Institute of Resilient Infrastructure
School of Civil Engineering
Faculty of Engineering

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Seismic Resistant Design of Connections with the use of Perforated Beams

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Fact

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

This can be called as:

- *Sustainable design*
- *Resilience*
- *Efficiency*
- *Optimisation*
- *Performance-based design*
- *Adaptive (eg. pneumatic) design*

Indeed the one-off nature of every civil-structural engineering project necessitates the use of rigorous studies and advanced techniques in the global and local level (as well as the material level) to drive efficiencies on the increasingly complex projects of today.

Inspired from…

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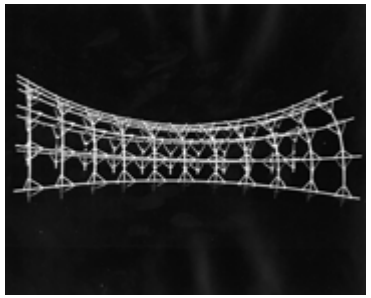
Robert le Ricolais, 1894-1977

An apparently simple sentence, *The art of structure is where to put the holes*, is his point of departure for an exposition on strength without weight in a tube shape that might create a new kind of subway tunnel.



David Hovey, Architect

I have spent my career thinking about how to design buildings economically and efficiently!

Perforated Beams

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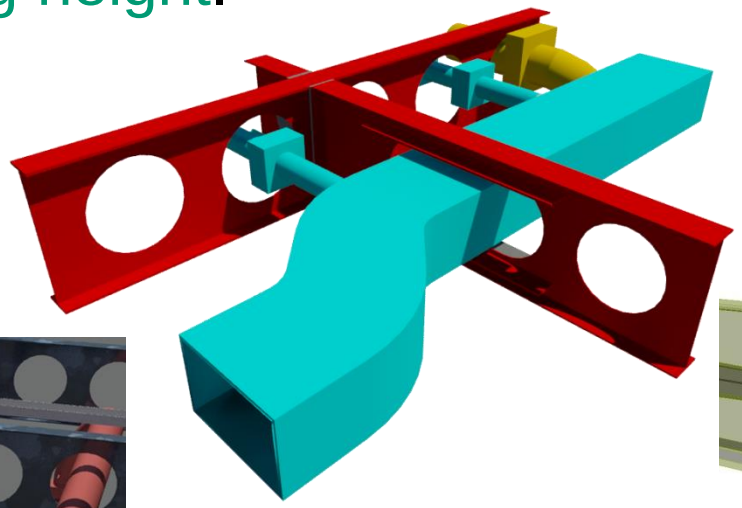
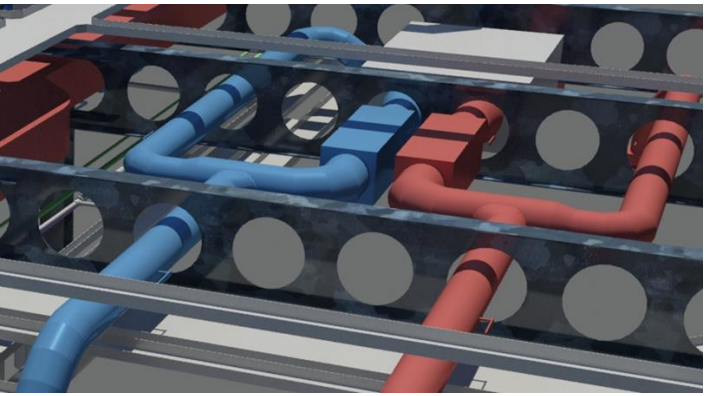
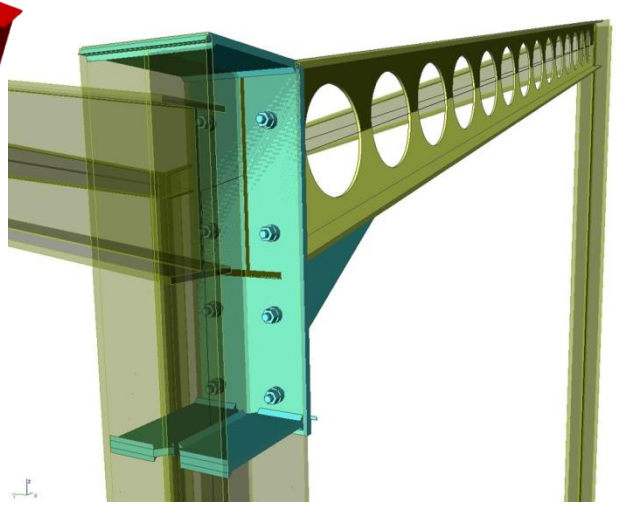
Perforations in the webs of steel beams are widely used nowadays in building construction due to their ability to provide lighter structural members, reduced material costs, in addition to the provision for greater flexibility in structural layouts particularly in the floor-to-ceiling height.







Perforated Beams (since 2005…)

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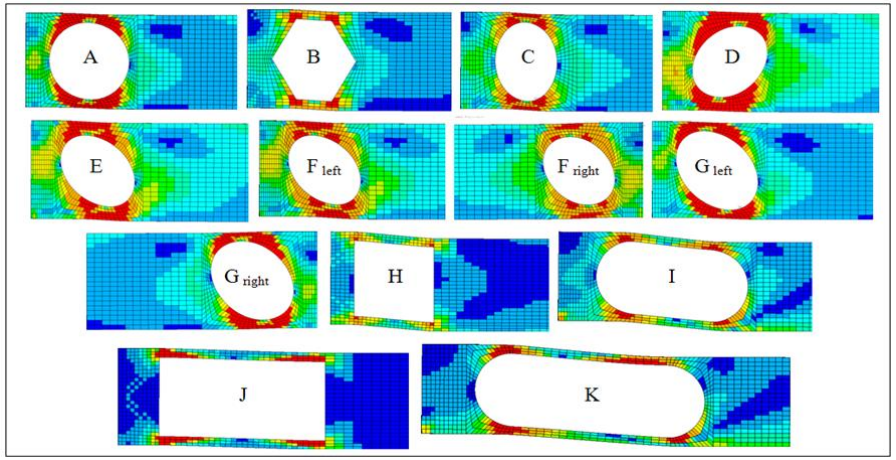

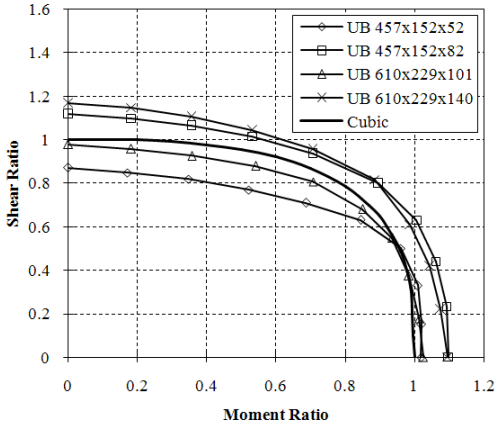

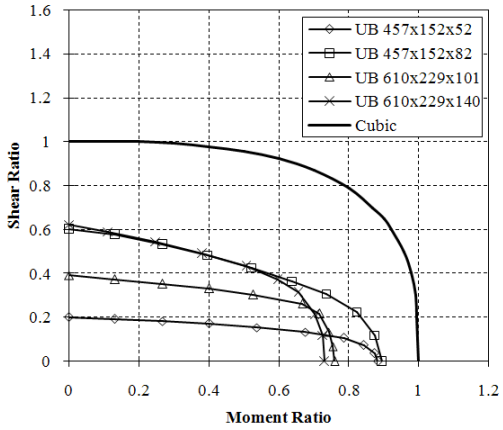

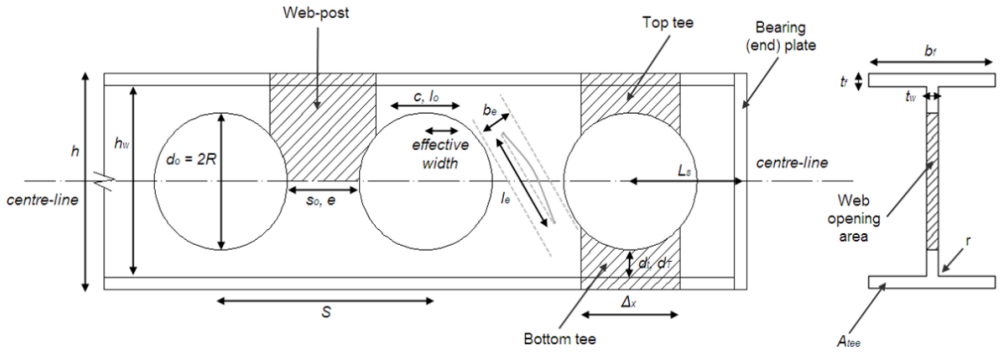

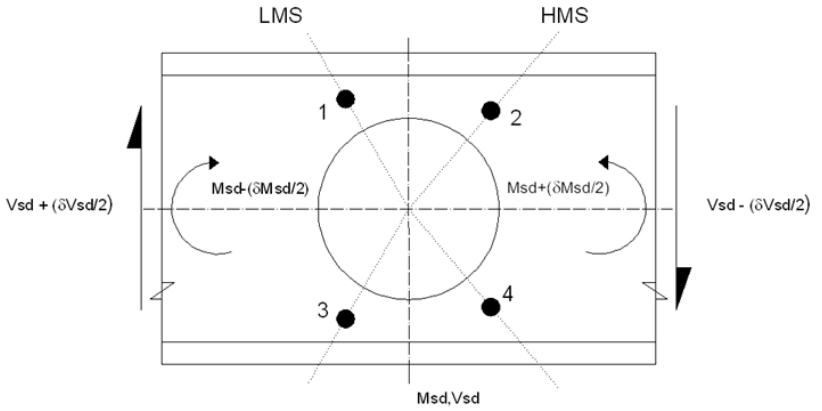

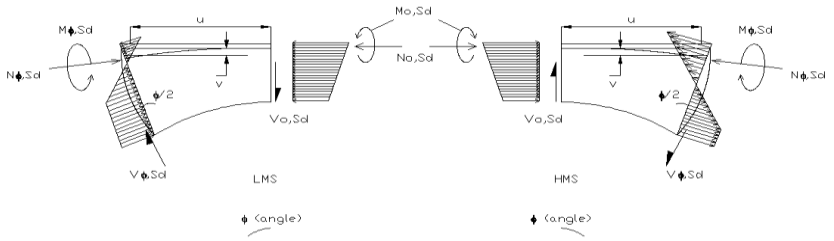

Perforated Beams (since 2005…)

