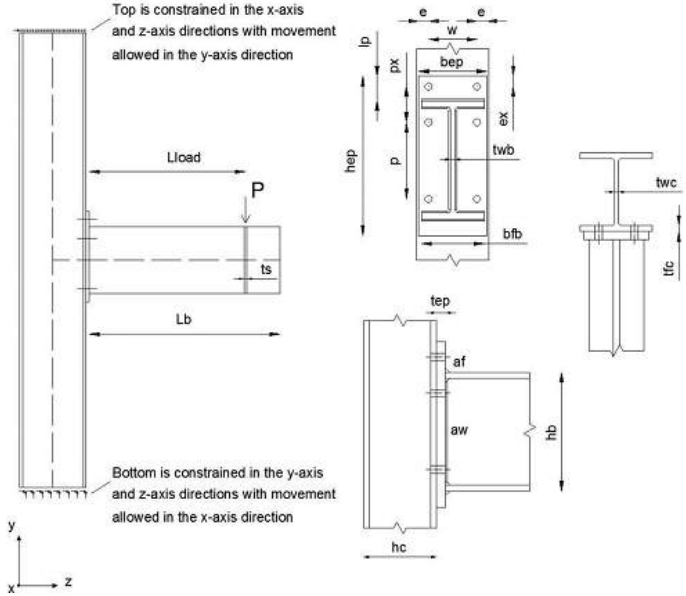
Welded

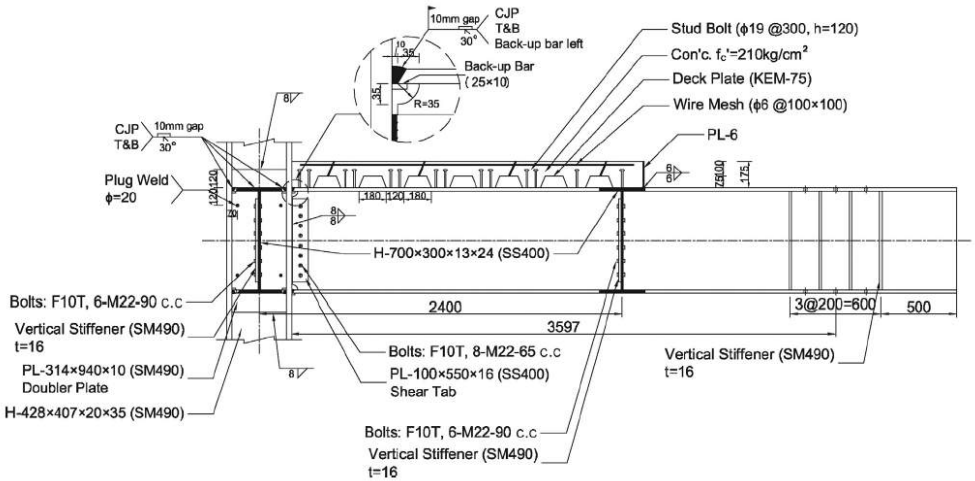


WUF-B



Extended end plate



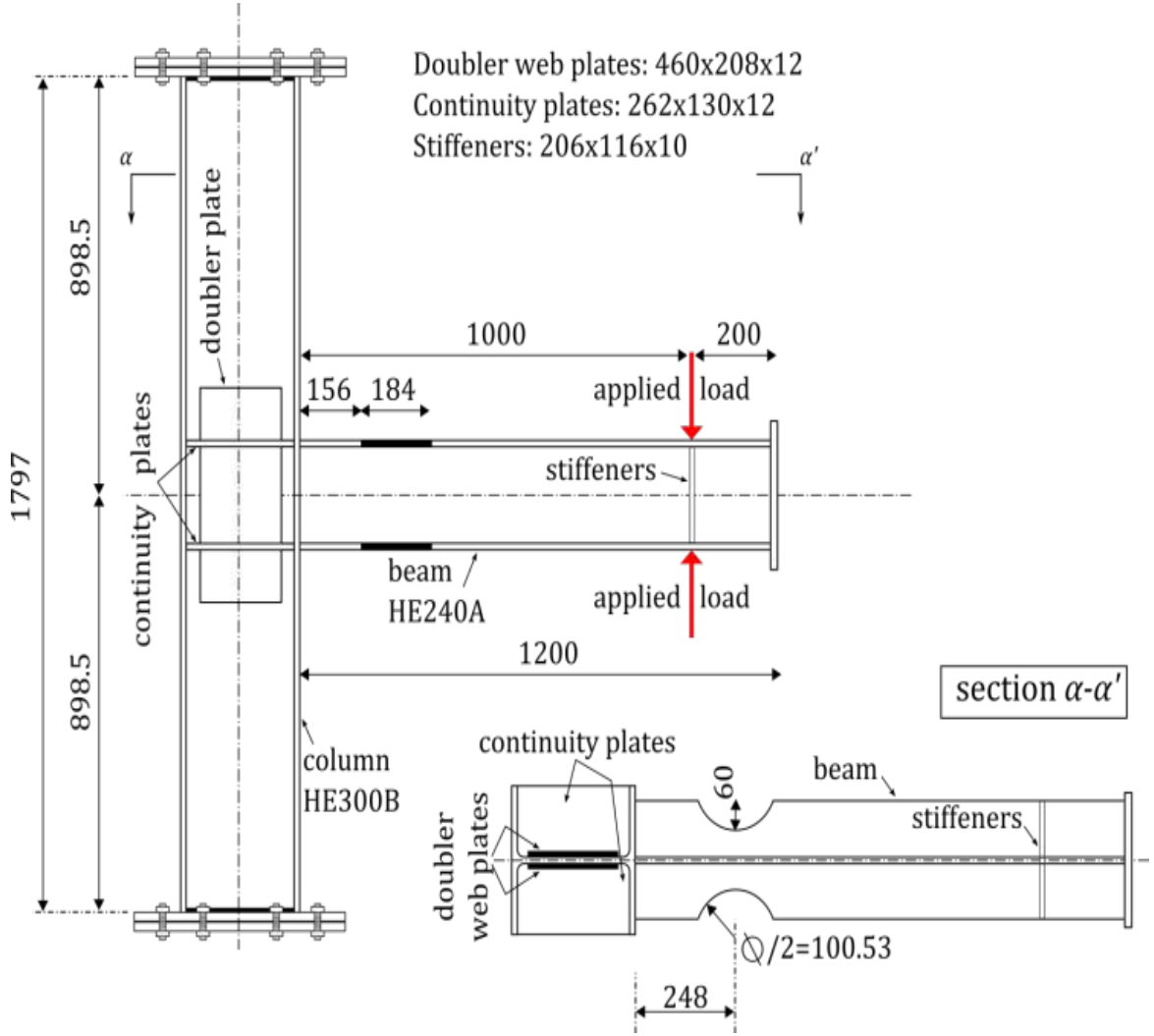


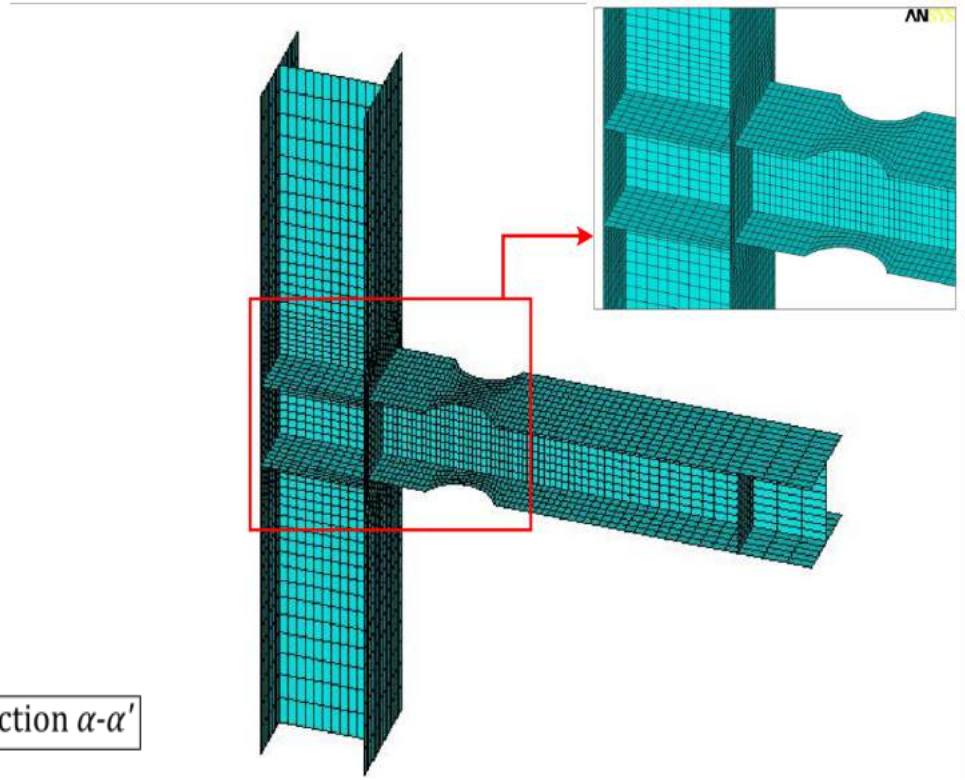
UNIVERSITY OF LEEDS

Welded Connections with isolated web opening

Test Apparatus

UNIVERSITY OF LEEDS



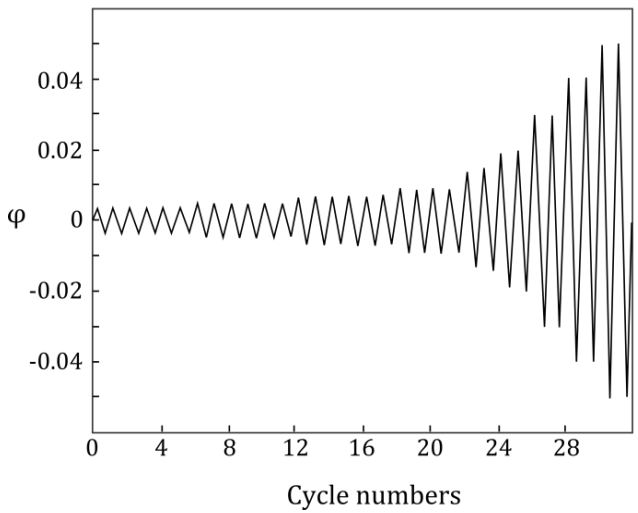


- ✓ **4-node Shell elements**
- ✓ **Manual (mapped) meshing**
- ✓ **Mesh convergence**
- ✓ **Eigen buckling employed**

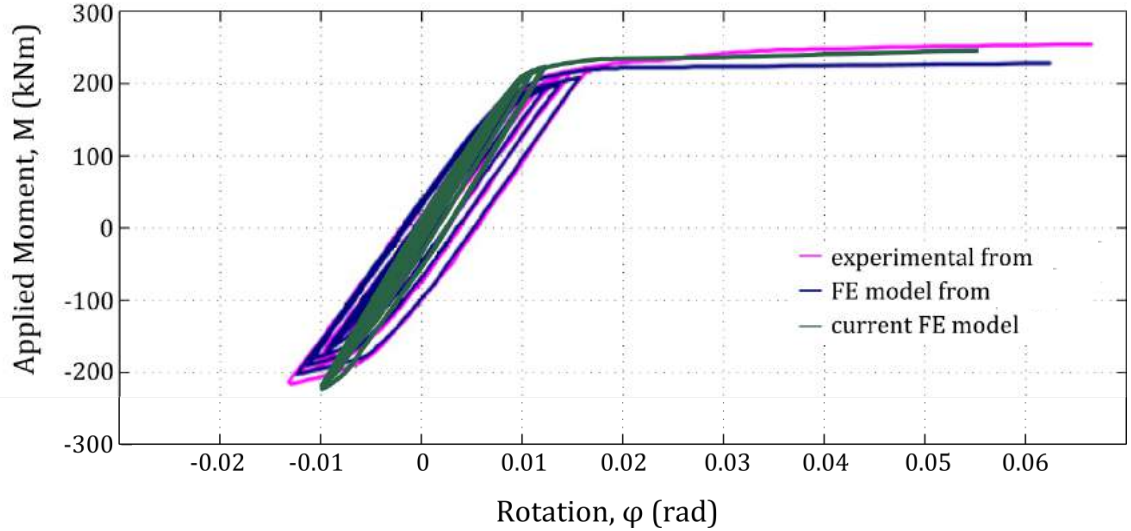
Pachoumis et al., 2009

Validation and Parametric Study

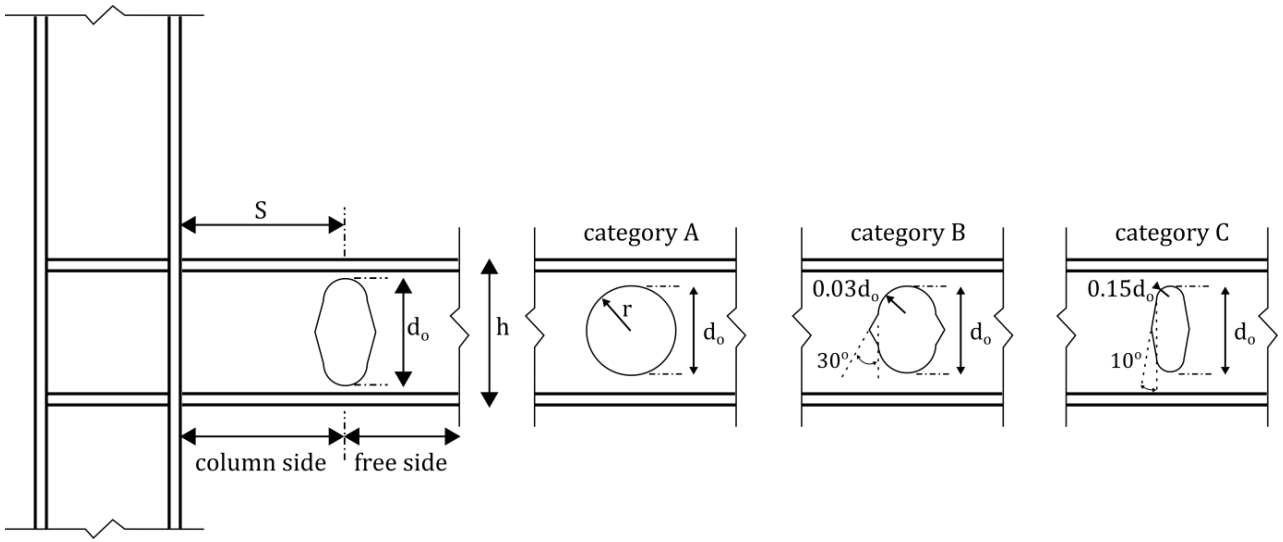
UNIVERSITY OF LEEDS



SAC protocol, FEMA 350/AISC



FE model vs. Experimental



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

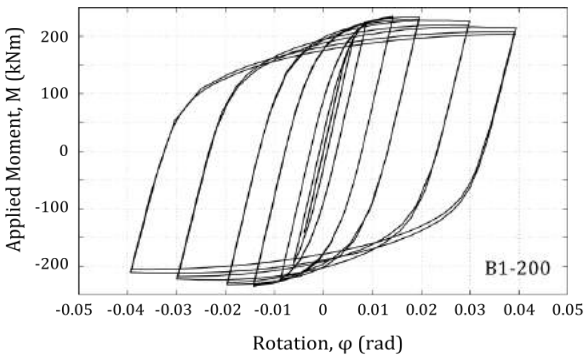
Number indicating the opening depth (d_o); (1: d_o=0.5h, 2: d_o=0.65h, 3: d_o=0.8h)

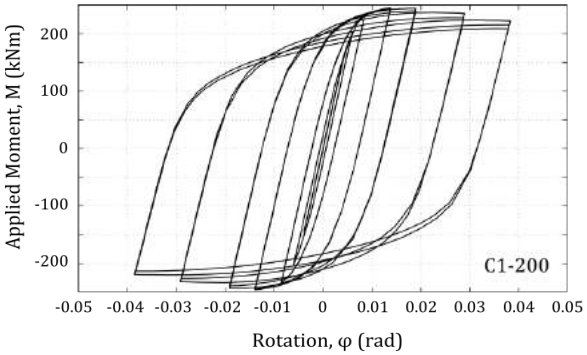
Letter representing opening's category; (A, B, C)

Hysteretic Behaviours

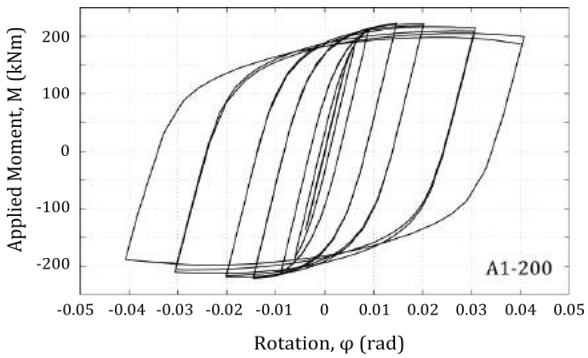
UNIVERSITY OF LEEDS

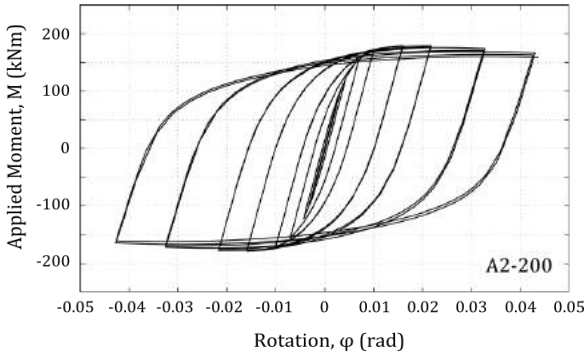
Novel web opening shapes

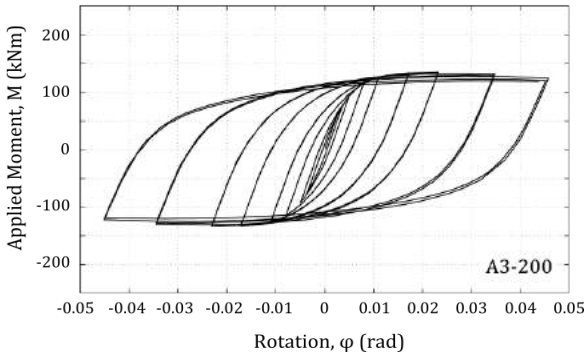




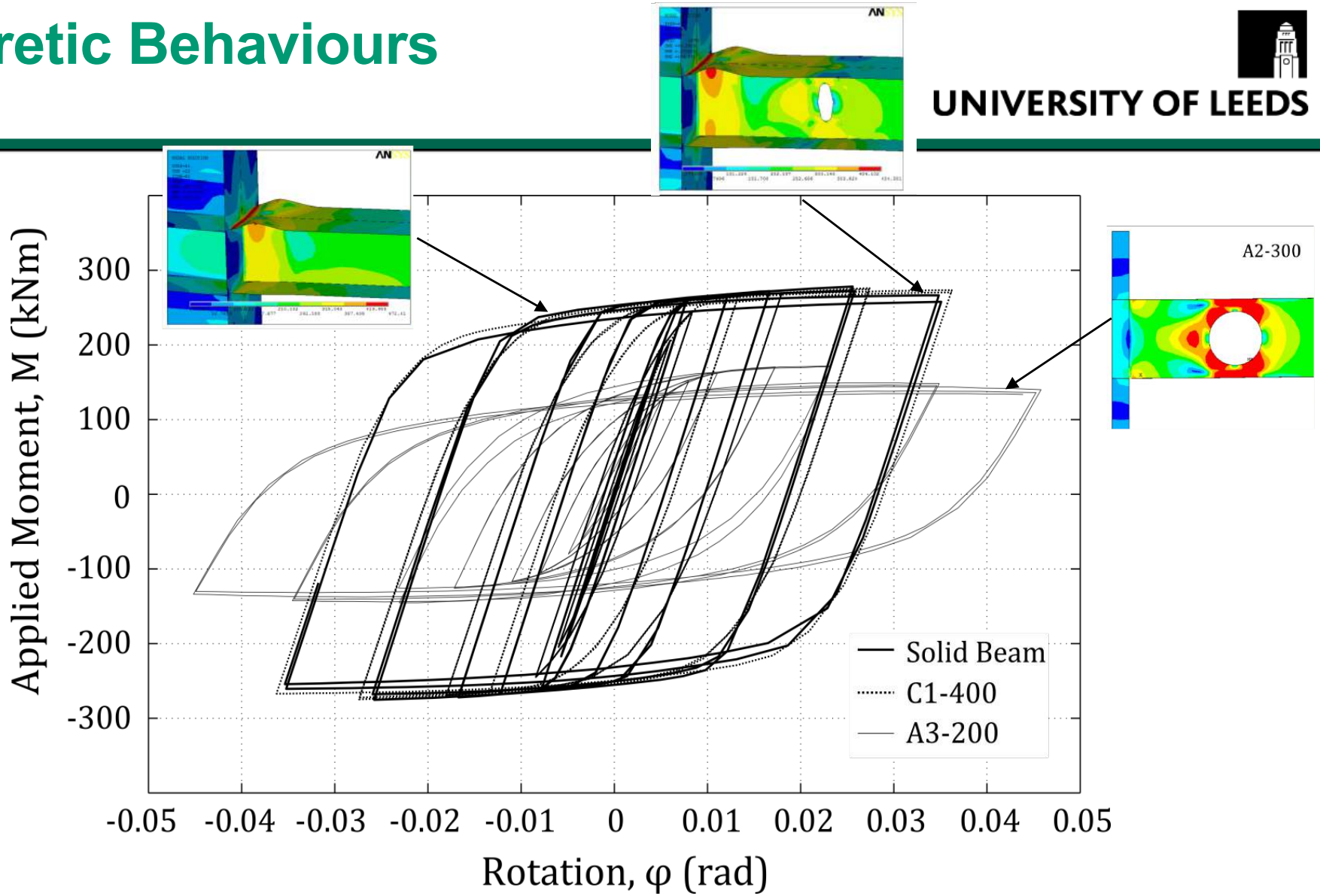
Circular web openings







Hysteretic Behaviours

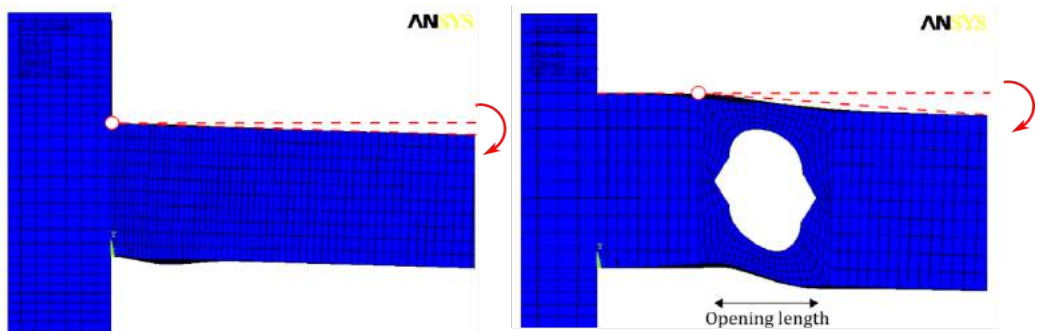


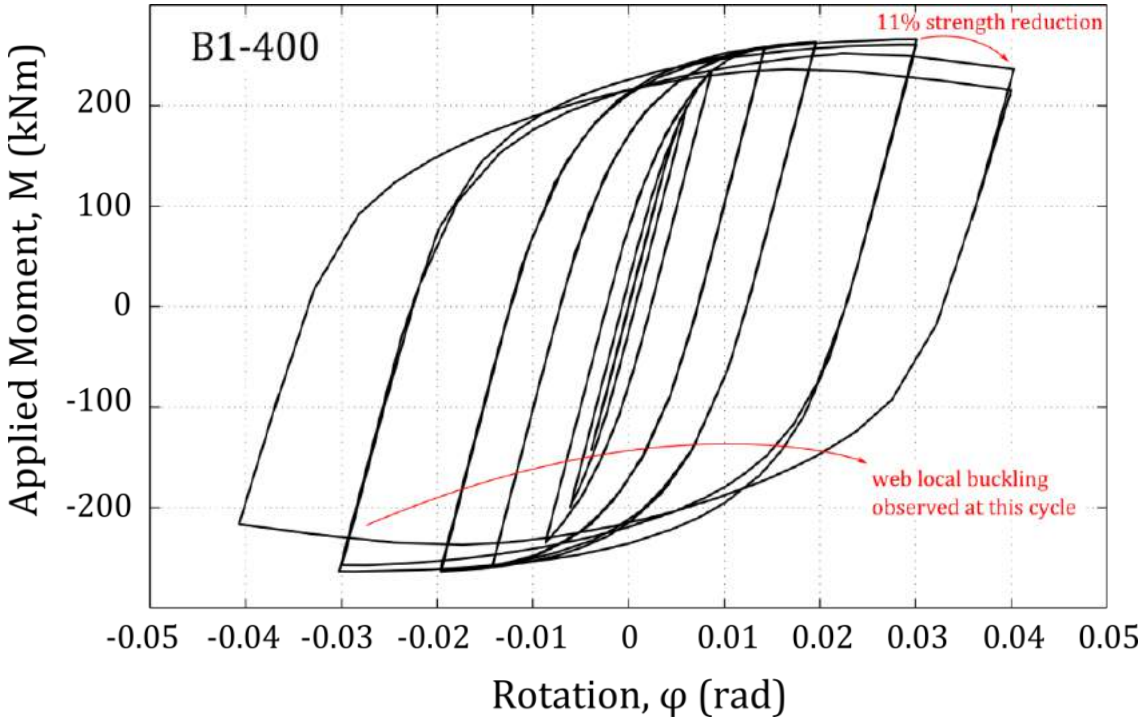
- ~ 50% lower load carrying capacity
- ~ +30% higher ductility capacity

Rotational Capacity

UNIVERSITY OF LEEDS

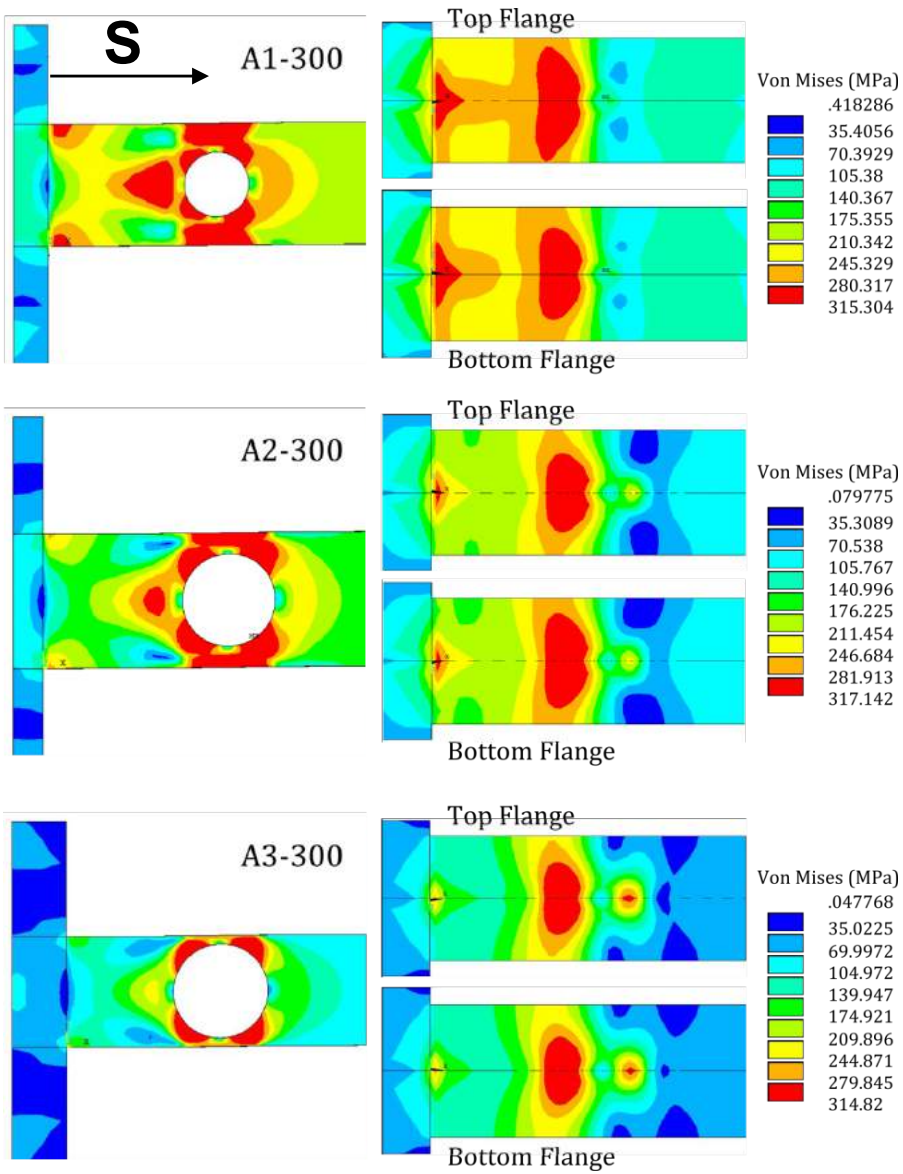
The **higher** the critical opening length - the **higher** is the strength degradation.





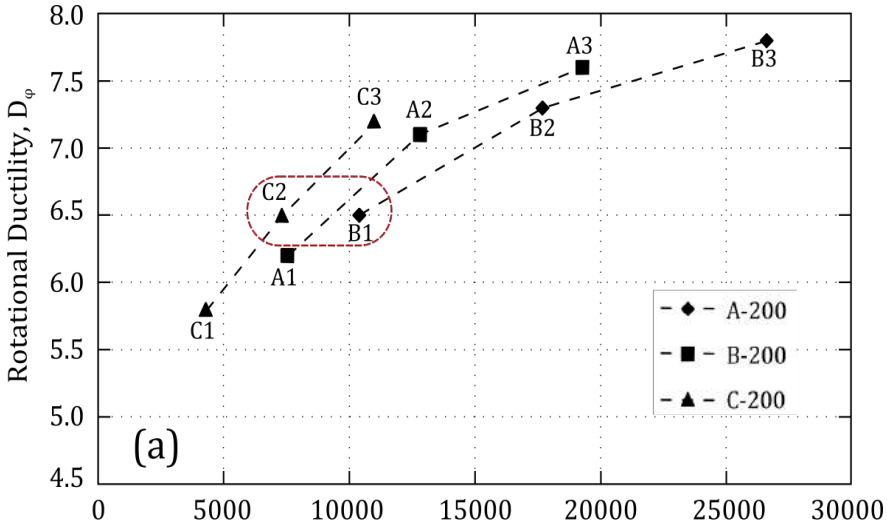
Vierendeel Mechanism

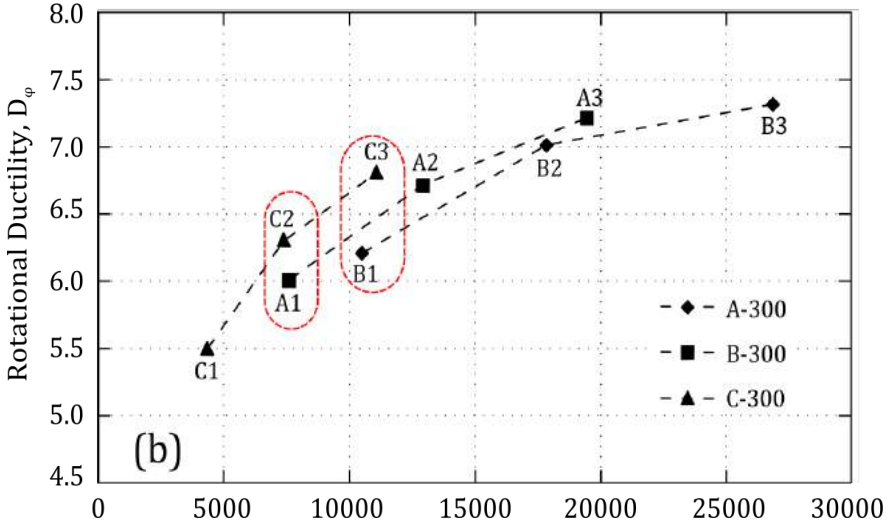
UNIVERSITY OF LEEDS

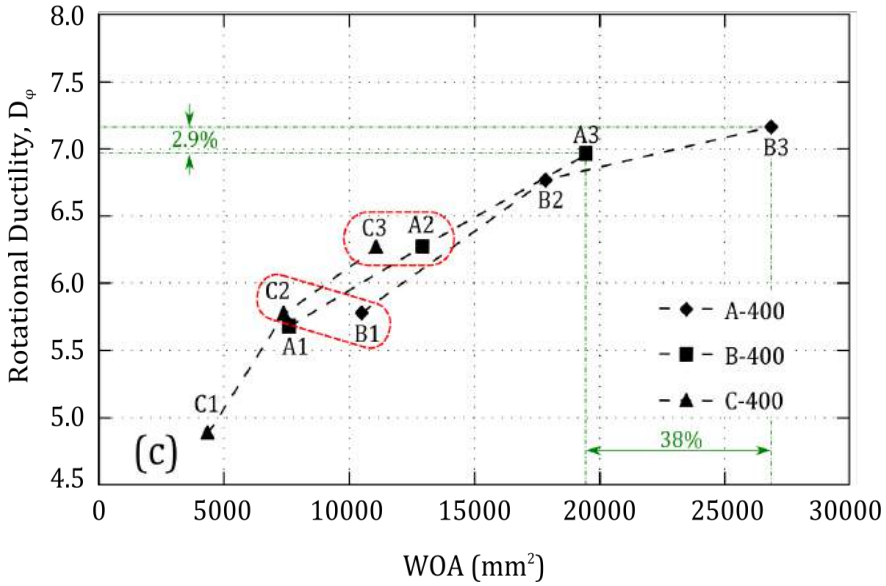


Effect of WOA on Ductility

UNIVERSITY OF LEEDS







Results

UNIVERSITY OF LEEDS

Specimen	M_y (kNm)	M_u (kNm)	θ_y (rad)	θ_u (rad)	[a]D_θ	[b]K_i (kNm/rad)	[c] WOA (mm²)	[d]E (kNm)(rad)
Solid	246	278.2	0.0072	0.0348	4.8	39109	-	80.0
RBS1	170	220	0.0070	0.0460	5.2	25000	-	-
A1-200	188	222.7	0.0063	0.0409	6.5	35662	10387	88.3
A1-300	194	237.1	0.0066	0.0409	6.2	35709	10387	92.4
A1-400	199.8	250.2	0.0070	0.0410	6.[illegible]	35889	10387	94.7
A2-200	142	179.2	0.0059	0.0431	7.3	30844	17671	85.1
A2-300	145	187.9	0.0061	0.0430	7.0	31293	17671	87.1
A2-400	145.8	197.2	0.0063	0.0429	6.8	31312	17671	89.0
A3-200	103	135.6	0.0059	0.0458	7.8	21220	26590	70.4
A3-300	105.5	140.4	0.0062	0.0458	7.3	21360	26590	72.1
A3-400	109	146.1	0.0063	0.0459	7.2	21403	26590	73.3
B1-200	200	235.3	0.0064	0.0398	6.2	36825	7524	88.1
B1-300	206	254.0	0.0067	0.0399	6.0	36847	7524	90.4
B1-400	214	265.9	0.0071	0.0403	5.7	36900	7524	93.1
B2-200	159	197.8	0.0059	0.0416	7.1	33766	12801	87.5
B2-300	164	208.7	0.0062	0.0414	6.7	33832	12801	88.1
B2-400	171	220.8	0.0065	0.0412	6.3	33938	12801	89.5
B3-200	121	155.5	0.0058	0.0438	7.6	25941	19262	77.3
B3-300	125	163.0	0.0061	0.0437	7.2	26162	19262	78.6
B3-400	130	171.6	0.0062	0.0437	7.0	26240	19262	80.1
C1-200	209	245.7	0.0066	0.0383	5.8	37576	4283	85.9
C1-300	217	262.3	0.0069	0.0381	5.5	37588	4283	87.8
C1-400	227	275.7	0.0073	0.0362	4.9	38589	4283	88.0
C2-200	175	215.0	0.0062	0.0403	6.5	35678	7303	87.1
C2-300	186	228.3	0.0064	0.0400	6.3	35767	7303	88
C2-400	191.5	243.0	0.0068	0.0397	5.8	35874	7303	89
C3-200	142	179.8	0.0058	0.0419	7.2	30793	10965	82.5
C3-300	149.8	189.9	0.0062	0.0415	6.7	30871	10965	83.4
C3-400	157	201.2	0.0065	0.0412	6.3	30998	10965	84.6

