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Seismic Resistant Design of Connections with the use of Perforated Beams

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School of Civil Engineering
Faculty of Engineering

4th International Conference on
Advanced Steel Structures
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Sustainable Lightweight Solutions

Optimisation

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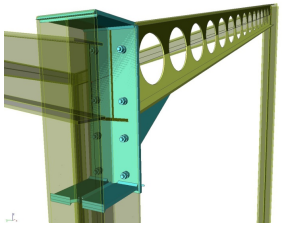
In the era of sustainable and resilient buildings, where the concept of redundancy plays a significant role, we should reconsider optimising **every single structure** to the best of its efficiency.



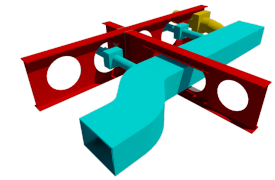
Perforated Members

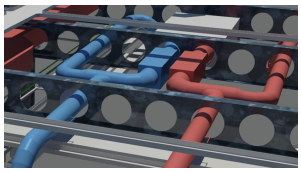
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Perforations in the webs of steel beams are widely used nowadays in **building construction** due to their ability to provide *lighter structural members, reduced material costs, in addition to the provision for greater flexibility in structural layouts particularly in the floor-to-ceiling height.*





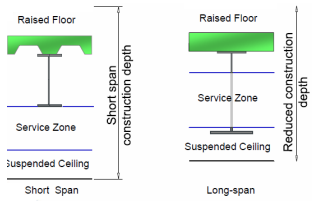


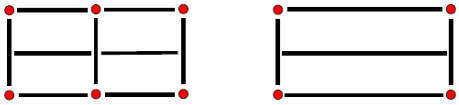


Advantages

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- ✓ 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)

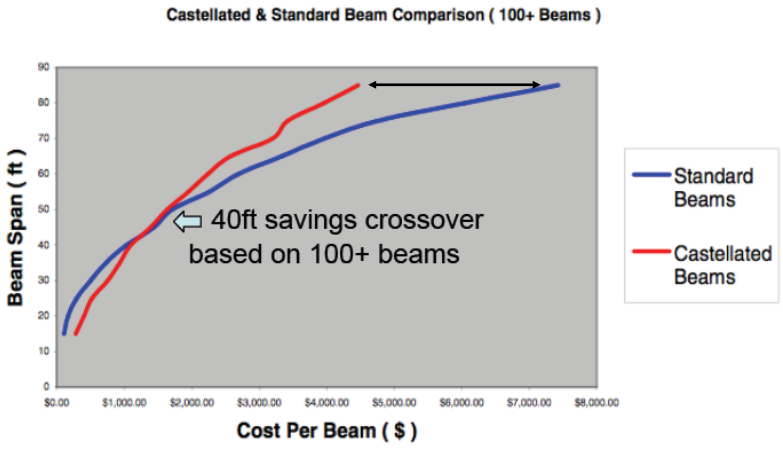






Market

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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.

Published Guidelines

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SCI P-100 (1994) → SCI P-355 (2011) → Eurocode 3 (soon)





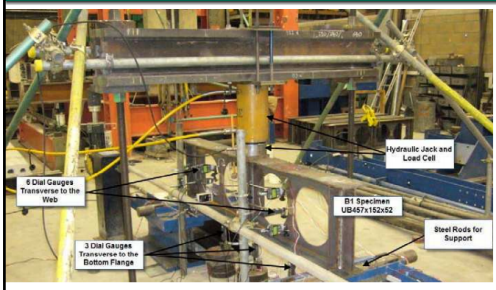
European Committee for Standardization

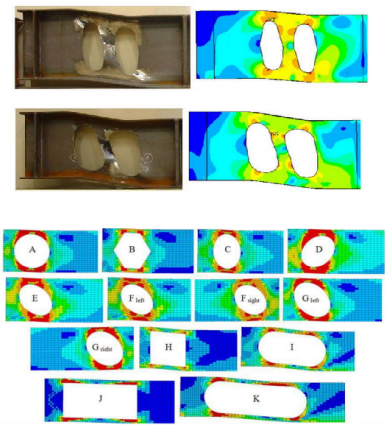
Task SC3.T4

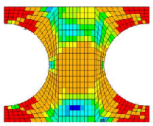
Sub-task 9: Development of Advanced Design Rules for Extended Girder Applications (Girders with Openings)

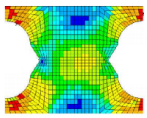
Research on Perforated Beams (2006~)

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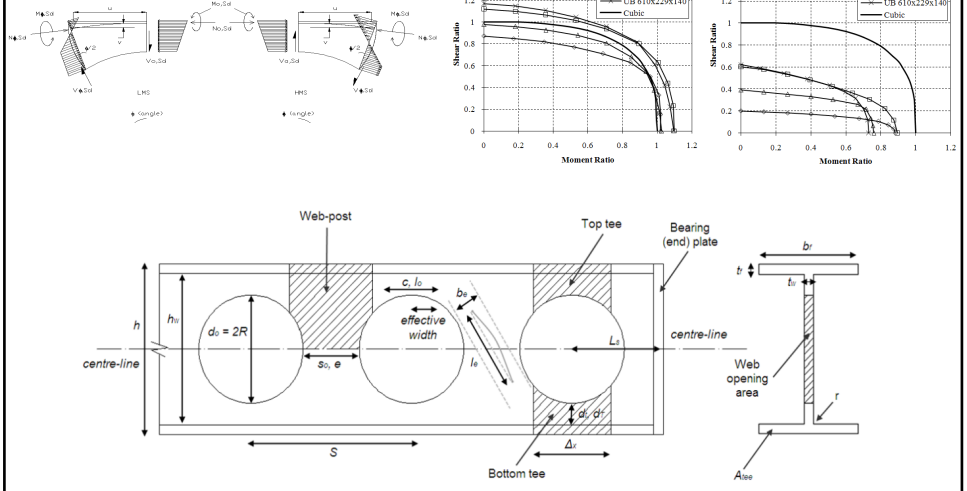




- Tsavdaridis, K.D. and D'Mello, C., Web Buckling Study of the Behaviour and Strength of Perforated Steel Beams with Different Novel Web Opening Shapes. ***Journal of Constructional Steel Research***, Vol. 67, Issue 10, **2011**, pp. 1605-1620
- Tsavdaridis, K.D. and D'Mello, C. Vierendeel Bending Study of Perforated Steel Beams with Various Novel Shapes of Web Openings, through Non-Linear Finite Element Analyses. ***Journal of Structural Engineering (ASCE)***, Vol. 138, Issue 10, **2012**, pp. 1214-1230
- Tsavdaridis, K.D. and D'Mello, C. Optimisation of Novel Elliptically-Based Web Opening Shapes of Perforated Steel Beams. ***Journal of Constructional Steel Research***, Vol. 76, **2012**, pp. 39-53

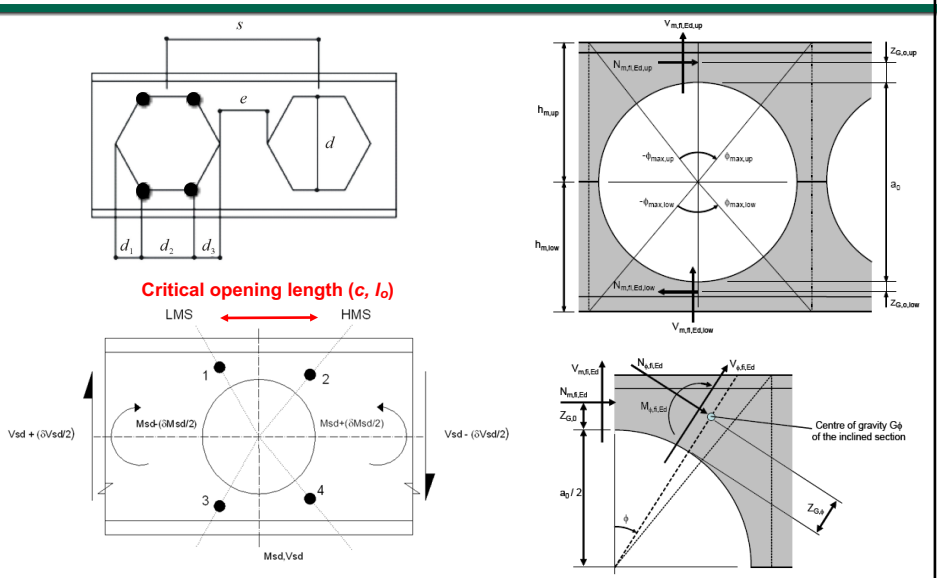
Research on Perforated Beams

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Research on Perforated Beams

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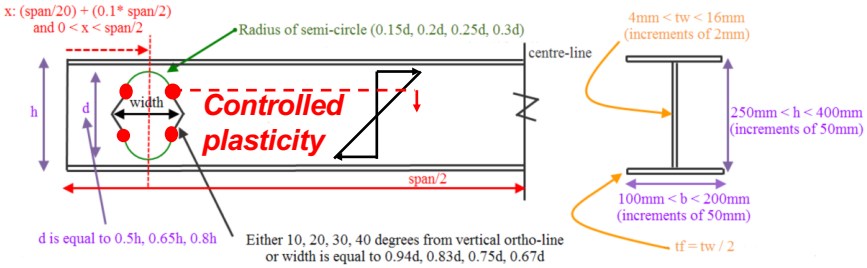


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Opitmisation Techniques

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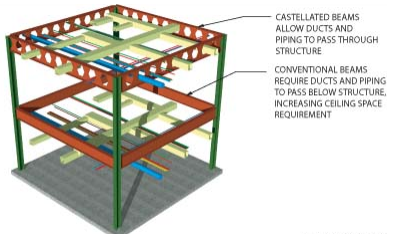
- Morphing Technology → ANSA (BETA CAE Systems S.A.)
- Topology Optimisation → HyperMesh/Optistruct (Altair Engineering)