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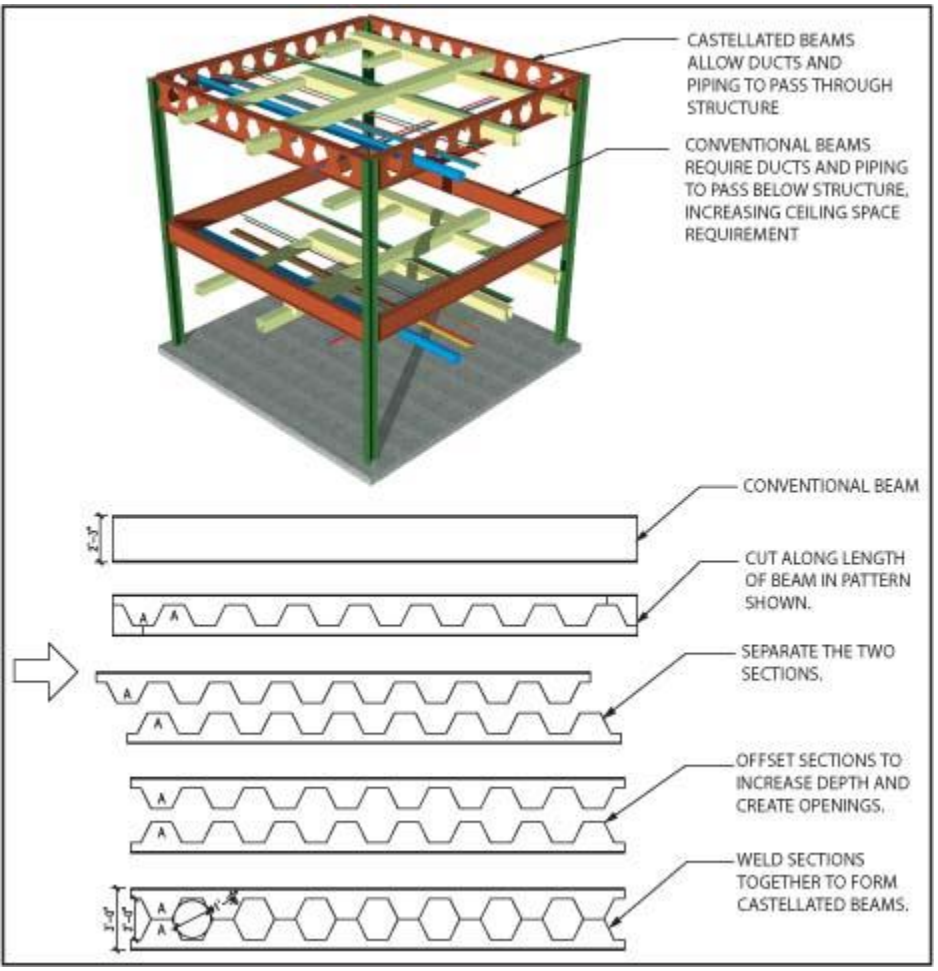
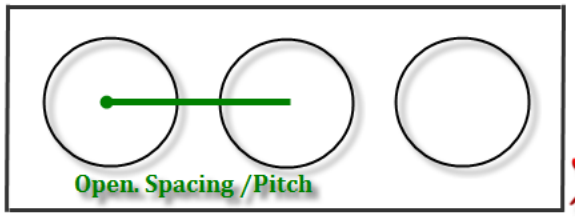
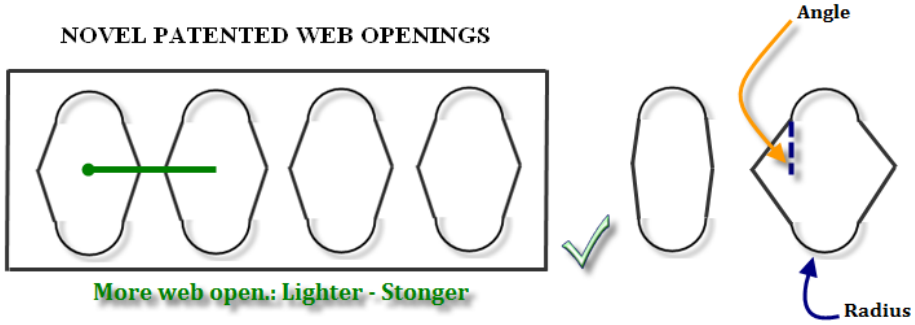
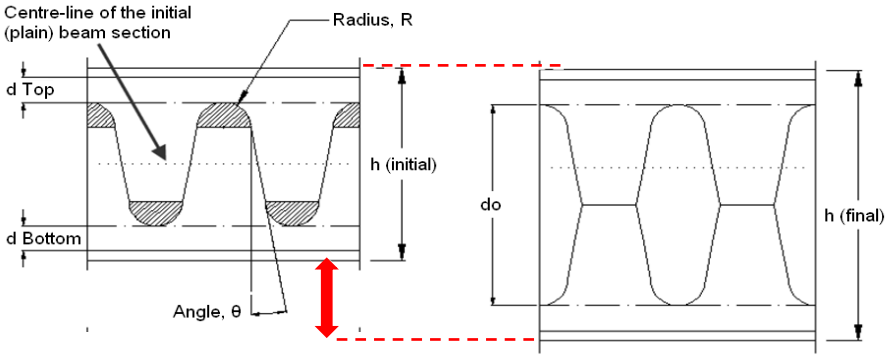


CIRCULAR WEB OPENINGS



NOVEL PATENTED WEB OPENINGS





Strengthening Techniques

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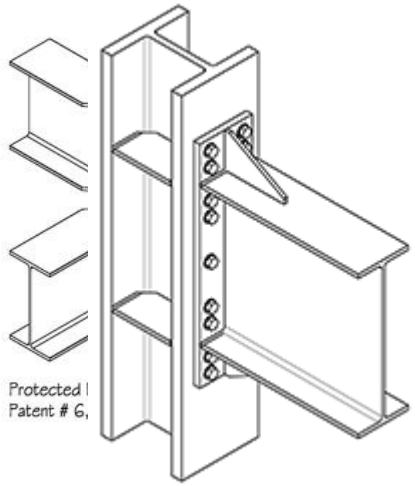
In order to enhance of (post-Northridge) connections, researchers provided high level of ductility and assured operation in connections by:

- Connection reinforcement/strengthening; a number of connections have been proposed in FEMA 350 such as the:
  - Bolted Flange Plate (BFP)
  - Bolted Unstiffened End-Plate (BUEEP)
  - Stiffened Extended End-Plate (BSEEP)
  - CONXTECH CONX and KAISER Bolted Bracket (KBB)



- Excess reinforcement leads to:
  - increasing welding and bolting processes
  - increasing connections rigidity and panel zone stresses
  - increase in weight and hence the seismic effects

Weakening Techniques - RBS

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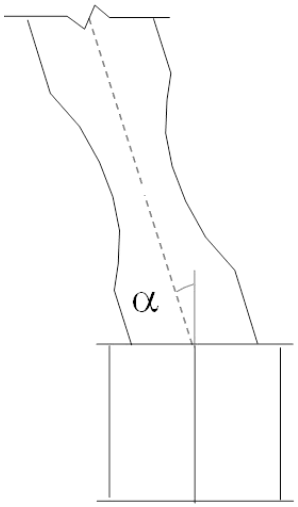
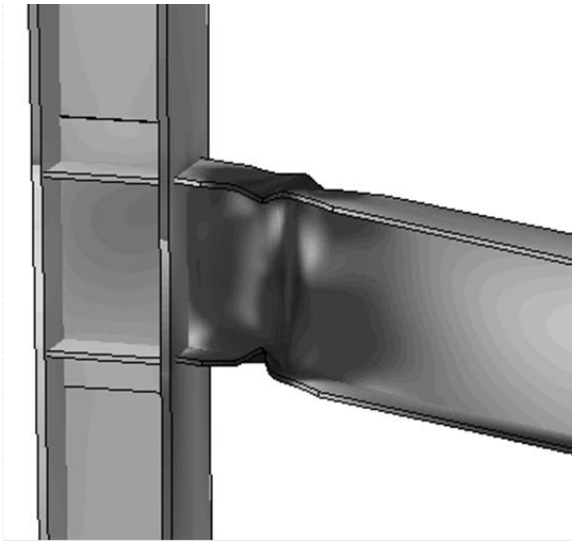
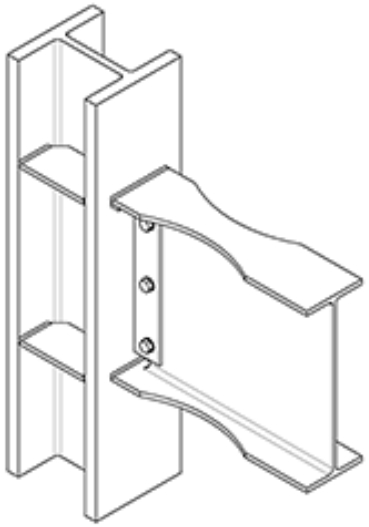
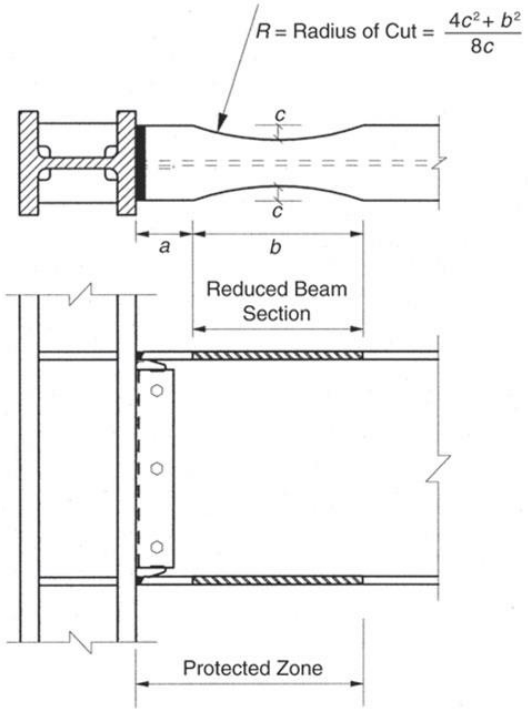
➢ Beam weakening by reducing the cross-sectional area of the beam locally at a certain distance from the connection to shift the stresses away from the column's face. One method to achieve this is by removing portions of the flanges locally, referred to as Reduced Beam Section (RBS). → **Economical solution !!**