-50%

+30%

Solid: lowest rotational capacity

A3-200: highest rotational capacity

Geometric Parameters

UNIVERSITY OF LEEDS

Parameter do

Bigger

Vierendeel

Reducing stress from the connection

Balance

Parameter S

Smaller

Vierendeel

Reducing stress from the connection

Opening Shape

Large novel B,C or Medium circular A

Control Vierendeel

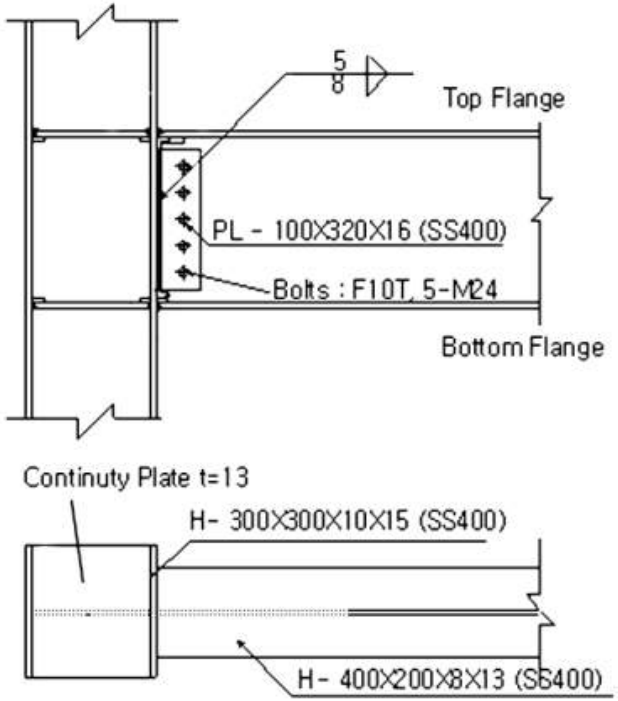
Control Plasticity via Shear Hinges

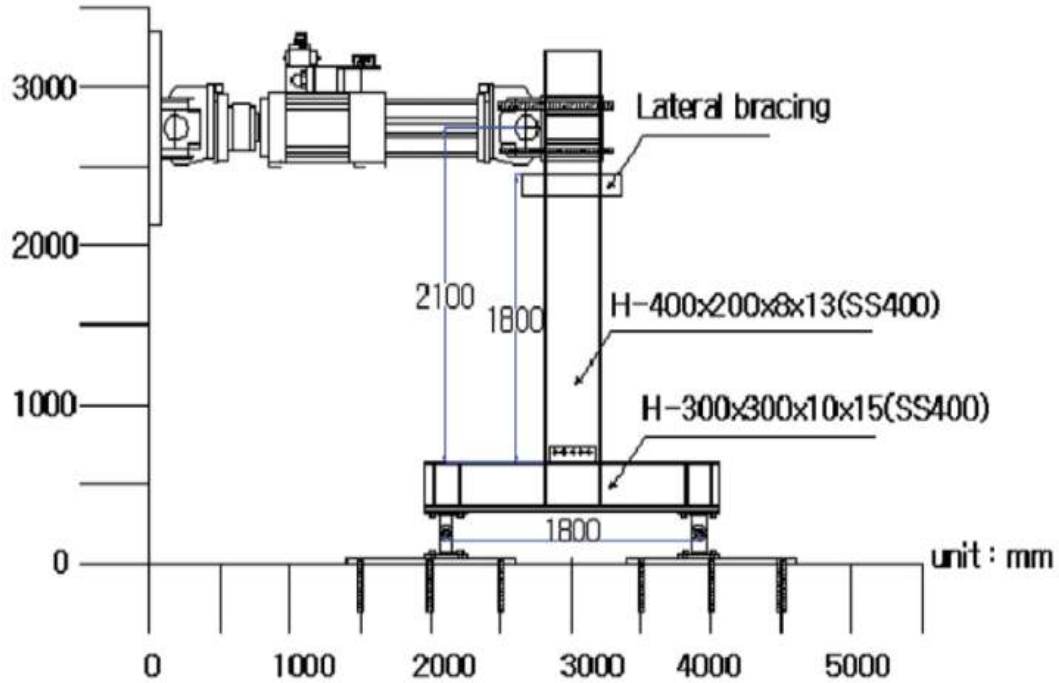
UNIVERSITY OF LEEDS

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

Test Apparatus

UNIVERSITY OF LEEDS



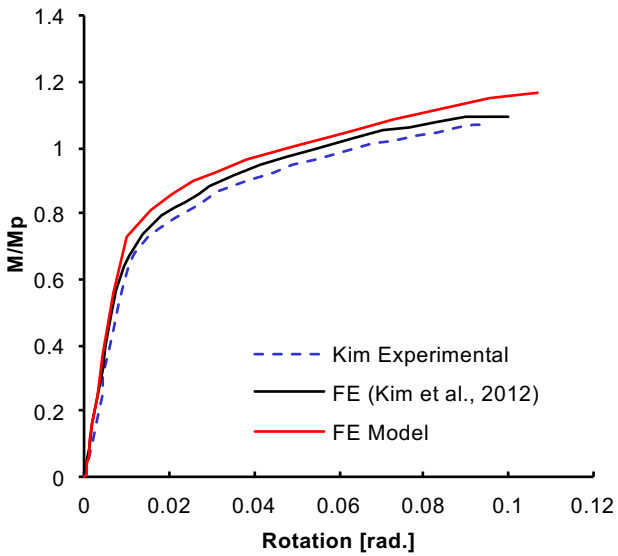


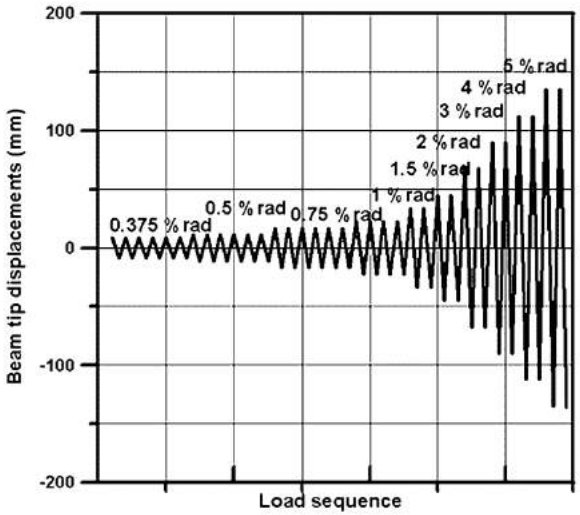
Member	Component	Yield Strength, f_y [MPa]	Ultimate Strength, f_u [MPa]
Beam	Flange	281	423
	Web	332	438
Column	Flange	281	433
	Web	304	450

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

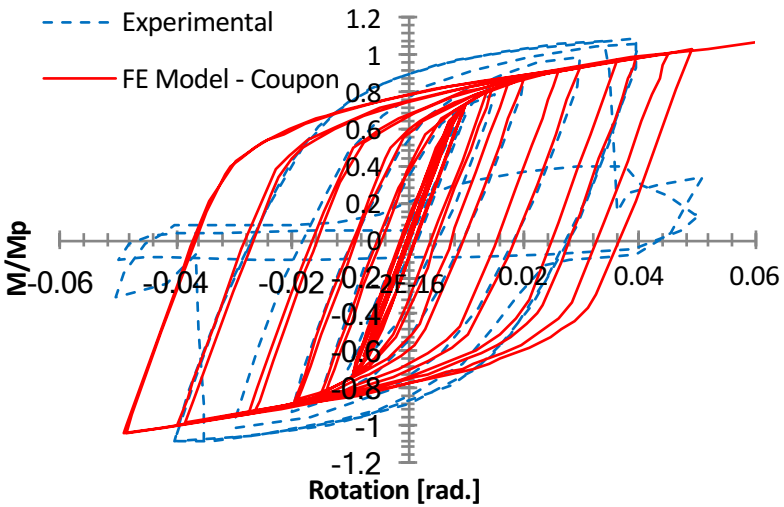
Validation and Parametric Study

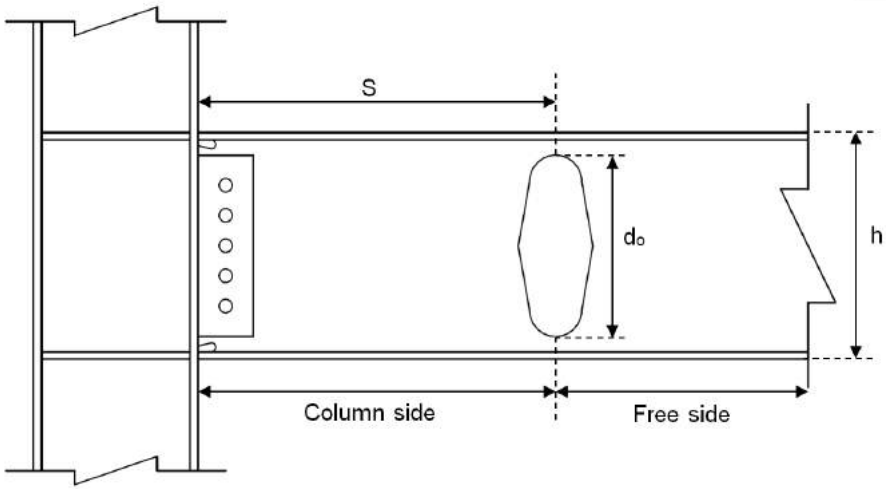
UNIVERSITY OF LEEDS

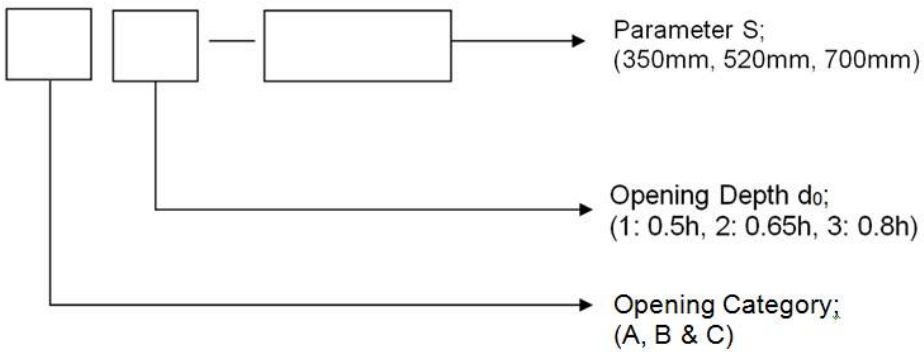




SAC protocol, FEMA/AISC

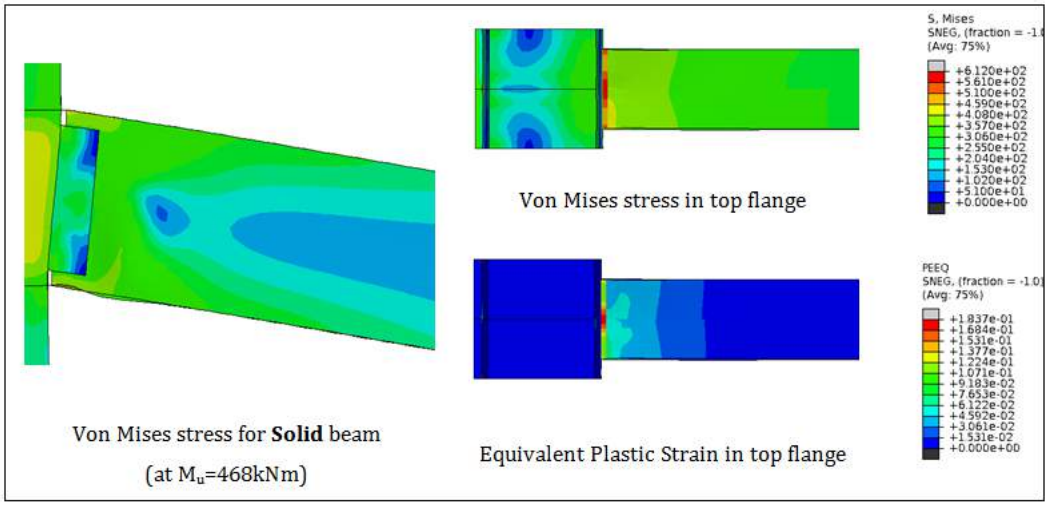


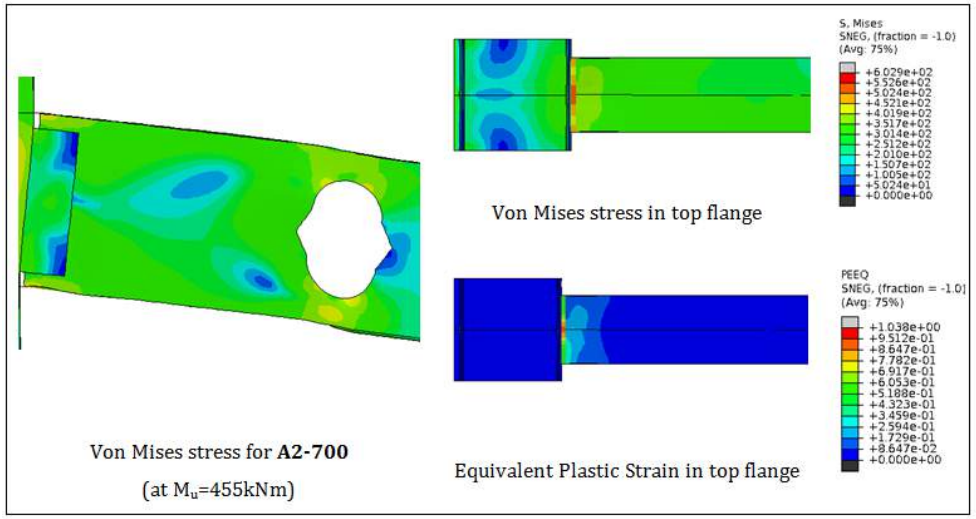


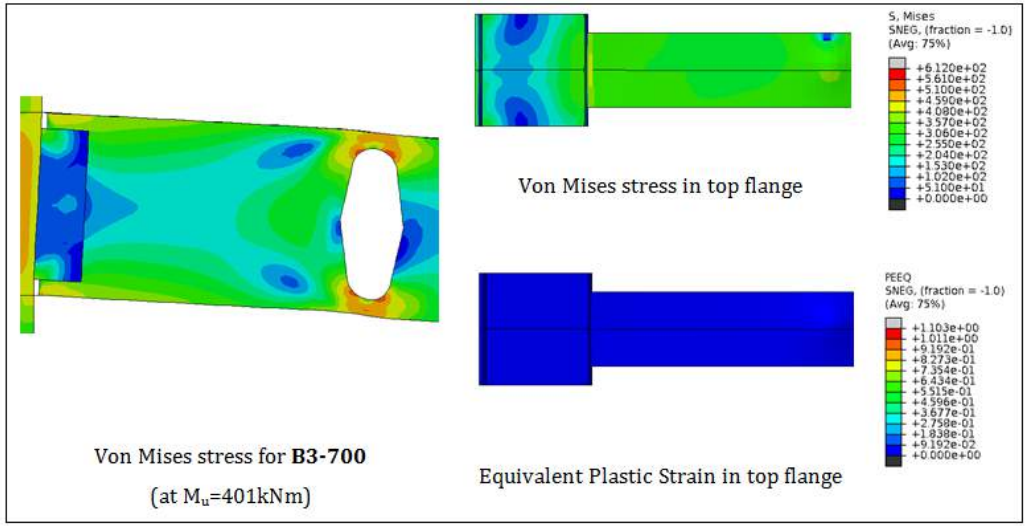


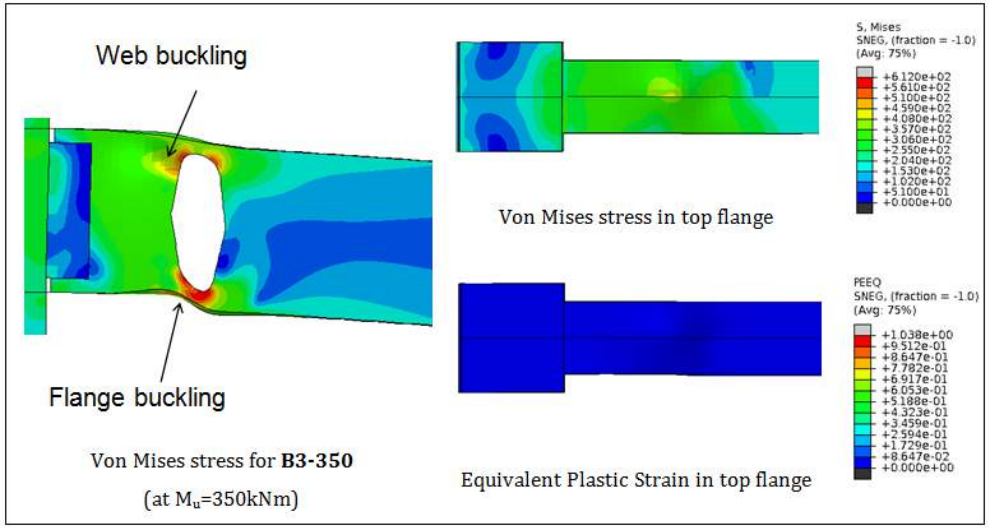
Vierendeel Mechanism

UNIVERSITY OF LEEDS





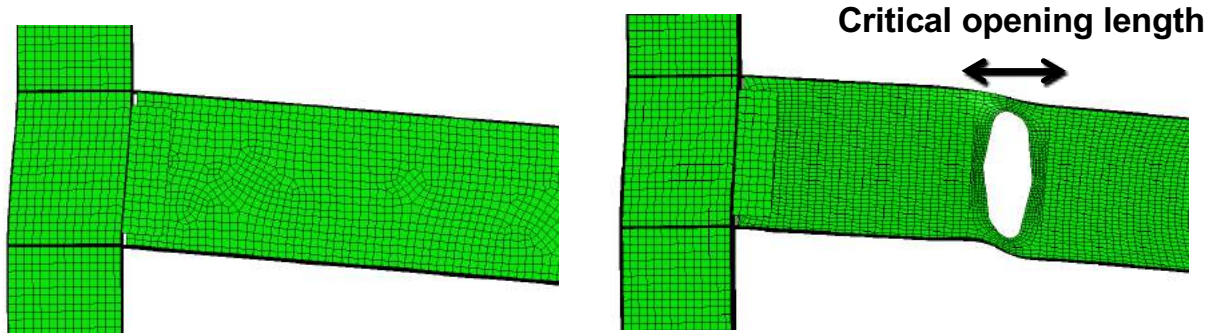




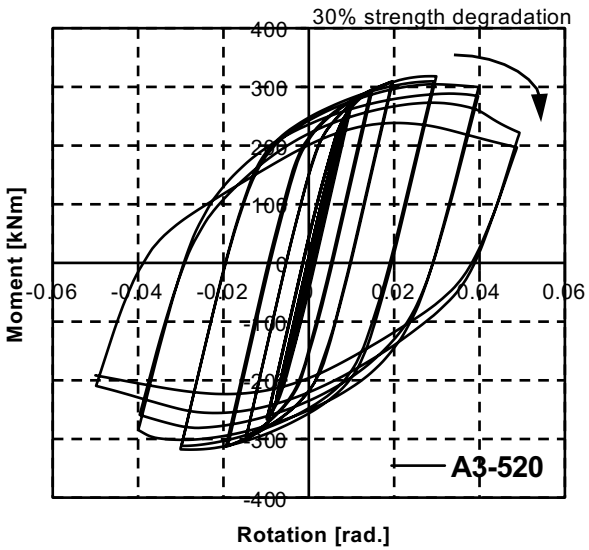
Rotational Capacity

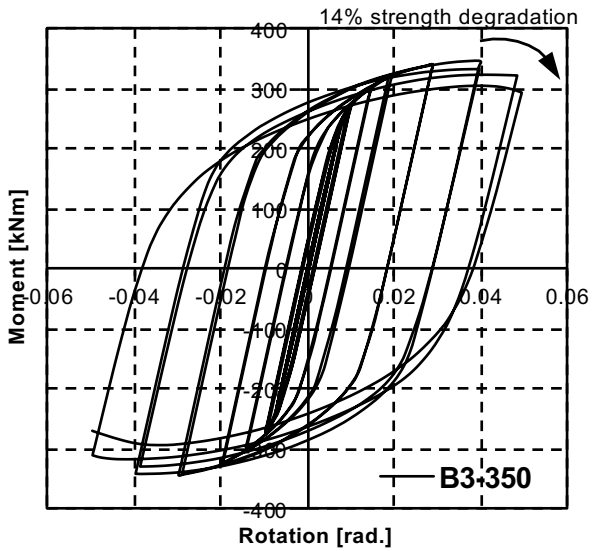
UNIVERSITY OF LEEDS

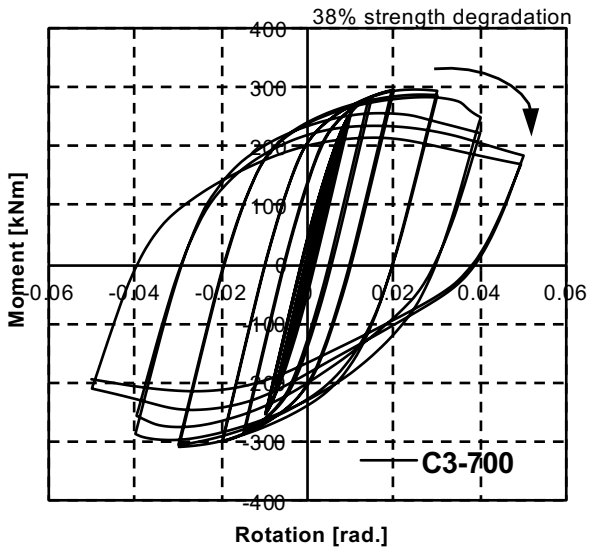
Centre of rotation for solid and perforated beams.



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

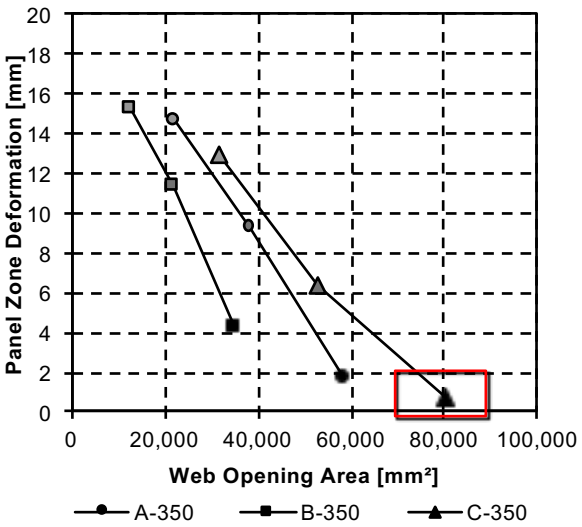


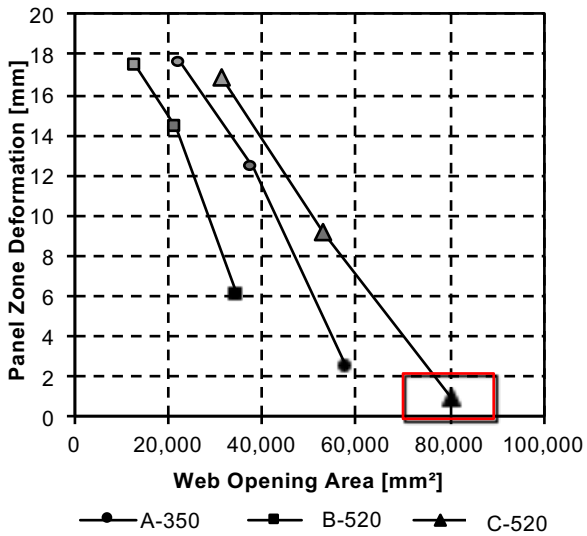


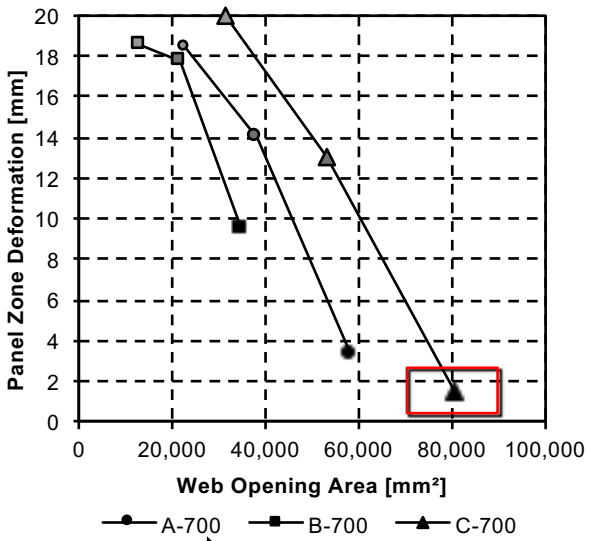


Panel Zone Deformation

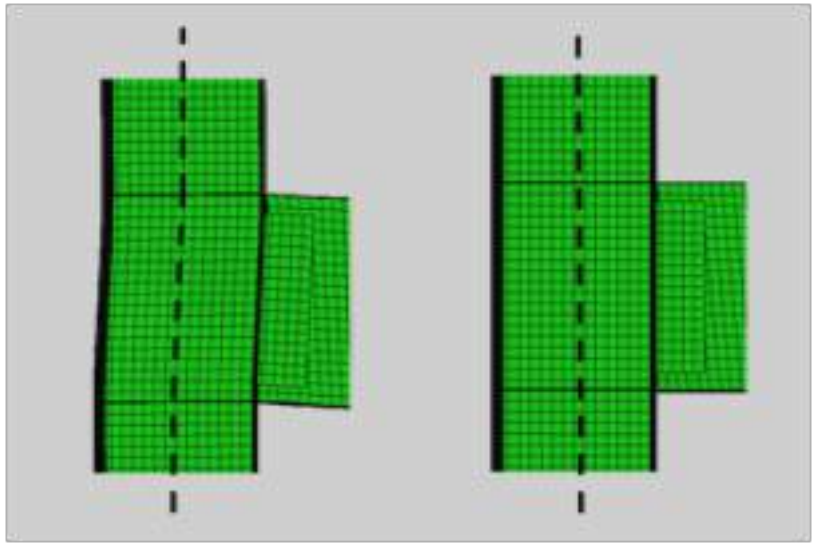
UNIVERSITY OF LEEDS







S increases



<u>Medium</u> and <u>Large</u> web openings placed <u>near</u> the connection.

Relative panel zone deformation from column centreline

Results

UNIVERSITY OF LEEDS

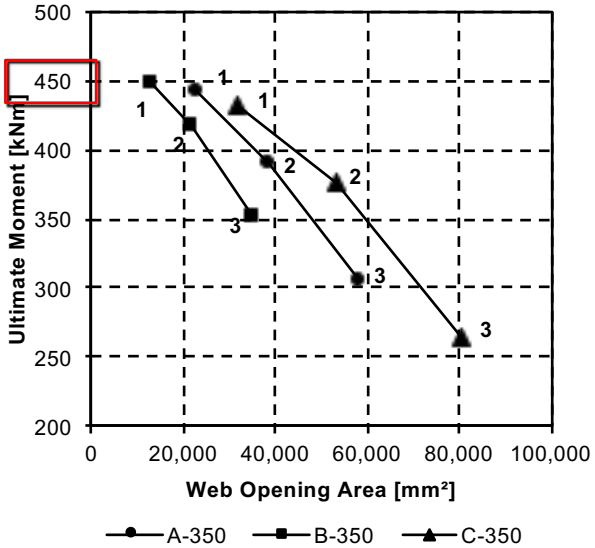
	Monotonic		Cyclic		Panel Zone		
Connection type	Ultimate moment, Mu [kNm]	Ultimate rotation, φ_u [rad.]	Ultimate moment, Mu [kNm]	Ultimate rotation, φ_u [rad.]	Rotation at maximum panel zone deflection [rad.]	Maximum panel zone deflection	Web Opening Area [mm^2]
Solid	468.5	0.1290	391.7	0.0500	0.2320	20.17	NA
A1-350	442.7	0.1163	390.4	0.0500	0.1260	14.58	22758
A1-520	462.5	0.1262	390.5	0.0500	0.1850	17.57	22758
A1-700	467.5	0.1279	390.7	0.0500	0.2170	18.44	22758
A2-350	390.0	0.0775	385.5	0.0497	0.0790	9.16	38457
A2-520	425.1	0.0943	389.7	0.0500	0.0960	12.36	38457
A2-700	454.9	0.1180	389.5	0.0500	0.1180	13.96	38457
A3-350	304.0	0.0231	331.7	0.0499	0.0240	1.70	58259
A3-520	322.5	0.0293	320.8	0.0500	0.0290	2.41	58259
A3-700	339.0	0.0368	335.8	0.0500	0.0620	3.34	58259
B1-350	447.2	0.1112	390.6	0.0499	0.1200	15.23	12949
B1-520	466.5	0.1277	390.5	0.0500	0.1980	17.40	12949
B1-700	467.8	0.1292	390.4	0.0500	0.2190	18.50	12949
B2-350	416.4	0.0940	389.2	0.0500	0.0970	11.27	21895
B2-520	442.3	0.1082	390.1	0.0499	0.1080	14.34	21895
B2-700	466.8	0.1280	390.0	0.0498	0.1370	17.82	21895
B3-350	350.4	0.0386	347.4	0.0500	0.0390	4.17	35062
B3-520	375.2	0.0542	371.5	0.0498	0.0560	6.05	35062
B3-700	401.2	0.0743	384.9	0.0500	0.0740	9.48	35062
C1-350	431.7	0.1087	382.0	0.0487	0.1110	12.99	31410
C1-520	454.9	0.1234	382.7	0.0493	0.1699	16.89	31410
C1-700	458.6	0.1254	389.7	0.0498	0.1466	19.99	31410
C2-350	375.7	0.0537	369.5	0.0495	0.0577	6.41	53083
C2-520	399.0	0.0710	380.9	0.0498	0.0710	9.16	53083
C2-700	429.2	0.0951	384.8	0.0479	0.1032	13.03	53083
C3-350	263.7	0.0184	260.8	0.0186	0.0192	0.77	80410
C3-520	277.5	0.0220	275.5	0.0198	0.0220	1.00	80410
C3-700	298.3	0.0257	295.1	0.0249	0.0257	1.49	80410

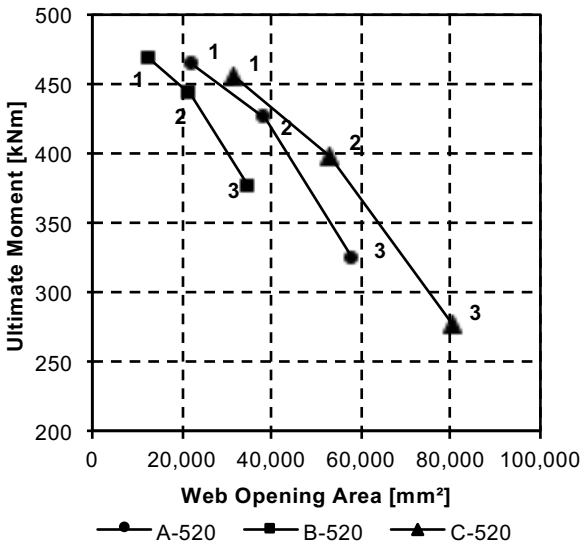
All connections with openings have effectively reduced the shear deformation of the panel zone.