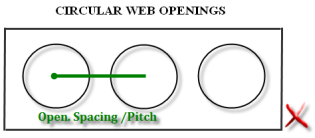
Optimum designs were investigated employing advanced algorithms
(e.g., “harmony search” and “particle swarm optimisers”)

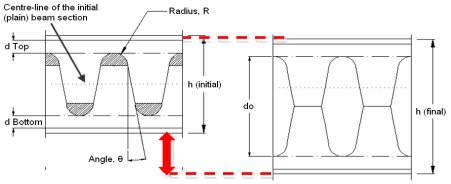
Novel Perforated Beams

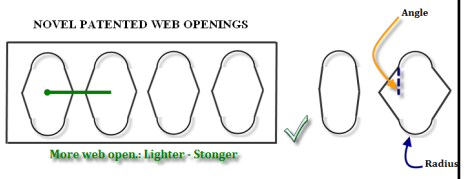
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- ✓ Structural Performance
- ✓ Manufacturability



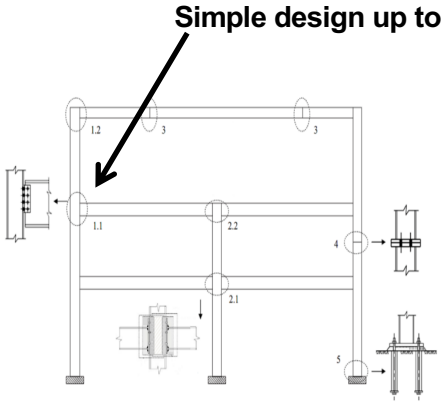


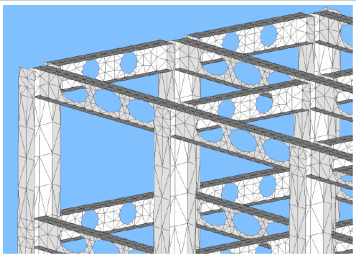


Control opening length and ductility

Simple Design Today

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YESTERDAY

- Pinned connections
- Rigid connections

TODAY

- Semi-rigid connections with rotational springs

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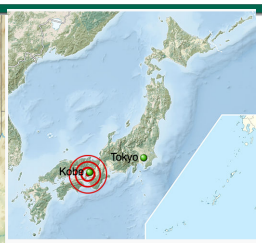
Sesmic-Resistant Design of Connections

Northridge 1994 / Kobe 1995 Earthquakes

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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



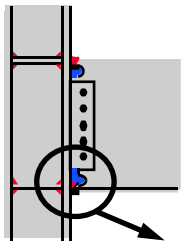
Date	January 17, 1995
Origin time	05:46:53 [1]
Magnitude	6.9 M_w [1]
Depth	17.6 km (10.9 mi) [1]
Epicenter	34.59°N 135.07°E [1]
Type	Strike-slip [2]
Areas affected	Japan
Total damage	$200 billion USD [3]
Max. intensity	Shindo 7
Peak acceleration	0.8 *g*
Casualties	5,502–6,434 killed [2] 36,896–43,792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





Connection Failures

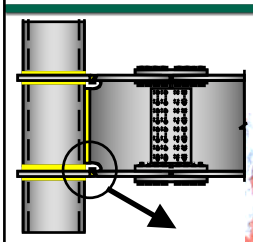
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Connection Failures

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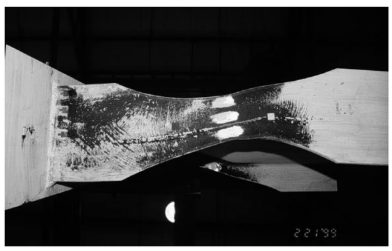


Connection Failures

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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.





orth Beam Bottom Flange RBS After Testing

past **now**

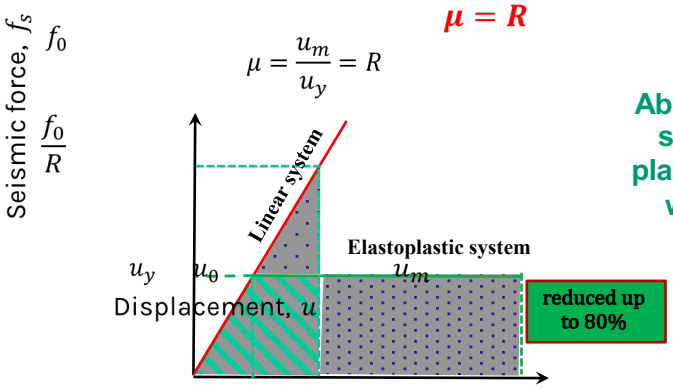
Ductility Provisions

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For long period system
Reduction factor = ductility factor

$$\mu = R$$

$$\mu = \frac{u_m}{u_y} = R$$

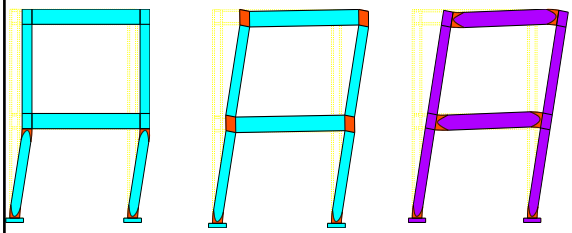


DUCTILITY

Ability of a structural system to deform plastically under load without fracture.

Plastic Hinge Locations

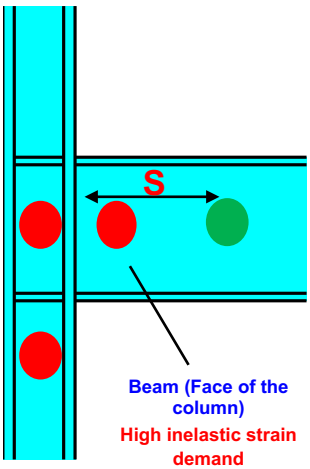
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Column (Flexural & Axial Yielding)
Story mechanism

Panel Zone (Shear Yielding)
Secondary stress

Beam (Flexural Yielding)
Desirable location

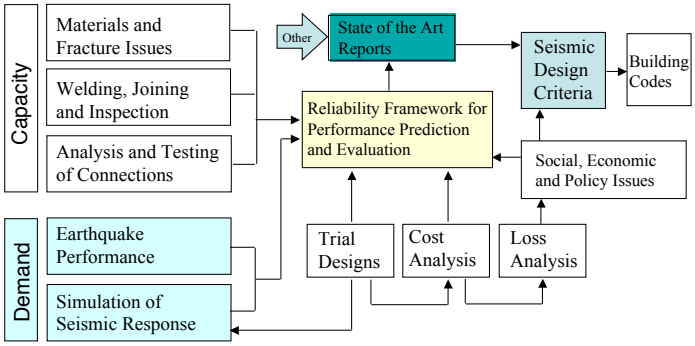


Beam (Face of the column)
High inelastic strain demand
lead to brittle failure

Lessons … to Eurocode 8

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SAC Venture → ASCE 41-06 → FEMA350 → FEMA355F → FEMA 356 → Eurocode 8



Lessons … to Eurocode 8

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SAC Venture → ASCE 41-06 → FEMA350 → FEMA355F → FEMA 356 → Eurocode 8

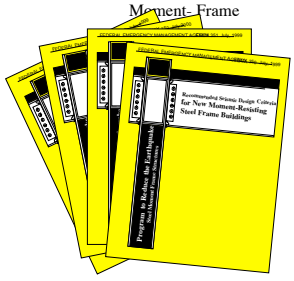
FEMA-350: Recommended Seismic Design Criteria for New Steel Moment-Frame Buildings.

FEMA-351: Recommended Seismic Evaluation and Upgrade Criteria for Existing Welded Steel Moment-Frame Buildings.

FEMA-352: Recommended Post-earthquake Evaluation and Repair Criteria for Welded, Steel Moment- Frame Buildings.

FEMA-353: Recommended Specifications Assurance Frame Construction for Seismic

FEMA-354: Policy Guide for Steel Frame



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Lessons … to Eurocode 8

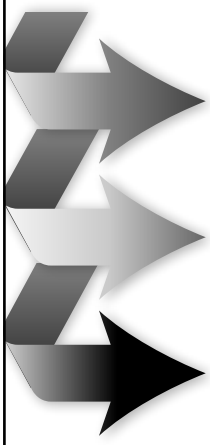
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SAC Venture → ASCE 41-06 → FEMA350 → FEMA355F → FEMA 356 → Eurocode 8

- Structures with dissipative zones shall be designed such that yielding of local building or other phenomena due to hysteretic behaviour do not affect the overall stability of the structure.
- Dissipative zones shall have adequate ductility and resistance. The resistance shall be verified in accordance with EN 1993.
- Dissipative zones may be located in the structural members or in the connections.
  - If dissipative zones are located in the structural members, the non-dissipative part and the connections of the dissipative parts to the rest of the structures shall have **sufficient over strength** to allow development of cyclic yielding in the dissipative parts.
  - When dissipative zones are located in the connections, the connected members shall have **sufficient over strength** to allow the development of cyclic yielding in the connections.

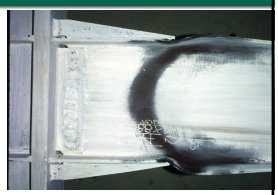
Rehabilitation Methods

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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.