FEMA 350 & EC8

Modelling of RBS

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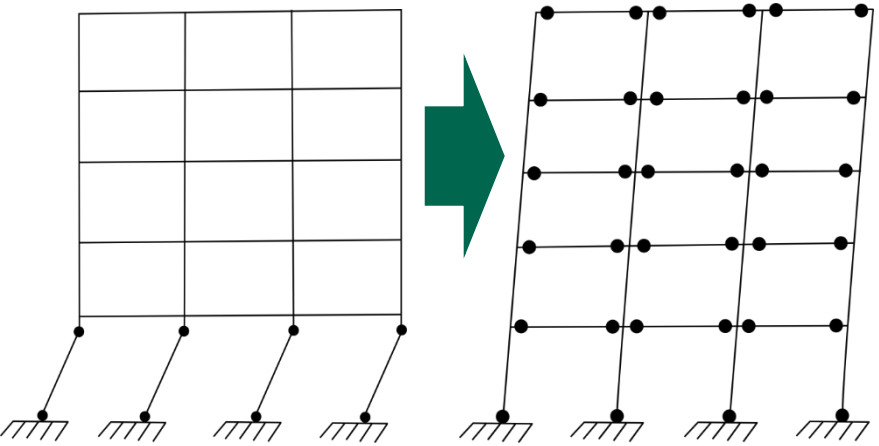
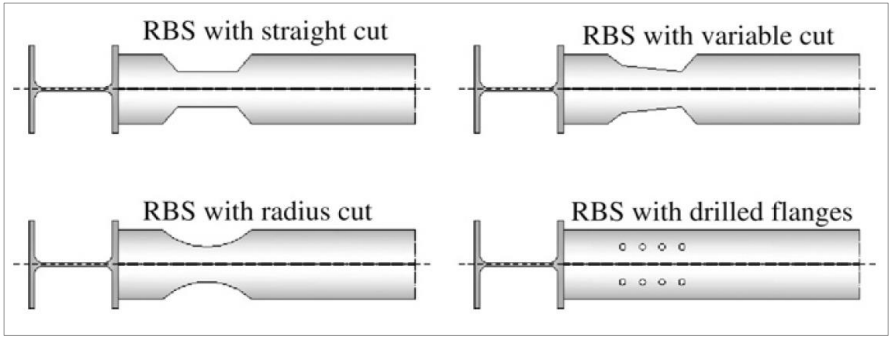
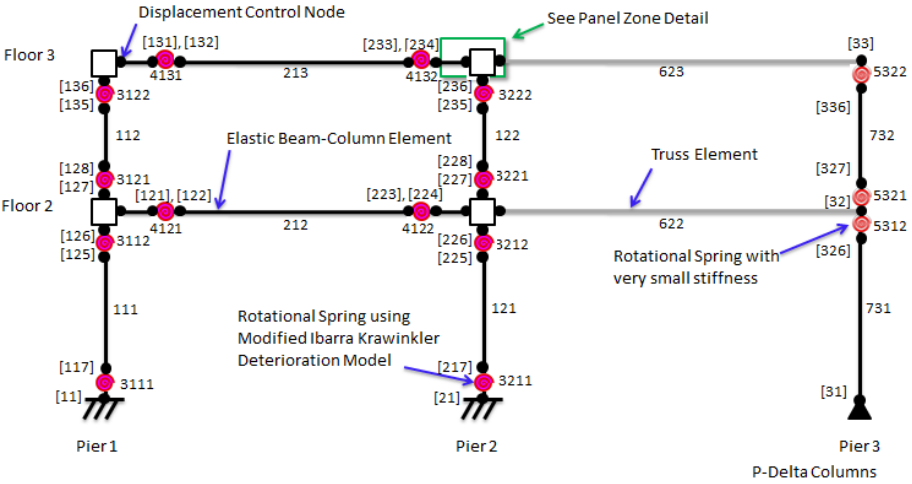
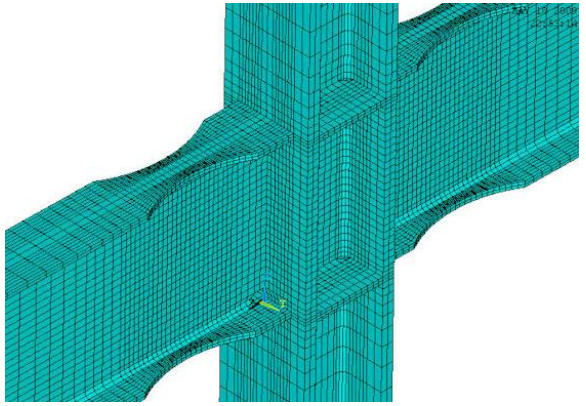
Strong column – weak beam









RBS vs RWS

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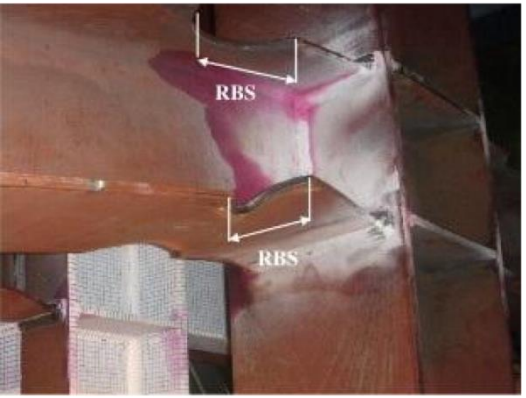
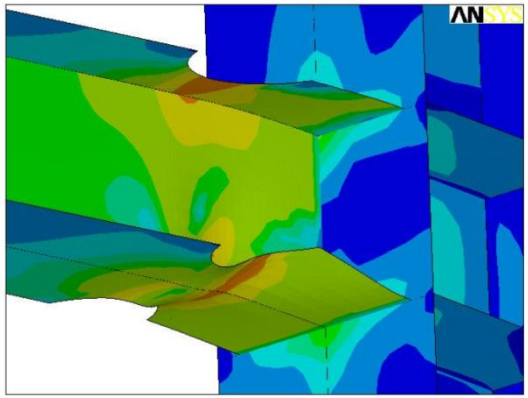




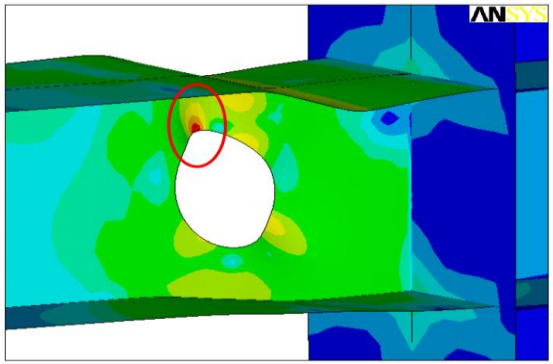
Pachoumis et al., 2009. Reduced Beam Section Moment Connections, Engineering Structures

RBS

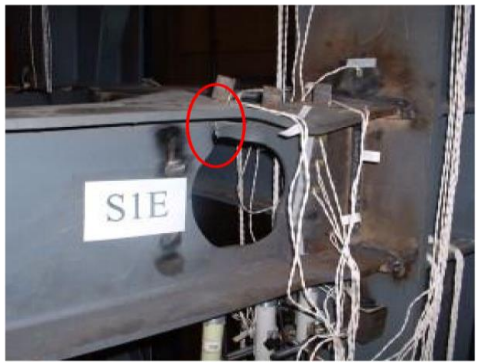
- ✓ Increased shear capacity
- ✓ Close to the connection
- ✓ Global instability issues (LTB)
- ✓ Time and cost of rehabilitation can be increased due to the slab

Reduced Web Section - RWS

- ✓ Easy access to cut during retrofitting (cut-out procces)
- ✓ Full shear connection between composite slab-shear studs-top flange (not affected)
- ✓ Easy to inspect & maintain
- ✓ Accomodate 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.

Fully-Welded Connections with isolated web openings

Test Apparatus

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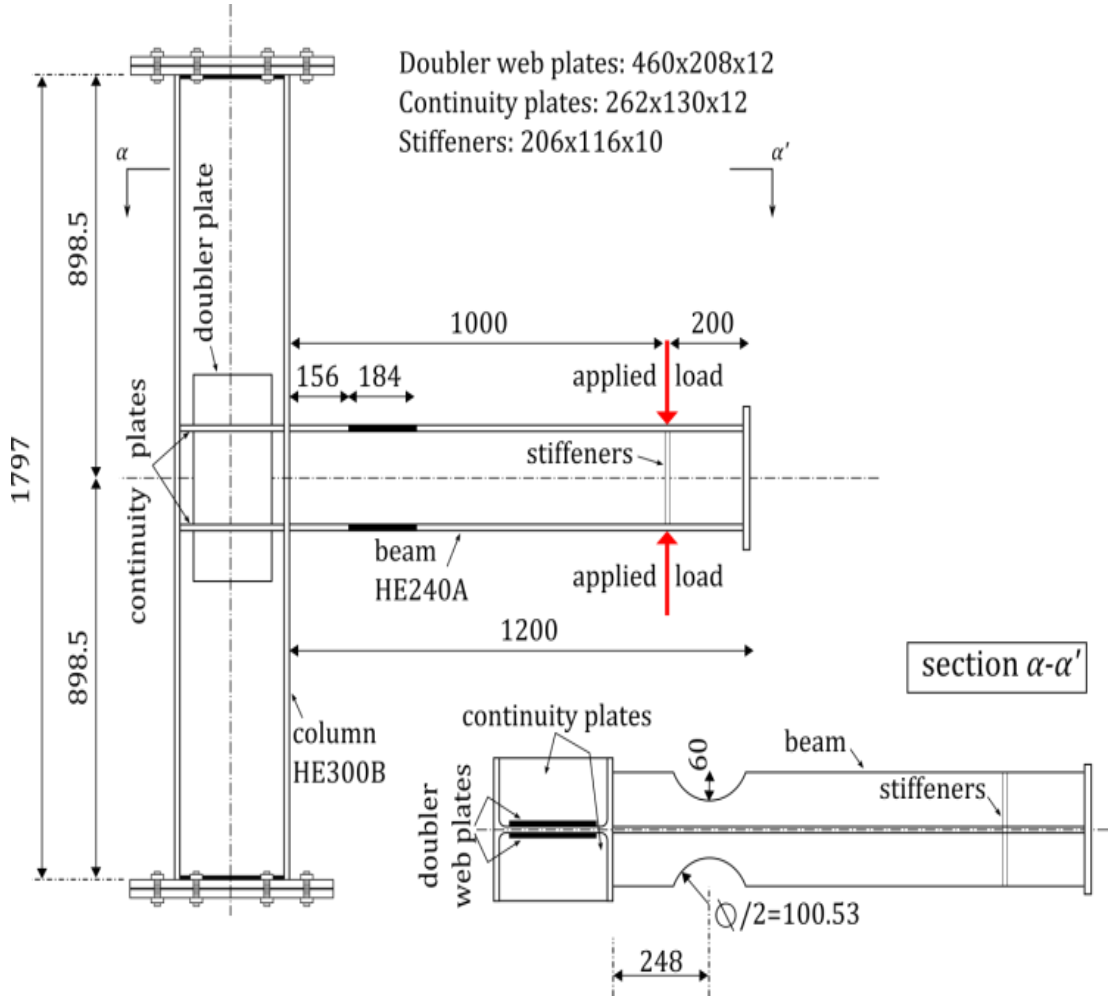

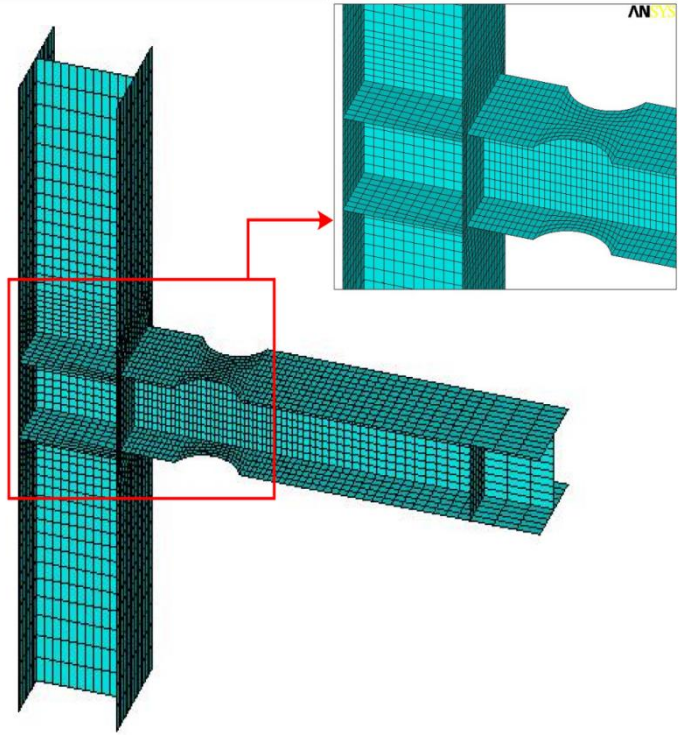

- ✓ 4-node Shell elements
- ✓ Manual (mapped) meshing
- ✓ Mesh convergence
- ✓ Eigen buckling employed