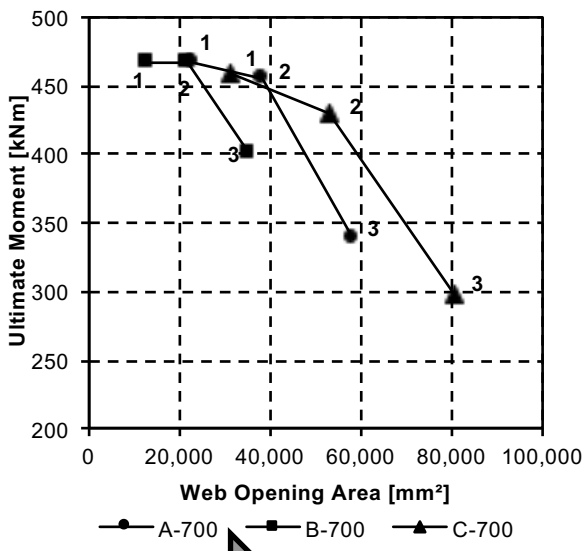
Moment Capacity against WOA

UNIVERSITY OF LEEDS

Monotonic

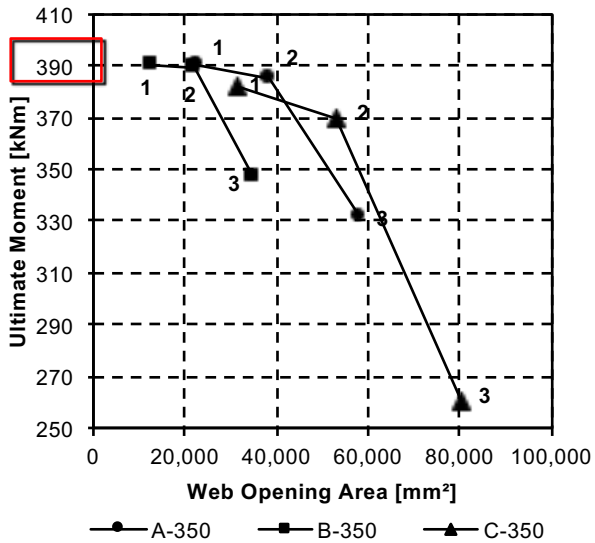


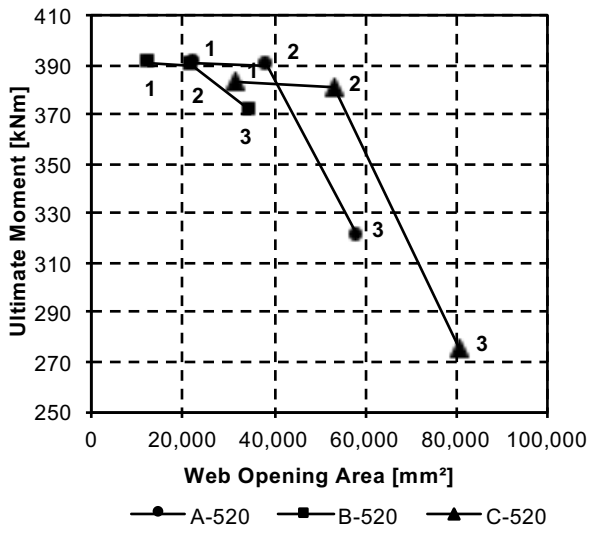


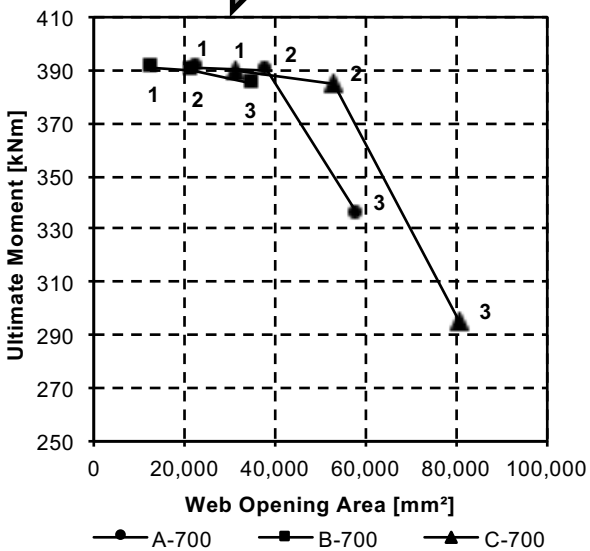


S increases

Cyclic







Results: Monotonic / Cyclic

UNIVERSITY OF LEEDS

Connection Type	Ultimate Rotation, φ_u [rad.]		Monotonic/Cyclic
	Cyclic Loading	Monotonic Loading	
Solid	0.04970	0.1290	2.60
A1-350	0.04996	0.1163	2.33
A1-520	0.04996	0.1262	2.53
A1-700	0.05000	0.1279	2.56
A2-350	0.04969	0.0775	1.56
A2-520	0.04996	0.0943	1.89
A2-700	0.04996	0.1180	2.36
A3-350	0.04993	0.0231	0.46
A3-520	0.04996	0.0293	0.59
A3-700	0.04995	0.0368	0.74
B1-350	0.04986	0.1112	2.23
B1-520	0.04996	0.1277	2.56
B1-700	0.04996	0.1282	2.57
B2-350	0.04996	0.0940	1.88
B2-520	0.04991	0.1082	2.17
B2-700	0.04981	0.1280	2.57
B3-350	0.04996	0.0386	0.77
B3-520	0.04977	0.0542	1.09
B3-700	0.04996	0.0743	1.49
C1-350	0.04870	0.1087	2.23
C1-520	0.0493	0.1234	2.50
C1-700	0.0498	0.1254	2.52
C2-350	0.0495	0.0537	1.08
C2-520	0.0497	0.0710	1.43
C2-700	0.0479	0.0951	1.98
C3-350	0.0187	0.0184	0.98
C3-520	0.0198	0.0220	1.11
C3-700	0.0249	0.0257	1.04

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

Geometric Parameters

UNIVERSITY OF LEEDS

Parameter do

Bigger

Vierendeel

Reducing stress from the connection

Balance

Parameter S

Smaller

Vierendeel

Reducing stress from the connection

Opening Shape

Large novel B or Medium other shape

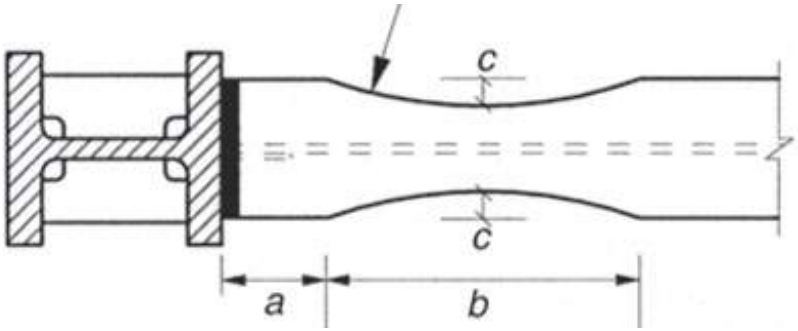
Control Vierendeel

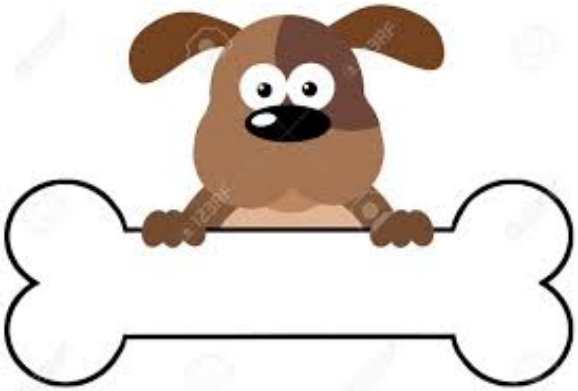
Control Plasticity via Shear Hinges

Let's Baptise it!

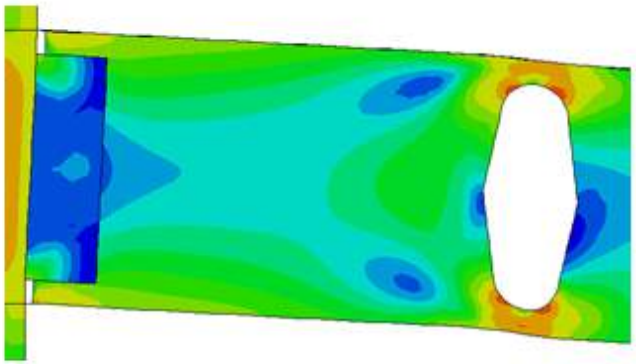
UNIVERSITY OF LEEDS

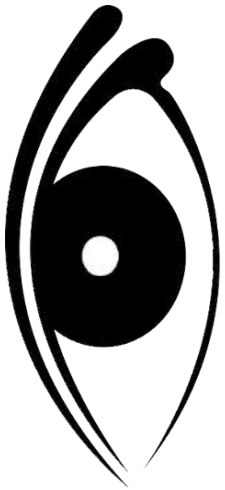
RBS → Dog-Bone Connection





RWS → Inverted-Eye Connection



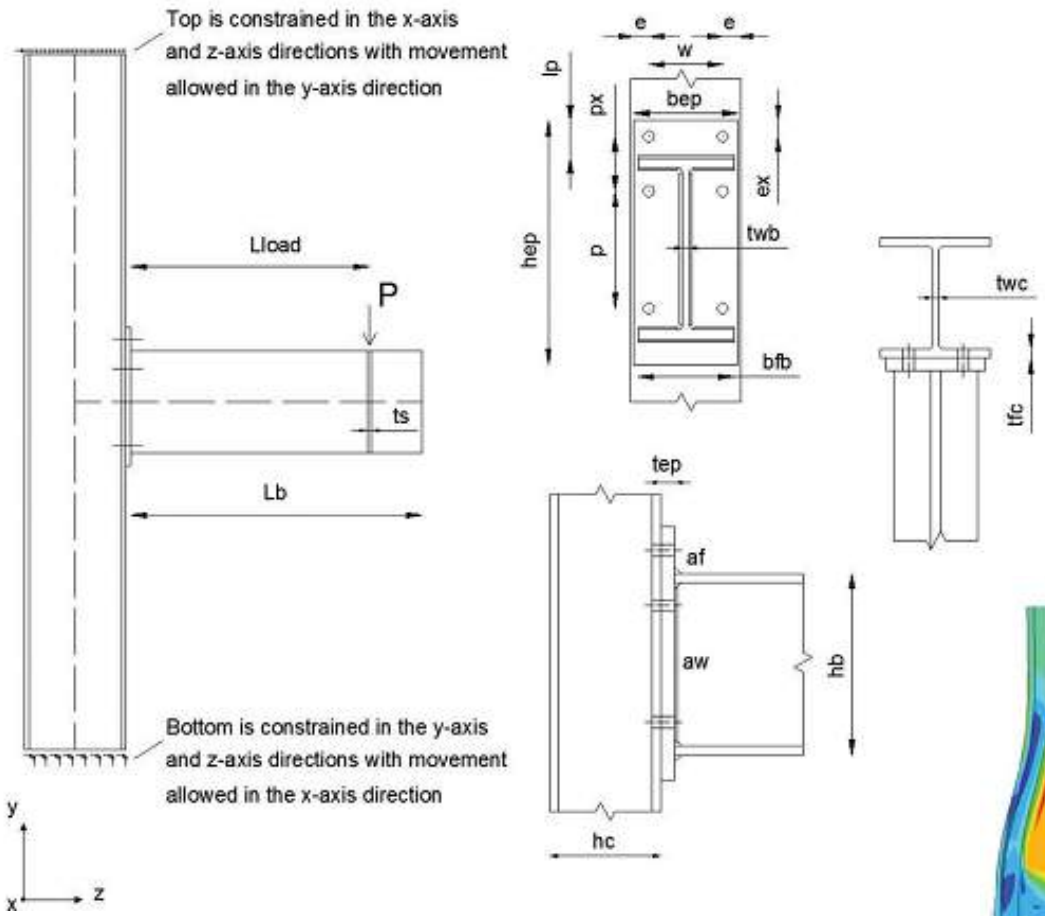


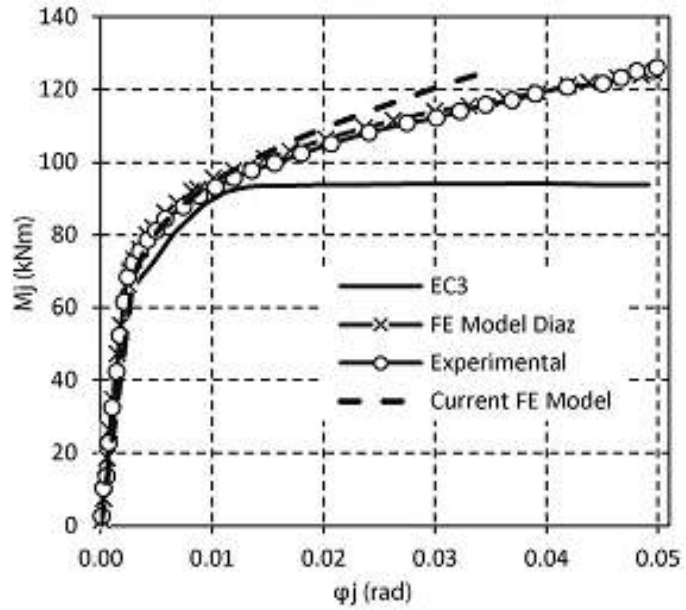
UNIVERSITY OF LEEDS

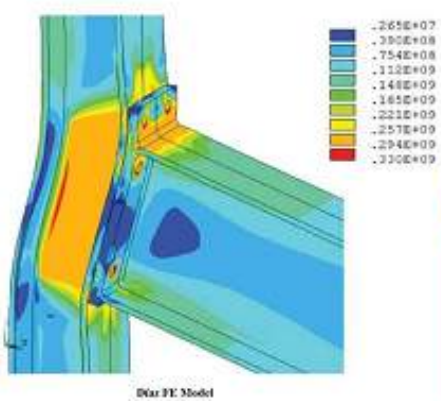
Bolted Connections with isolated web openings and perforated beams

Test Apparatus and Validation Study

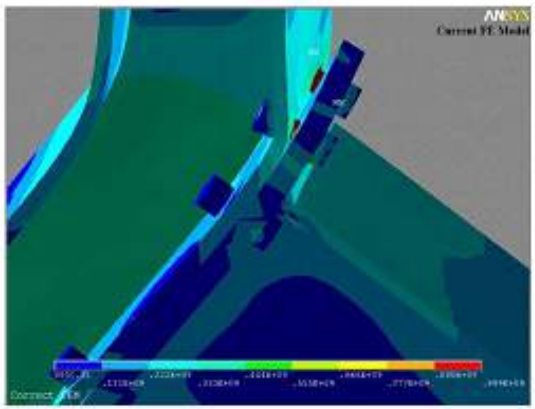
UNIVERSITY OF LEEDS







(a) $M_{j,u}$ = 124.1kNm

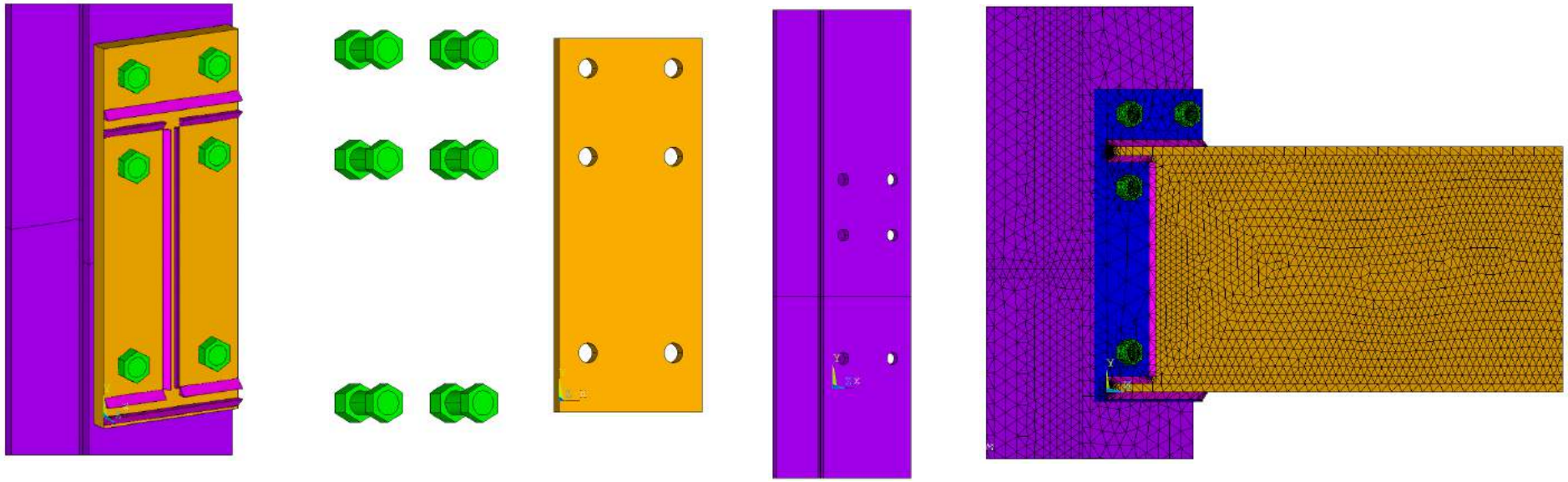


(b) $M_{j,u}$ = 124.1kNm

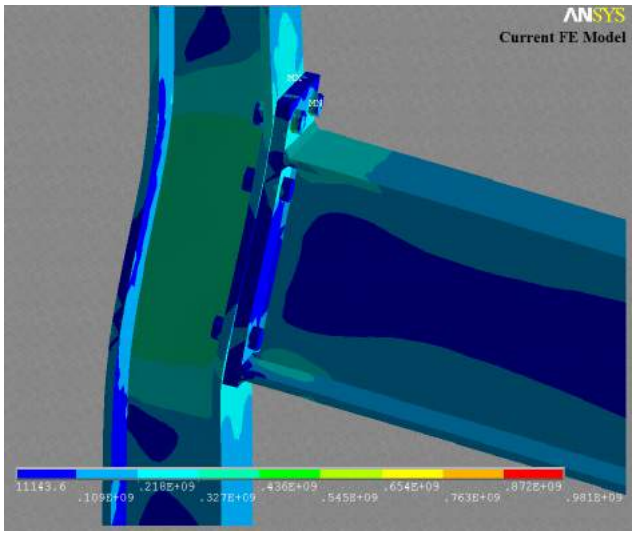
C. Díaz, M. Victoria, P. Marti, O. Querin, FE model of beam-to-column extended endplate joints, J. Constr. Steel Res. 67 (2011) 1578–1590

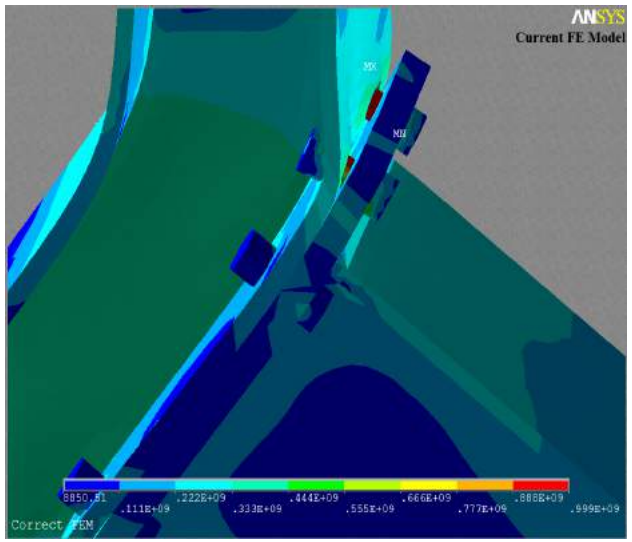
FE Modelling

UNIVERSITY OF LEEDS



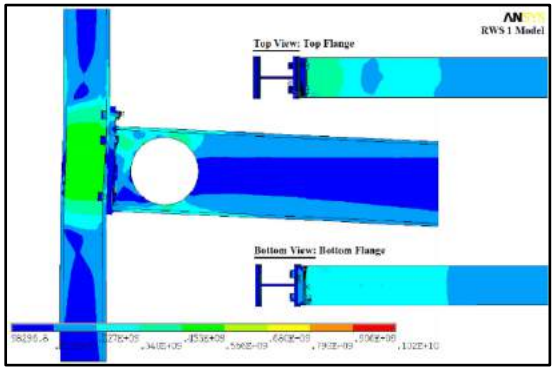
- Solid elements
- Contact elements
- Mapped meshing and manual refinements
- Mesh convergence
- Eigen buckling