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Strengthening Techniques

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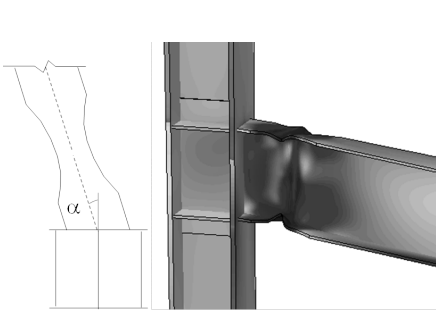
- **Shortening span**
- **Adding beams**
- **Replacement**
- **Post-tensioning (external pre-stressing)**
- **Enlarging section**
  - **Welding plates**
  - **Introducing composite action**

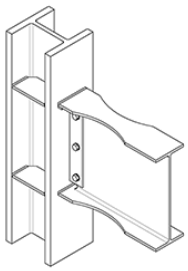
Weakening Techniques - RBS

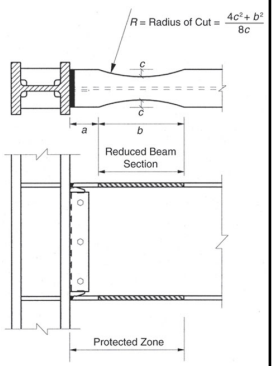
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ANSI/AISC 358-10 and 358s1-11 & EC8

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.

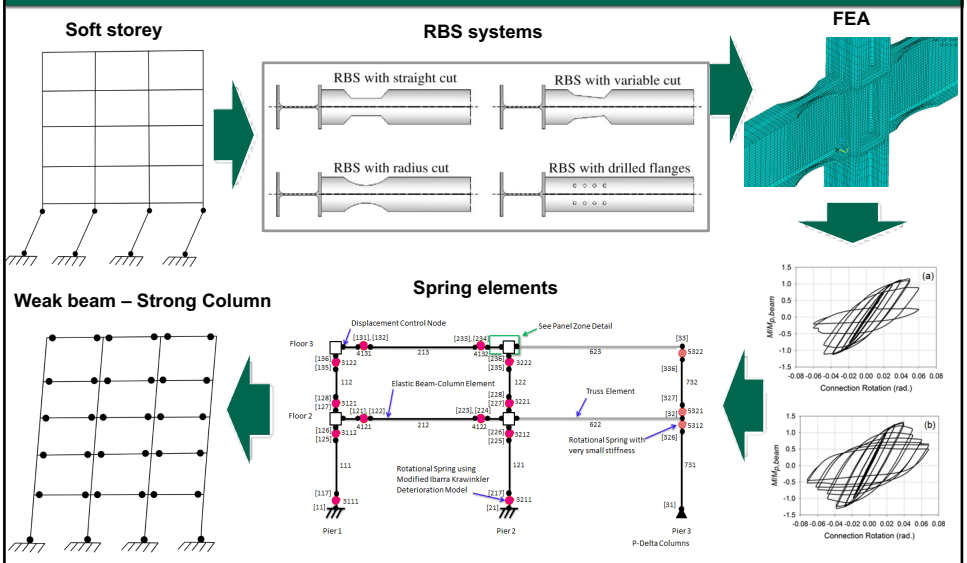






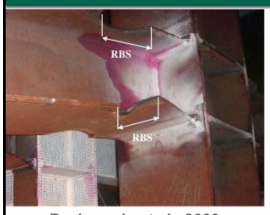
Analysis Methodology Using RBS

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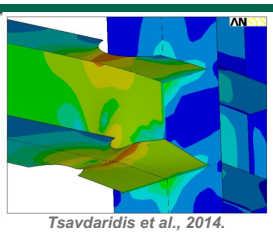


RBS versus RWS

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Pachoumis et al., 2009. Reduced Beam Section Moment Connections, Engineering Structures



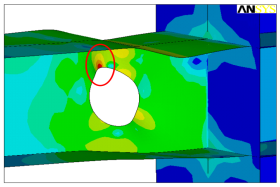
Tsavdaridis et al., 2014. Perforated Steel Beam-to-Column Connections, Journal of Earthquake Engineering

Reduced Beam Section (RBS)

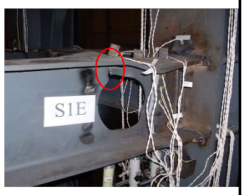
- ✓ High vertical shear capacity
- ✓ Not far away from the joint
- ✓ Global instability issues (LTB)
- ✓ Time and cost of rehabilitation can be increased due to the slab presence

Reduced Web Section (RWS)

- ✓ Easy to cut during retrofitting (cut-out procces)
- ✓ Good shear interaction between concrete slab-shear studs-top flange (not affected)
- ✓ Easy to inspect & maintain
- ✓ Accommodate services



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.

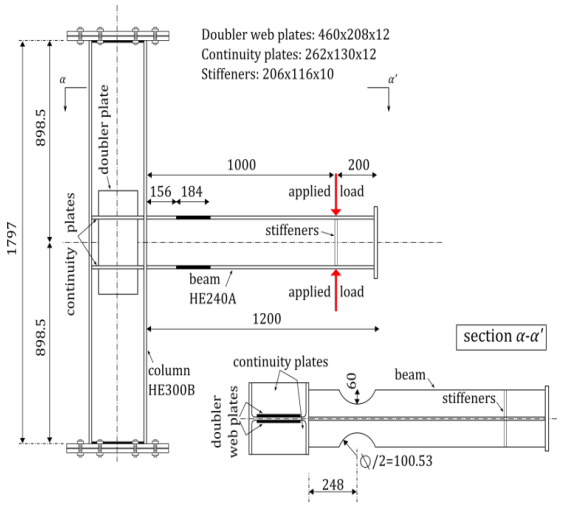
Study 1 (2011)

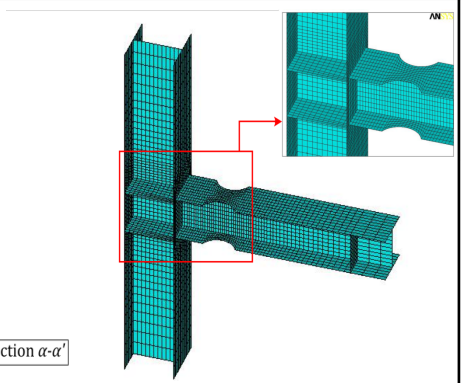
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Welded Connections with isolated web opening

Test Apparatus

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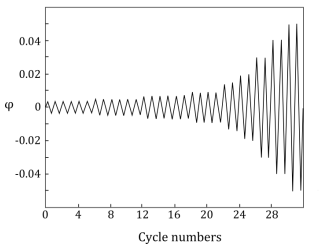


- ✓ 4-node Shell elements
- ✓ Manual (mapped) meshing
- ✓ Mesh convergence
- ✓ Eigen buckling employed

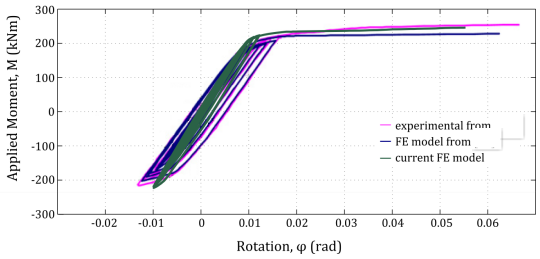
Pachoumis et al., 2009

Validation and Parametric Study

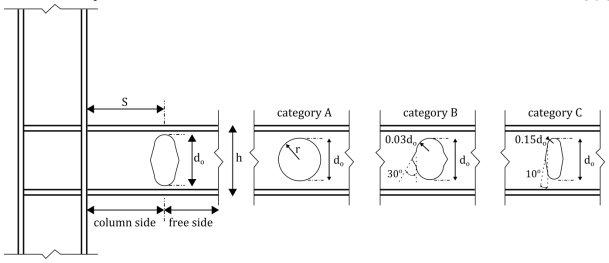
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SAC protocol, FEMA 350/AISC



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)

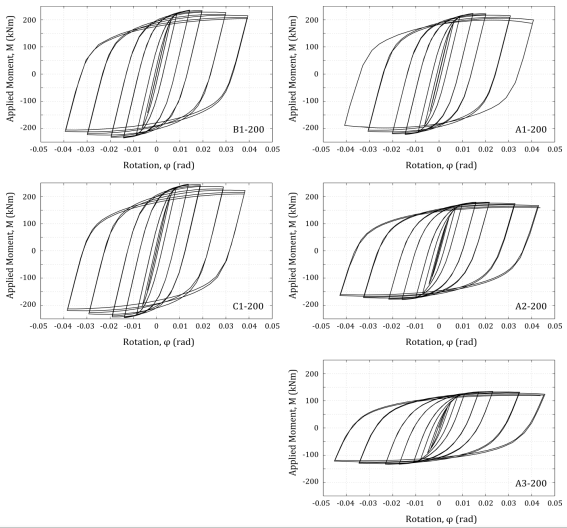
Letter representing opening's category; (A, B, C)

Hysteretic Behaviours

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Novel web opening shapes

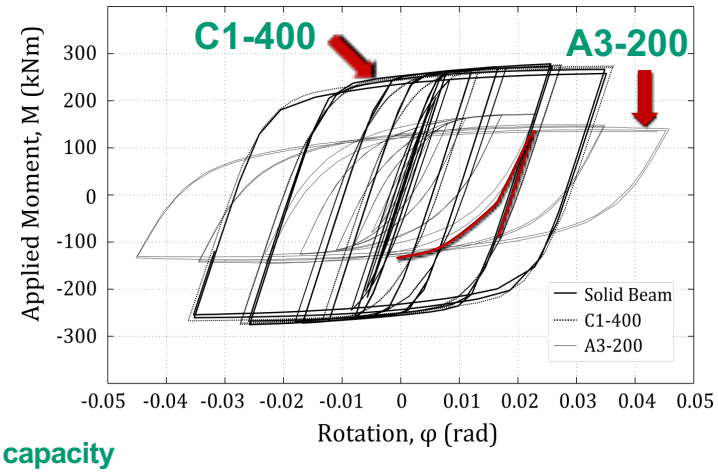
Circular web openings



Advanced Steel Structures, Singapore, Nov 2017 Prof. Konstantinos Daniel Tsavdaridis