Parametric Study

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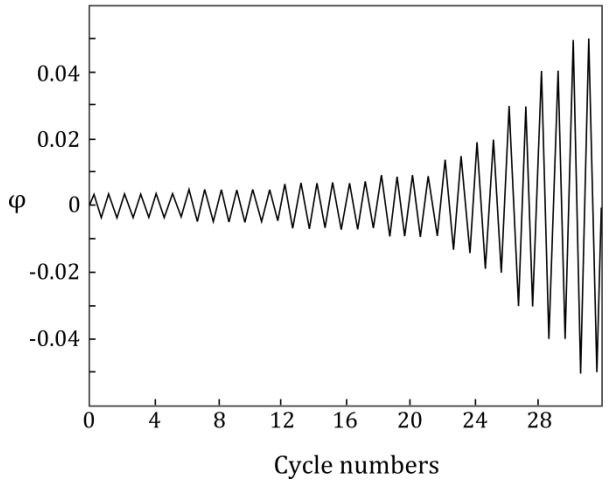
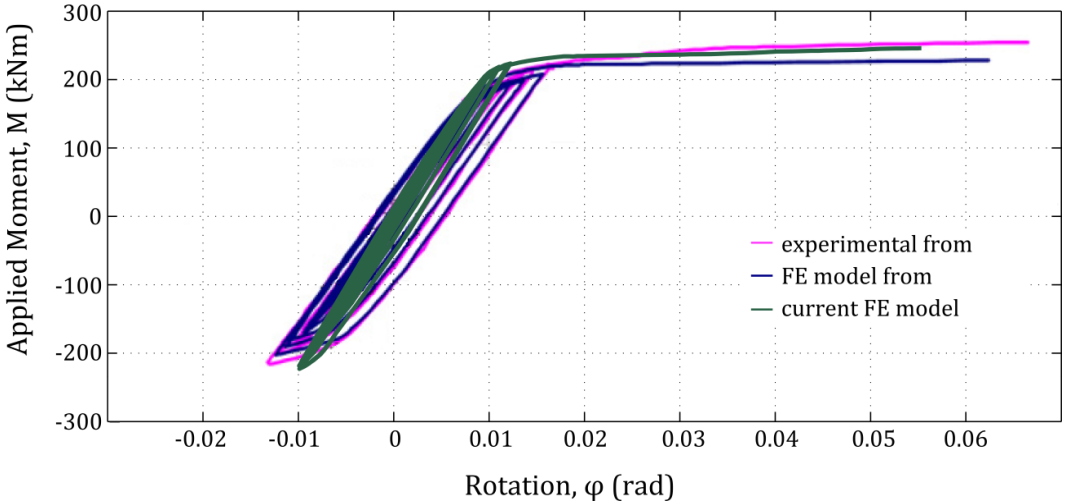
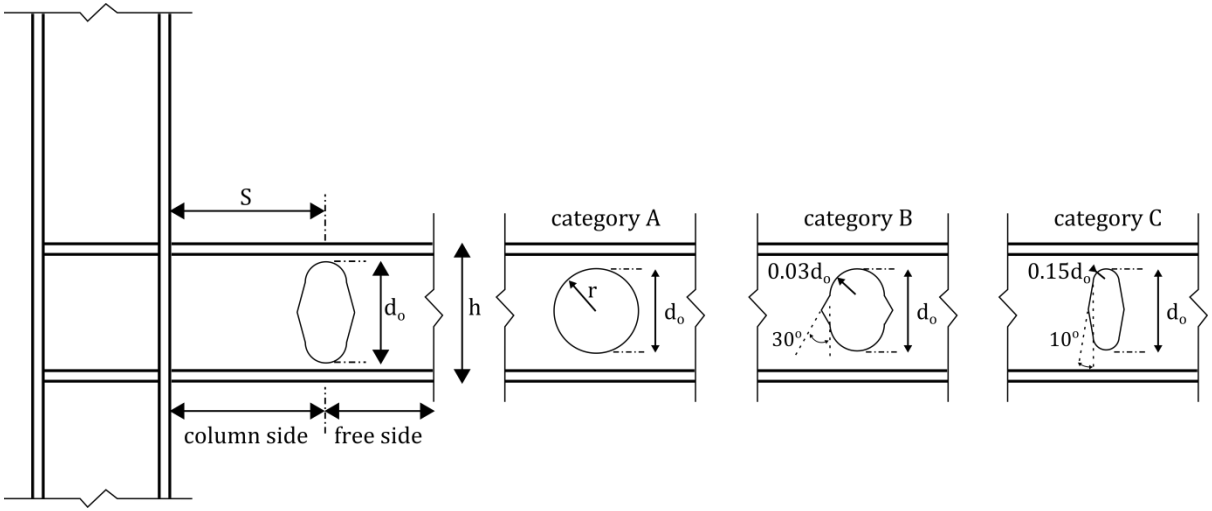


SAC protocol, FEMA 350/AISC



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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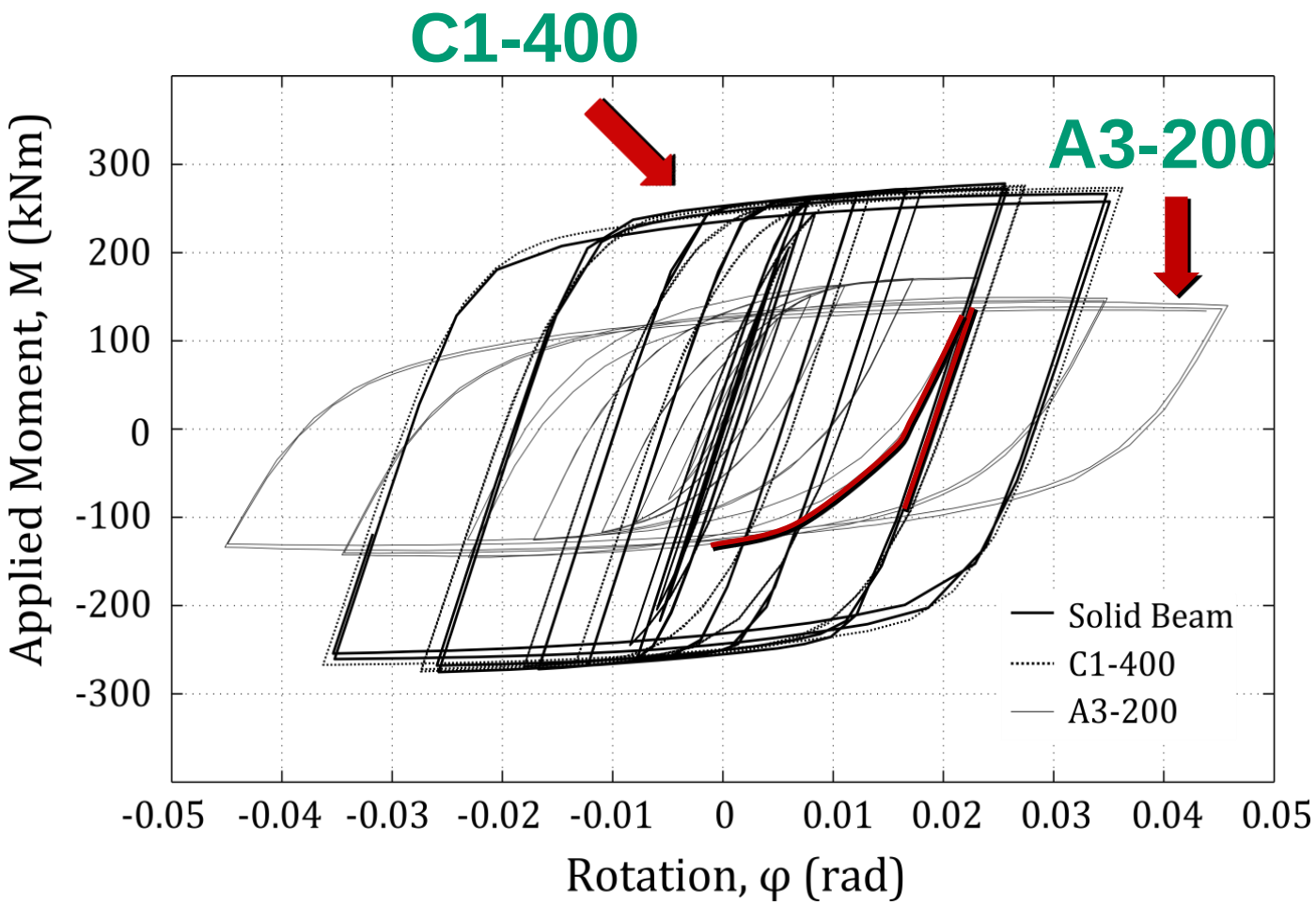