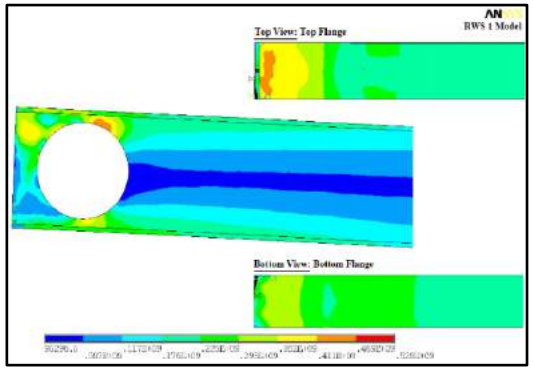




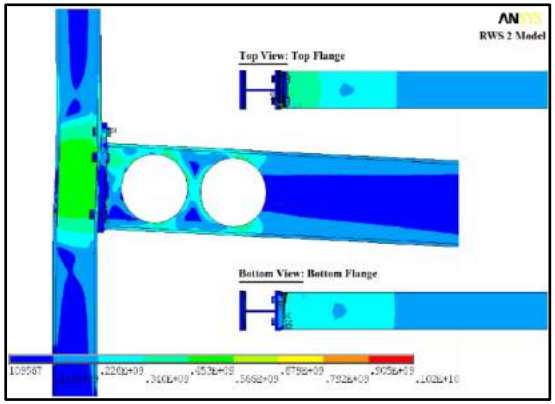
Beam Failure Mode & RWS

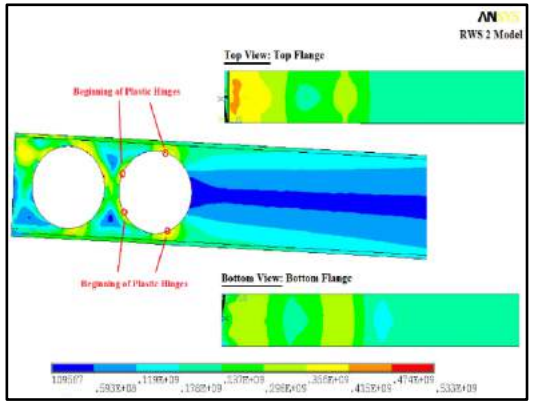
UNIVERSITY OF LEEDS



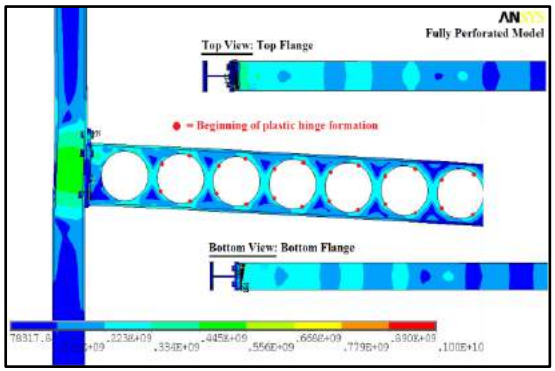


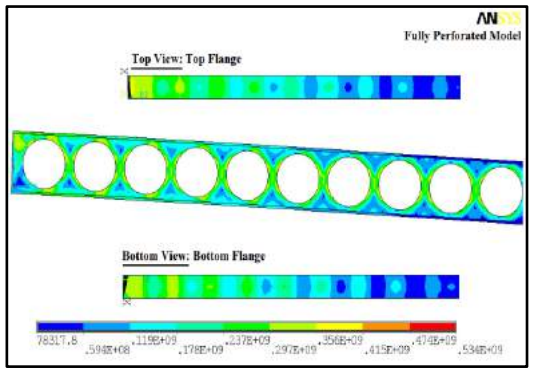
RWS → Vierendeel (Shear) mechanism



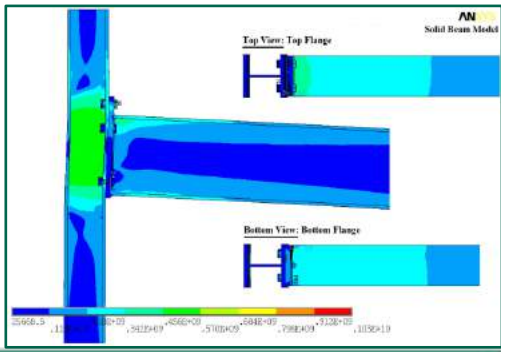


RWS → Web-post Buckling mechanism



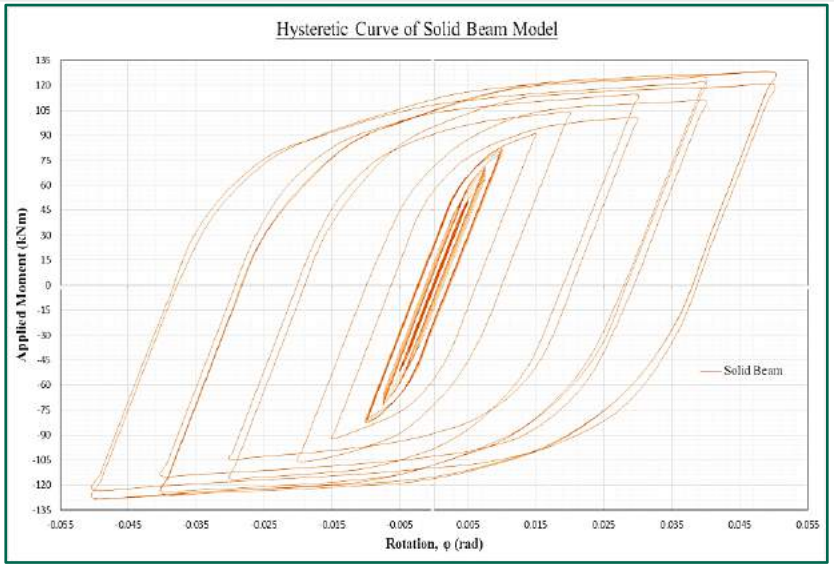


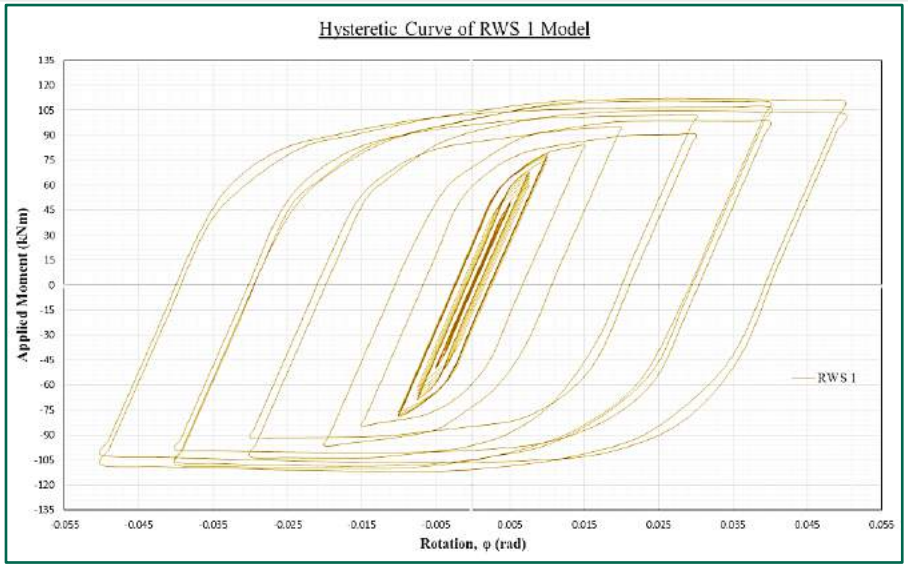
RWS → LTB mechanism

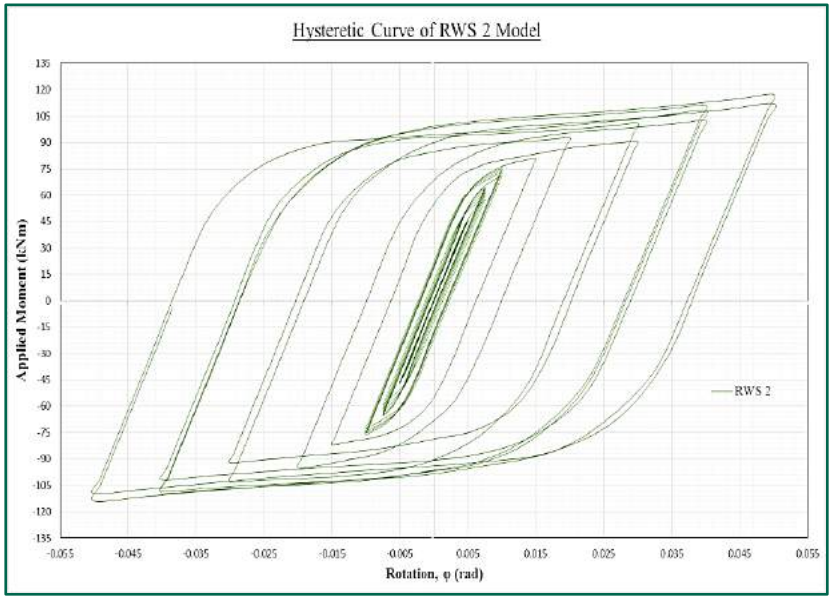


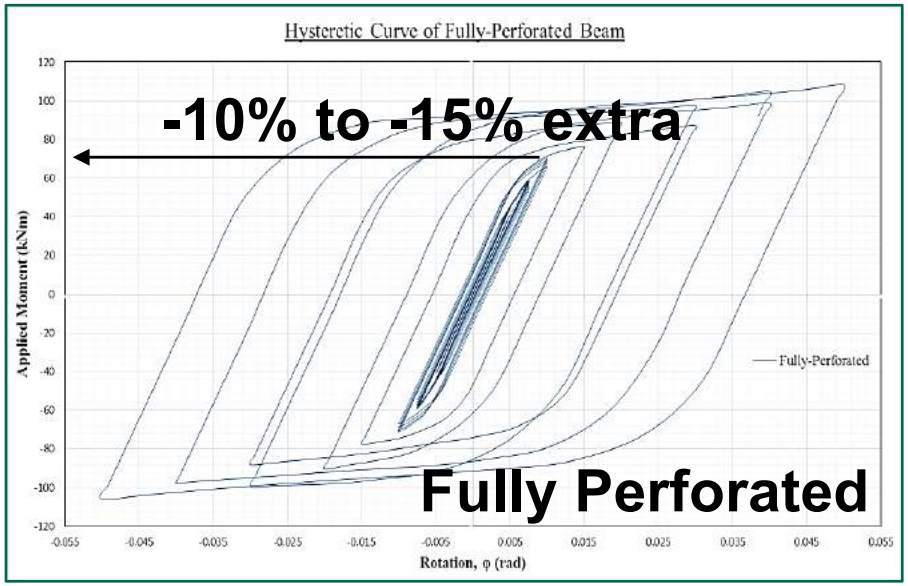
Reduced Moment Capacity

UNIVERSITY OF LEEDS



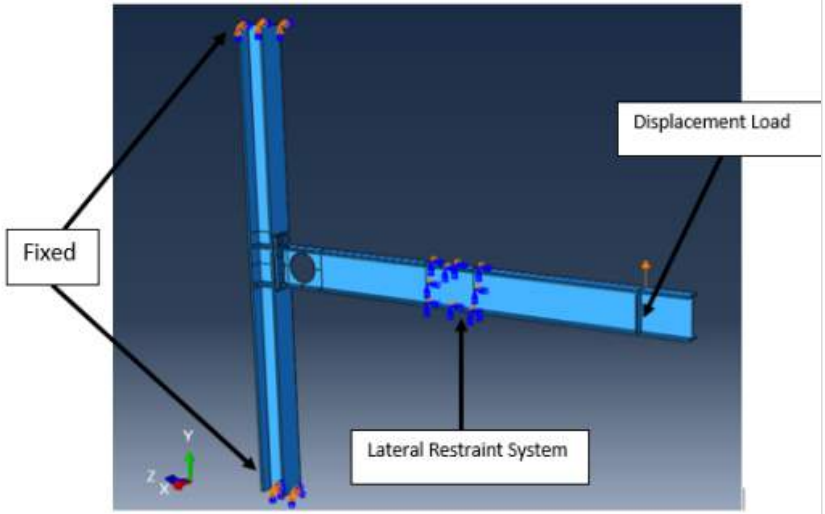


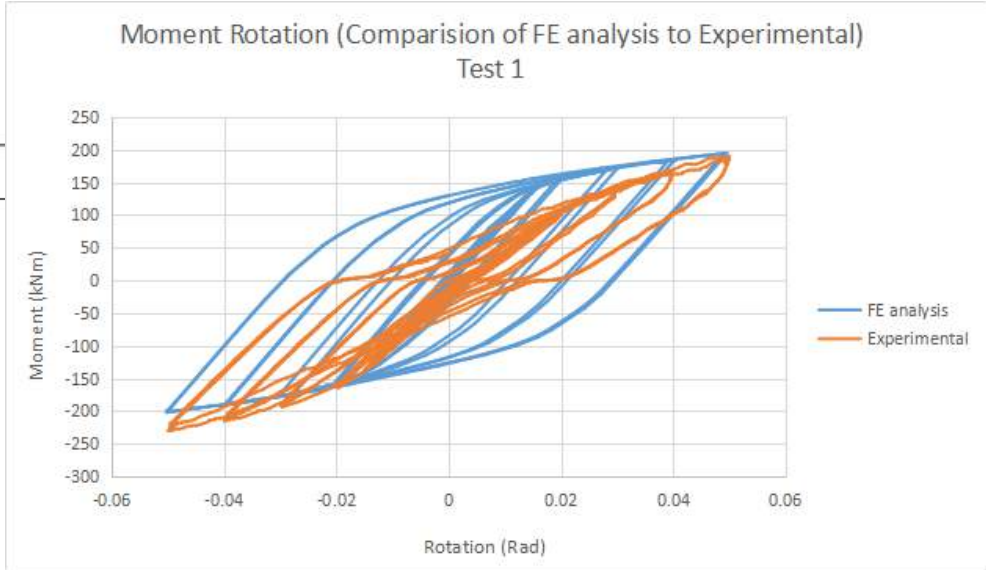




Current Experimental Campaign

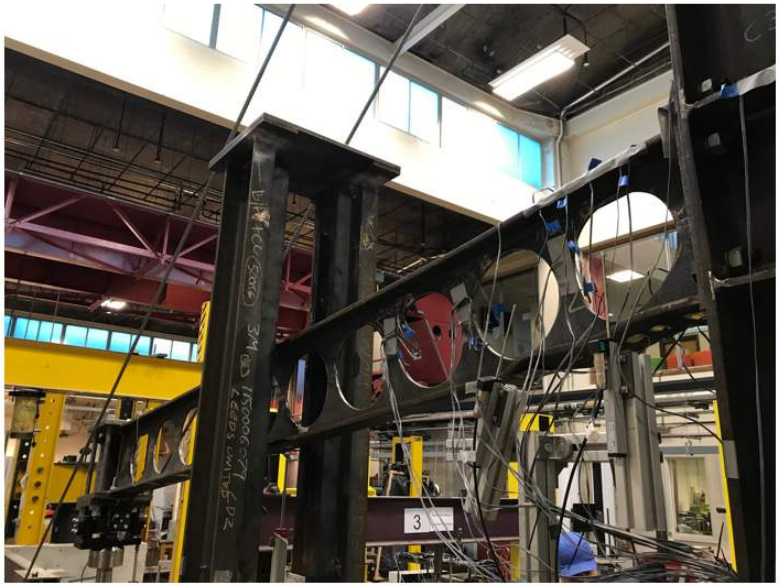
UNIVERSITY OF LEEDS

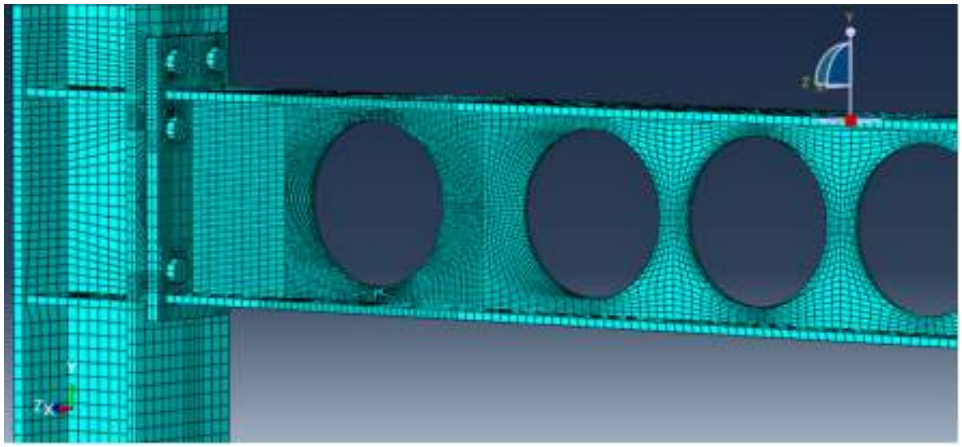


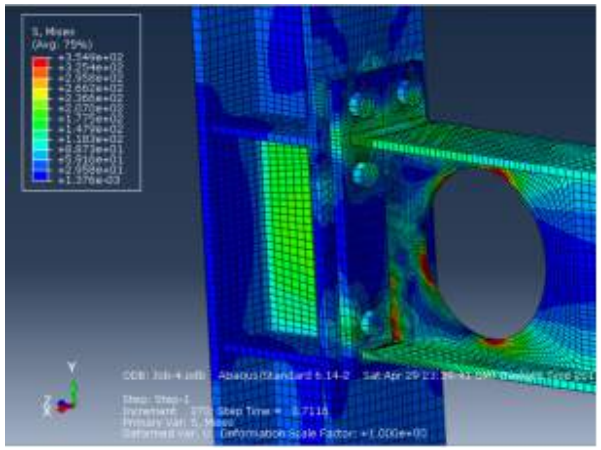


Current Experimental Campaign

UNIVERSITY OF LEEDS





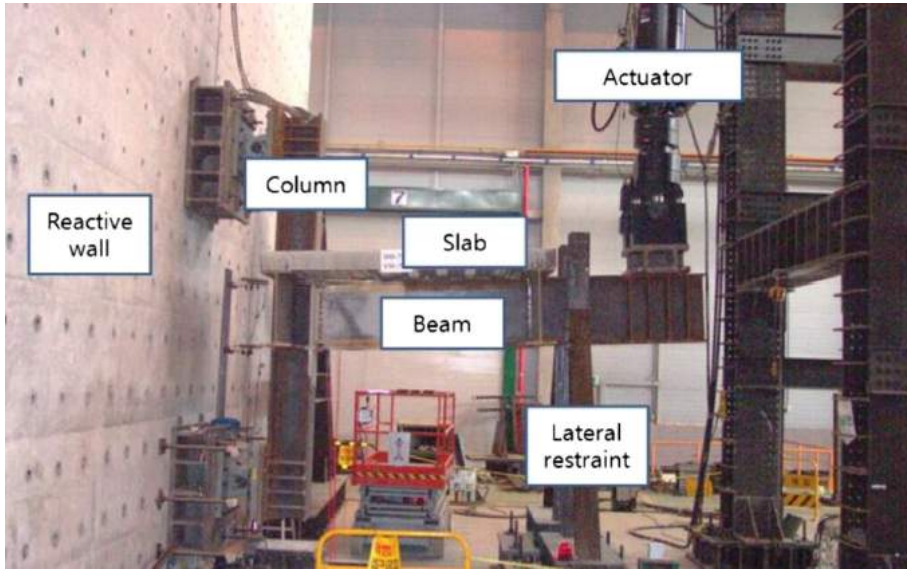


UNIVERSITY OF LEEDS

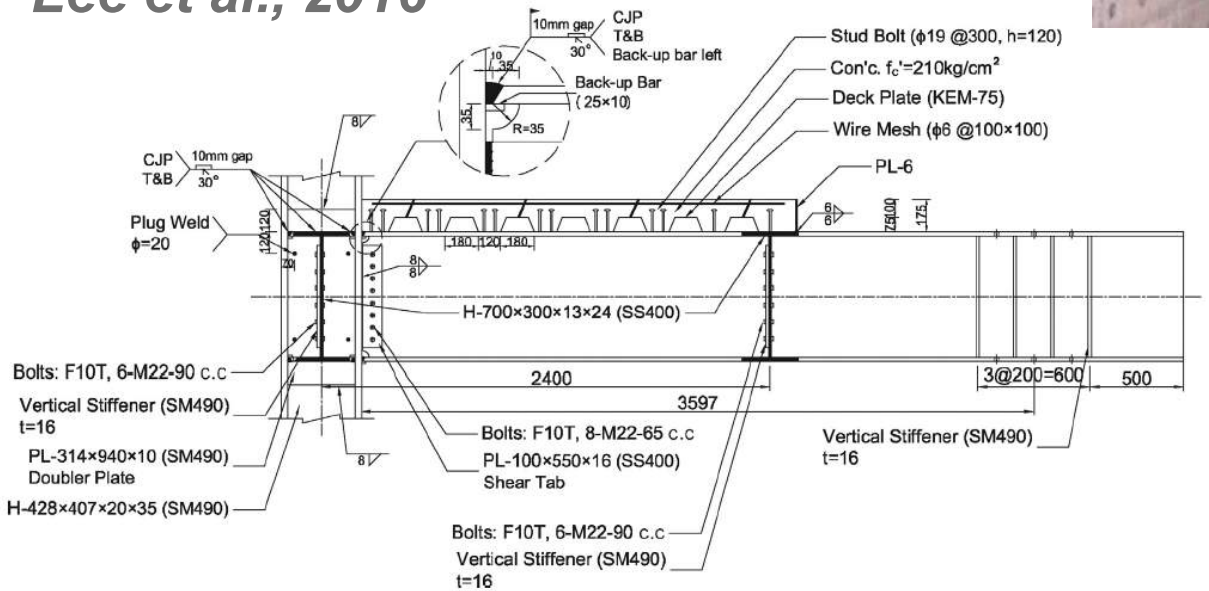
Composite WUF-B Connections with isolated web openings

Test Apparatus

UNIVERSITY OF LEEDS



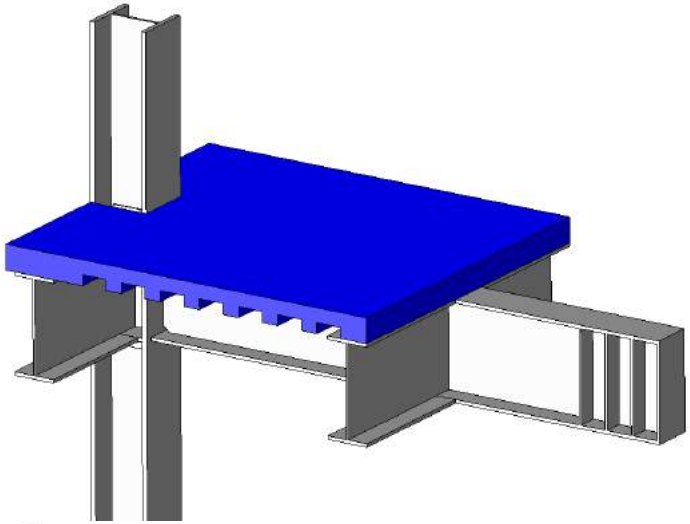
Lee et al., 2016

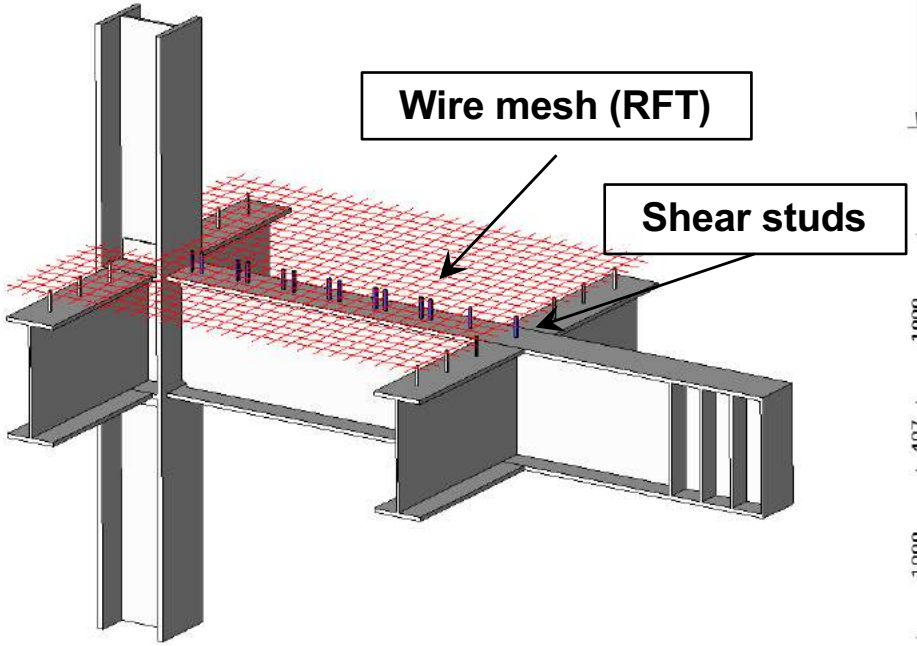


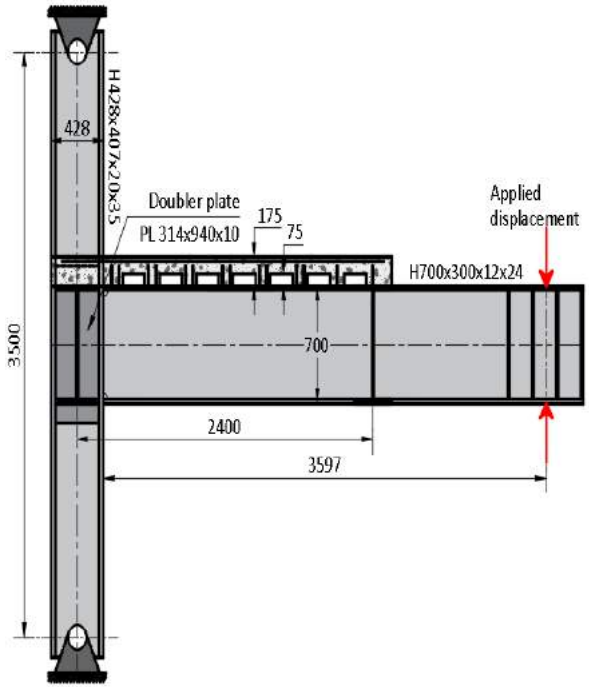
Validation Study

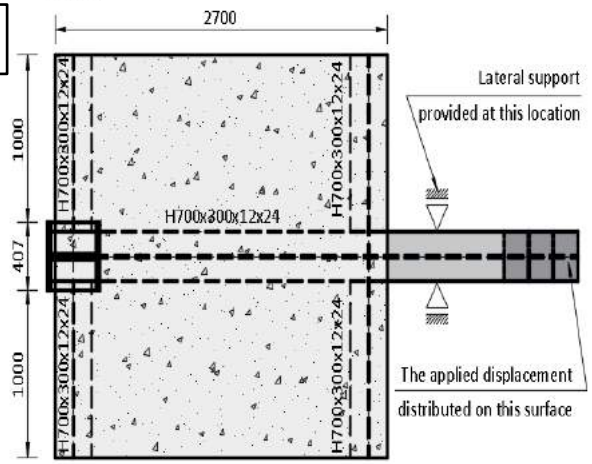
UNIVERSITY OF LEEDS

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



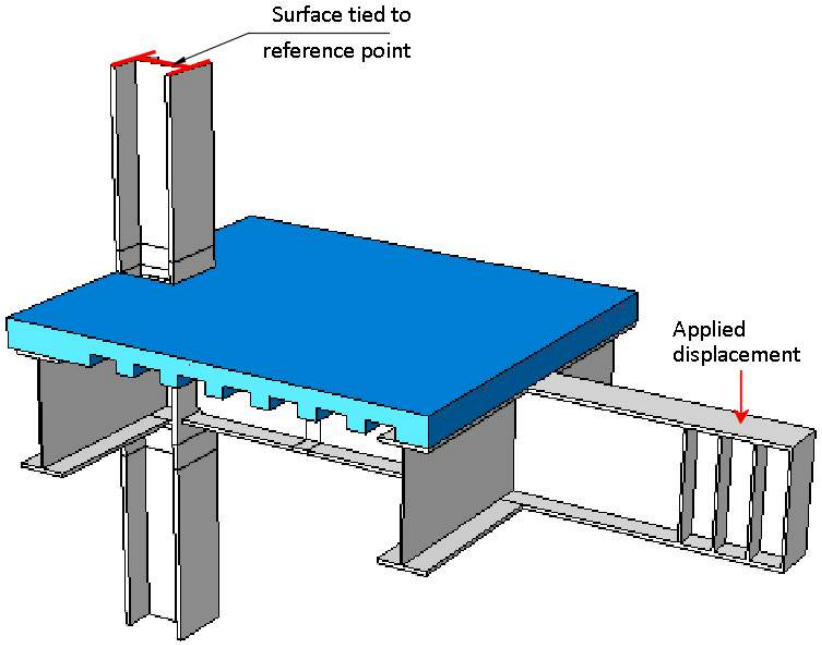




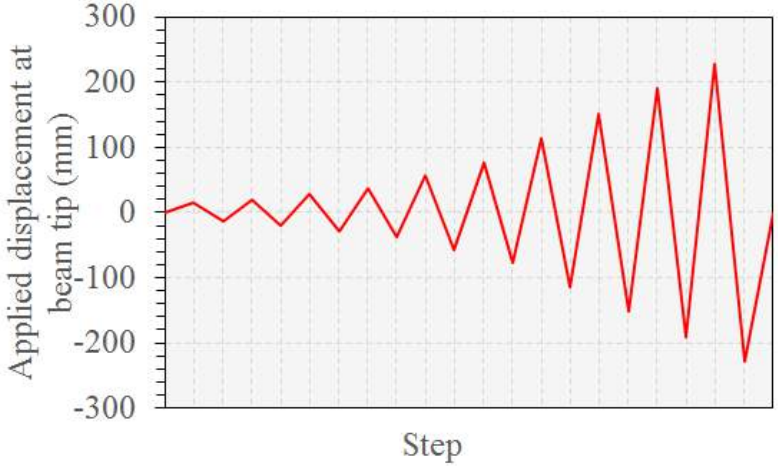


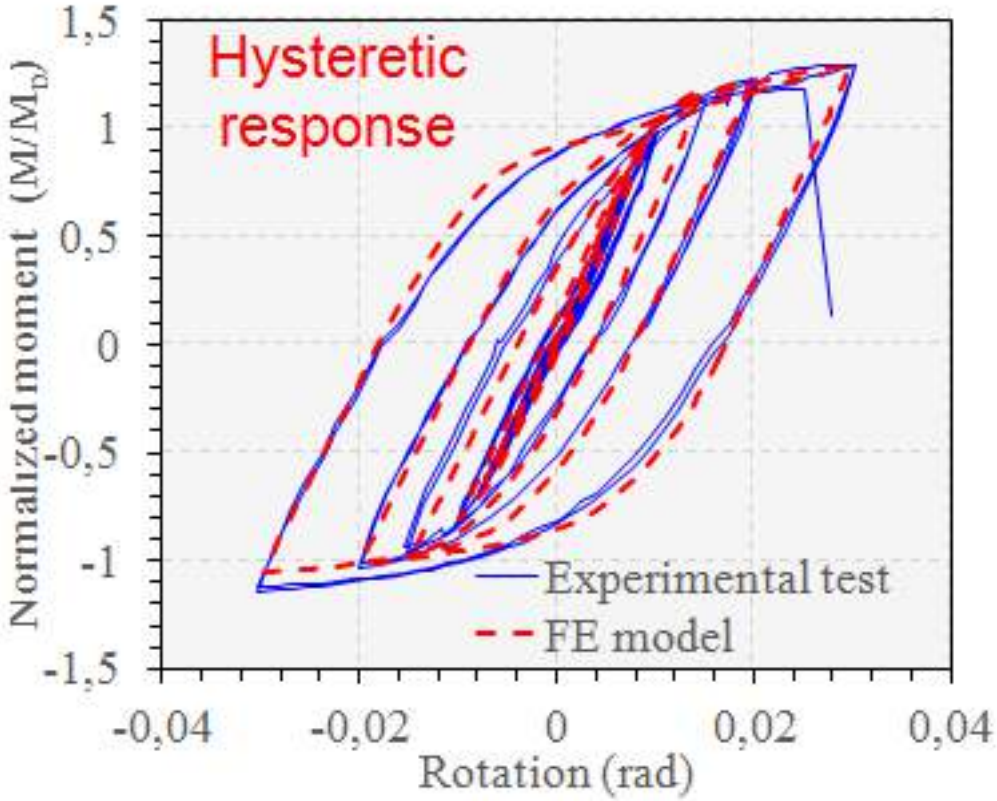
Validation Study

UNIVERSITY OF LEEDS



AISC cyclic seismic loading protocol

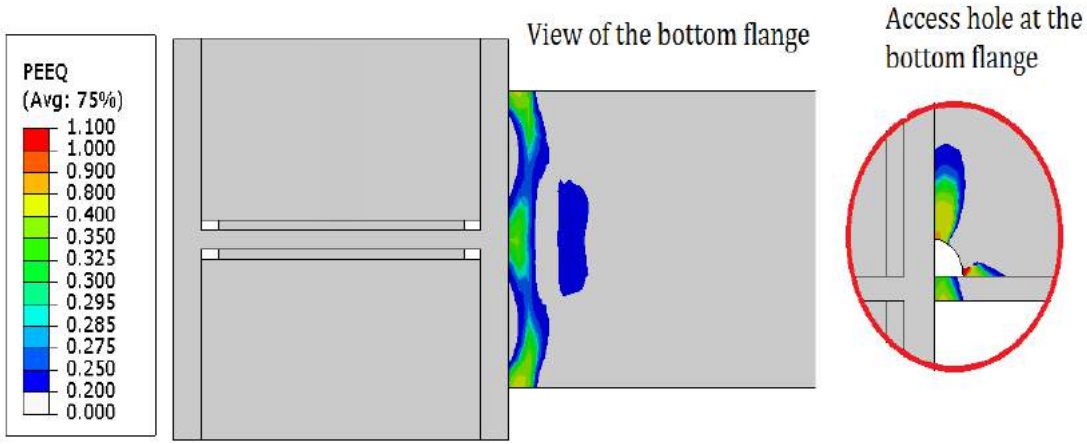




Validation Study

UNIVERSITY OF LEEDS

Rupture of the bottom flange



Parametric Study

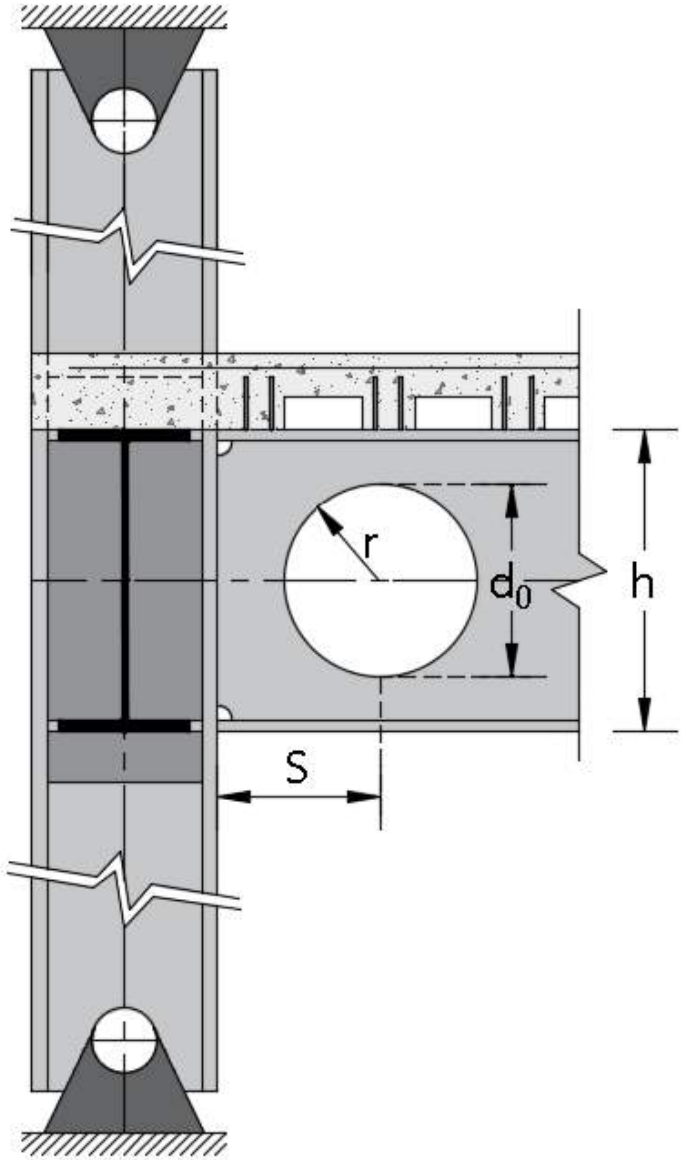
UNIVERSITY OF LEEDS

P - 75d - 150S

Representing the percentage of the edge distance to the *h*.
For instance **150*S*** means ***S*=150%*h***

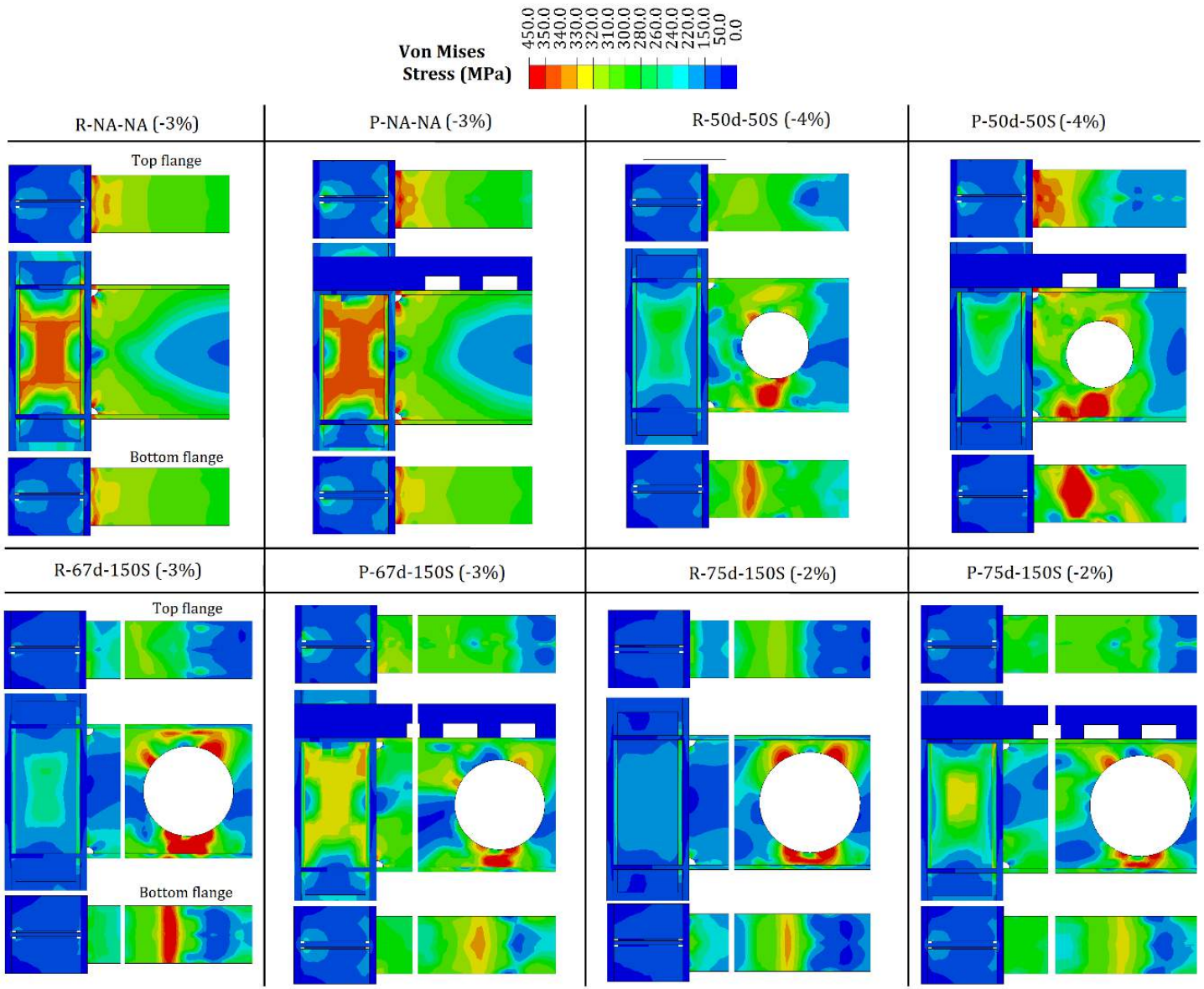
Indicating the percentage of the opening depth to the *h*.
For instance **75*d*** means d_0=75%*h*

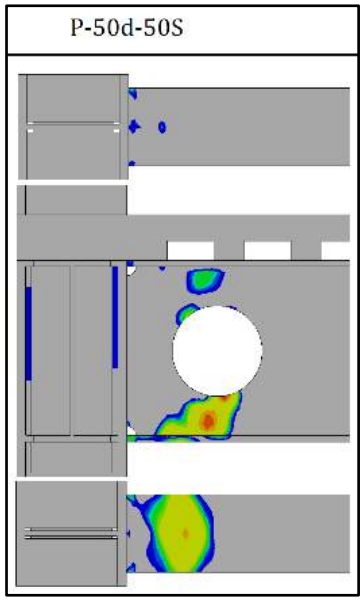
Letter representing the connection type (R=Bare, P=Composite connection).



Stress Distribution

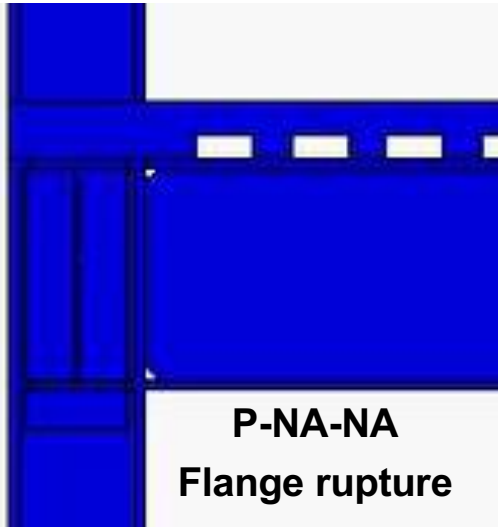
UNIVERSITY OF LEEDS

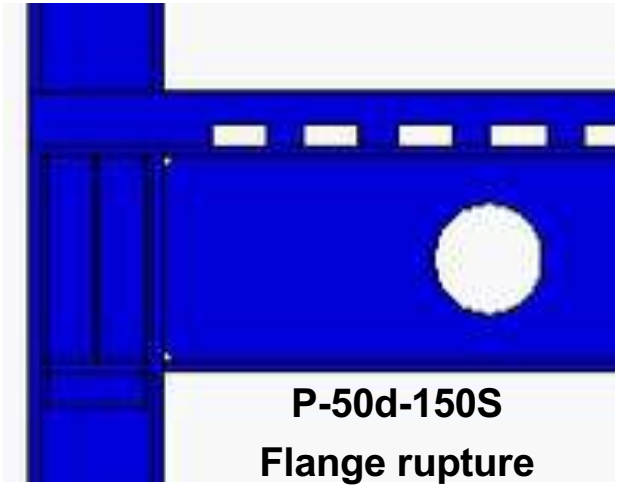


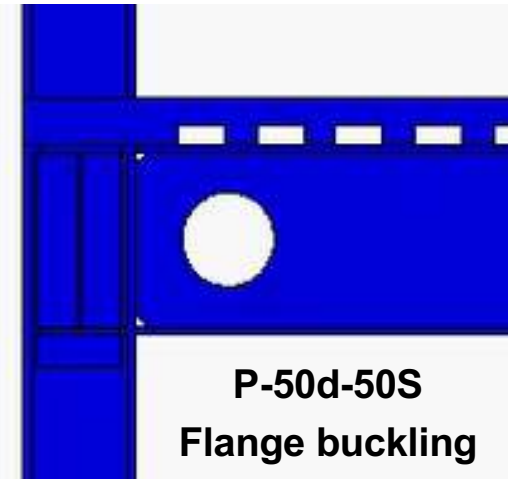


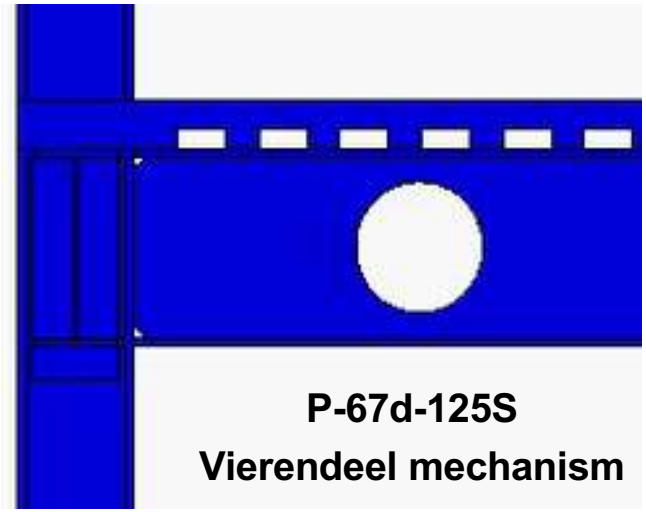
Failure Modes

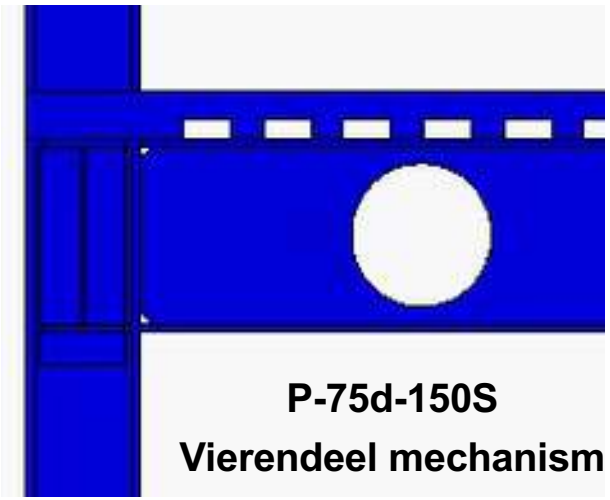
UNIVERSITY OF LEEDS







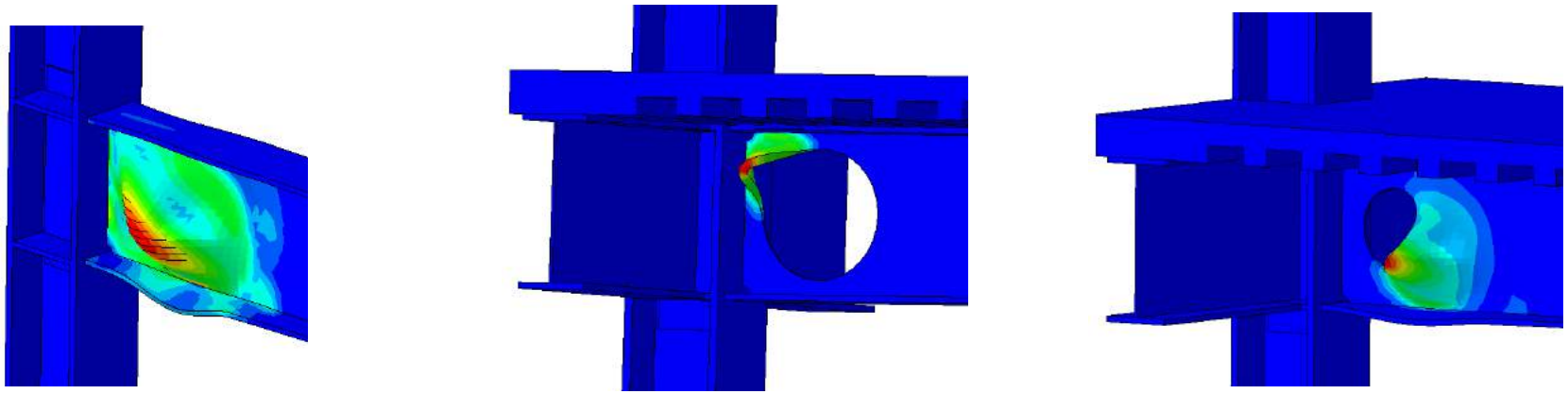




Effect of Composite Action

UNIVERSITY OF LEEDS

Web opening		0.5h	0.67h	0.75h
Composite contribution % in positive direction	⇨	25%	43%	65%
Composite contribution % in negative direction	⇨	3%	16%	31%