Hysteretic Behaviours

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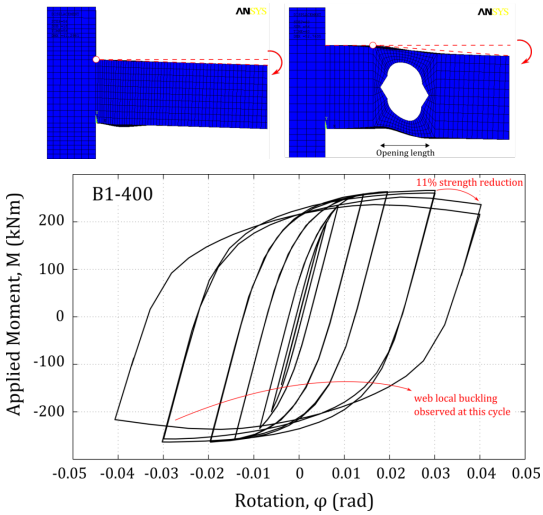


- 50% lower capacity
- 28% higher ductility

Rotational Capacity

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



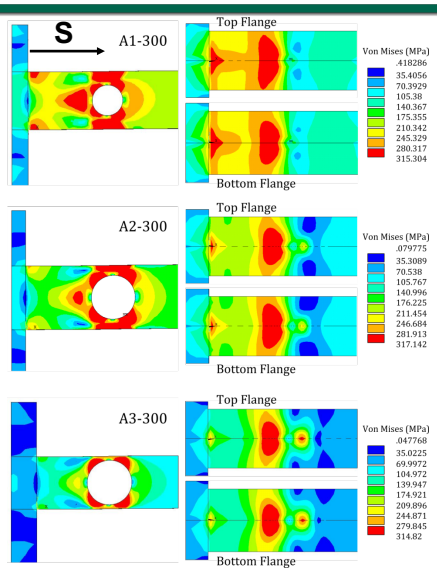
Vierendeel Mechanism

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Effect of depth, d_o

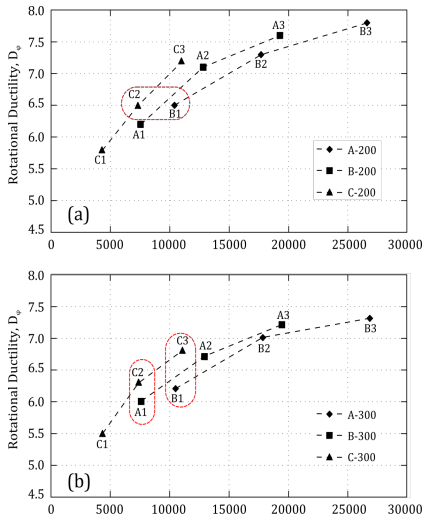
Vierendeel deformation is introducing additional rotation to the RWS connections at the position of the opening, unlike to the connections with solid beams.

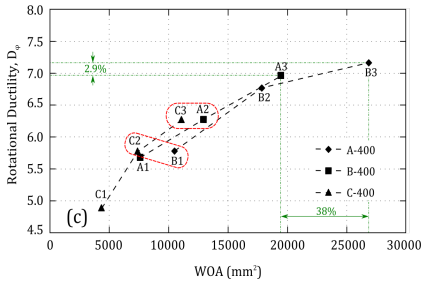
This is the well-known Vierendeel mechanism and it is controlled by the critical opening length, *c*.



Effect of WOA on Ductility

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Results

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Specimen	M_y (kNm)	M_u (kNm)	θ_y (rad)	θ_u (rad)	[a]D_b	[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	0.0360	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	197.8	250.2	0.0070	0.0410	5.9	35644	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

+31.6%

Solid: lowest rotational capacity

A3-200: highest rotational capacity

Geometric Parameters

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Parameter do → Bigger ↔ (Balance) ↔ Smaller ← **Parameter S**

Bigger → Vierendeel → Reducing stress from the joint

Smaller → Vierendeel → Reducing stress from the joint

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

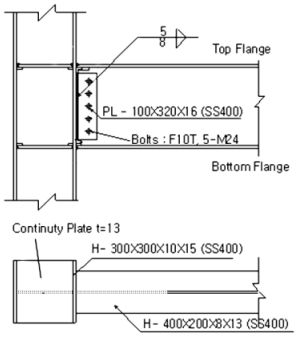
Study 2 (2012)

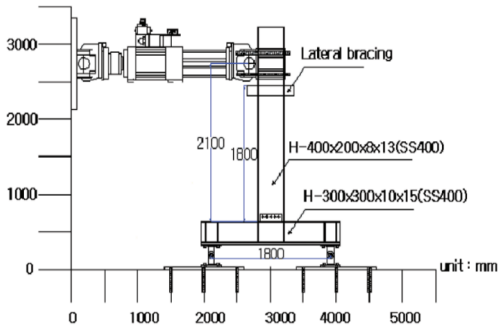
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(Northridge) Welded Unreinforced Flange-Bolted (WUF-B) Connections with isolated web opening

Test Apparatus

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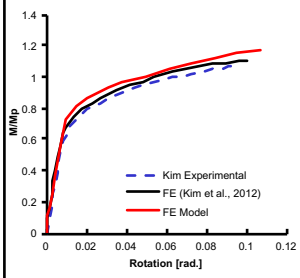
Member	Component	Yield Strength, f_y [MPa]	Ultimate Strength, f_u [MPa]
Beam	Flange	281	423
	Web	332	438
Column	Flange	281	433
	Web	304	450

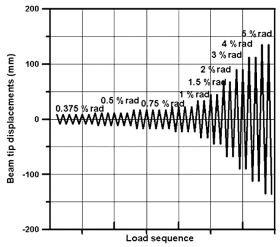
Kim et al., 2012. Collapse resistance of unreinforced steel moment connections, The Struct. Design of Tall and Special Build., 21(10), 724-735

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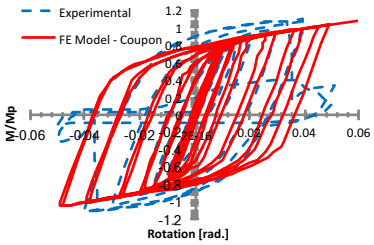
Validation and Parametric Study

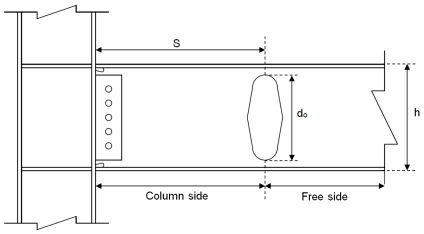
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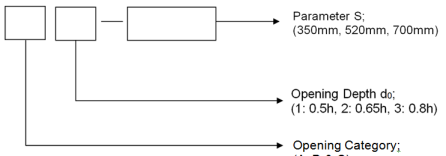




SAC protocol, FEMA/AISC



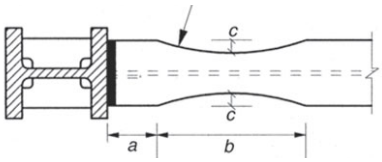




…the so-called…

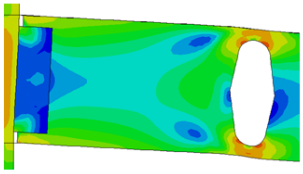
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RBS → Dog-Bone Connection