Rotational Capacity

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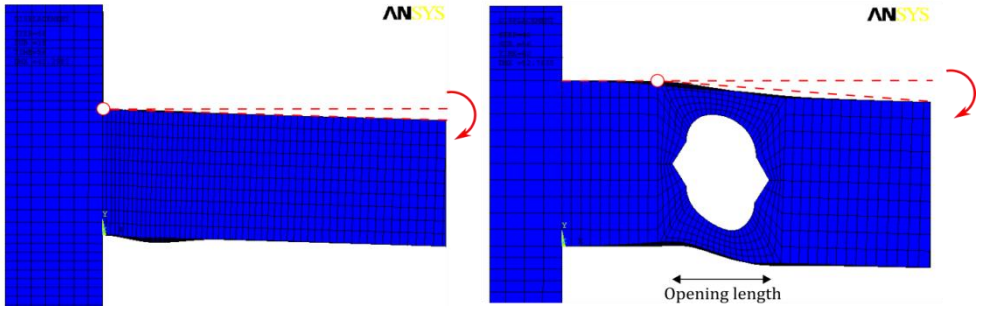
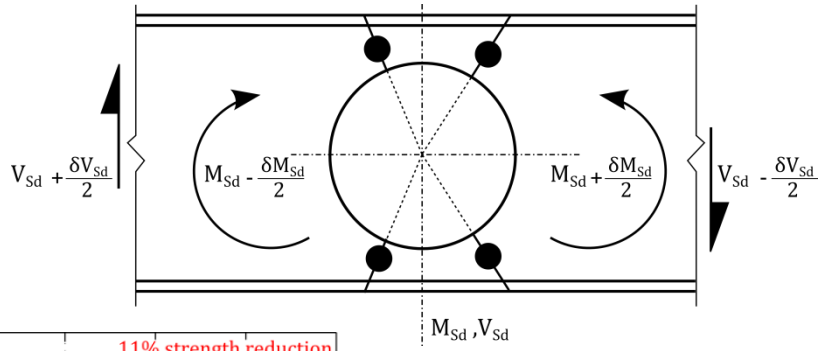
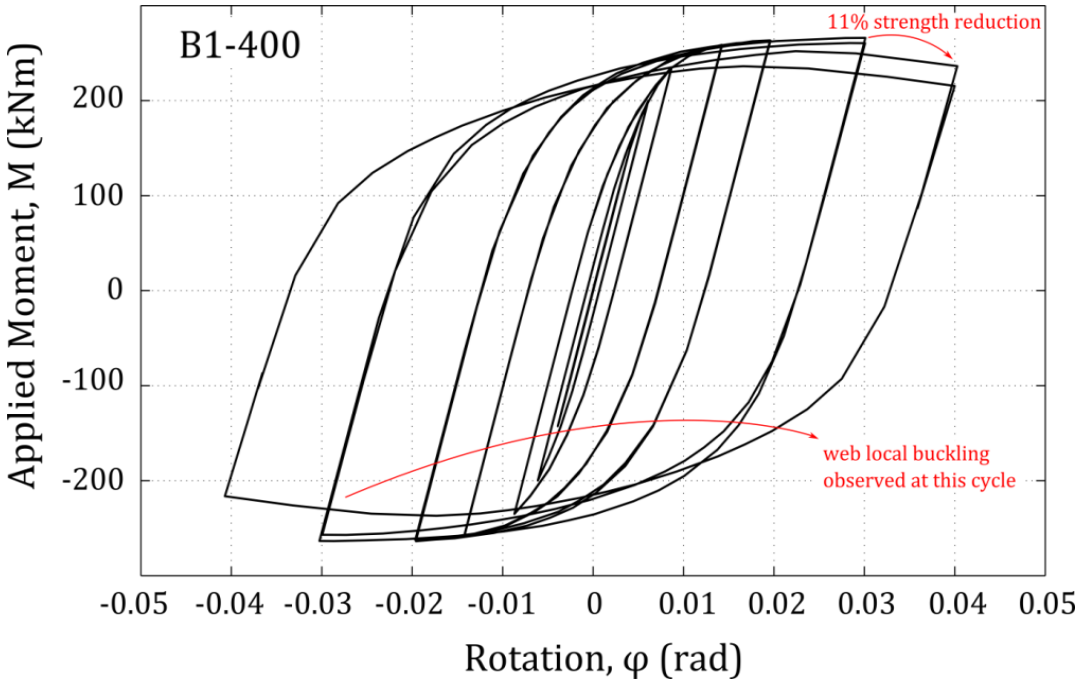
The higher the critical opening length,c → the higher is the strength degradation.







Vierendeel (Vert. Shear) Mechanism

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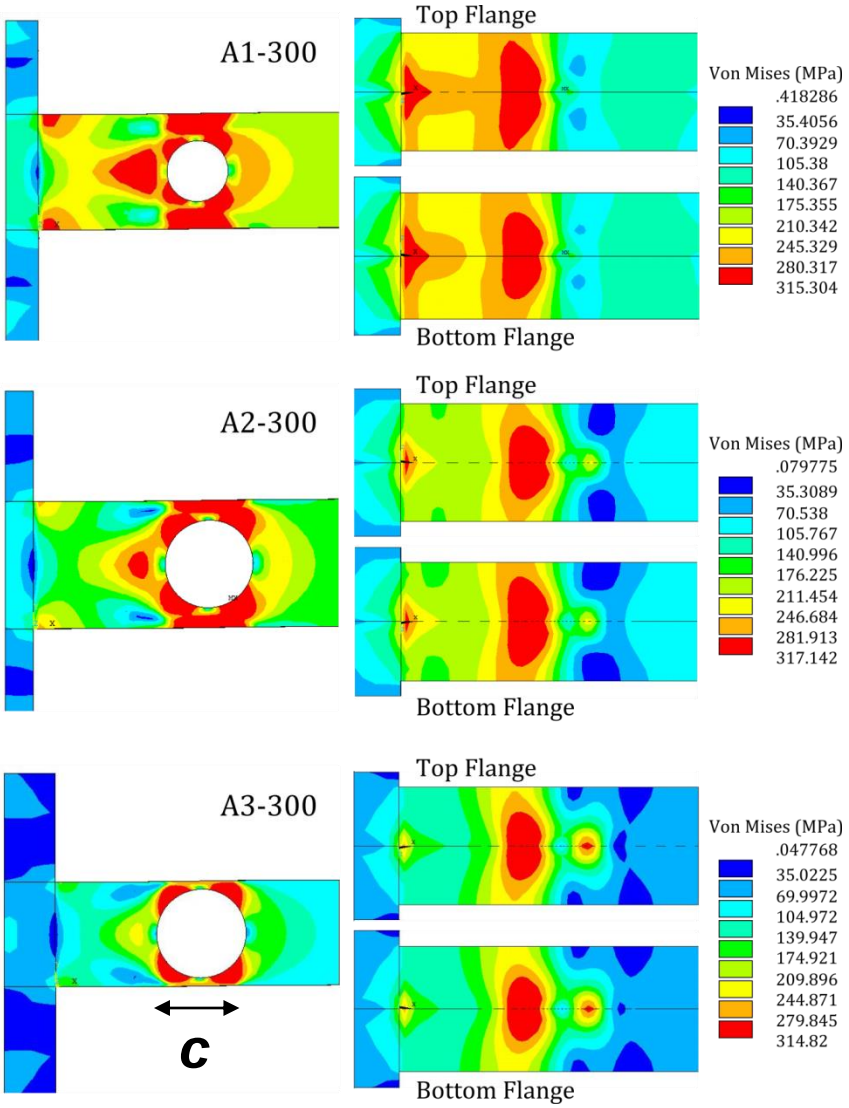
Vierendeel deformation is introducing additional rotation to the RWS connections at the position of the opening, unlike to the connections with solid beams.

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

Traditional cellular beams showed a premature formation of plastic hinges compared to the novel perforated beams.



Position and Movement of Plastic Hinges

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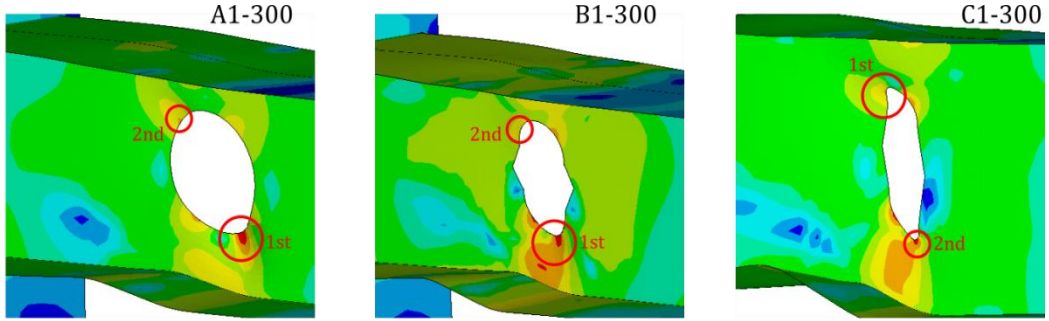


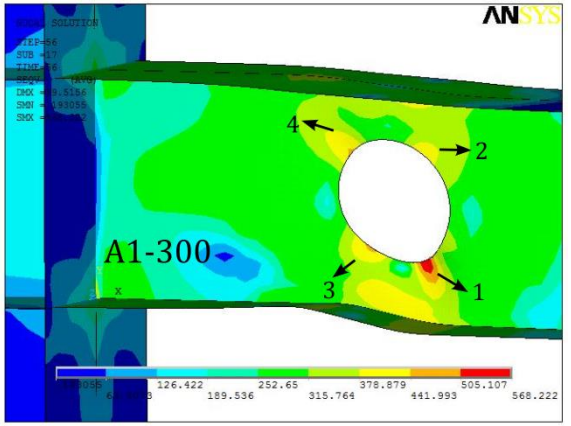
Cycle 27 (applied displ. =34.5mm) out-of-plane displ. =4.19mm

Cycle 29 (applied displ. =46mm) out-of-plane displ. =7.06mm

Cycle 29 (applied displ. =46mm) out-of-plane displ. =8.06mm

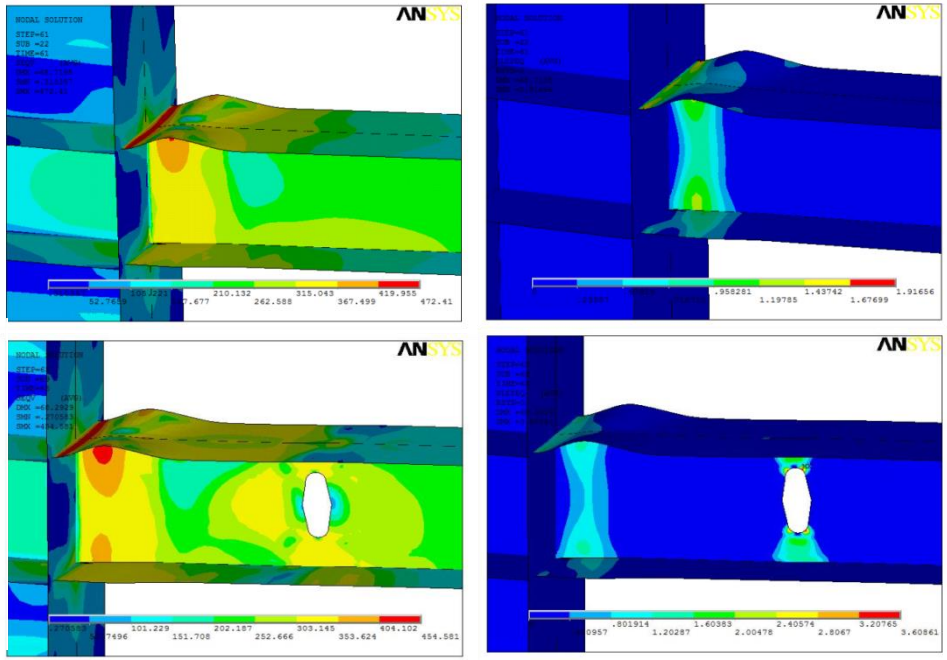
Von-Mises stress contour plot and Plastic hinge formation; left: at cycle 29, right: at cycle 27

Web local buckling

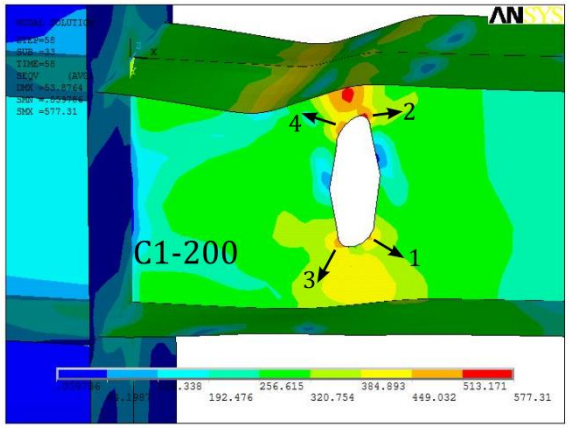


Solid beam

C1-400



Von-Mises stress (left) and EPEQ (right) contour plots at cycle 31 (loading at 57.5mm)