UNIVERSITY OF LEEDS

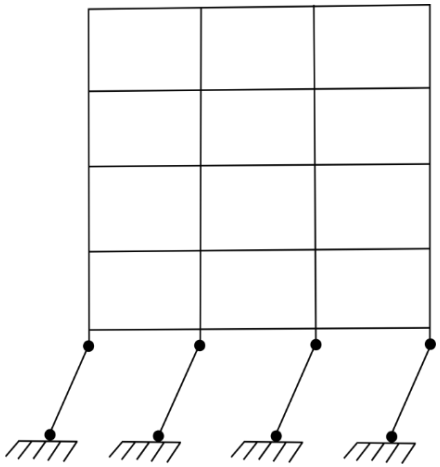
Frame Analysis
(Incremental Dynamic Analysis - IDA)

Dr Konstantinos Daniel TSAVDARIDIS

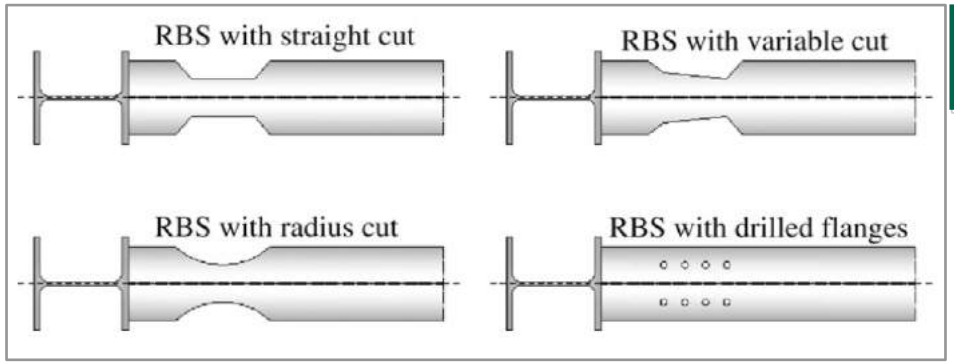
Analysis Methodology

UNIVERSITY OF LEEDS

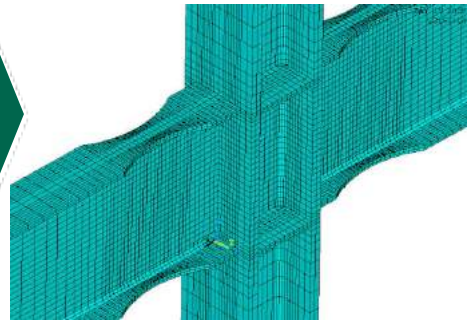
Soft storey

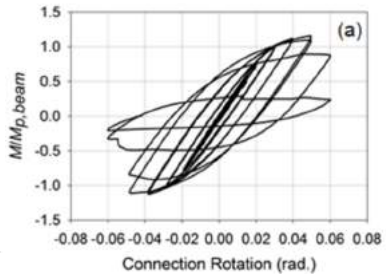


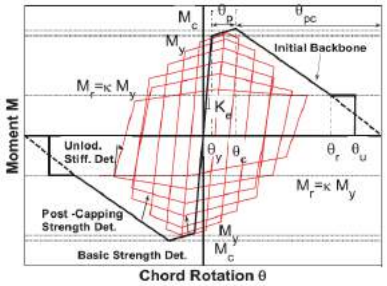
RBS/RWS systems



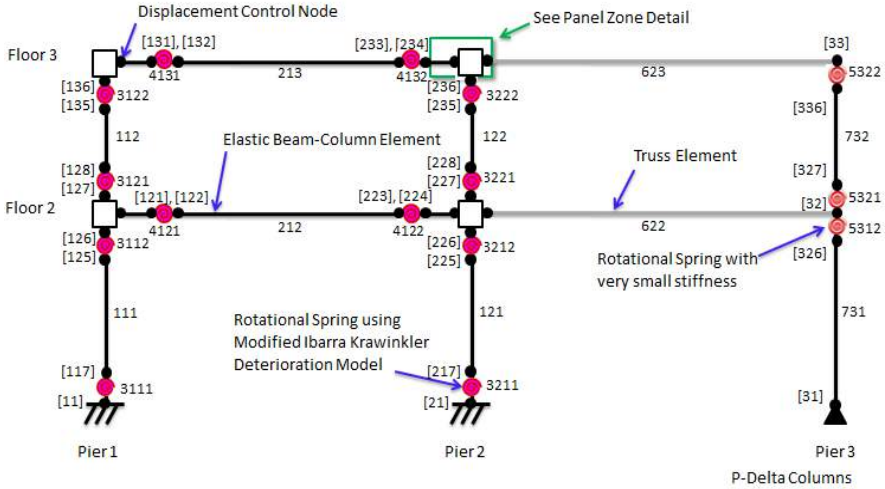
FEA



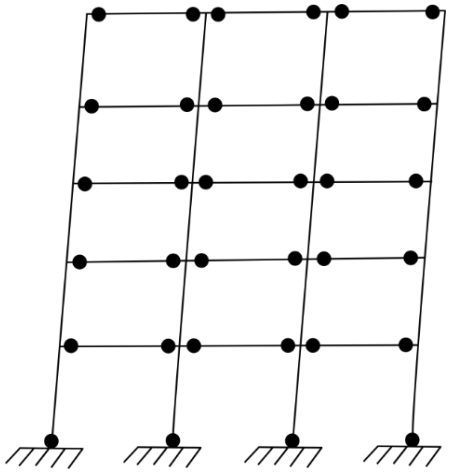




Spring elements



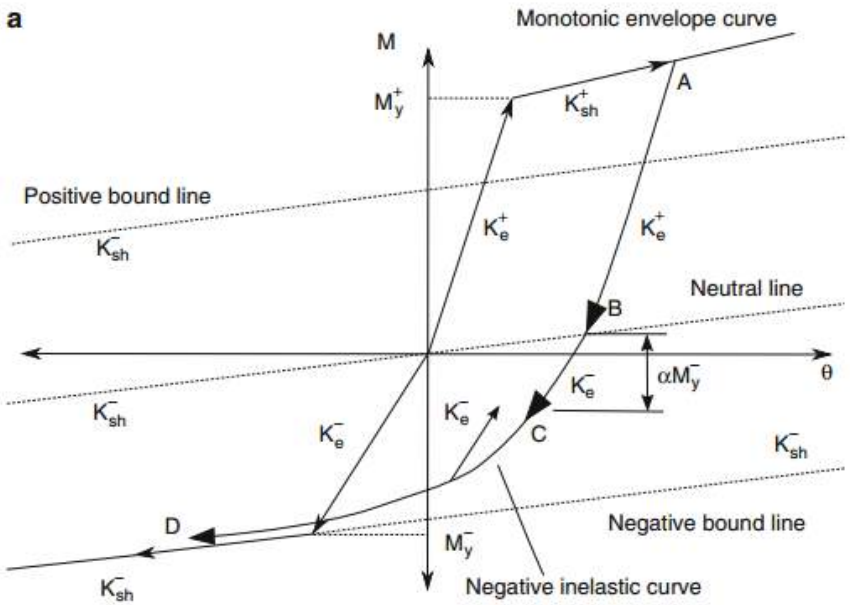
Weak beam – Strong Column



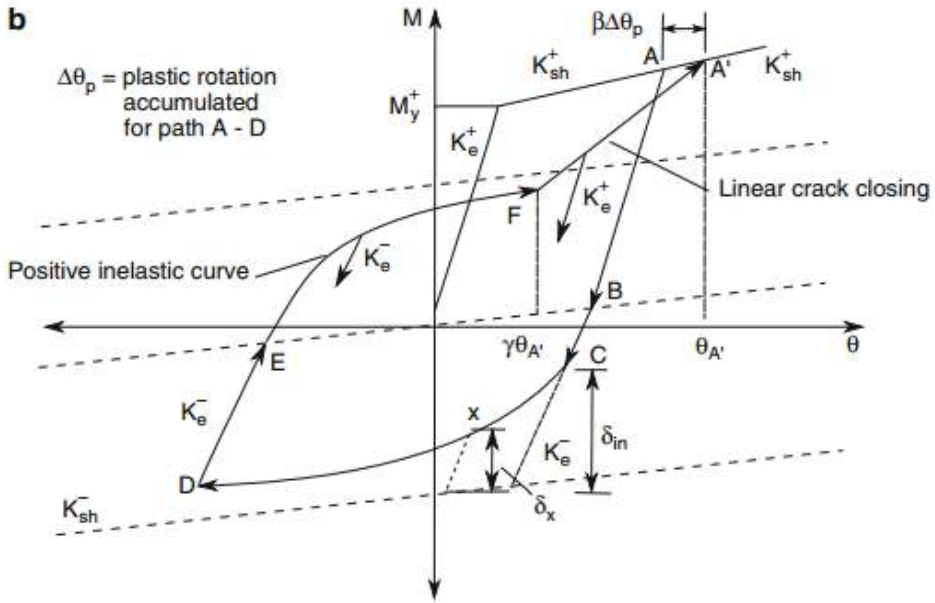
Connection Properties

UNIVERSITY OF LEEDS

Monotonic Model

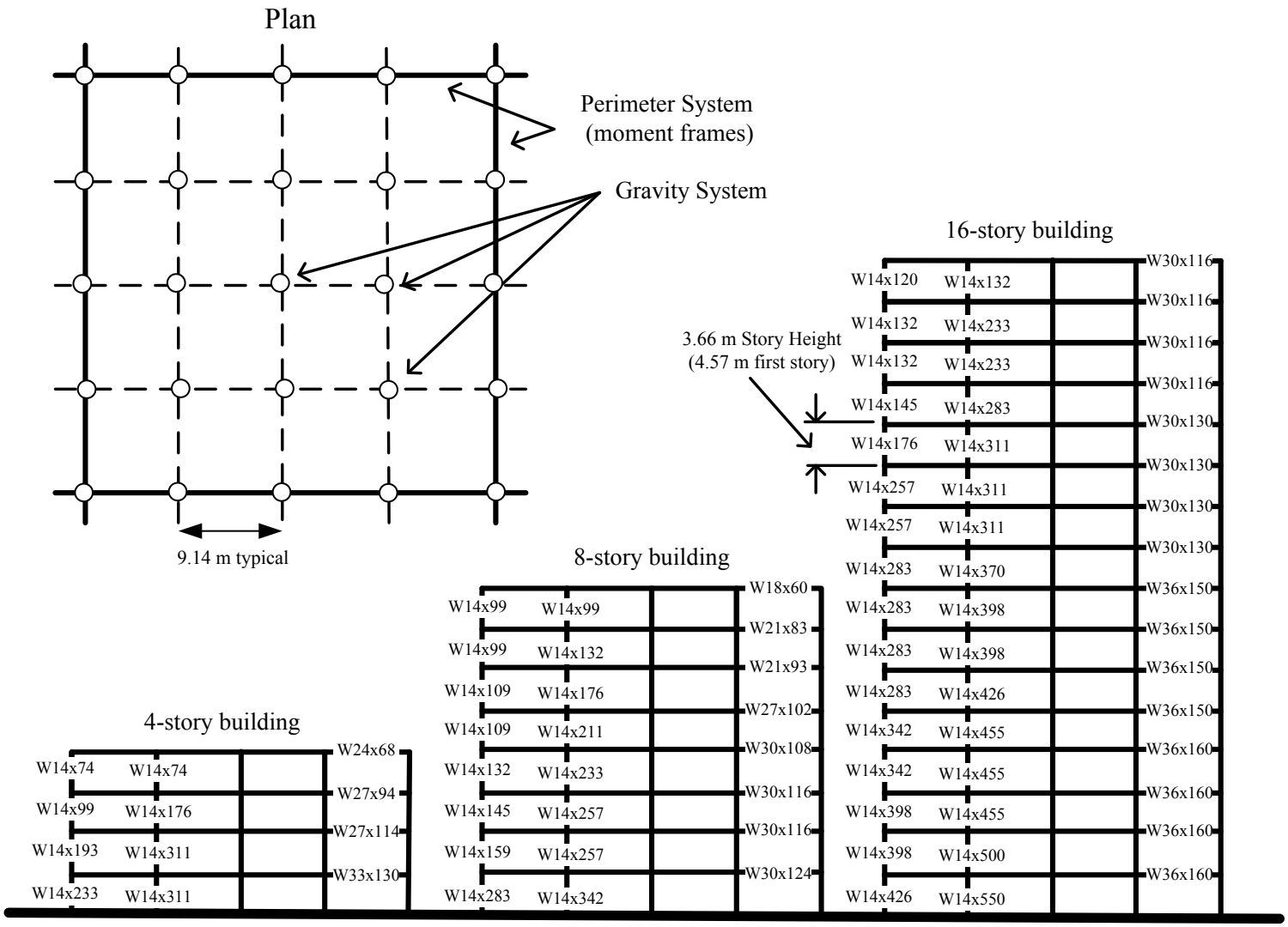


Hysteretic Model



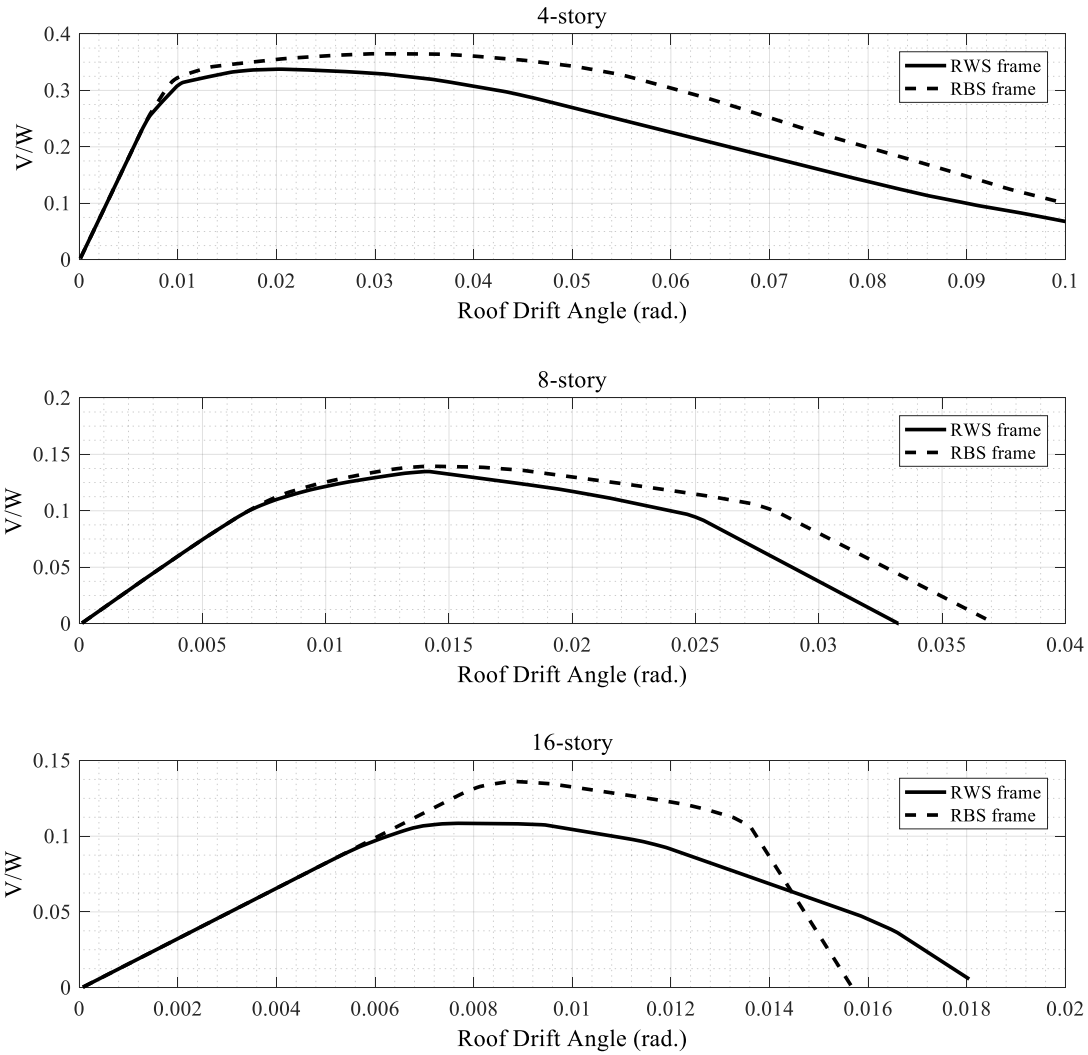
- Tsavdaridis, K.D. Seismic Analysis of Steel-Concrete Composite Buildings, to the section: Structural Engineering - Structural Analysis: Numerical Modelling, ***Encyclopedia of Earthquake Engineering***, Springer Verlag, **2014**, pp. 1-36

Frame Analysis



Push-Over Curves

UNIVERSITY OF LEEDS



Ground Motion Records

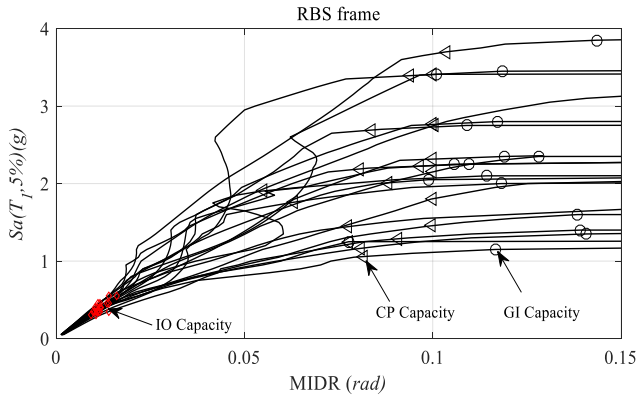
UNIVERSITY OF LEEDS

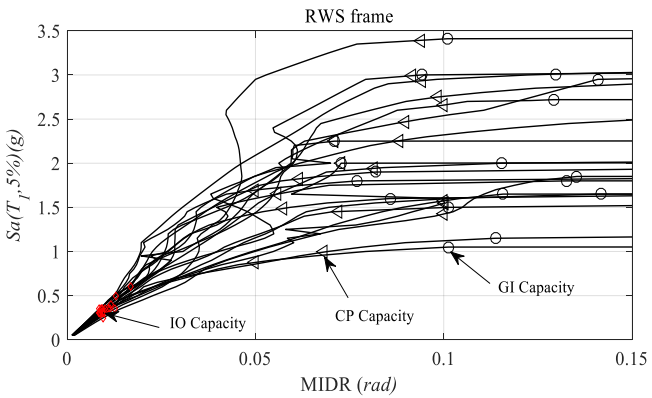
EQ Index	Mag	Year	Earthquake Name	Fault Type
1	6.5	1979	Imperial Valley	Strike-slip
2	6.5	1979	Imperial Valley	Strike-slip
3	7.5	1999	Kocaeli,Turkey	Strike-slip
4	7.3	1992	Landers	Strike-slip
5	6.9	1989	Loma Prieta	Strike-slip
6	6.9	1995	Kobe, Japan	Strike-slip
7	6.9	1989	Loma Prieta	Strike-slip
8	7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

IDA Curves

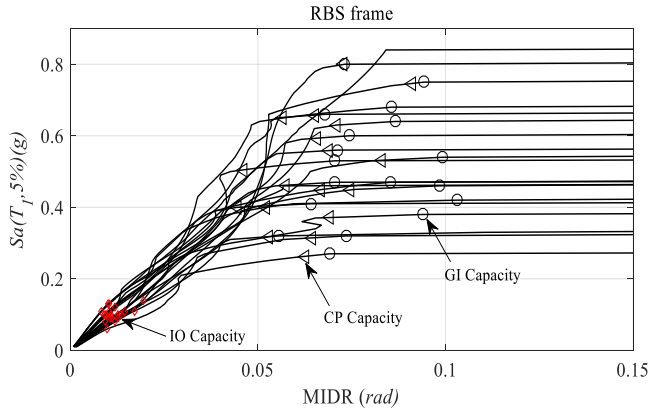
UNIVERSITY OF LEEDS

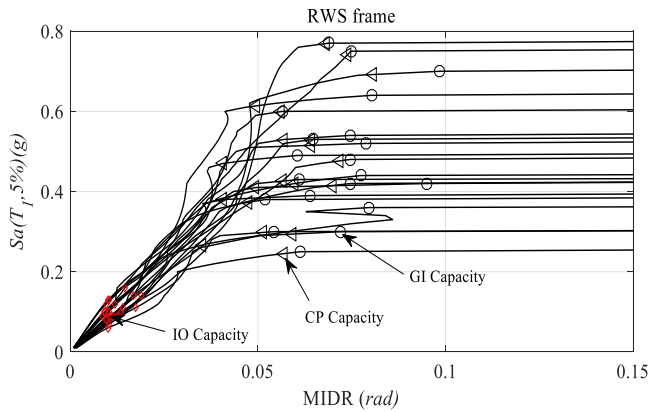
4-story



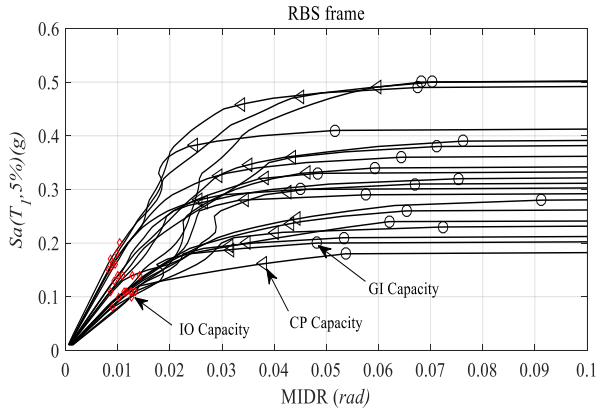


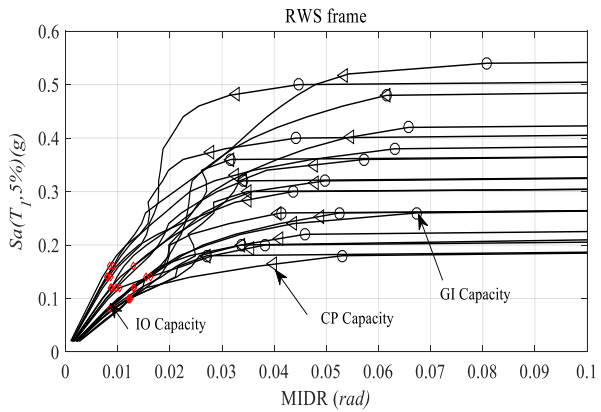
8-story





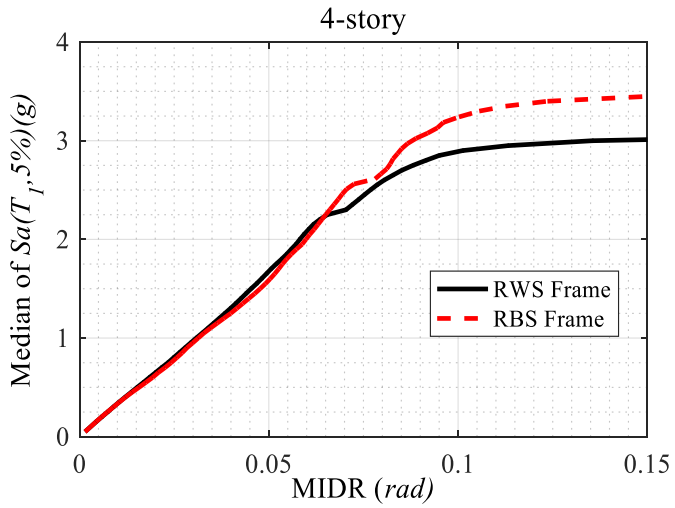
16-story

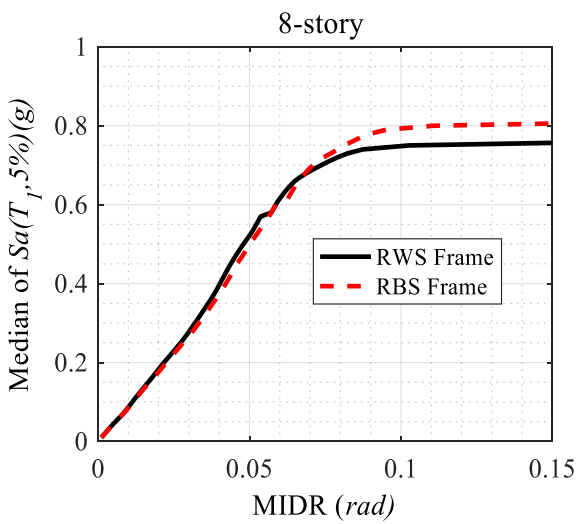


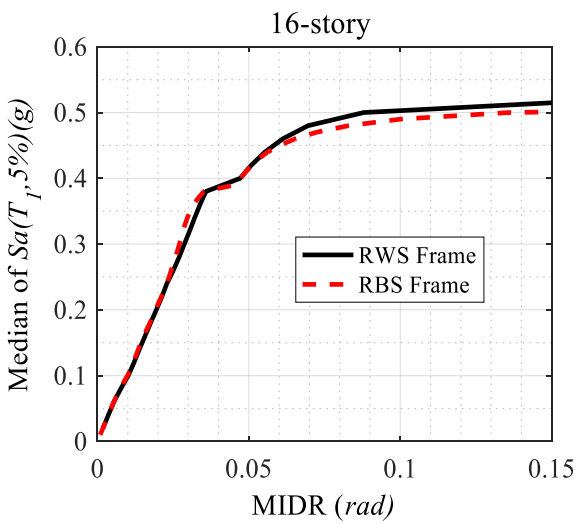


(Geometric) Median of IDA Curves

UNIVERSITY OF LEEDS

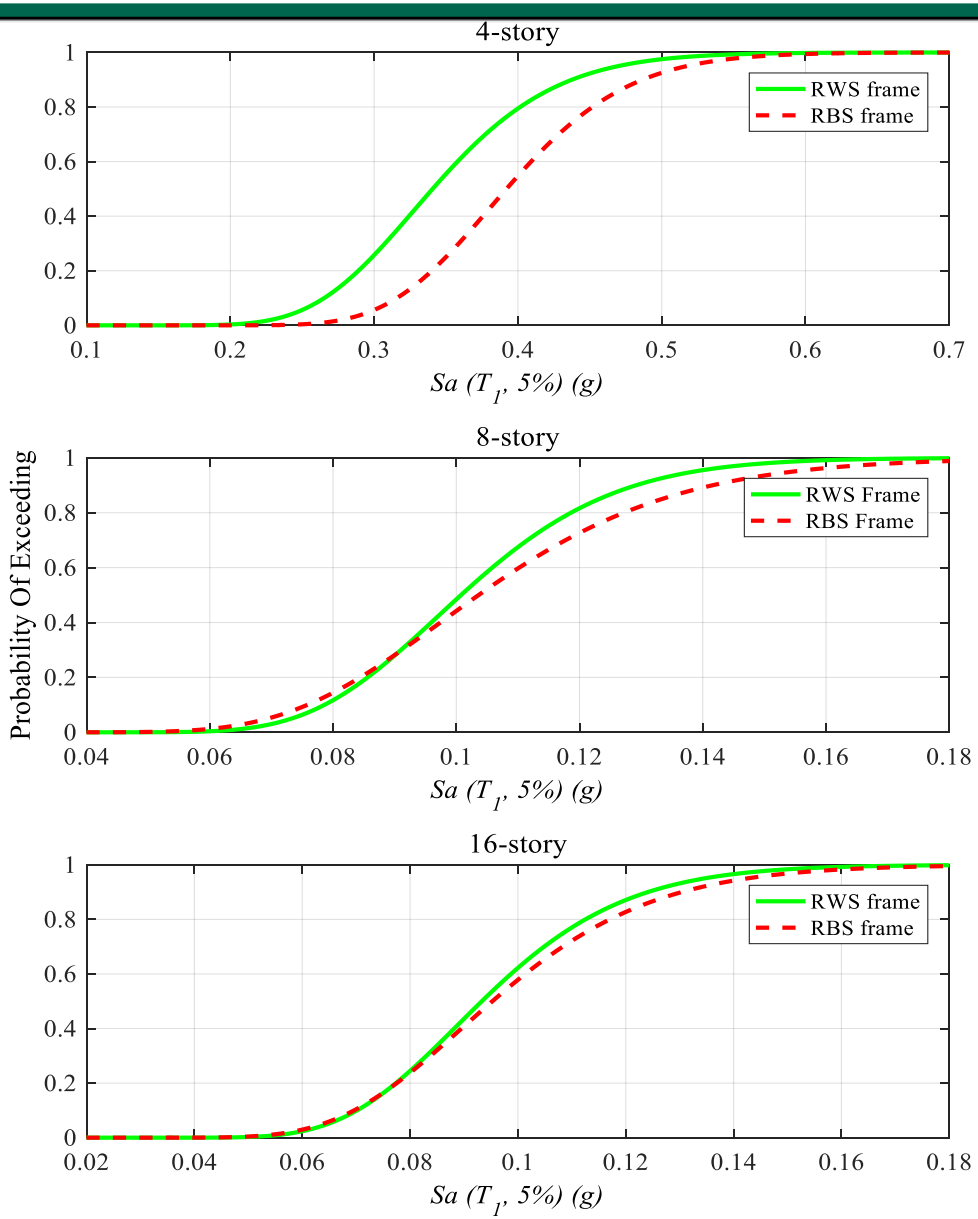






Fragility Curves

UNIVERSITY OF LEEDS



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

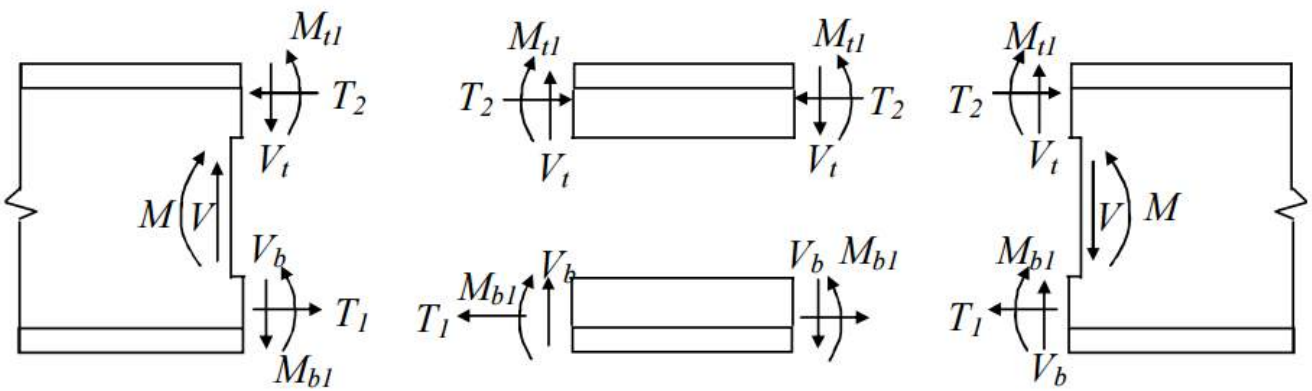
Dr Konstantinos Daniel TSAVDARIDIS

Design Method for WUF-B Connections

UNIVERSITY OF LEEDS

Rotational Moment Capacity of RWS/WUF-B Connections

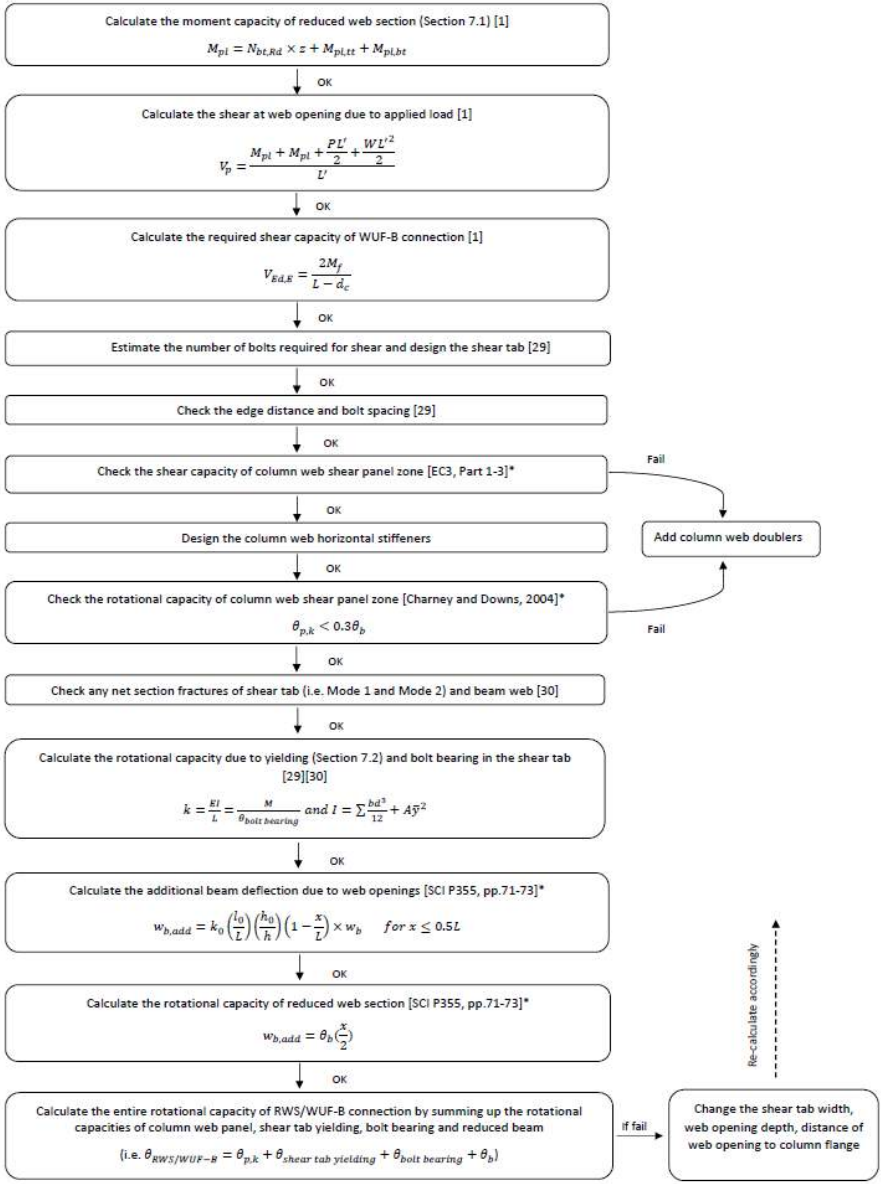
1. Column bending in rotation (EC3, 2005 and P-358, 2014)
2. Yielding of beam web in rotation (EC3, 2005 and P-358, 2014)
3. Bolt bearing failure in fin plate in rotation (EC3, 2005 and P-358, 2014)
4. Yielding of fin plate in rotation
5. Vierendeel bending at reduced web section in rotation