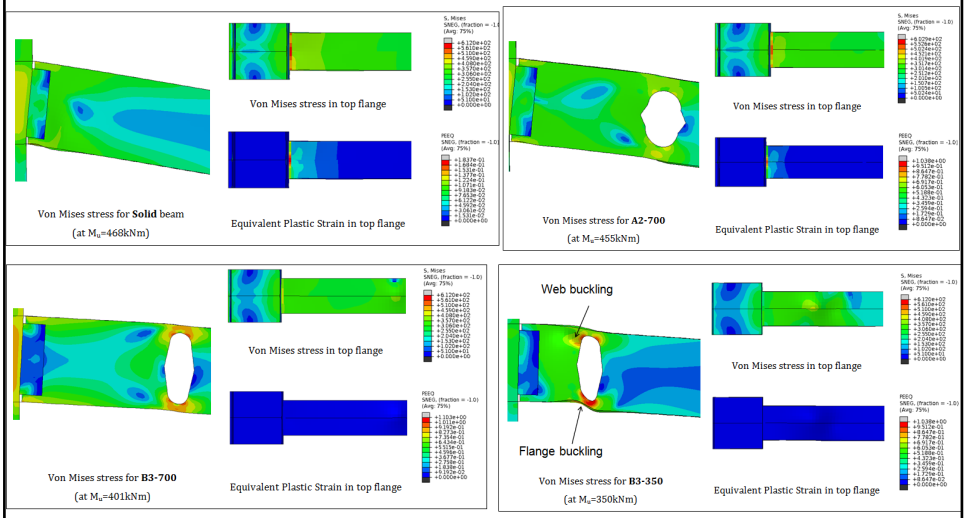
RWS → Inverted-Eye Connection





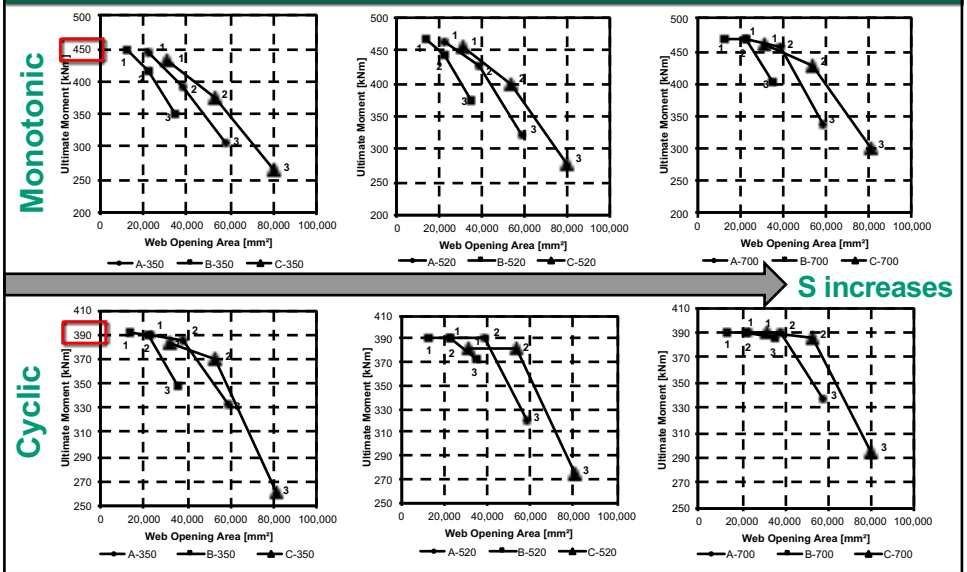
Vierendeel Mechanism

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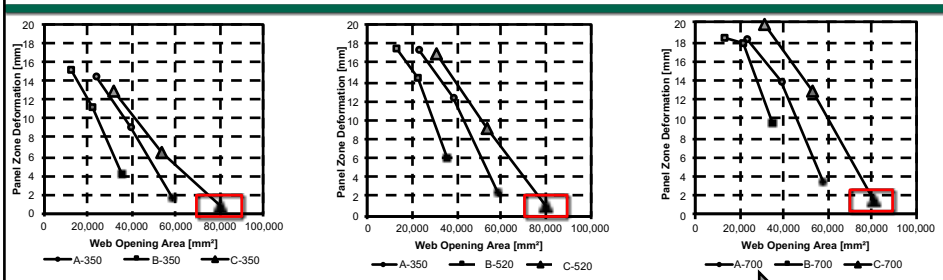
Moment Capacity against WOA

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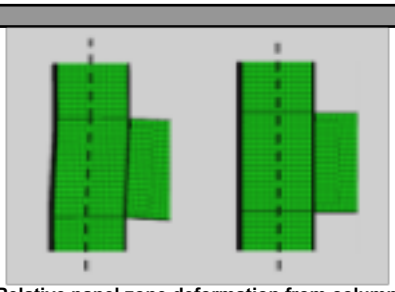


Panel Zone Deformation

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S increases





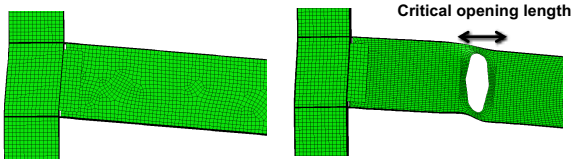
Medium and Large web openings placed near the joint.

Relative panel zone deformation from column centreline

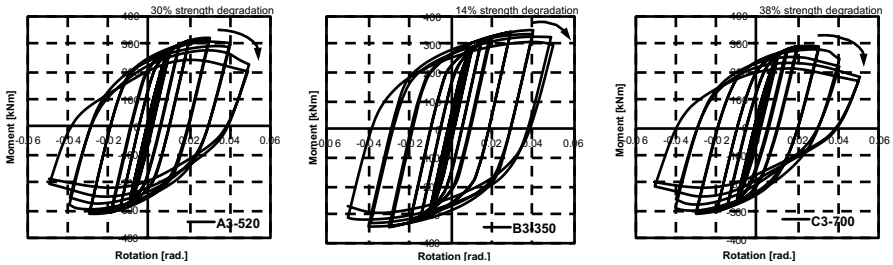
Rotational Capacity

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Centre of rotation for solid and perforated beams.



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



Results

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	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 [mm²]
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.

Results: Monotonic / Cyclic

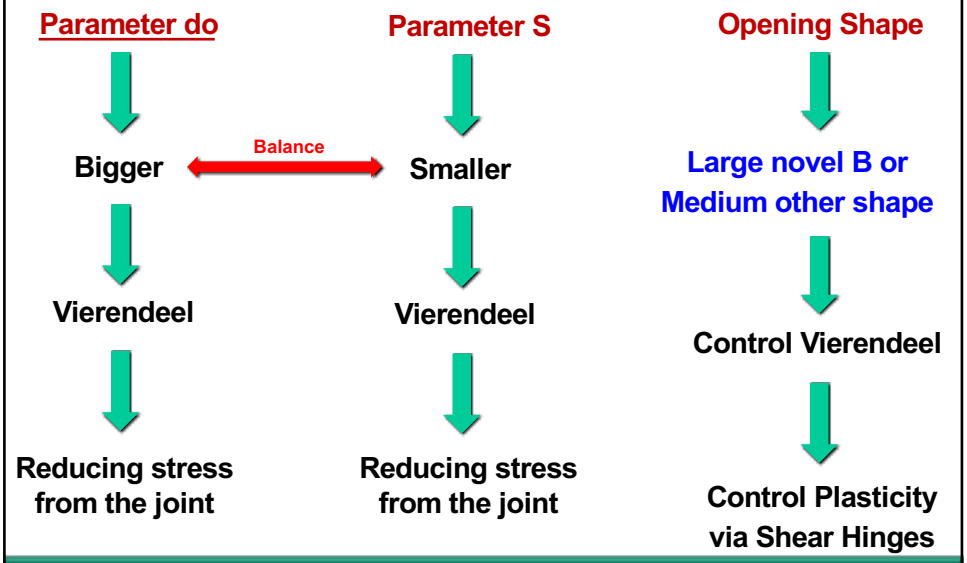
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Connection Type	Ultimate Rotation, φ_u [rad.]		Monotonic/Cyclic
	Cyclic Loading	Monotonic Loading	
Solid	0.04970	0.1290	2.60
A1-350	0.04996	0.1163	2.33
A1-520	0.04996	0.1262	2.53
A1-700	0.05000	0.1279	2.56
A2-350	0.04969	0.0775	1.56
A2-520	0.04996	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

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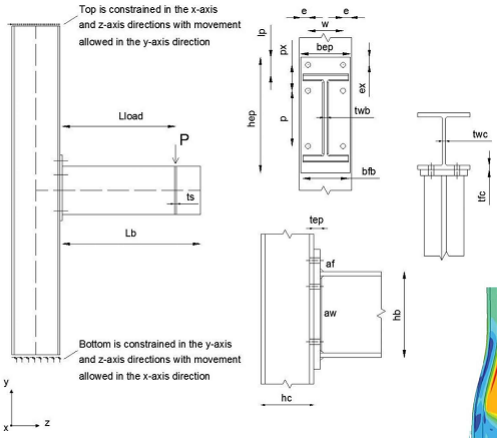
Study 3 (2013)

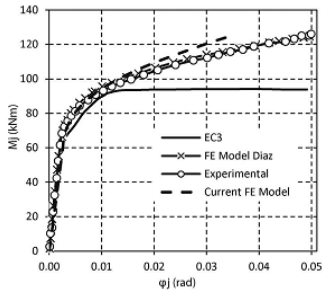
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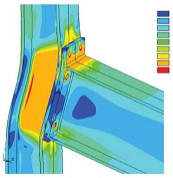
Bolted Connections with isolated web openings and perforated beams

Test Apparatus and Validation Study

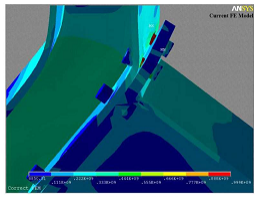
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(a) $M_{j,R} = 124.1$kNm

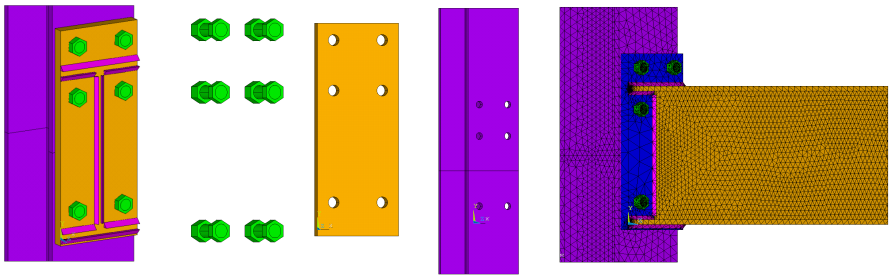


(b) $M_{j,R} = 124.1$kNm

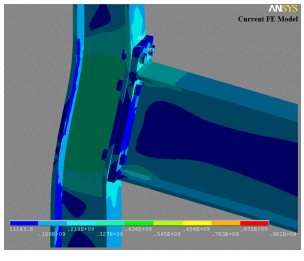
C. Díaz, M. Victoria, P. Marti, O. Querin, FE model of beam-to-column extended endplate joints, J. Constr. Steel Res. 67 (2011) 1578–1590