Effect of WOA on Ductility

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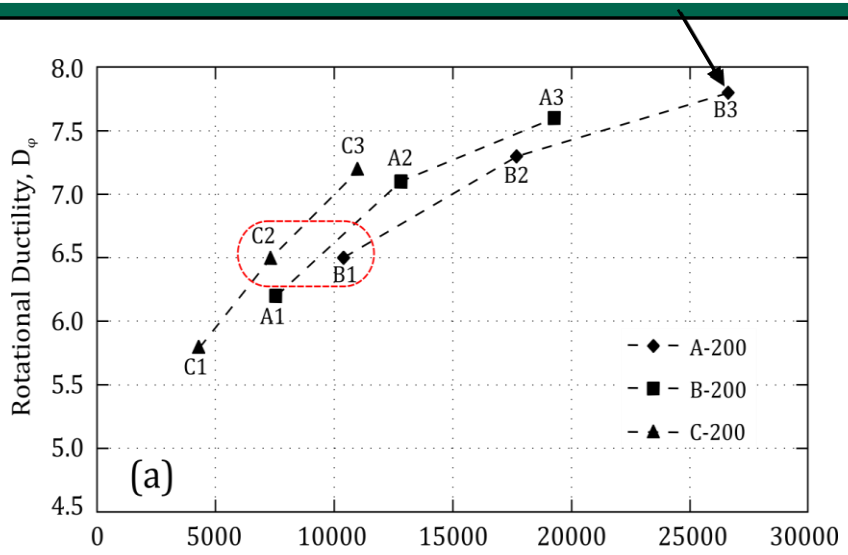

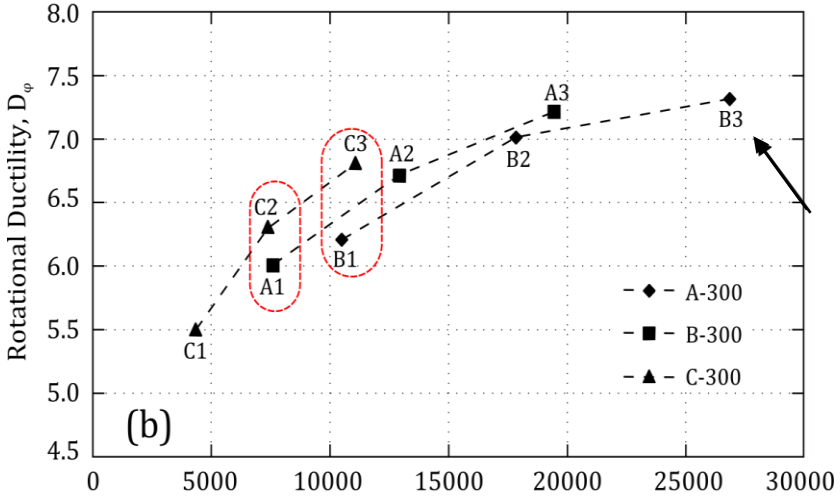

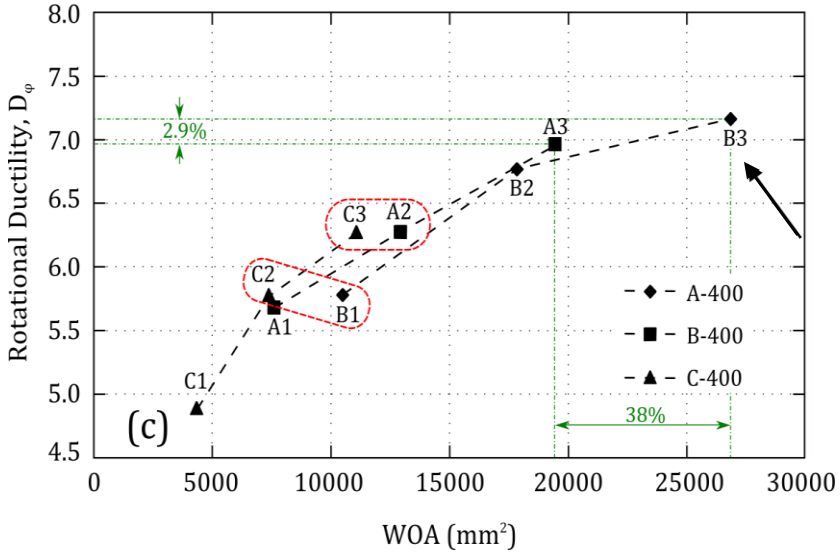

Geometric Parameters

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Parameter do

Bigger

Vierendeel

Reducing stress from the joint

Balance

Parameter S

Smaller

Vierendeel

Reducing stress from the joint

Ideal Design

Large novel B,C or Medium circular A

Controlled Vierendeel

Controlled Plasticity

Concluding Remarks

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The study presented examined the behaviour of **isolated web openings** in enhancing the ability of a pre-Northridge connection.

- Introduction of the web openings resulted in some reduction of strength.
- When small web openings were used, there was not any beneficiary effect.
- Isolated large 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 and double plates).
- Specimens with novel openings, compared to the traditional circular openings, were found to be stronger and attain a higher ultimate rotation for the same opening depth.
- **RWS connections achieved higher inelastic rotational capacity in comparison to the RBS connection and they are capable of reaching beyond 0.035 radian [FEMA 350; GSA 2003; DoD 2005].**

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

Test Apparatus

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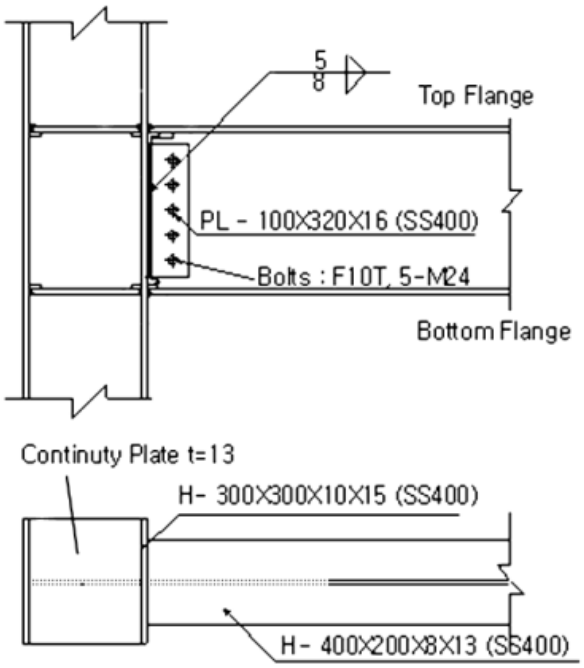

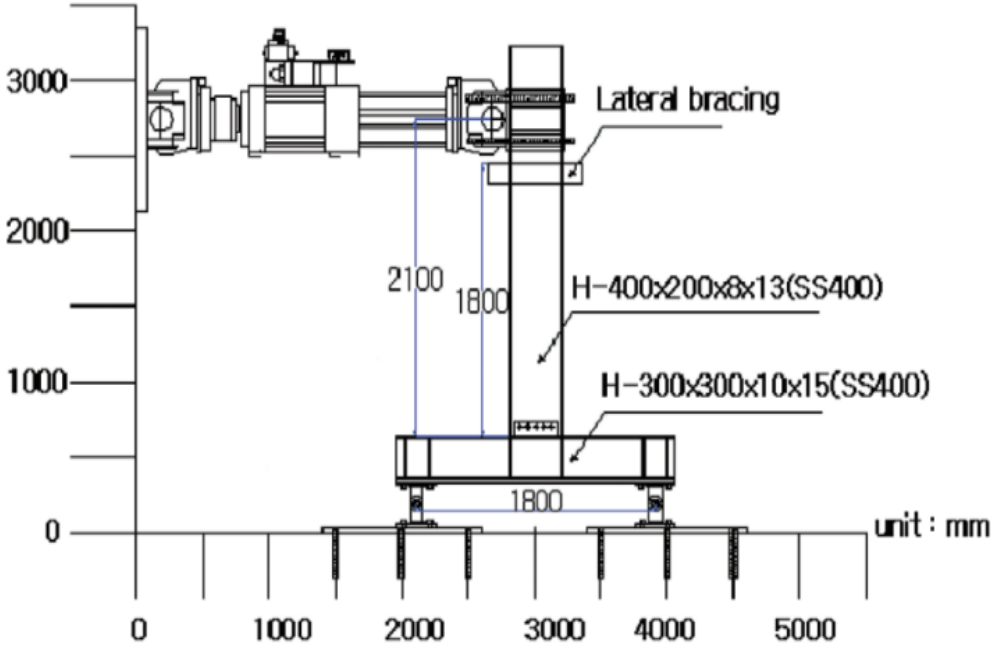

Member	Component	Yield Strength, f_y [MPa]	Ultimate Strength, f_u [MPa]
Beam	Flange	281	423
	Web	332	438
Column	Flange	281	433
	Web	304	450