Shear and moment interaction at reduced web section

Design Method for WUF-B Connections

UNIVERSITY OF LEEDS



Design Method for WUF-B Connections

UNIVERSITY OF LEEDS

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]

$$V_p = \frac{M_{pl} + M_{pl} + \frac{PL'}{2} + \frac{WL'^2}{2}}{L'}$$

Vierendeel Bending at Reduced Section

UNIVERSITY OF LEEDS

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

UNIVERSITY OF LEEDS

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]

$$k = \frac{EI}{L} = \frac{M}{\theta_{bolt\ bearing}} \ and\ I = \sum \frac{bd^3}{12} + A\bar{y}^2$$

Design Method for WUF-B Connections

UNIVERSITY OF LEEDS

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

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

↓ OK

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

$$w_{b,add} = \theta_b(\frac{x}{2})$$

↓ OK

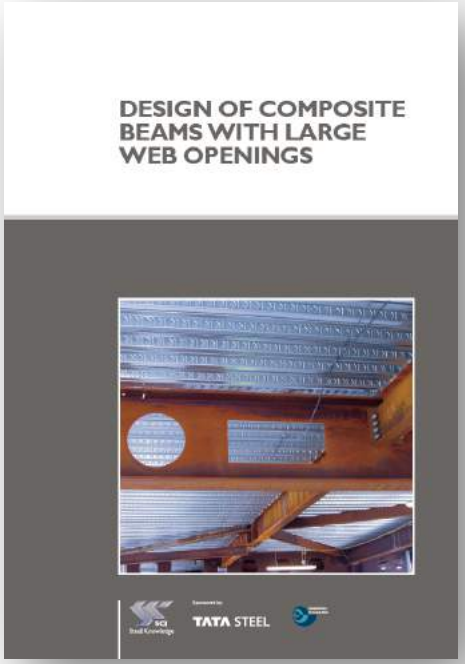
Calculate the entire rotational capacity of RWS/WUF-B connection by summing up the rotational capacities of column web panel, shear tab yielding, bolt bearing and reduced beam

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

Standardisation

UNIVERSITY OF LEEDS

SCI P-100 (1994) → SCI P-355 (2011) → Eurocodes



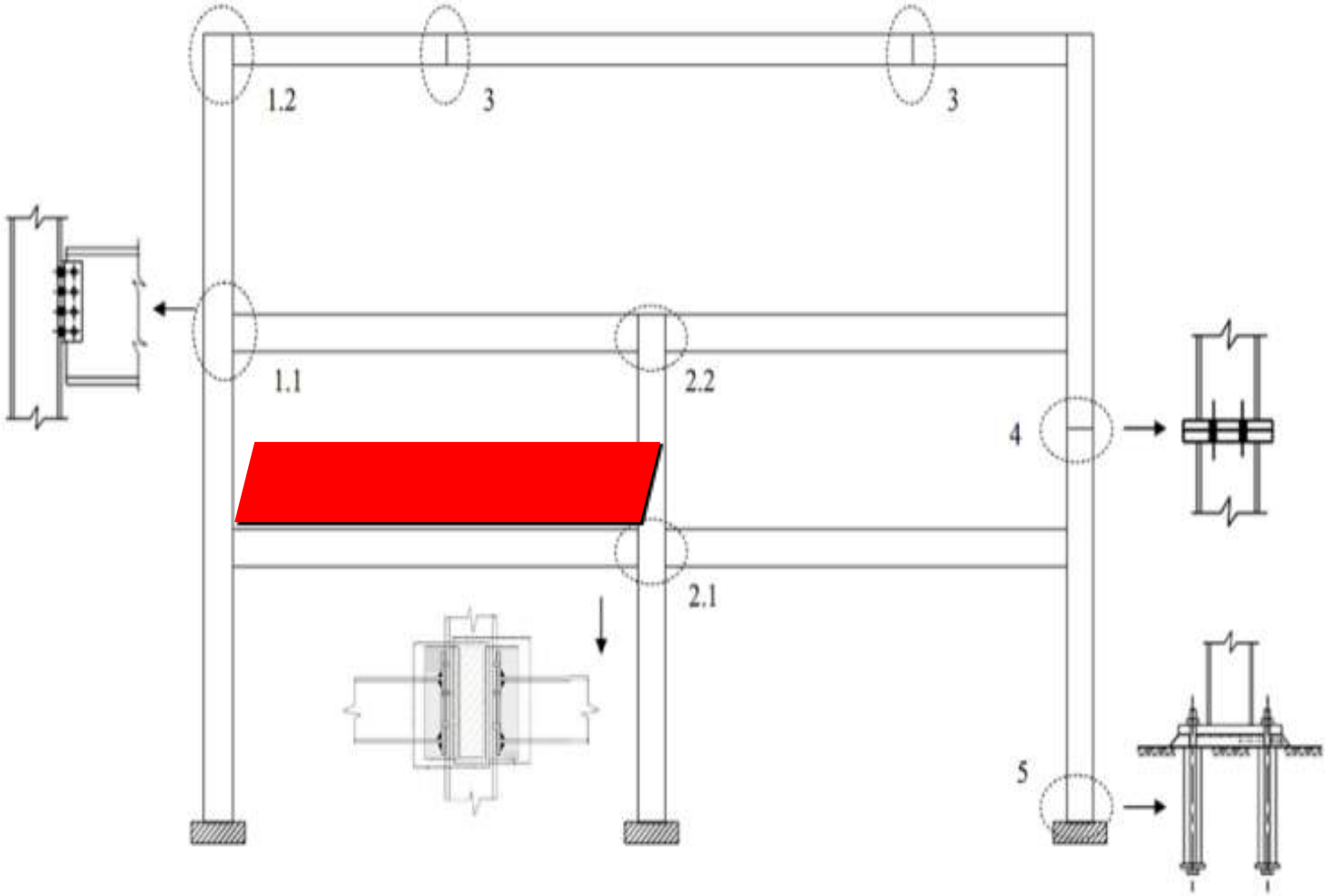
European Committee for Standardization

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

&

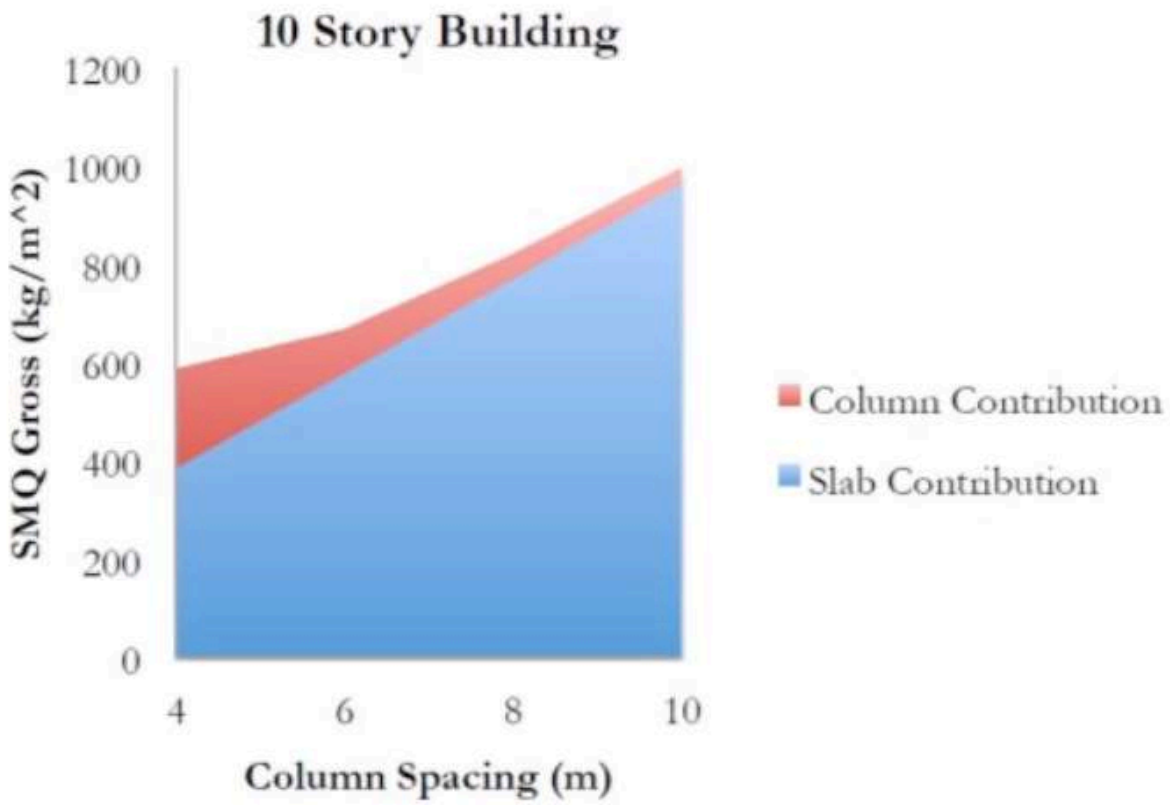
EC8 WG2/TC13 (Earthquake Engineering: Strengthening of Existing Structures

Slabs



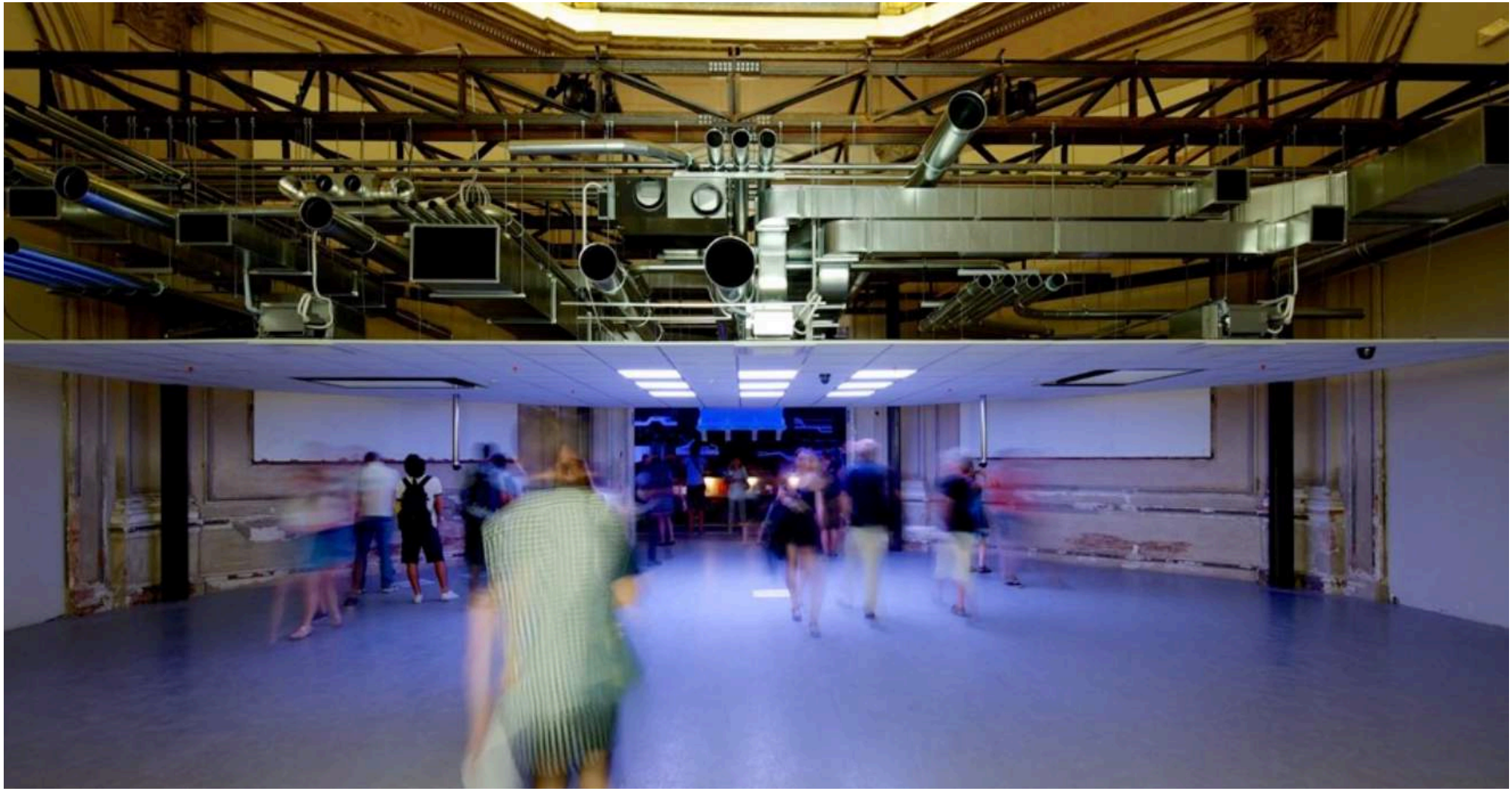
Slabs Design Impact

UNIVERSITY OF LEEDS



Slabs Design Impact

UNIVERSITY OF LEEDS

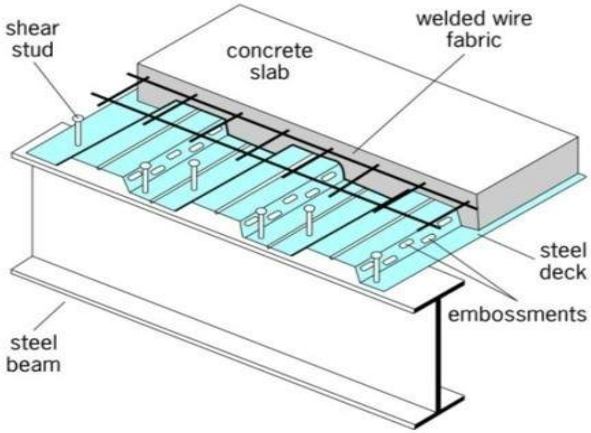


Slabs Design Impact

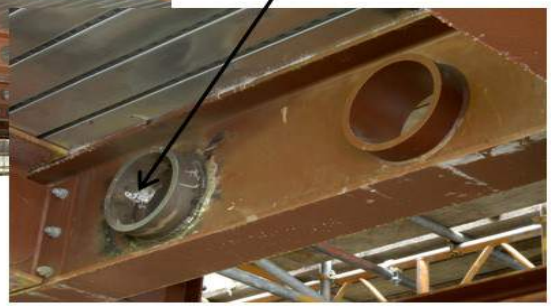
UNIVERSITY OF LEEDS

Development of Flooring Systems

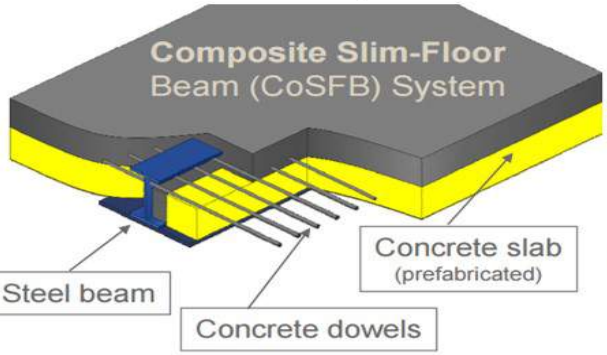
UNIVERSITY OF LEEDS

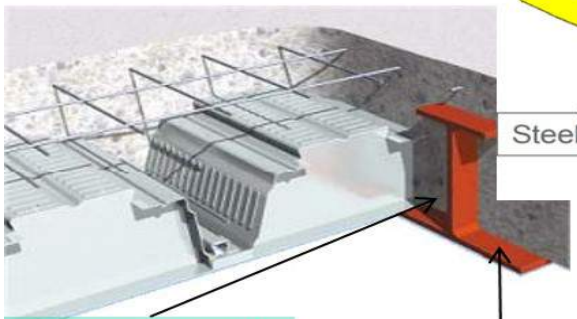


Farringdon Road, London



Steel stiffener
Improves the shear capacity at holes close to support





Concrete infill (without steel reinforcement)

Steel un-perforated (solid)section

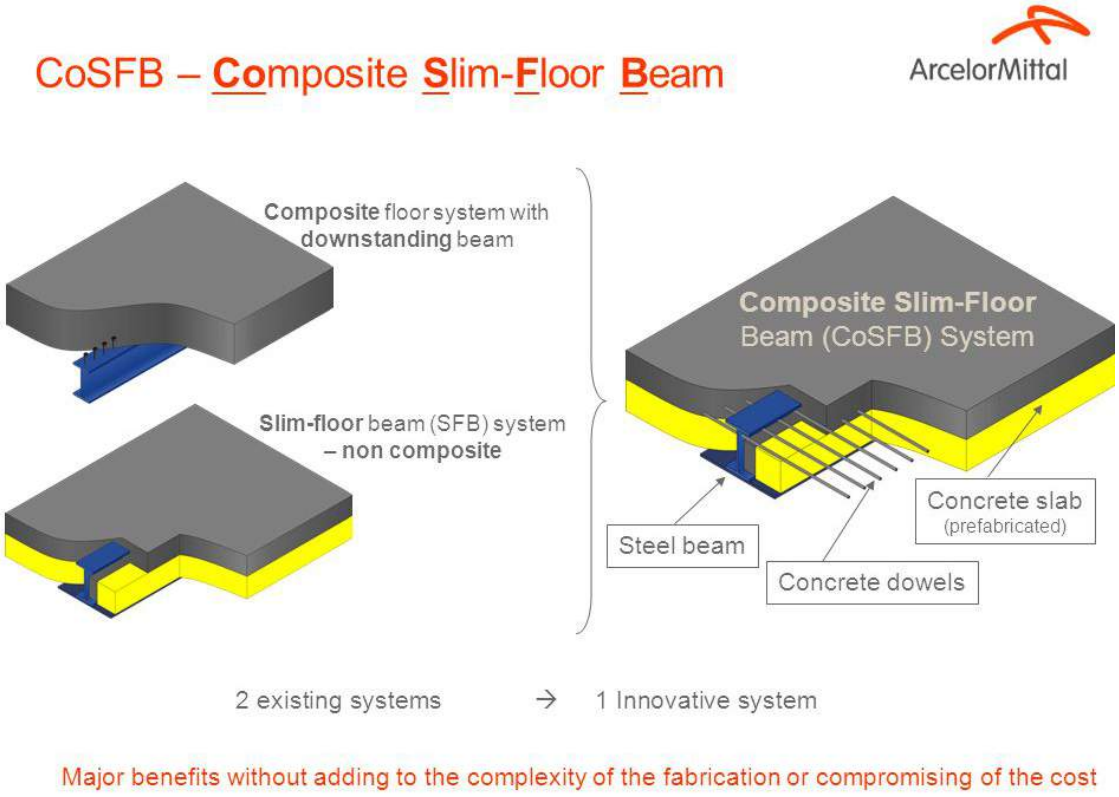
0.5h to 0.75h

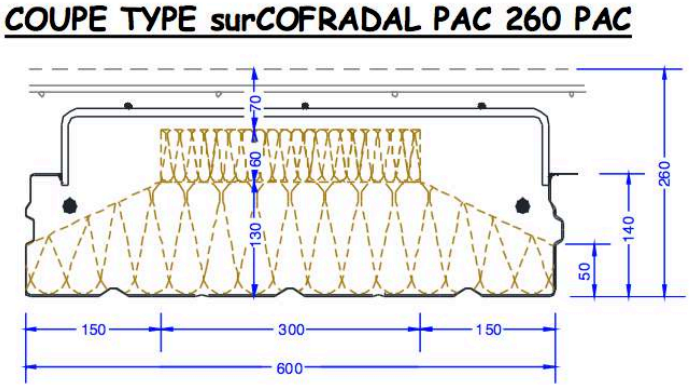
Concrete infill (with or without steel reinforcement)

Milliners Wharf, Manchester

State-of-the-art

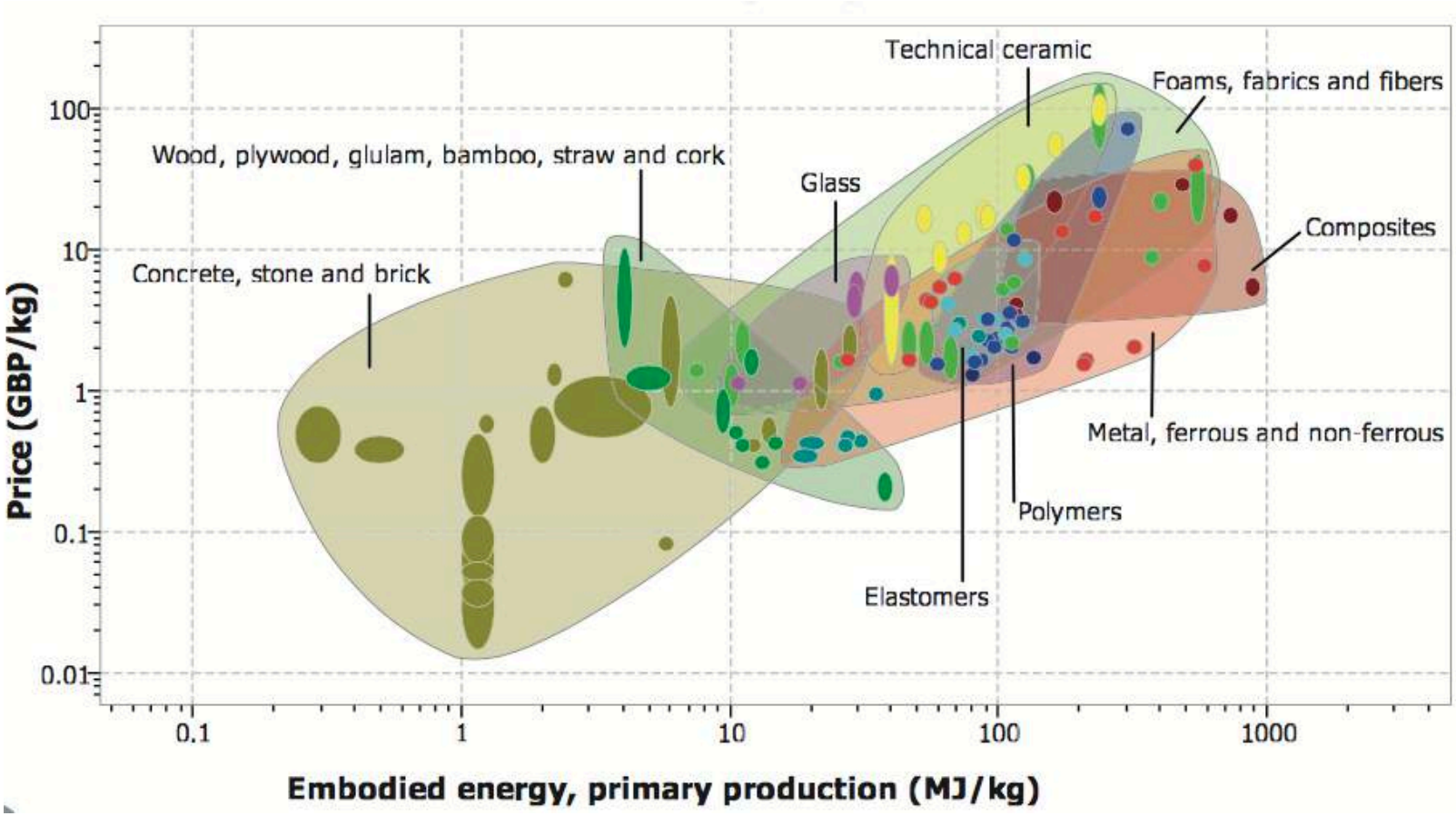
UNIVERSITY OF LEEDS





Sustainable Materials Matrix

UNIVERSITY OF LEEDS



[The Structural Engineer, Feb 2018]

Proposed Slab System

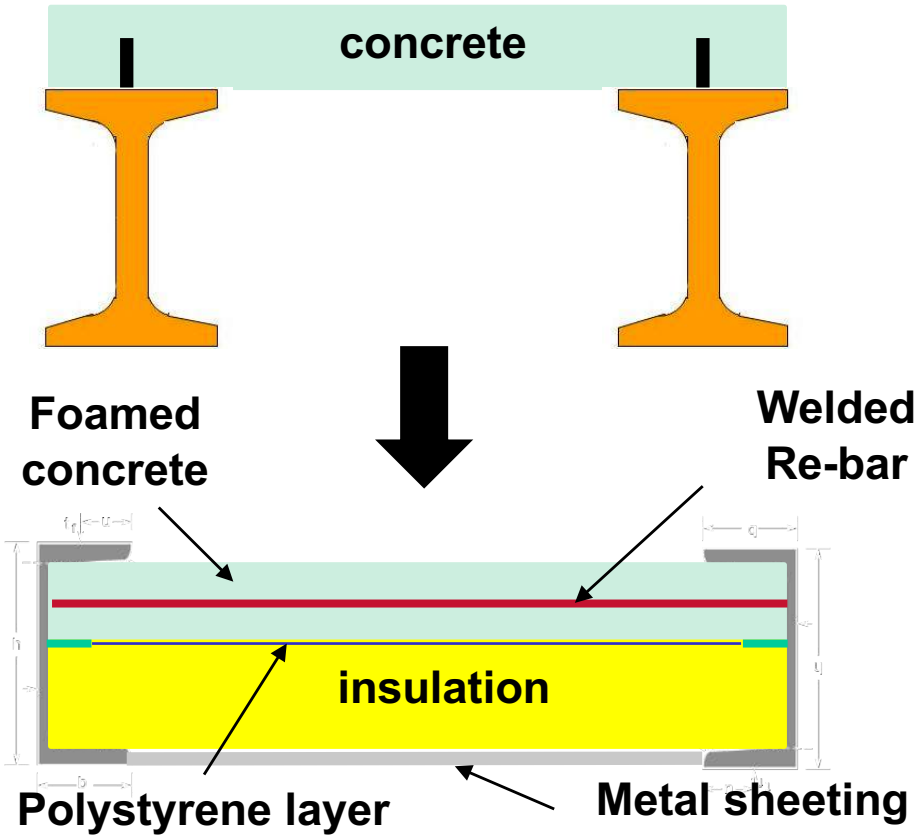
UNIVERSITY OF LEEDS

- **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

UNIVERSITY OF LEEDS

- **Production Stage:**

$$EE_{-P} = \sum_{i=1}^{n} \left(W_i \times EE_{(i)-LCI}\right) \qquad (1)$$

$$EC_{-P} = \sum_{i=1}^{n} \left(W_i \times EC_{(i)-LCI}\right) \qquad (2)$$

- **Transportation Stage:**

$$EE_{-T} = \sum_{i=1}^{n} \left(W_i \times D_i \times EE_{(i)-LCI(TR)}\right) \qquad (3)$$

$$EC_{-T} = \sum_{i=1}^{n} \left(W_i \times D_i \times EC_{(i)-LCI(TR)}\right) \qquad (4)$$

- **End of life Stage:**

Steel recycling according to substitution method (Hammond et al., 2008)

$$EE_{-ST-EOL} = \sum_{i=1}^{n} \left(W_i \times EE_{(i)-LCI(EOL)}\right) + \sum_{i=1}^{n} \left(W_i \times D_i \times EE_{(i)-LCI(TR)}\right) \qquad (5\ \&\ 6)$$

Concrete demolition (Hammond et al., 2008)

$$EE_{-CON-EOL} = \sum_{i=1}^{n} \left(W_i \times EE_{(i)-LCI(EOL)}\right) + \sum_{i=1}^{n} \left(W_i \times D_i \times EE_{(i)-LCI(TR)}\right) \qquad (7\ \&\ 8)$$

Life Cycle Inventory (LCI)

UNIVERSITY OF LEEDS

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

Material	Embodied Energy Coefficient (MJ/kg)	Embodied Carbon Coefficient ($kgCO_2e/kg$)
Cement	5.5	0.93
Sand	0.081	0.0048
Gravel	0.083	0.0052
Water	0.01	0.001
Fly ash	0.1	0.008
Silica fume	0.1	0.014
Super-plasticizer	9.0	0.25
Reinforcing steel bar	17.4	1.31
Metal Deck	22.6	1.54
Steel Section	21.50	1.42
Rock wool Insulation	16.8	1.12
Expanded Polystyrene	88.6	3.29

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

Material	Embodied Energy Coefficient (MJ/kg)	Embodied Carbon Coefficient ($kgCO_2e/kg$)
Steel recycling	13.1	0.75
Reinforcing steel bar recycling	11	0.74
Concrete demolition	0.007	0.00054
Rock wool Insulation	N.D.A	N.D.A
Expanded Polystyrene	N.D.A	N.D.A

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

Transportation	Embodied Energy Coefficient (MJ/tkm)	Embodied Carbon Coefficient ($kgCO_2e/tkm$)	Distance (km)
vehicle	2.4	0.15	100

LCA Results

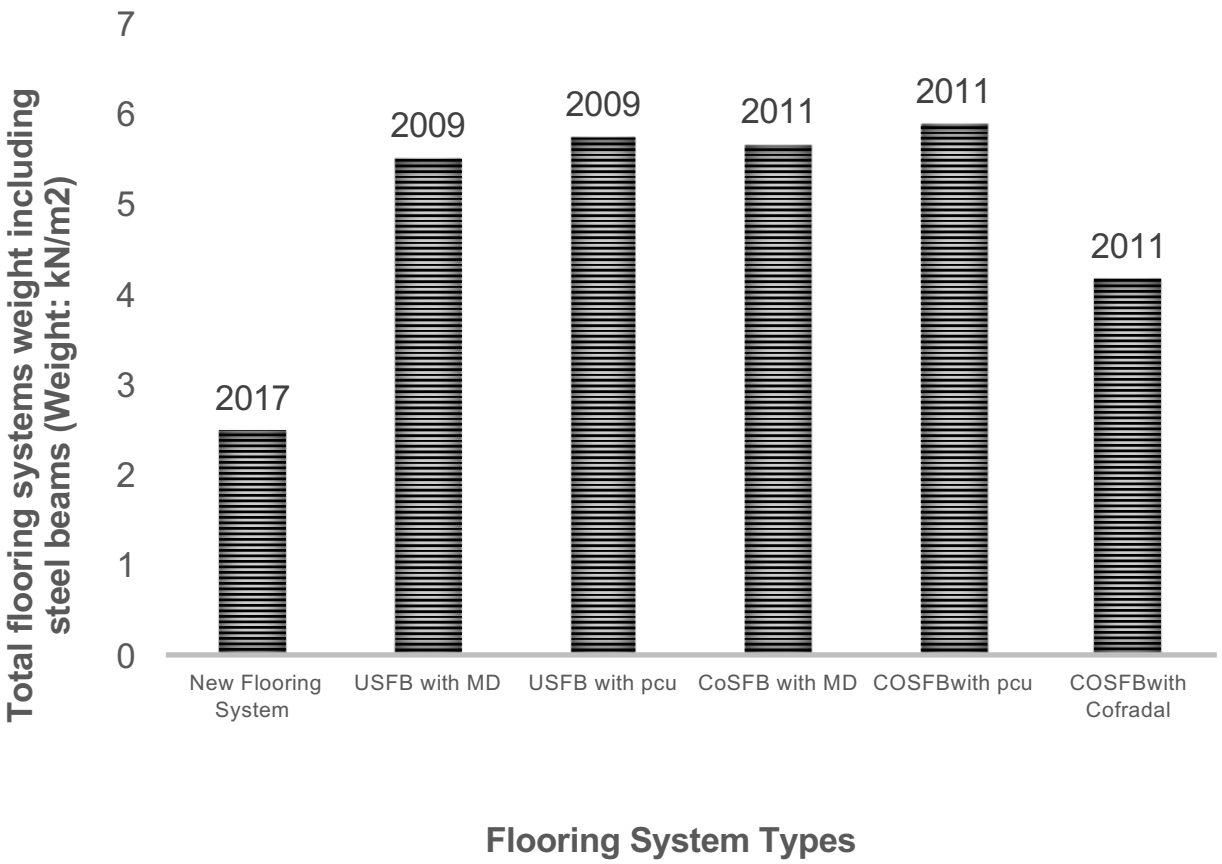
UNIVERSITY OF LEEDS

Embodied Carbon and Embodied Energy Comparison of flooring systems

Stage	Embodied Energy (GJ)	Embodied Carbon (tonne CO_2e)	Embodied Energy (GJ)	Embodied Carbon (tonne CO_2e)	% Reduction in Embodied Energy	% Reduction in Embodied Carbon
	CoSFB with Cofradal 260mm flooring system		Proposed System			
Production	106.25	8.69	90.19	8.67	15	0.23
Transport	5.24	0.32	3.01	0.19	42	40
End of Life	46.63	3.10	36.54	2.12	21	31