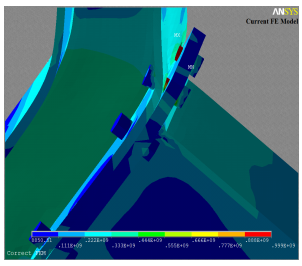
FE Modelling

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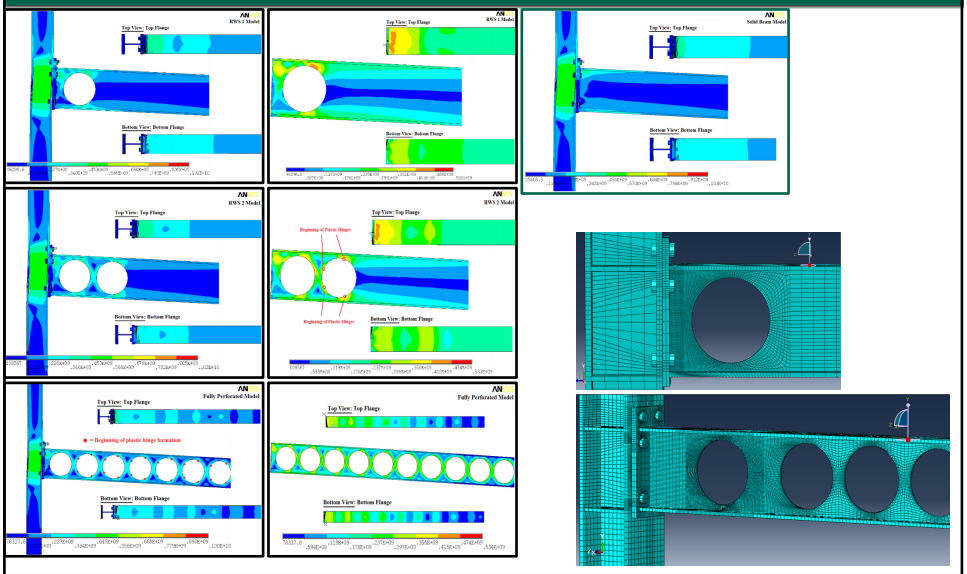
- Solid elements
- Contact elements
- Free/auto mesing
- Manual refinements
- Mesh convergence
- Eigen buckling





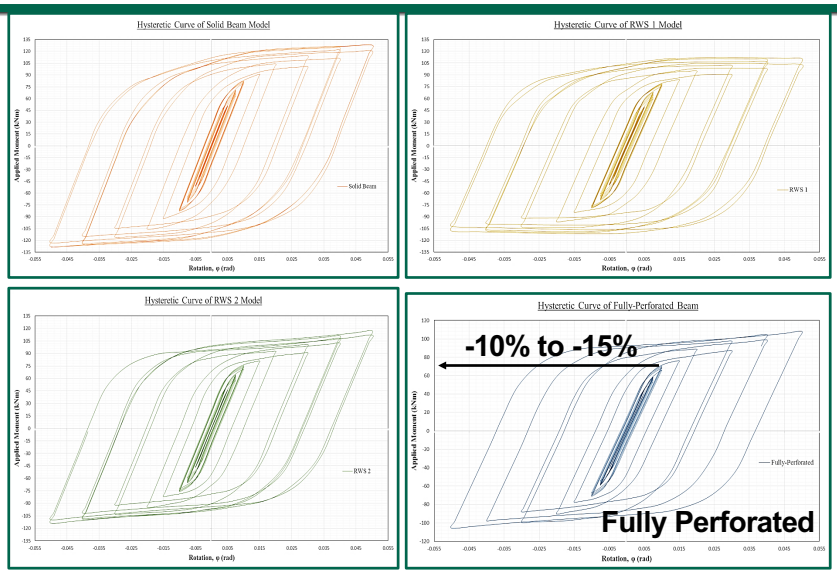
Parametric Study on Circular Openings

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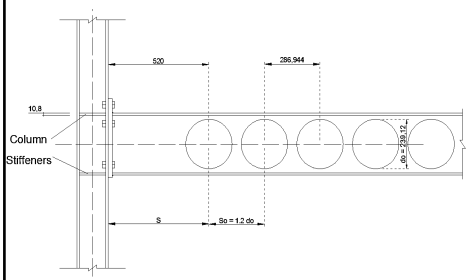
Moment Capacity

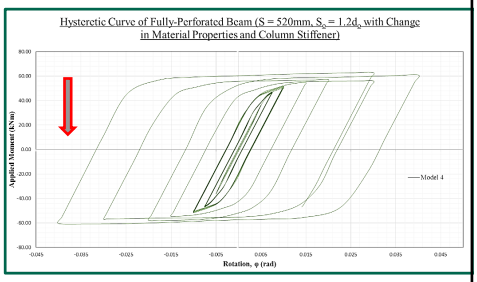
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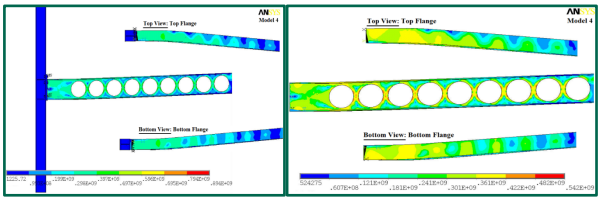


New Connection Design 1

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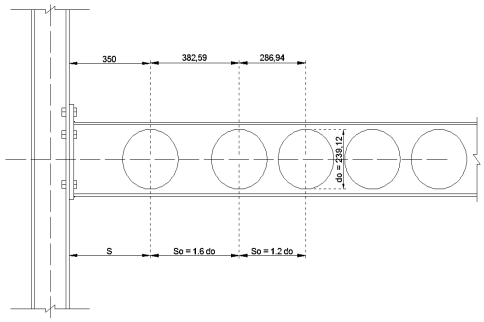


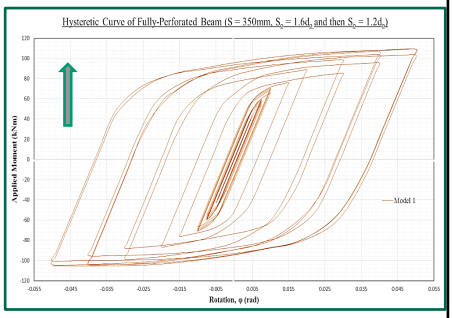


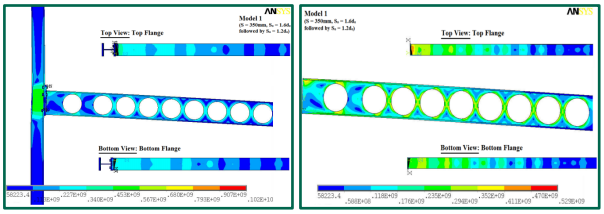
"the energy did not get dissipated and the beam failed at an low load by LTB"

New Connection Design 2

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" ~40% improved design in terms of strength"

Non-composite Connections

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Study 4 (2015)

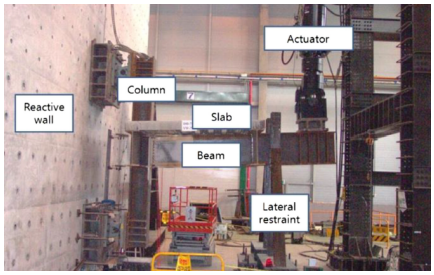
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Composite WUF-B Connections with isolated web openings

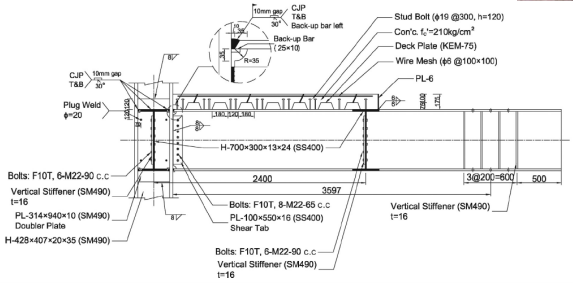
Test Apparatus

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Lee et al., 2016

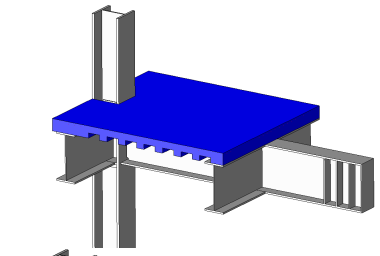


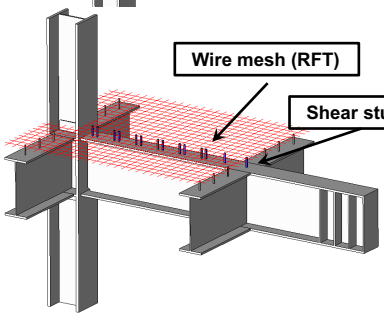


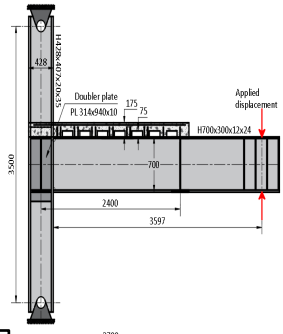
Validation Study

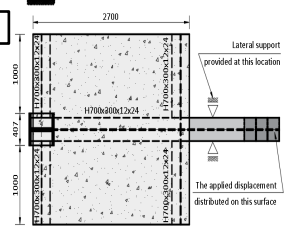
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- Height of the column 3500mm
- Beam length 3597mm
- Column section H428x407x20x35
- Beam section H700x300x12x24
- Stud D19@300, height=120mm
- Wire mesh D6@100x100





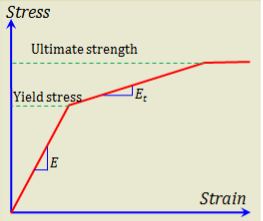




Material Constitutive Laws

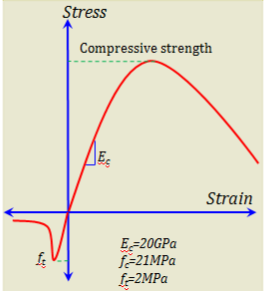
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Beams and column