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

Parametric Study

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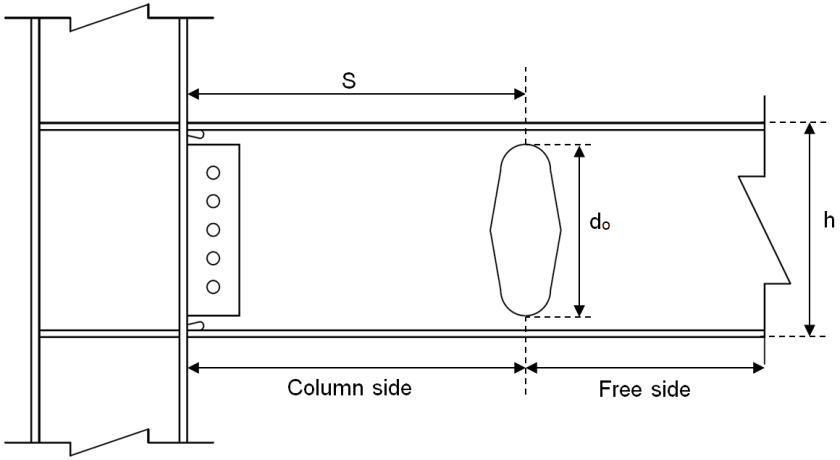
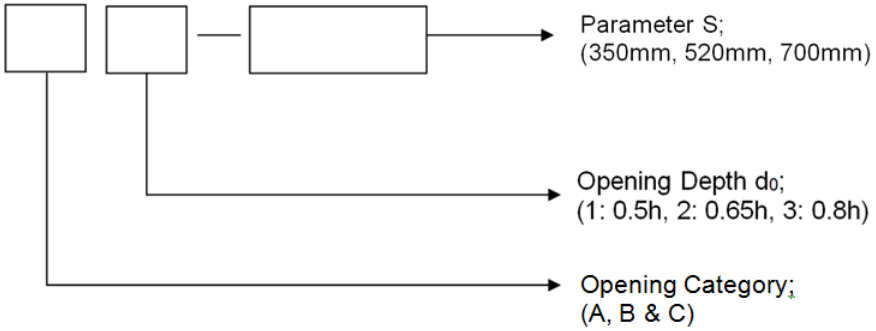
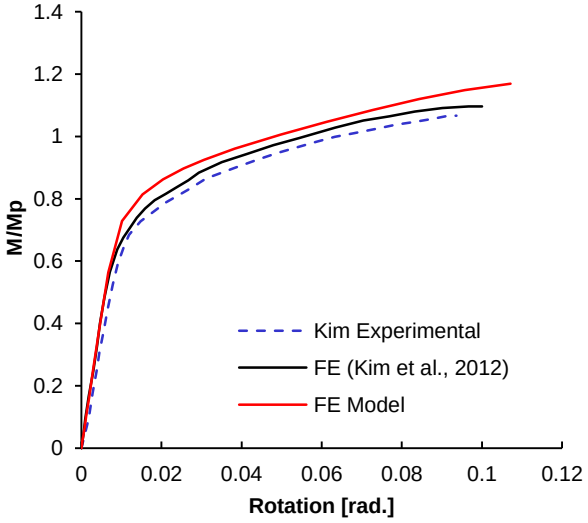
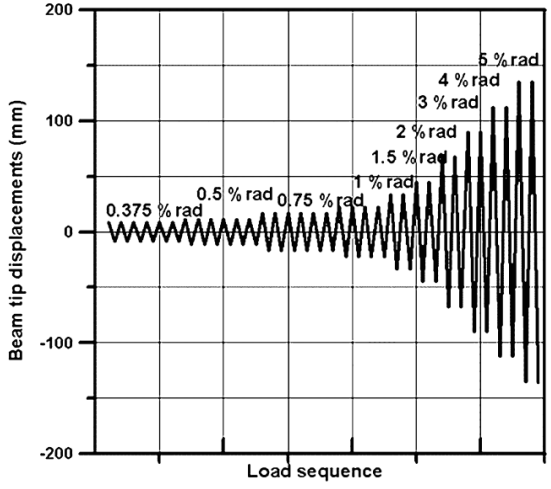
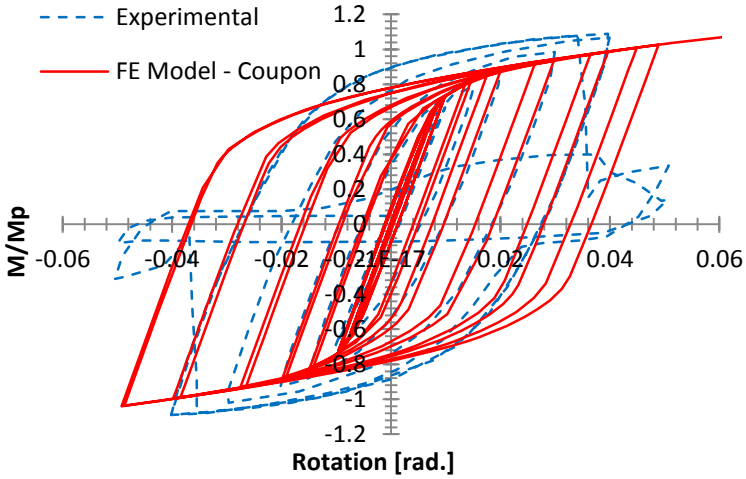








SAC protocol, FEMA/AISC



Vierendeel (Vert. Shear) Mechanism

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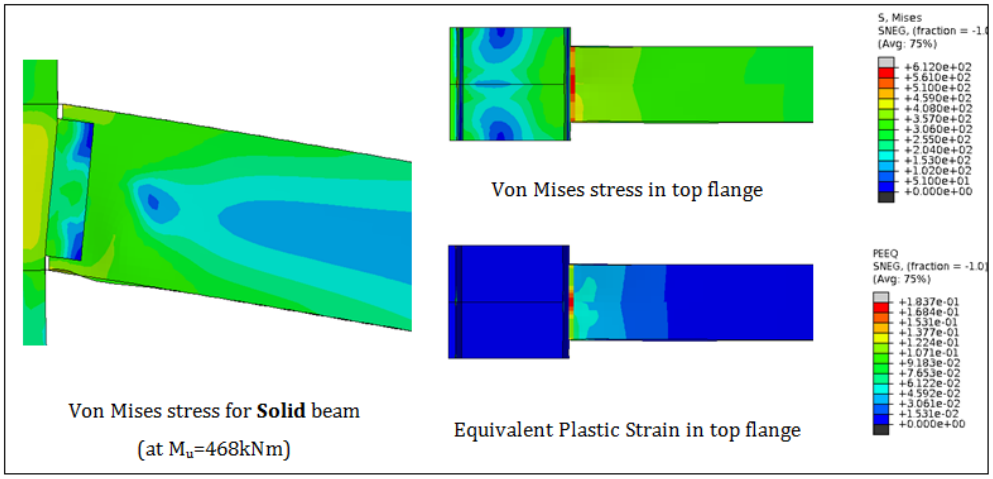

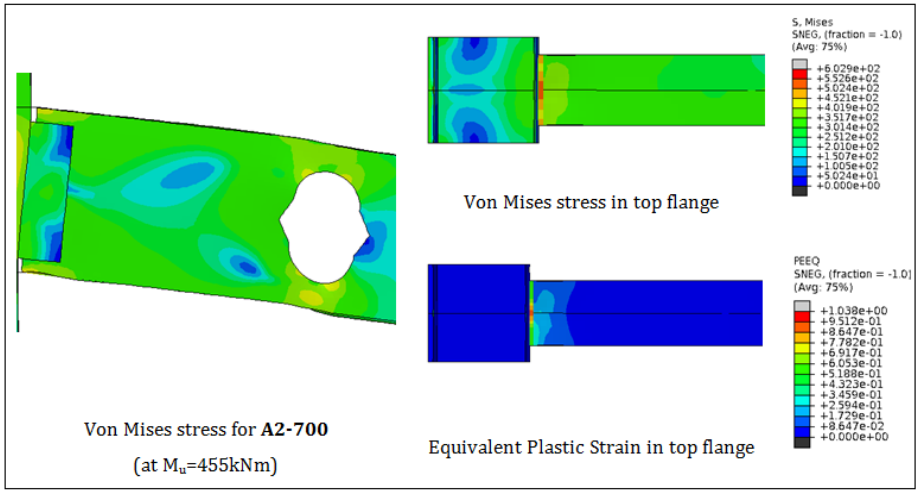

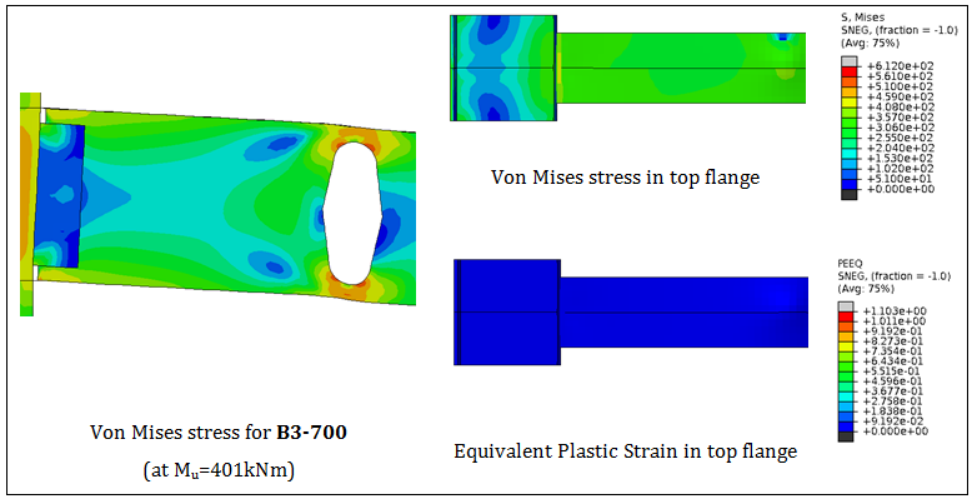

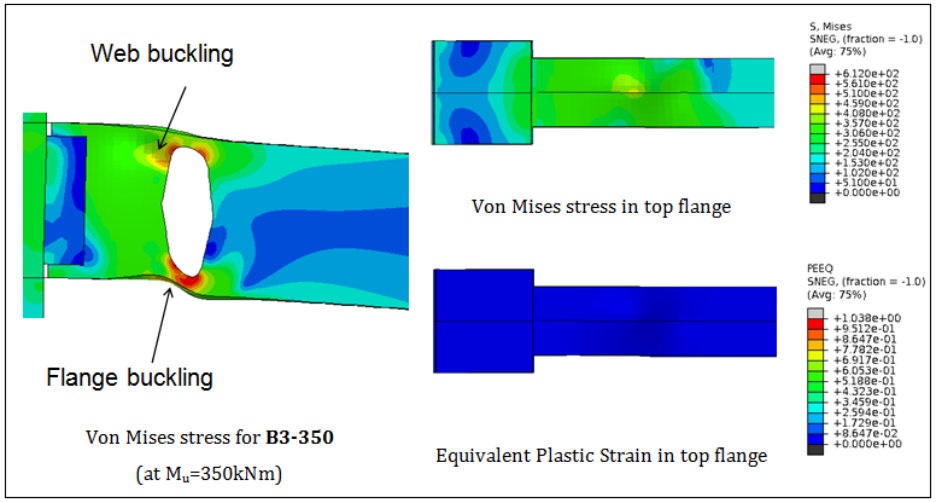

Rotational Capacity

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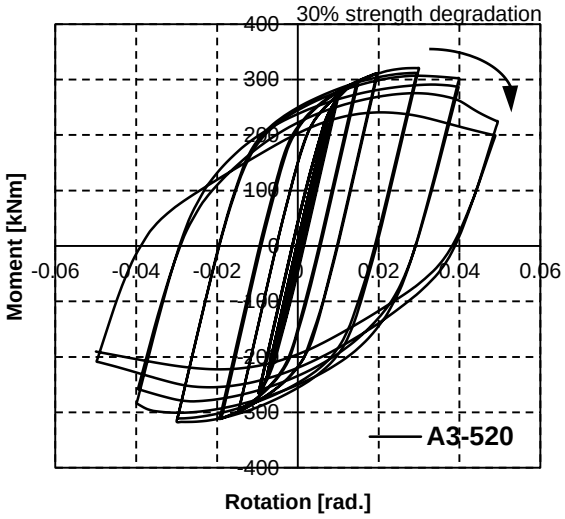
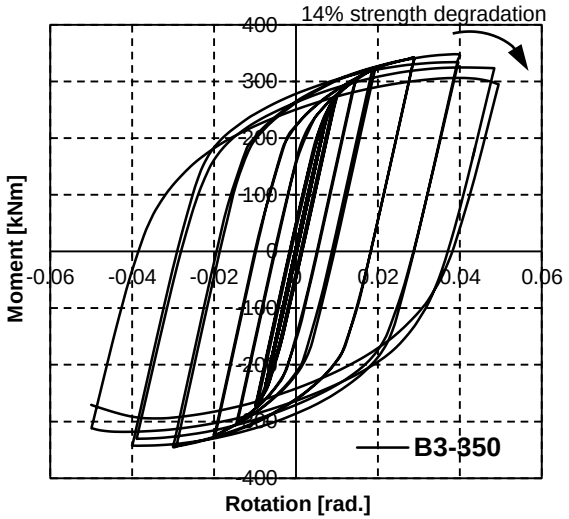
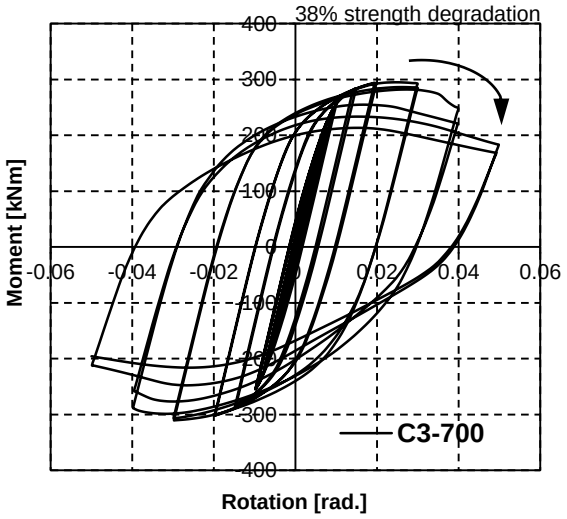
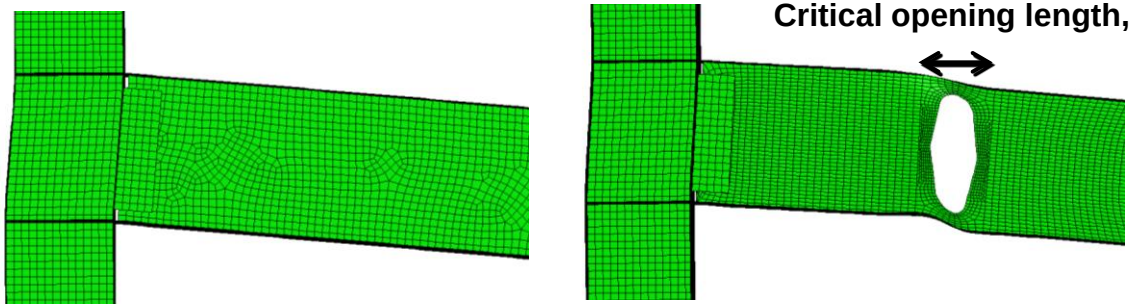
The higher the critical opening length, c → the higher is the strength degradation.