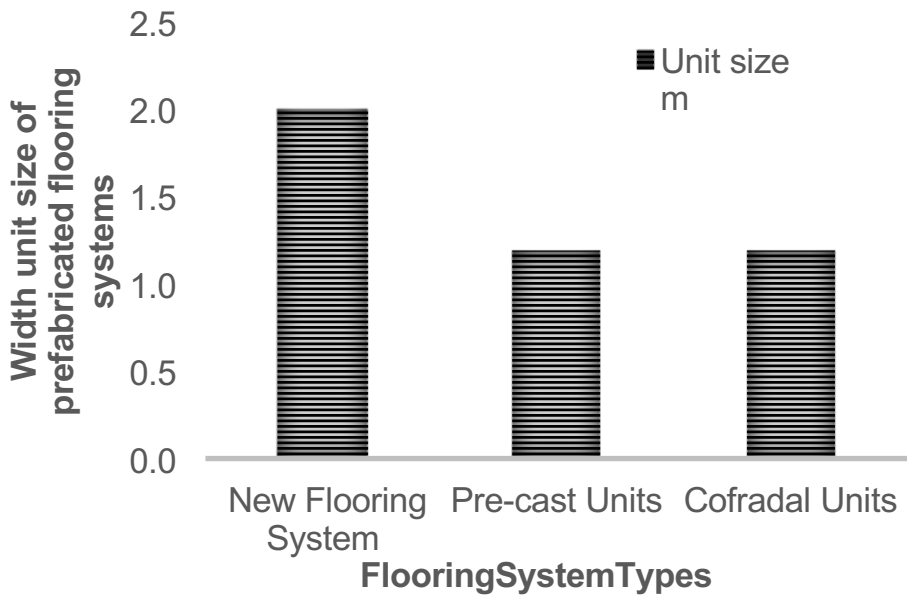
UNIVERSITY OF LEEDS

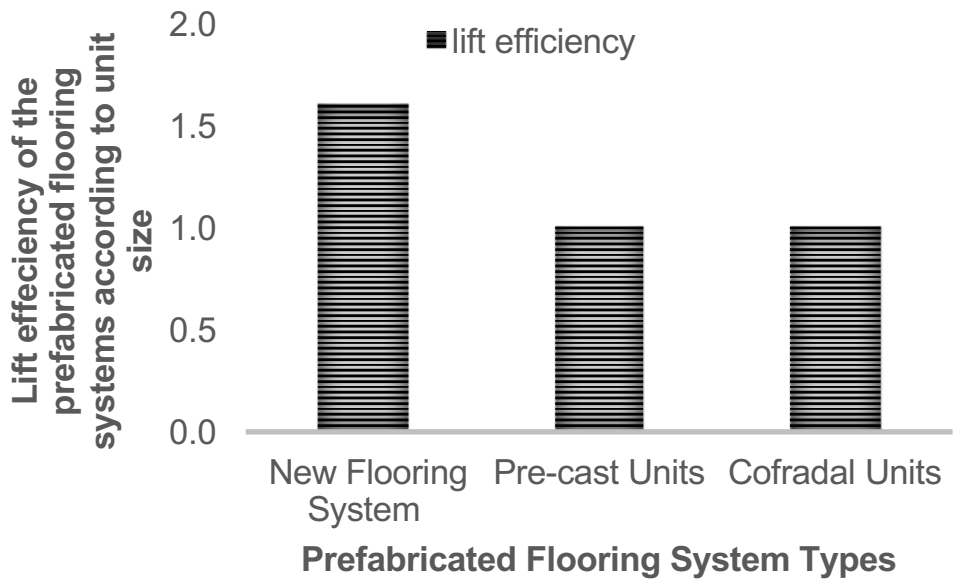
Weight and Size Comparison of the Flooring Systems



Life Efficiency Comparison

UNIVERSITY OF LEEDS





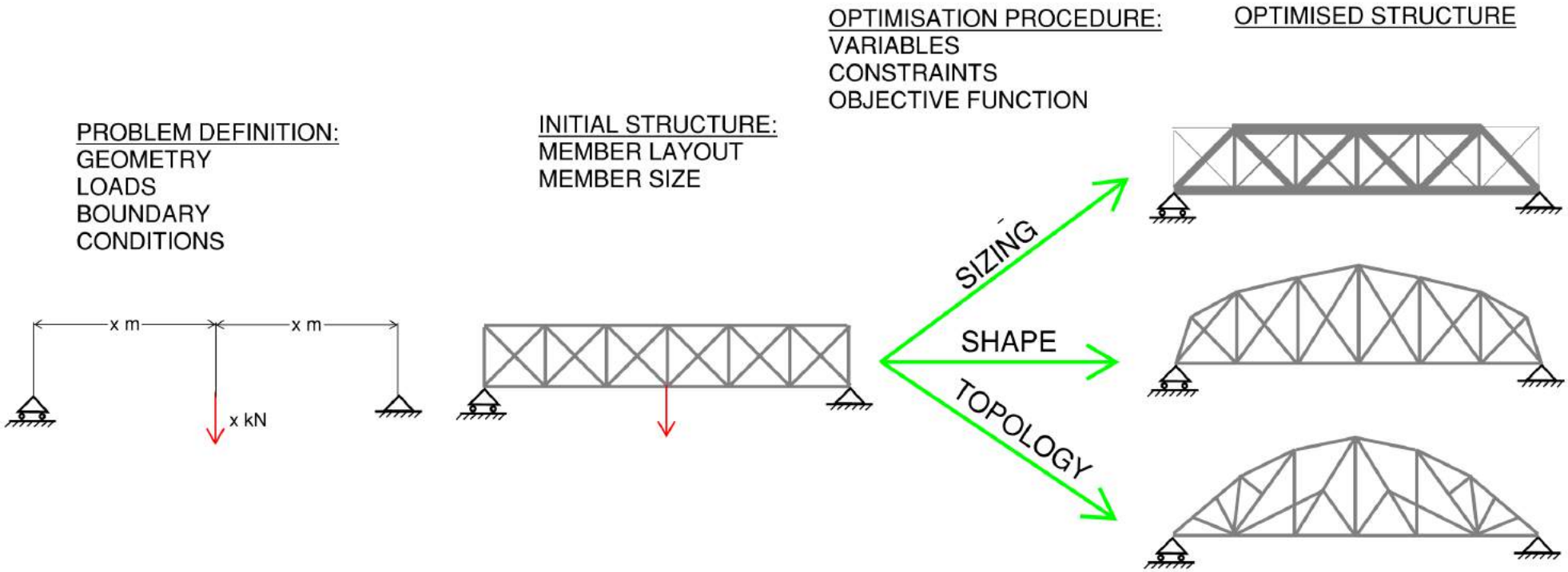
- ✓ **Lower weight and larger prefabricated width unit size than other prefabricated/precast units which enhancing the lift efficiency by about 60% !**

Structural Topology Optimisation
&
3D Printing

Structural Topology Optimisation (STO)

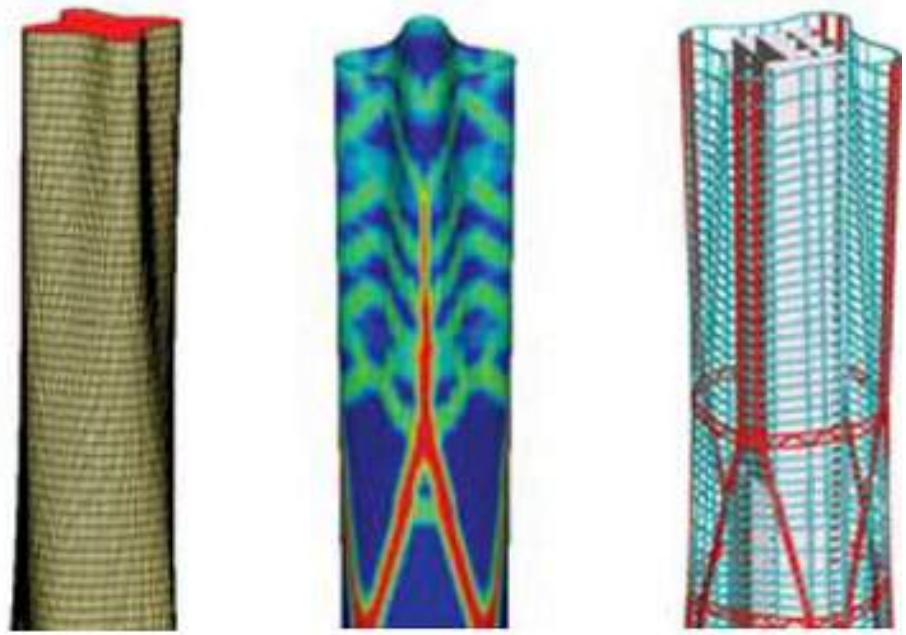
UNIVERSITY OF LEEDS

"Achieving the most with the least…"



Global STO

UNIVERSITY OF LEEDS

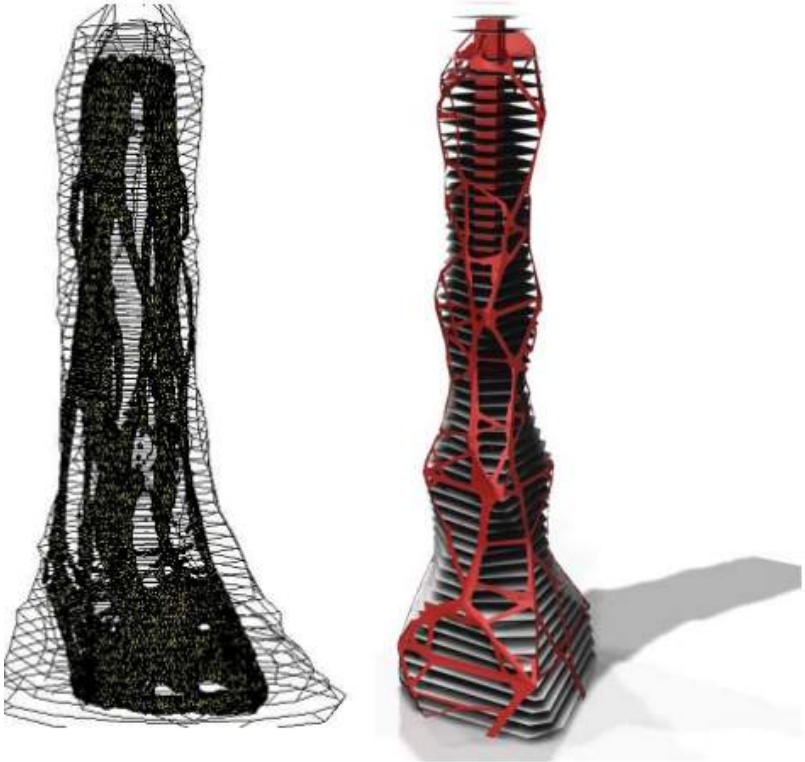


White Magnolia Plaza building in Shanghai demonstrates how topology optimisation can be used to inspire the structural engineer. The form of the tower was envisaged, by the architect, as being complexly curved. The project engineers, used topology optimisation to visualise the distribution of forces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

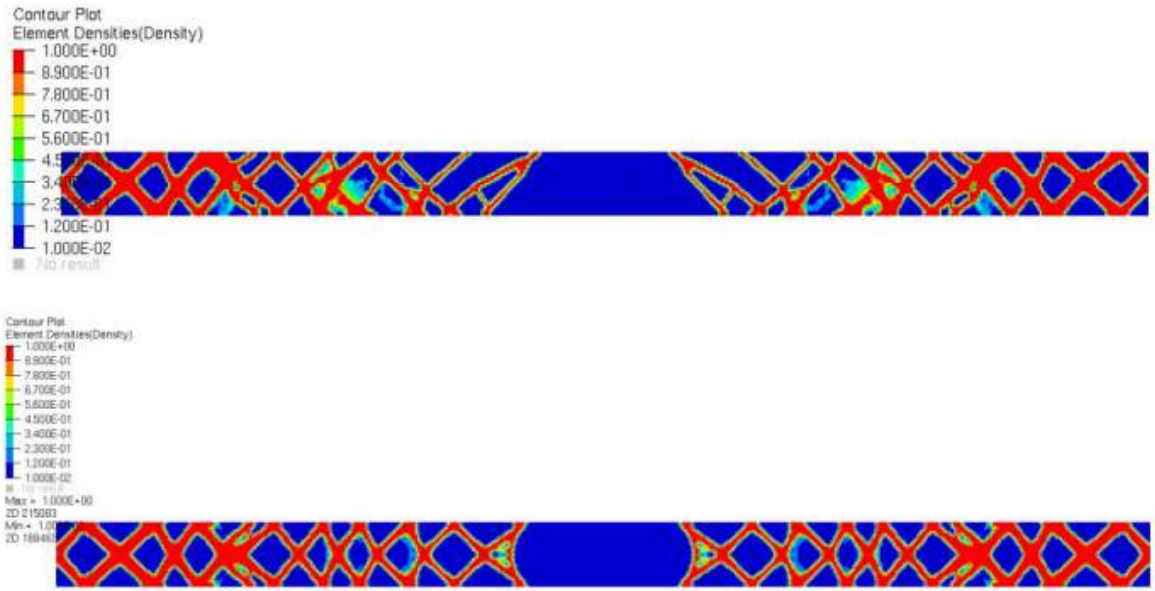
Arata Isozaki envisaged a design that mimicked the Sidra tree for the structural support of a canopy to shelter the convention centre in Doha, Qatar. The form of the canopy structure was found using topology optimisation, specifically the BESO technique that mimics actual process by which trees grow.

Global and Local STO Studies

UNIVERSITY OF LEEDS



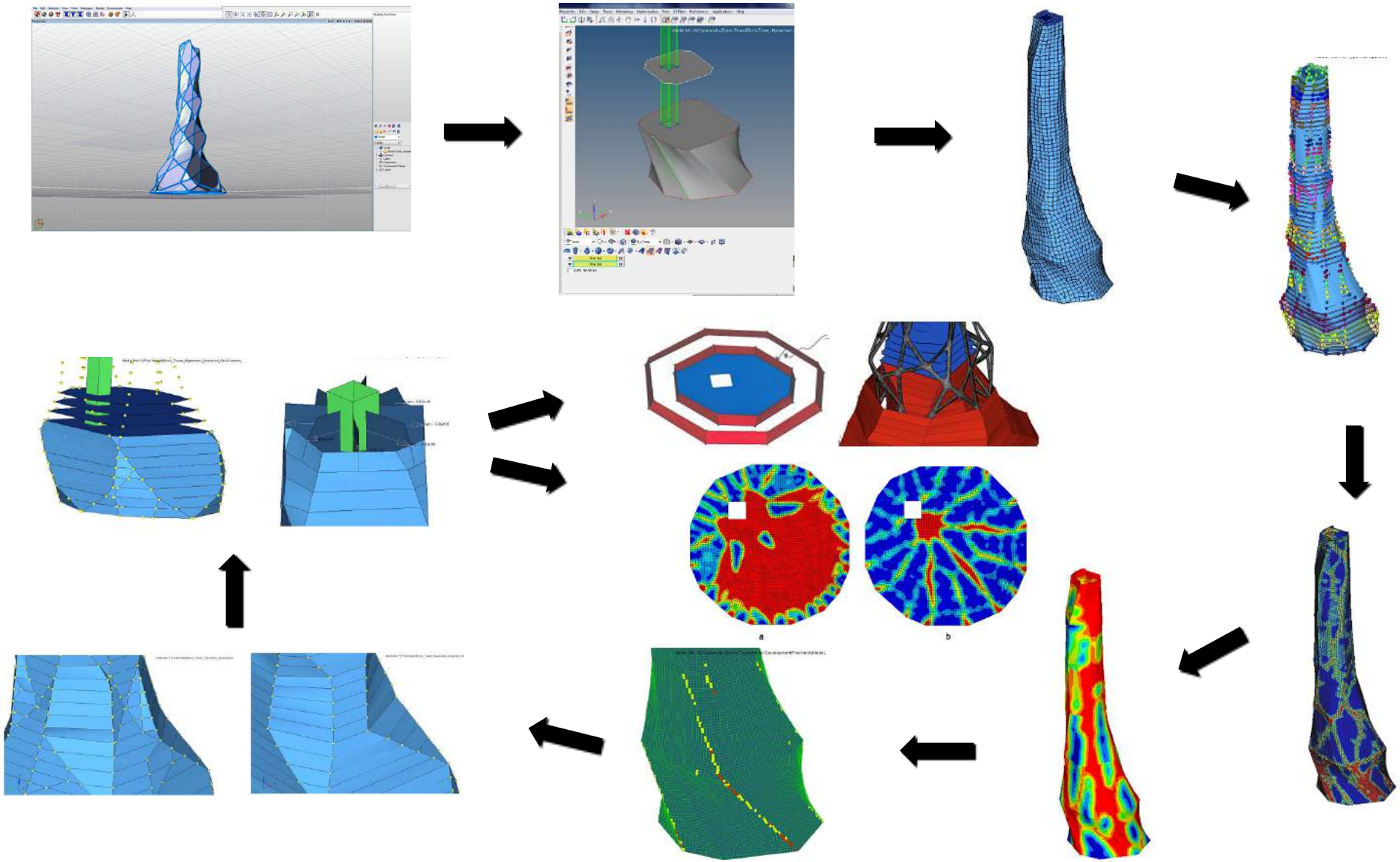
Optimisation of exoskeleton structures



Optimised perforated beams without (top) and with (bottom) symmetric constraints active

LAVA Architects Projects

UNIVERSITY OF LEEDS



STO & Perforated Beams

UNIVERSITY OF LEEDS

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

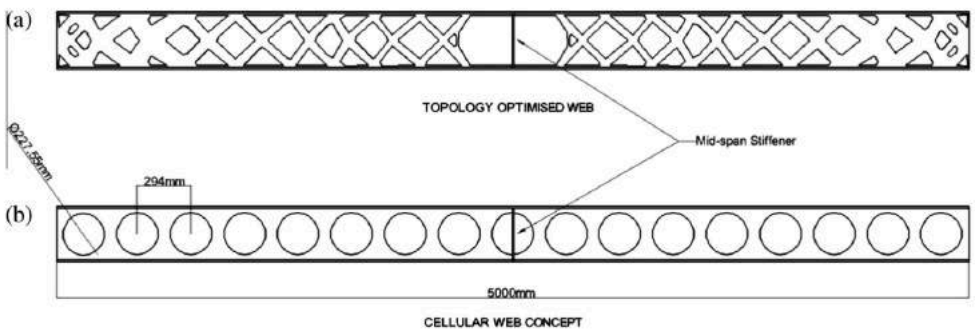
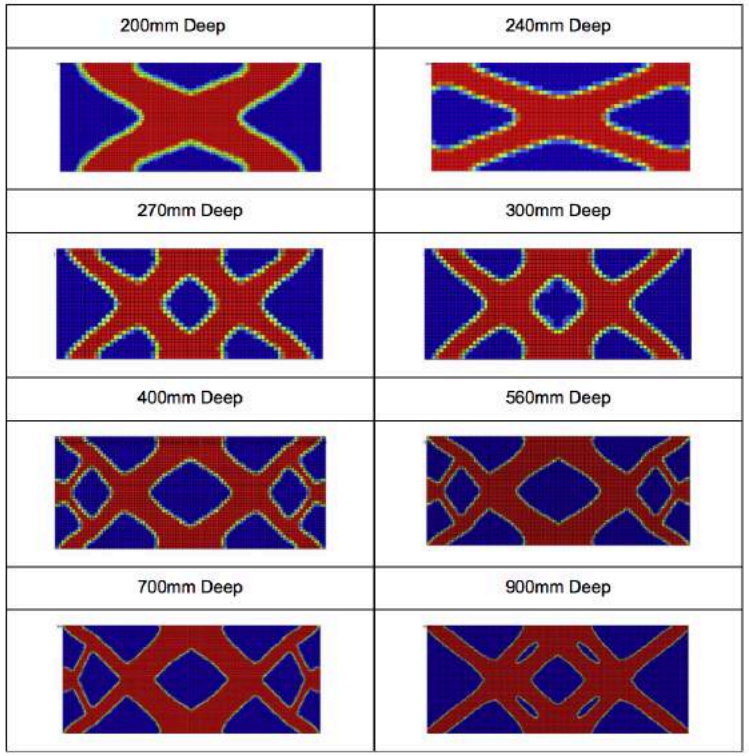
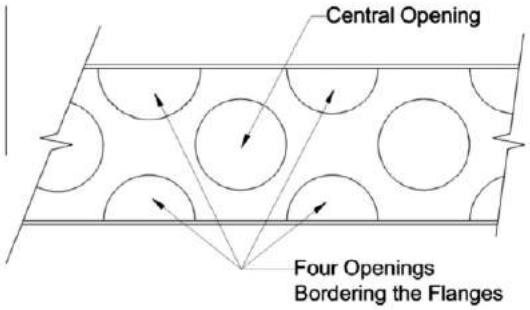
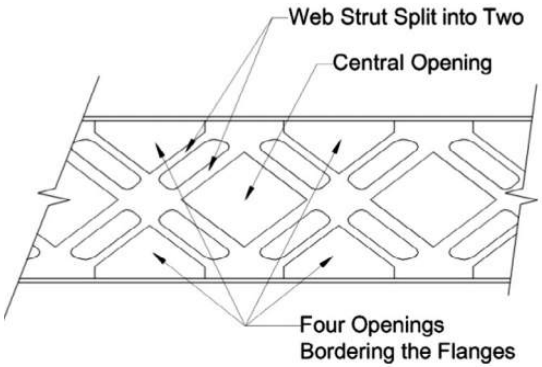
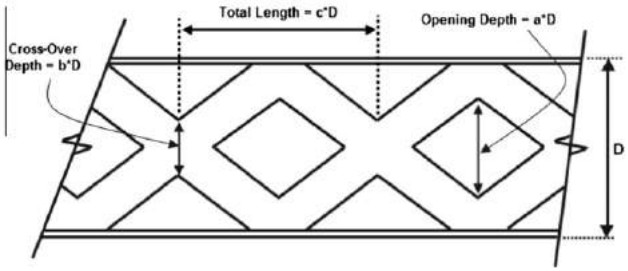


Fig. 6. Beam models compared: (a) topology optimised beam web design, (b) cellular beam design.





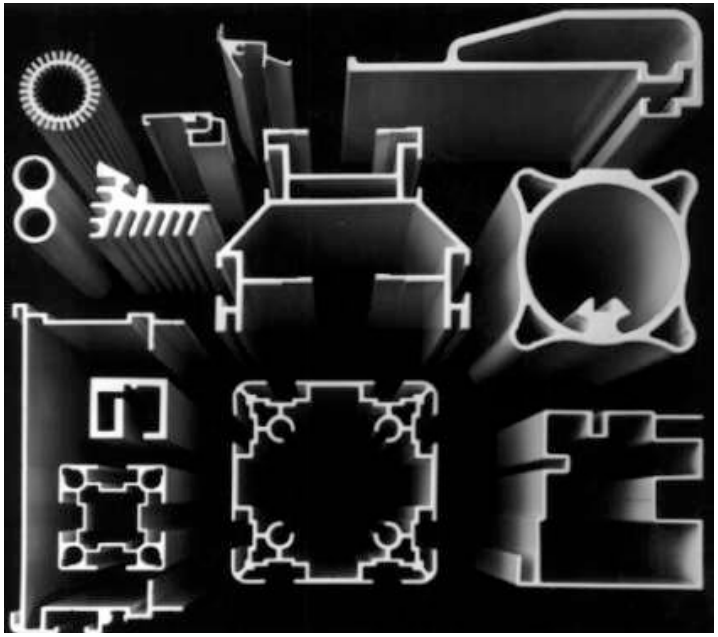




Aluminium Members

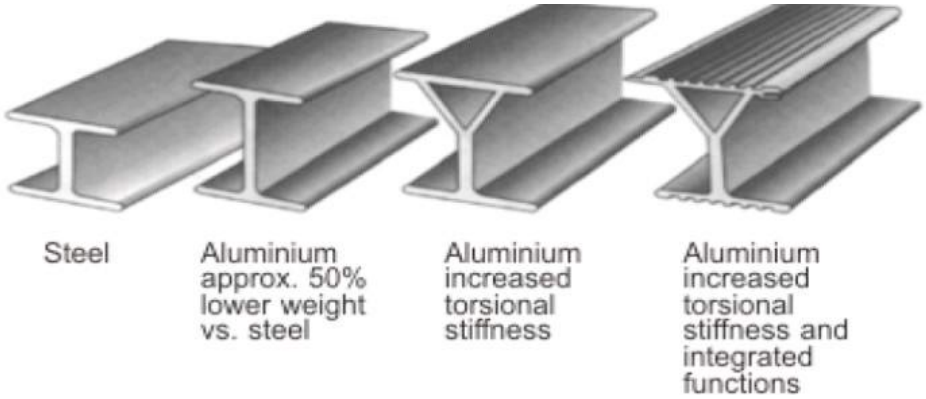
UNIVERSITY OF LEEDS

Non-structural members



(Randolph & Kissel, 2002)

Structural members



(Mazzolani, 2008)

Stiffness…

UNIVERSITY OF LEEDS

RULE: Stiffer → Deeper→ Increased inertia → More slender → <u>Susceptible to buckling</u>.

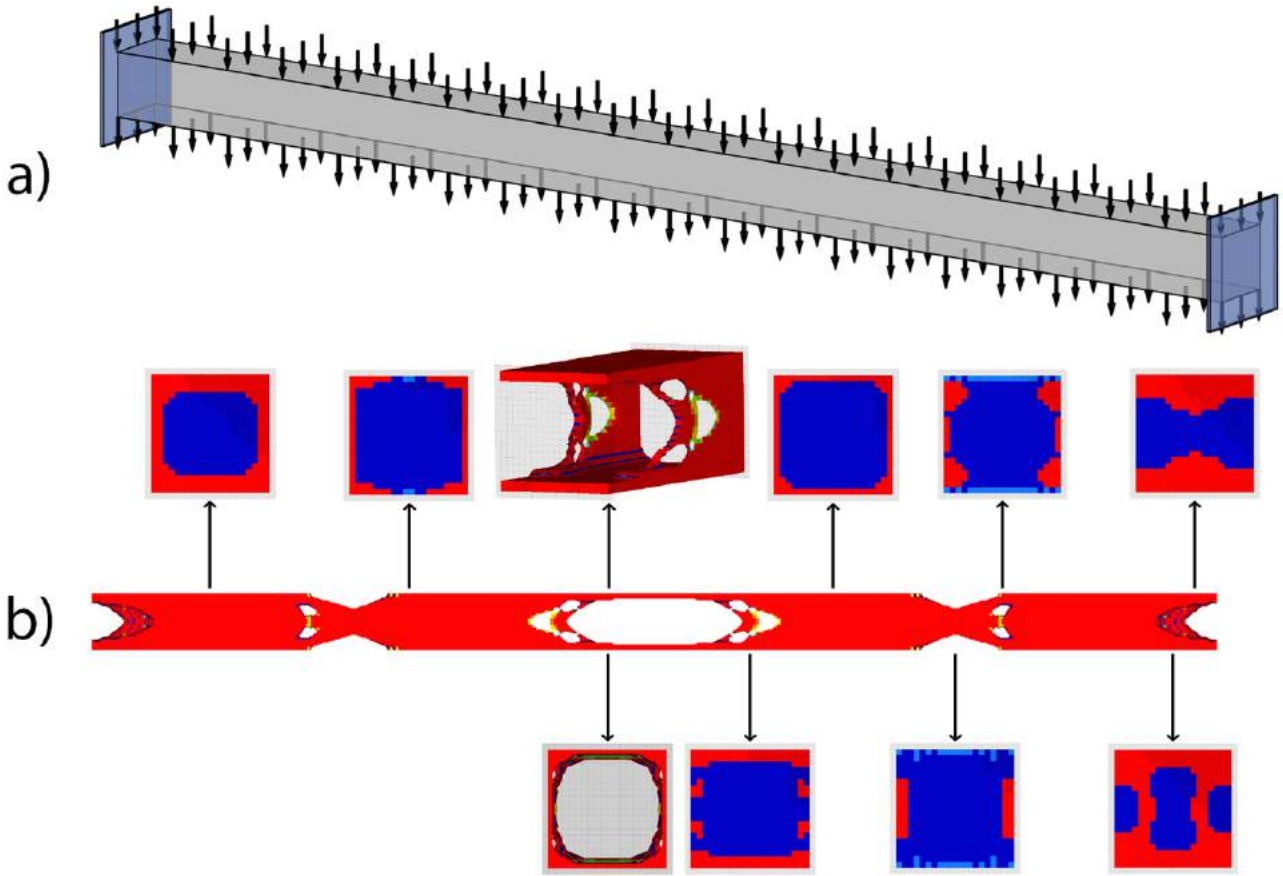
Aluminium + Low Modulus of Elasticity → Large Deflections and Local Instabilities