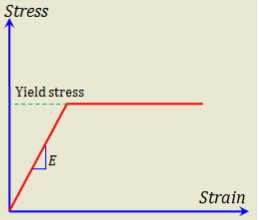
E=200GPa
E_t=1000MPa
f_y=304MPa (beams), 343MPa (column)
f_u=455MPa (beams), 512MPa (column)

Concrete



E_c=20GPa
f_c=21MPa
f_t=2MPa

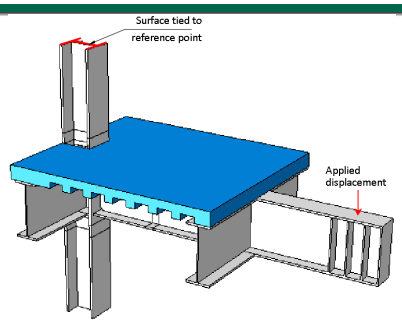
Stiffeners and studs

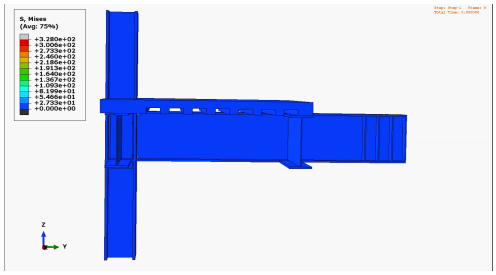


E=200GPa
f_y=304MPa (stiffeners)
f_y=340MPa (Studs)

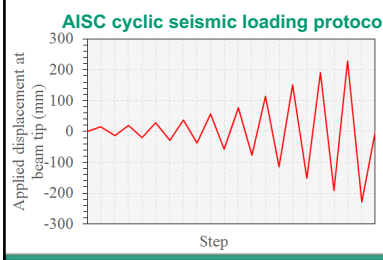
Validation Study

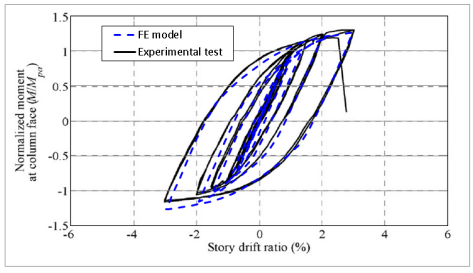
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AISC cyclic seismic loading protocol





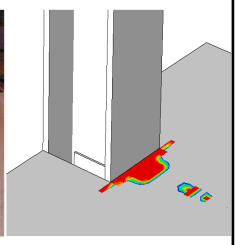
Validation Study

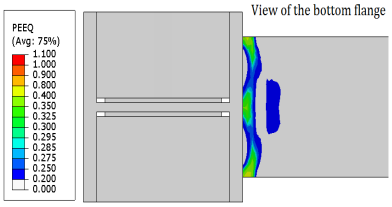
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Rupture of the bottom flange









View of the bottom flange

Access hole at the bottom flange

Parametric Study

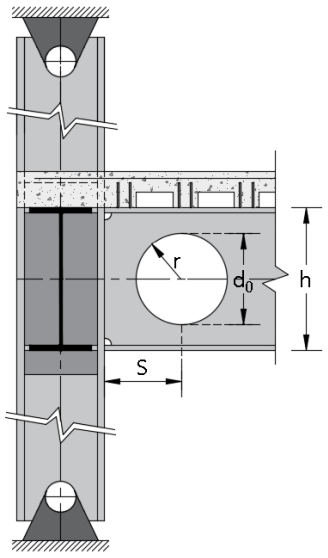
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P - 75d - 150S

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

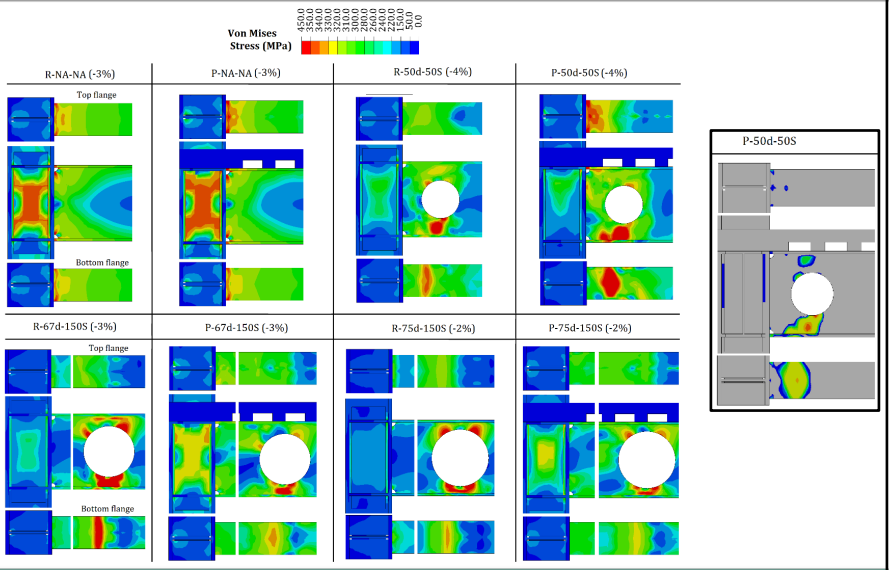
Indicating the percentage of the opening depth to the h.
For instance **75*d*** means d_0=75%h

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



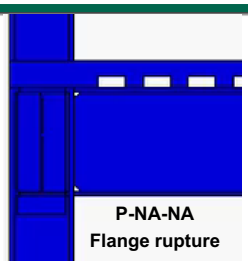
Stress Distribution

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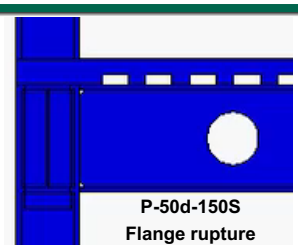


Failure Modes

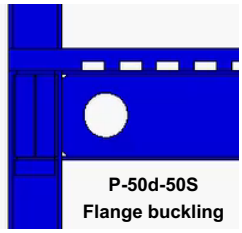
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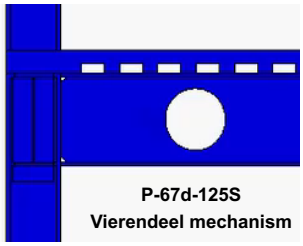
P-NA-NA
Flange rupture



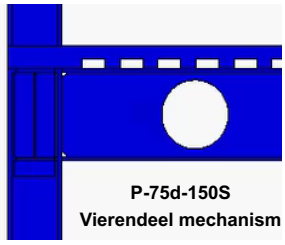
P-50d-150S
Flange rupture



P-50d-50S
Flange buckling



P-67d-125S
Vierendeel mechanism



P-75d-150S
Vierendeel mechanism

Results

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

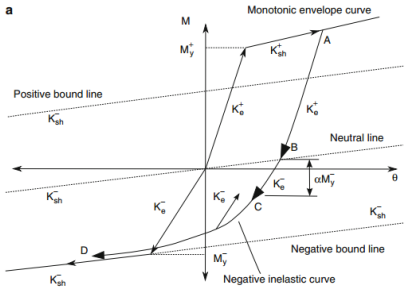
Study 5 (2015)

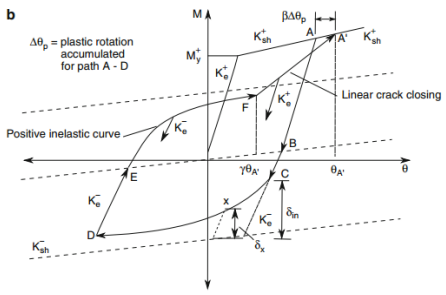
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Frame Analysis
(Incremental Dynamic Analysis)

Monotonic Model

Hysteretic Model

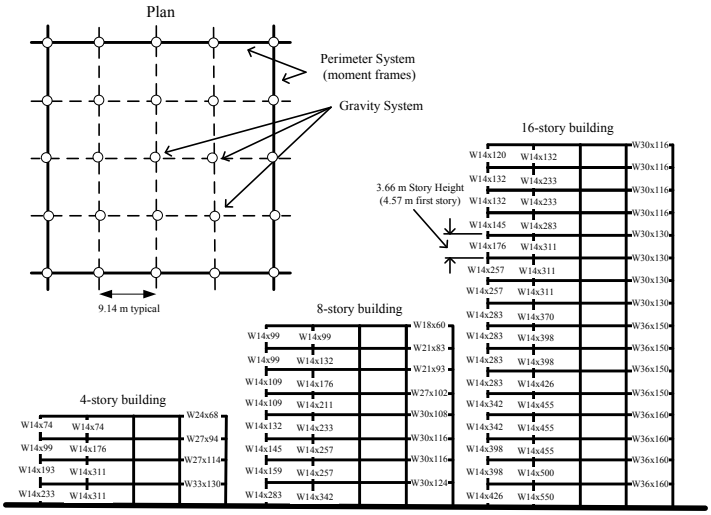




- Tsavdaridis, K.D. Seismic Analysis of Steel-Concrete Composite Buildings, to the section: Structural Engineering - Structural Analysis: Numerical Modelling, ***Encyclopedia of Earthquake Engineering***, Springer Verlag, **2014**, pp. 1-36

Frame Analysis

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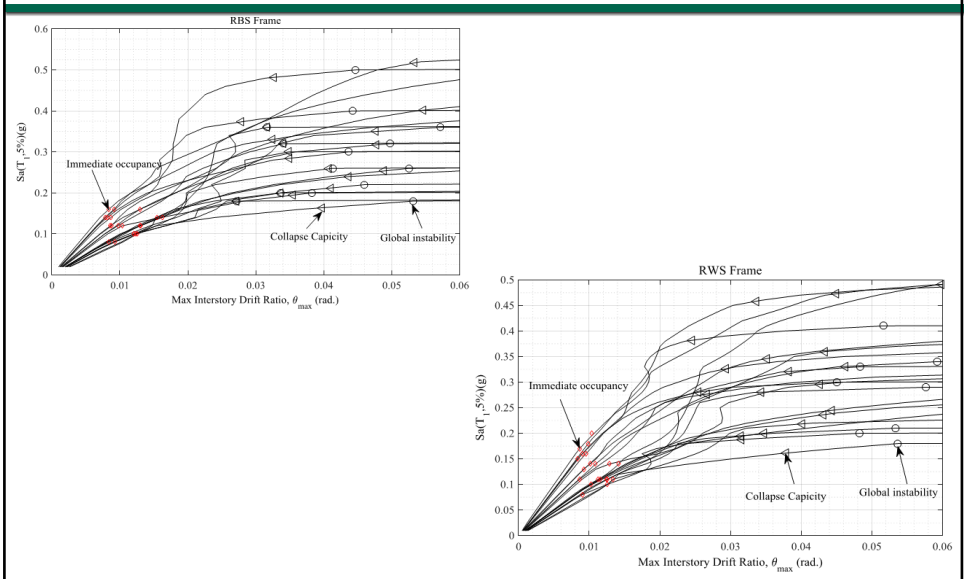
Ground Motion Records

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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

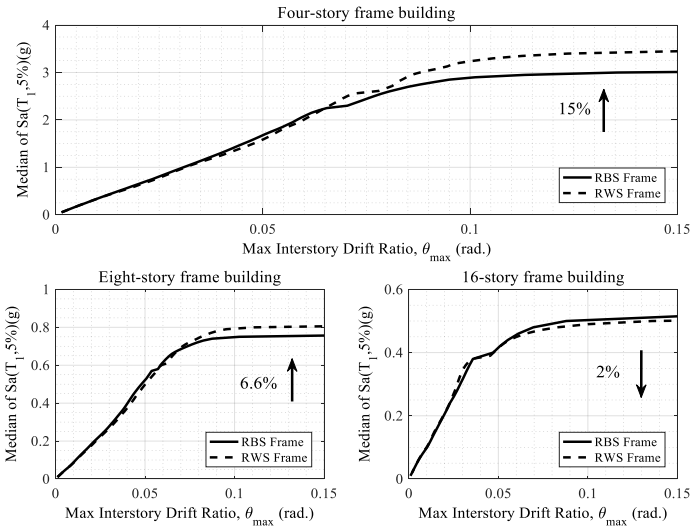
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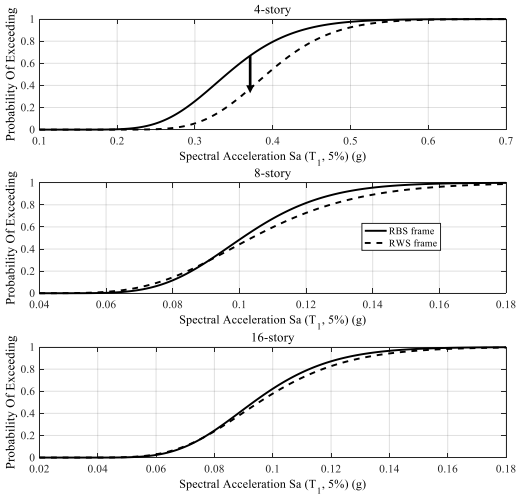
Median IDA Curves

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Median IDA Curves

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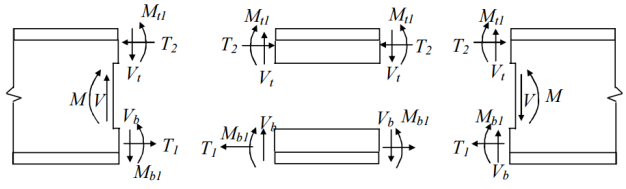
Design Recommendations for non-composite RWS connections

Design Method for WUF-B Connections

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Rotational Moment Capacity of RWS/WUF-B Connections

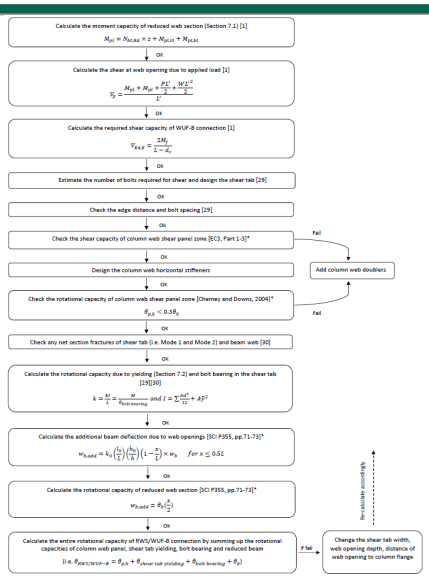
1. Column bending in rotation (EC3, 2005 and P-358, 2014)
2. Yielding of beam web in rotation (EC3, 2005 and P-358, 2014)
3. Bolt bearing failure in fin plate in rotation (EC3, 2005 and P-358, 2014)
4. Yielding of fin plate in rotation
5. **Vierendeel bending at reduced web section in rotation**



Shear and moment interaction at reduced web section

Design Method for WUF-B Connections

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Design Method for WUF-B Connections

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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]

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

Advanced Steel Structures, Singapore, Nov 2017 Prof. Konstantinos Daniel Tsavdaridis

Vierendeel Bending at Reduced Section

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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:

$$A_{bt} = b_{fb} t_{fb} + (\frac{h_b - d_0}{2} - t_{fb}) \times t_{wb}$$

Design Method for WUF-B Connections

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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]

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

Design Method for WUF-B Connections

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

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

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

Concluding Remarks

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- ✓ **Large isolated web openings** can prevent excessive shear deformation as well as reduce the stress intensity in the vicinity of the beam-to-column weld in contrast to other reinforcing methods (eg. stiffeners, double plates, etc.).
- ✓ RWS connections achieved **higher inelastic rotational capacity** in comparison to the RBS connection and they are capable of reaching beyond 0.035 radian (between 0.05 radian and 0.07 radian).
- ✓ Beams with **novel openings**, compared to the commonly used circular openings, were found to be stronger and attain a higher ultimate rotation for the same opening depth.
- ✓ RWS connections examined are ideal for **low-story buildings**.
- ✓ RWS connections, and particularly those with novel web opening shapes, can be fully customised for the bespoke requirements of the steel frame with the **effective CONTROL of the plasticity (replacing moment plastic hinges with shear plastic hinges)**.
- ✓ **Critical opening length 'c'**, **end-distance 'S'**, and **web opening depth 'd_o'** are the dominant parameters to precisely define the ductility of RWS connections.
- ✓ **WOA** is not a decisive parameter.

Partners/Funders

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The Institution of Structural Engineers

kloeckner metals
UK | Westok

SCI
Steel Knowledge

Westok

COMMONWEALTH SCHOLARSHIPS

SCI

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TATA STEEL

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University of Leeds



Miss Faezeh Faghih
MSc, PhD Candidate
City University London



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Tokyo Institute of Tech., Japan



Mr Mohamed Shaheen
MSc in Structures
Uni. of Cairo, Egypt
Tokyo Institute of Techn., Japan



Dr Toshihide Kashima
Senior Research Engineer
Building Research Institute, Japan

Publications

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- Tsavdaridis, K.D., Faghih, F. and Nikitas, N. (**2014**) Assessment of Perforated Steel Beam-to-Column Connections Subjected to Cyclic Loading. ***Journal of Earthquake Engineering***. 18(8), pp. 1302-1325
- Tsavdaridis, K.D. (**2014**) Strengthening Techniques: Code-Deficient Steel Buildings, to the section: Structural Engineering - Structural Design, ***Encyclopedia of Earthquake Engineering***, Springer Verlag, pp. 1-26
- Tsavdaridis, K.D. and Papadopoulos, T. (**2016**) A FE Parametric Study of RWS Beam-to-Column Bolted Connections with Cellular Beams. ***Journal of Constructional Steel Research***, Vol. 116, pp. 92-113
- Tsavdaridis, K.D., Pilbin, C. and Lau, C.K. (**2017**) FE Parametric Study of RWS/WUF-B Moment Connections with Elliptically-Based Beam Web Openings under Monotonic and Cyclic Loading. ***International Journal of Steel Structures***. 17, pp. 677-694
- Shaheen, M.A., Tsavdaridis, K.D. and Yamada, S. (**2017**) A Comprehensive FE Study of the Hysteretic Behaviour of Steel-Concrete Composite and Non-Composite RWS Beam-to-Column Connections. ***ASCE Journal of Structural Engineering***. (in press)
- Naughton, D.T., Tsavdaridis, K.D., Maraveas, C. and Nicolaou, A. (**2017**) Pushover Analysis of Steel Seismic Resistant Frames with RWS and RBS Connections. ***Frontiers in Built Environment (EPFL)*** (in press)
- Kiani, J. and Tsavdaridis, K.D. (**2017**) Seismic Performance of RBS and RWS Building Frames using IDA: A Comparative Study. ***Journal of Constructional Steel Research***. (under review)
- Tsavdaridis, K.D. (**2018**) Reduced Web Section (RWS) Beam-to-Column Connections - A Review of the Experimental Campaign and FEA Investigations, ***Frontiers in Built Environment (EPFL), Research Topic: Resilient Pre-Engineered Metal Based Connections - Accidental Effects and Design Aspects***. (submitted)

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Thank you for your time!

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