⇩

Optimum Material Distribution

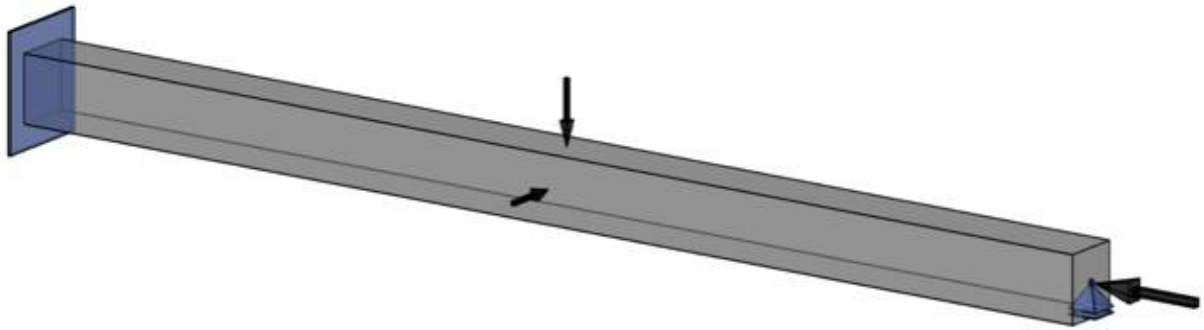
Element Optimisation – Global Approach

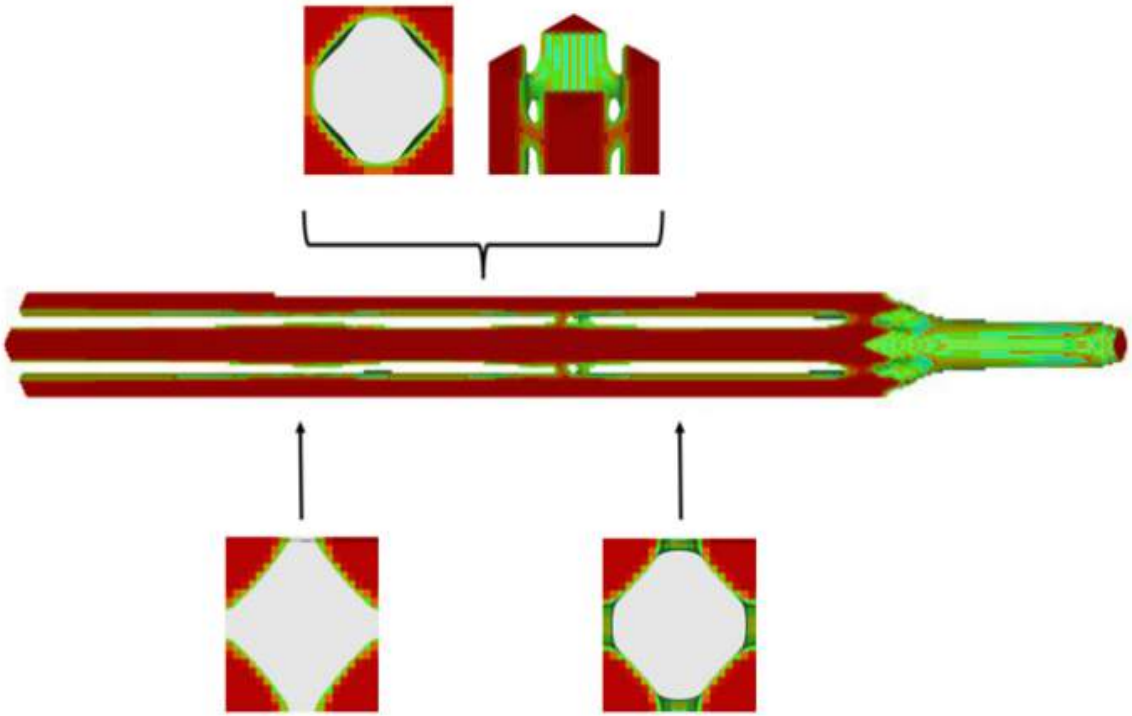
UNIVERSITY OF LEEDS



Element Optimisation – Global Approach

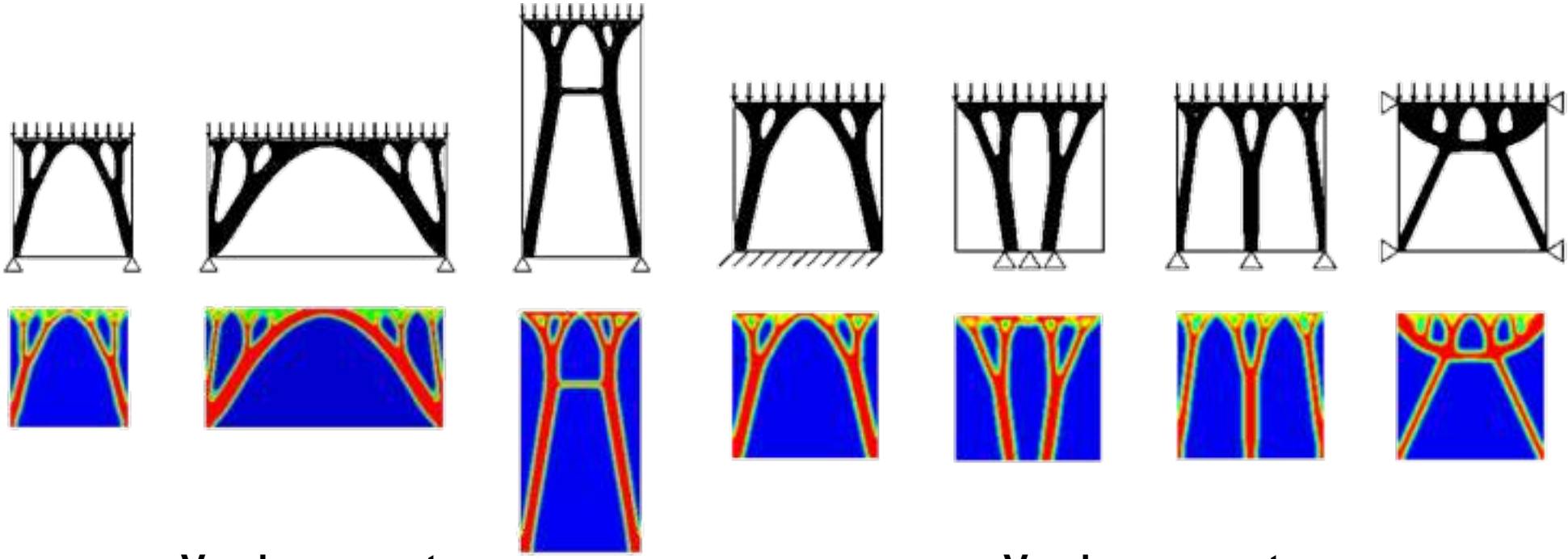
UNIVERSITY OF LEEDS





2D Optimisation - Beams

UNIVERSITY OF LEEDS

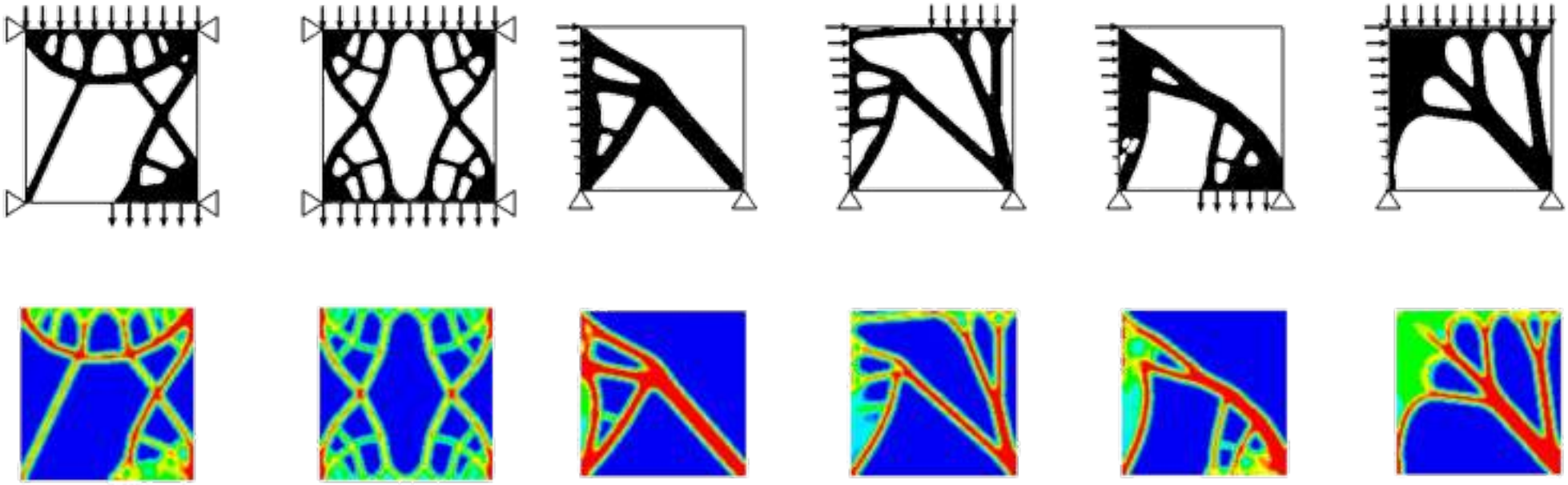


Varying aspect ratios

Varying support conditions

2D Optimisation - Columns

UNIVERSITY OF LEEDS

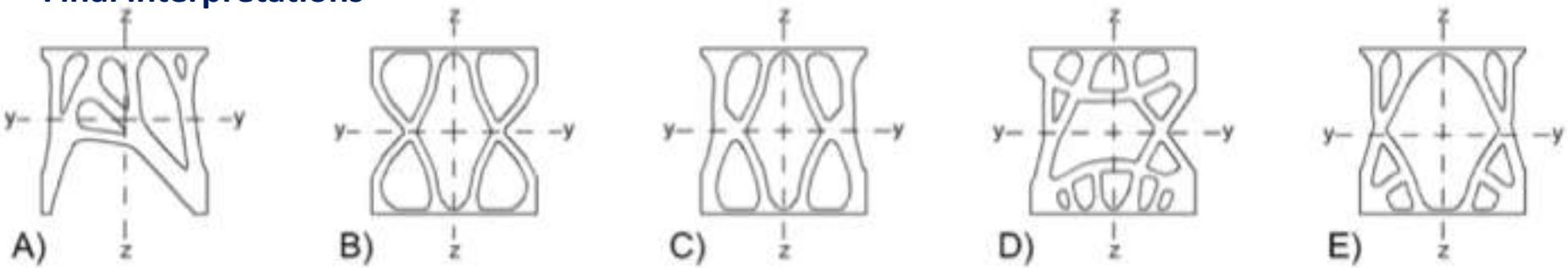


UNIVERSITY OF LEEDS

Sectional Optimisation Method via X-rays

Overlaid results

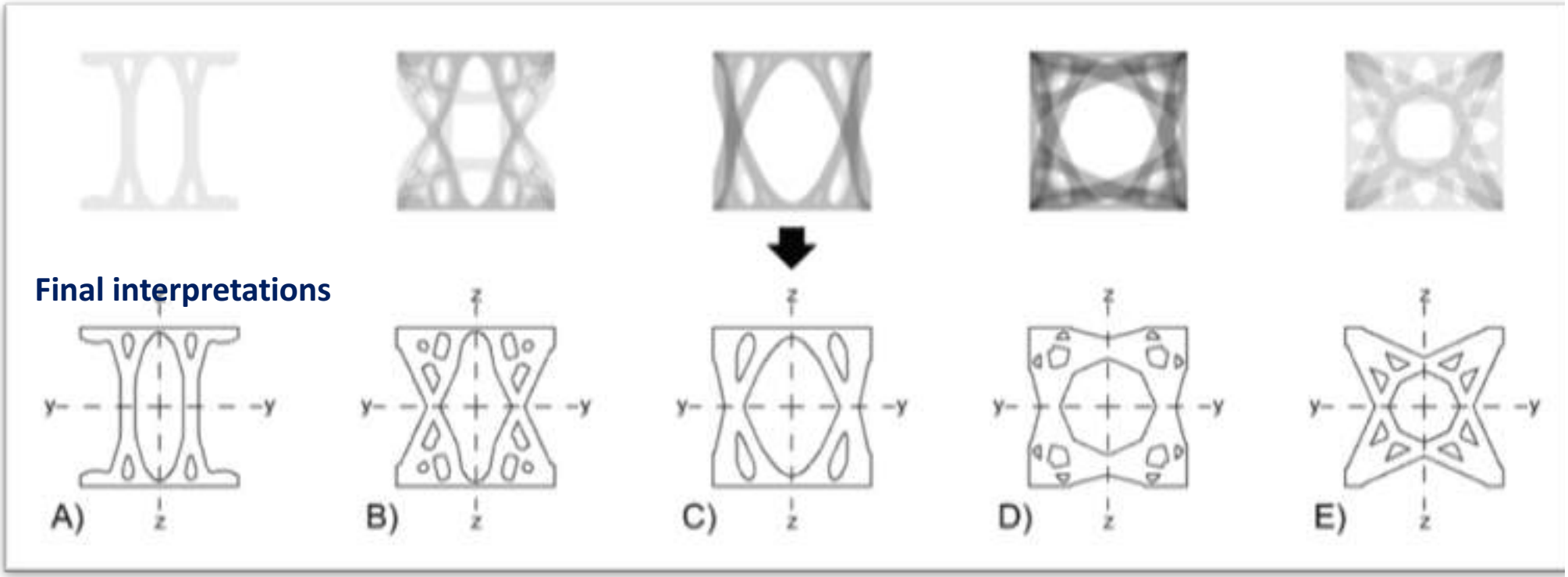
Final interpretations



UNIVERSITY OF LEEDS

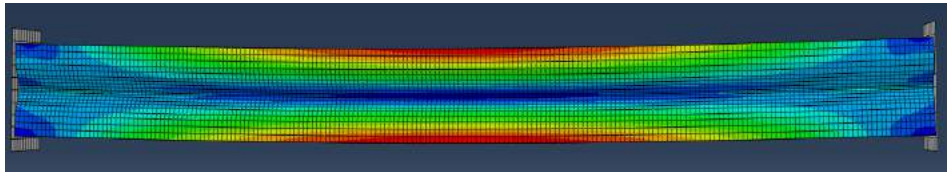
Sectional Optimisation Method via X-rays

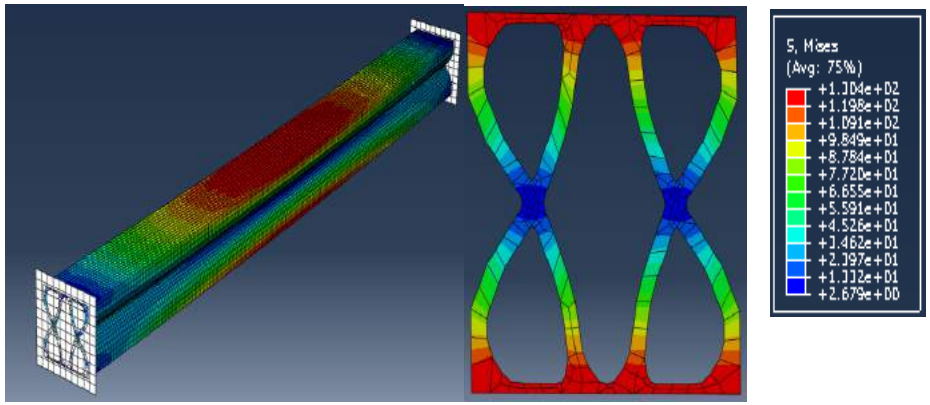
Overlaid results

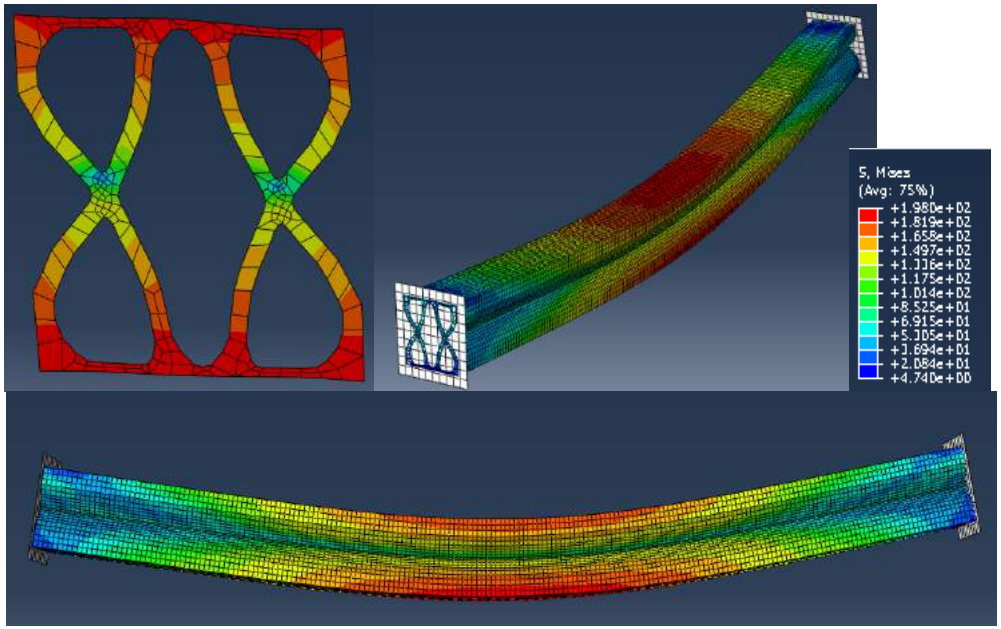


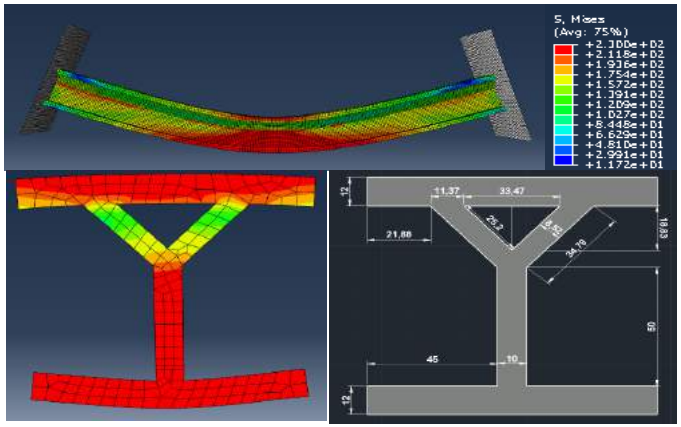
Bi-axial with Bending

UNIVERSITY OF LEEDS

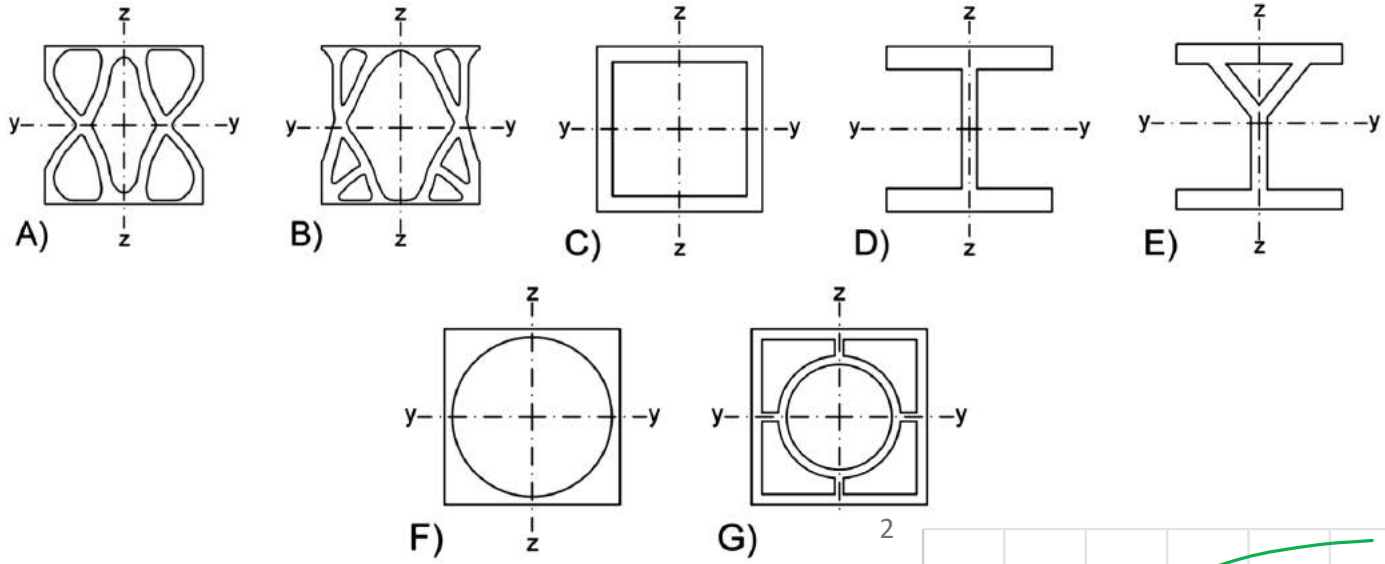


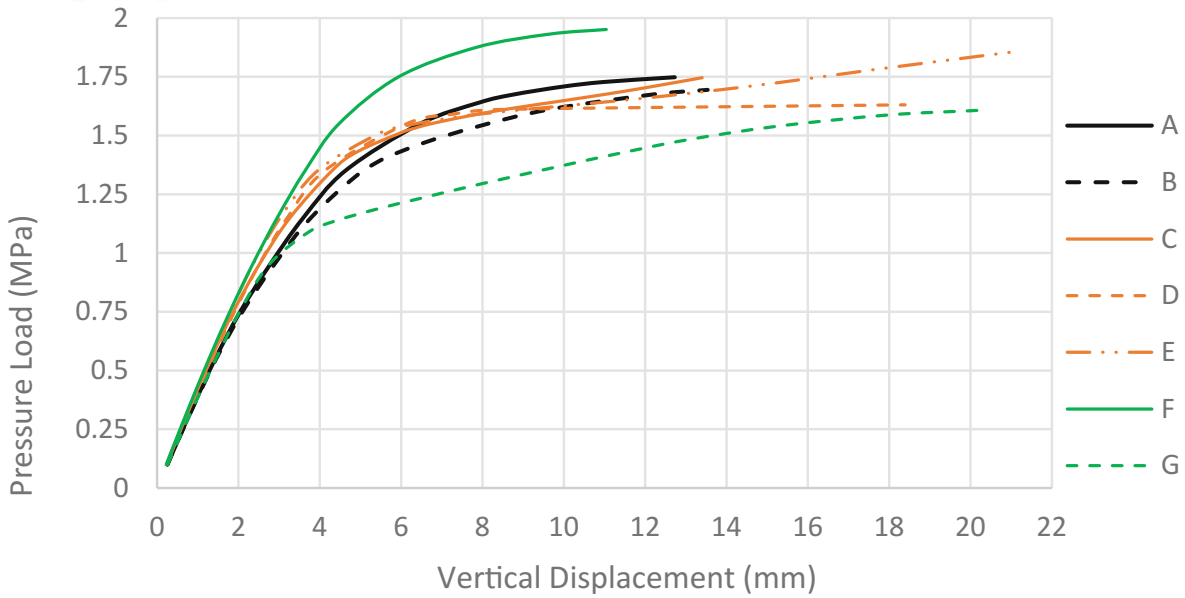






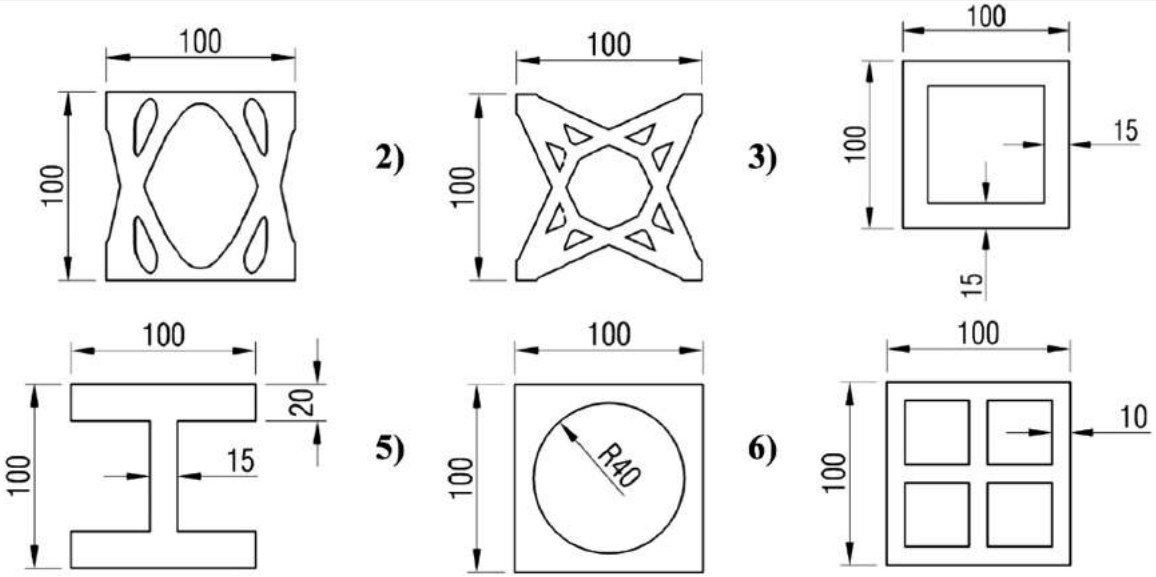
Beams

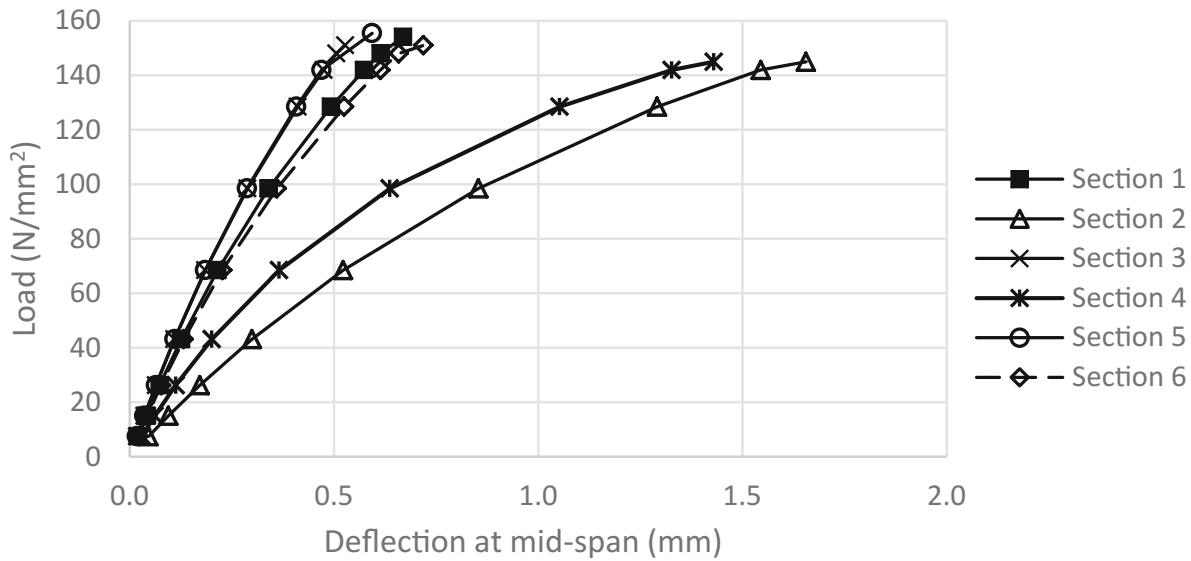

A)
B)
C)
D)
E)
F)
G)
z
y
-y


Pressure Load (MPa)
Vertical Displacement (mm)
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
0
2
4
6
8
10
12
14
16
18
20
22
A
B
C
D
E
F
G

Columns

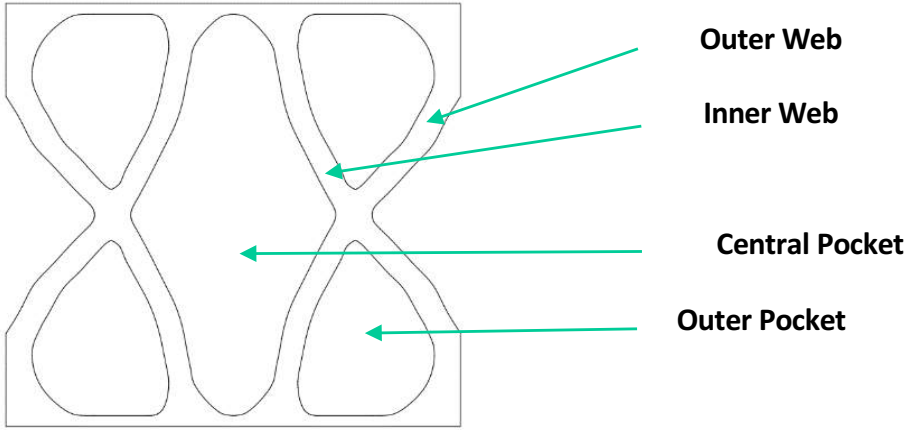
UNIVERSITY OF LEEDS

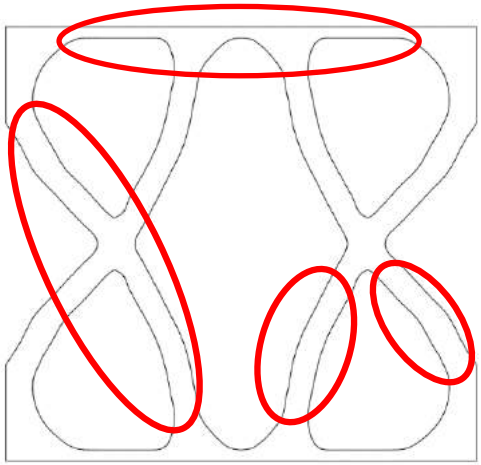


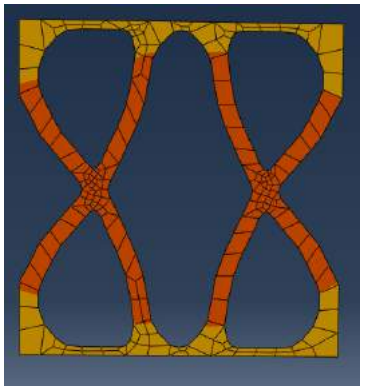


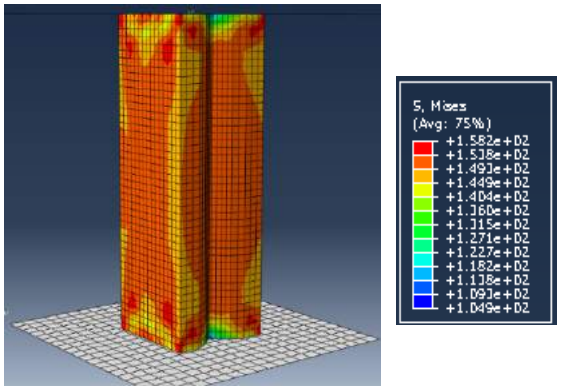
Cross-Section Classification

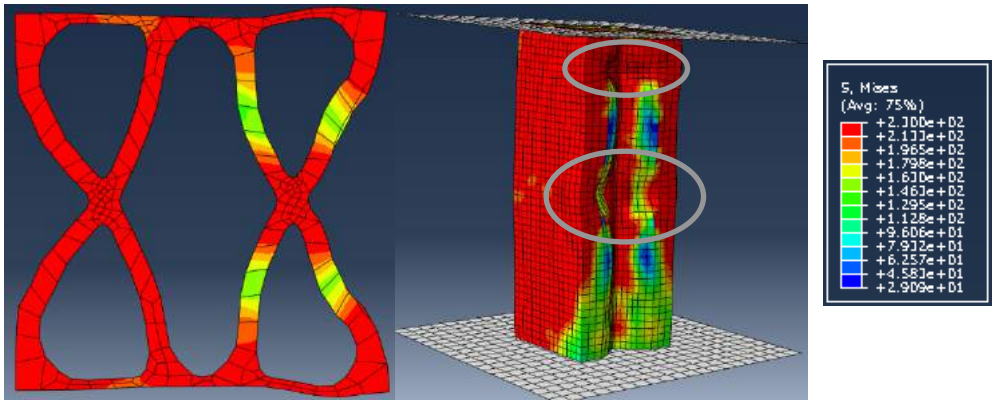
UNIVERSITY OF LEEDS







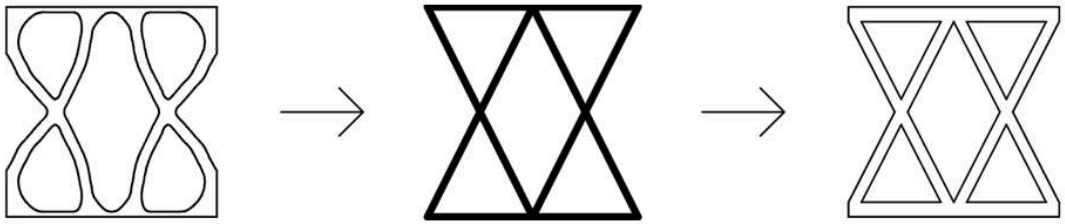




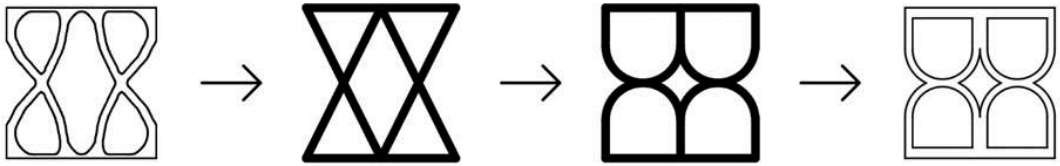
Morphogenesis

UNIVERSITY OF LEEDS

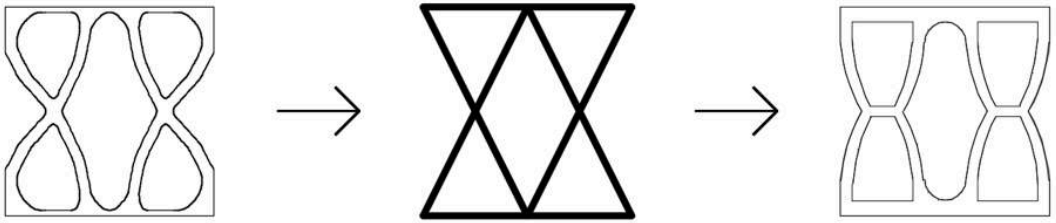
Section 1

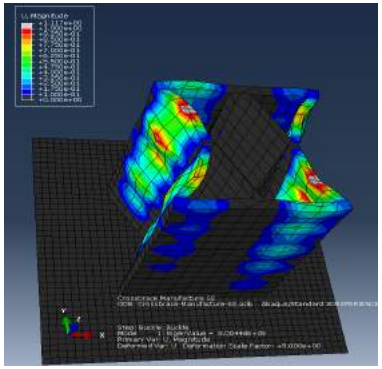


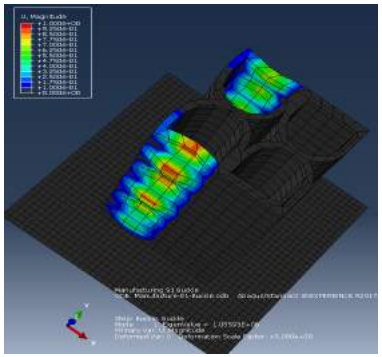
Section 2

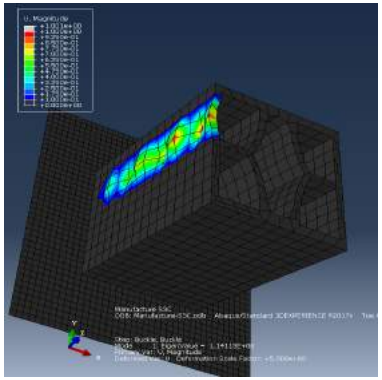


Section 3









Cross-section classification via EC9

UNIVERSITY OF LEEDS

Using properties of EN AC-43300 T64

Assumed straight parts

Part	b (mm)	t (mm)	η	$\beta = \eta \frac{b}{t}$
Outer web	25	4.1	0.7	4.3
Inner Web	30	5.5	0.7	3.8
Inner Flange	25	5.5	1	4.5
Outer Flange	12	2	1	6

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 β as follows:

Parts in beams
- $\beta \le \beta_1$: class 1
- $\beta_1 < \beta \le \beta_2$: class 2
- $\beta_2 < \beta \le \beta_3$: class 3
- $\beta_3 < \beta$: class 4

Parts in struts
- $\beta \le \beta_2$: class 1 or 2
- $\beta_2 < \beta \le \beta_3$: class 3
- $\beta_3 < \beta$: class 4

Table 6.2 - Slenderness parameters β_1/ε, β_2/ε and β_3/ε

Material classification according to Table 3.2	Internal part			Outstand part		
	β_1/ε	β_2/ε	β_3/ε	β_1/ε	β_2/ε	β_3/ε
Class A, without welds	11	16	22	3	4,5	6
Class A, with welds	9	13	18	2,5	4	5
Class B, without welds	13	16,5	18	3,5	4,5	5
Class B, with welds	10	13,5	15	3	3,5	4
$\varepsilon = \sqrt{250/f_o}$, f_o in N/mm^2						

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

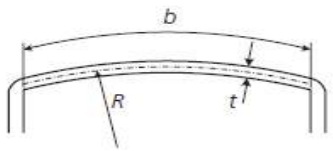
$$\beta_1 = 3 \times 1.41 = 4.23$$

$$\beta_2 = 4.5 \times 1.41 = 6.345$$

$$\beta_3 = 6 \times 1.41 = 8.46$$

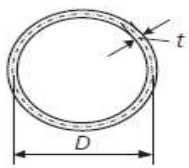
Table 6.3. Slenderness β for curved cross-section parts

Shallow curved unreinforced internal part



$$\beta = \frac{b}{t} \frac{1}{\sqrt{1 + 0.006 \frac{b^4}{R^2 t^2}}}$$

Thin-walled round tube



$$\beta = 3\sqrt{\frac{D}{t}}$$

Shape - Complexity - Limiting Factor

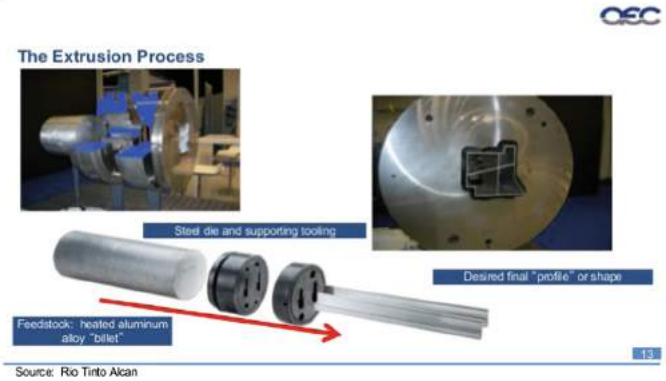
UNIVERSITY OF LEEDS

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

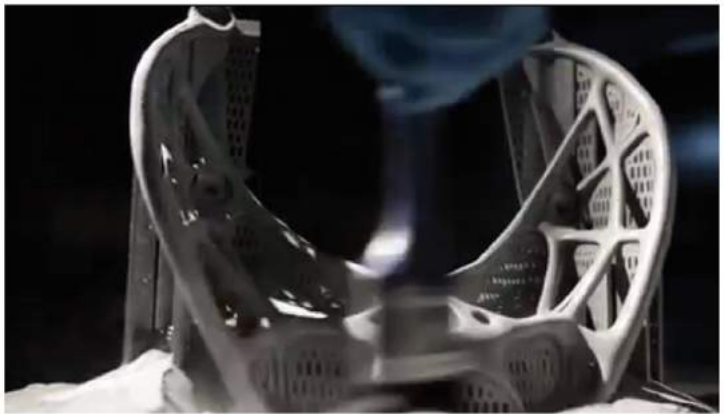
Sky is the Limit…

UNIVERSITY OF LEEDS

(a)



(b)



Sciaky EBAM 300

Company: Sciaky Inc

Process: Metal Filament 3D Printing

Build Size: 5791 x 1219 x 1219 mm

Today is the Future…

UNIVERSITY OF LEEDS

Research Team (PhD students & Post-Docs)

UNIVERSITY OF LEEDS

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, MIStructE, PhD Candidate,
Network Rail Senior Engineer
University of Leeds

Dr M. Abambres
Research Fellow
University of Lisbon

Research Team (MEng & MSc students)

UNIVERSITY OF LEEDS

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

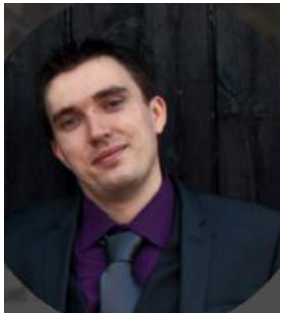
Mr Grekavicious
MEng in Civil Eng.
University of Leeds

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

Aknowledgments

UNIVERSITY OF LEEDS

The Institution of Structural Engineers

DIDECO

kloeckner metals
UK | Westok

Westok

COMMONWEALTH SCHOLARSHIPS

SCI
Steel Knowledge

TATA STEEL

Leca

wsp

CADS

masonclark associates

LYTAG®
lightweight aggregate

Severfield

Research Fund for Coal & Steel

EPSRC
Engineering and Physical Sciences Research Council

EUROPEAN COMMISSION / European Research Area / Coal & Steel

SCI

Thank you!

UNIVERSITY OF LEEDS

http://kostasdaniel.blogspot.co.uk