Centre of rotation for solid and perforated beams.



Panel Zone Deformation

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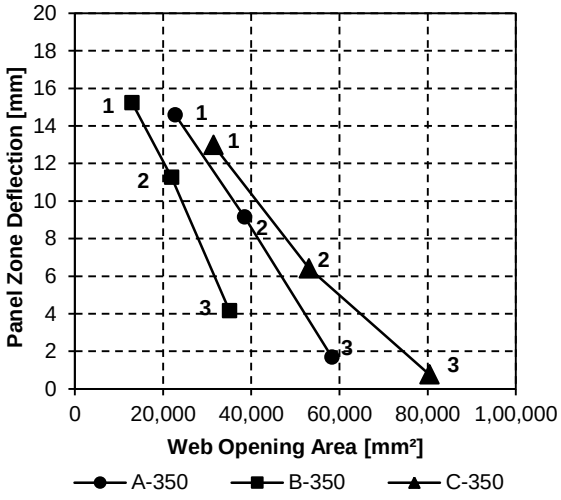
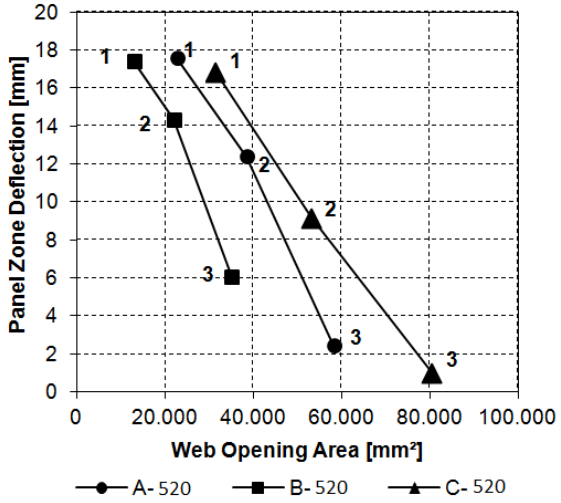
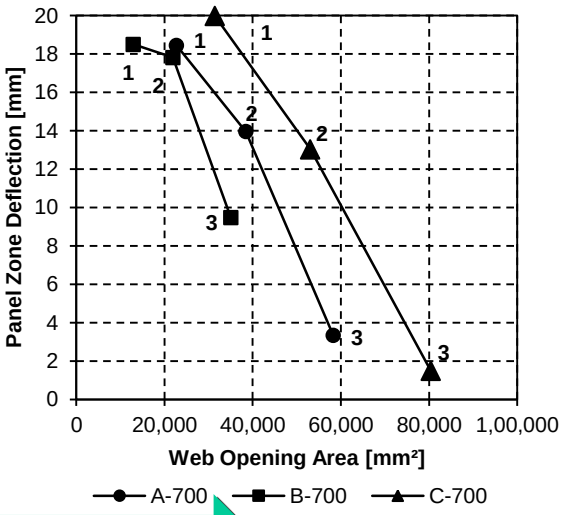
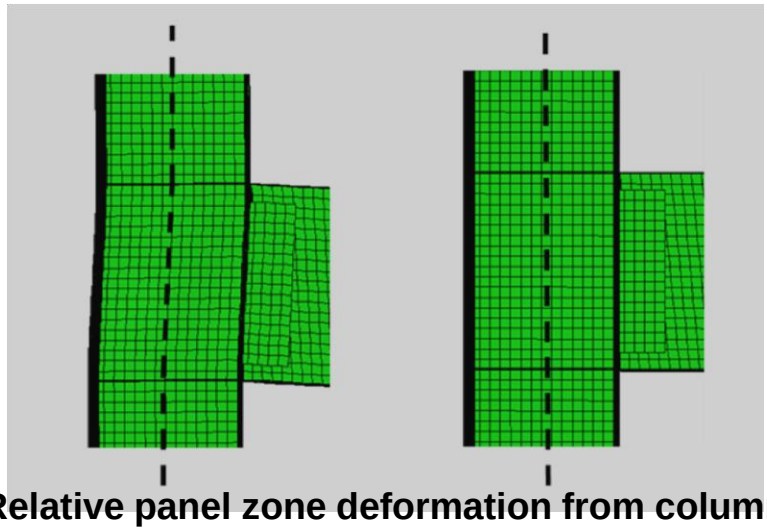


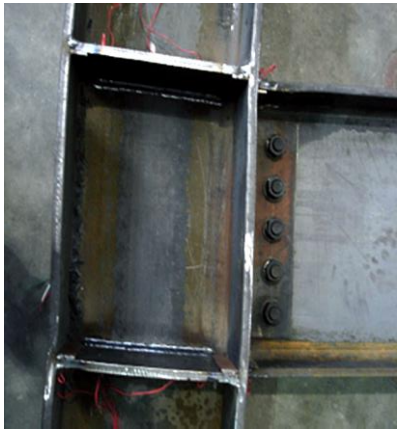




S increases



Relative panel zone deformation from column centreline



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

Cheaper solution instead of using stiffeners...

Geometric Parameters

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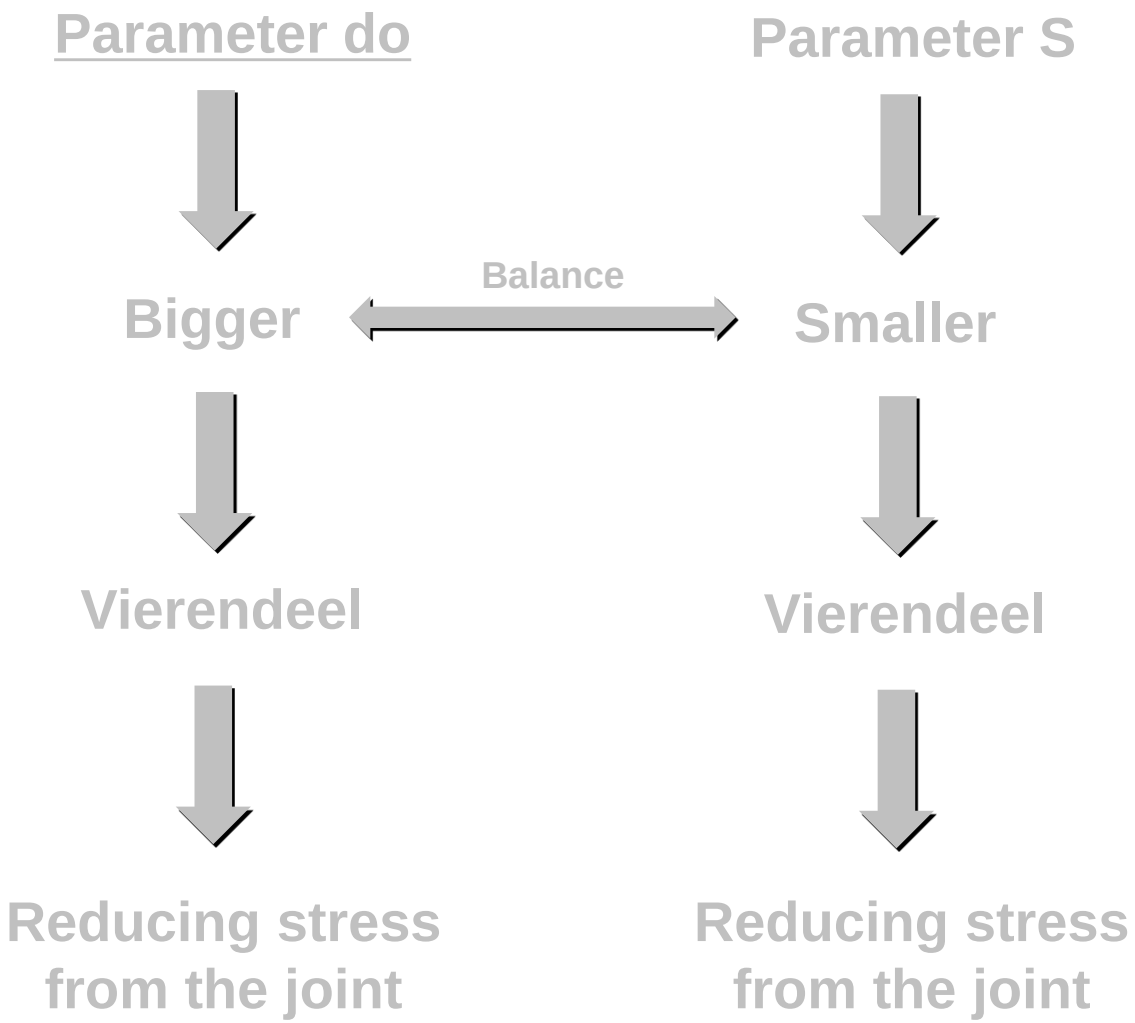

Ideal Design

Large novel B or Medium A, C

Controlled Vierendeel

Controlled Plasticity

Further Concluding Remarks

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- The use of large openings was found to be the most effective at moving the plastic region away from the column's face and the bolts, while reducing the shear zone panel deflection.
- The most effective design was considered when a large narrow elliptically-based web opening was employed.
- The use of such narrow novel openings is ideal as the connection is not that sensitive to geometric changes.
- The actual position, shape and size of the perforation is of critical importance to the effective ductile design.

Extended End-plate Bolted Connections with isolated as well as periodically spaced circular web openings

Test Apparatus

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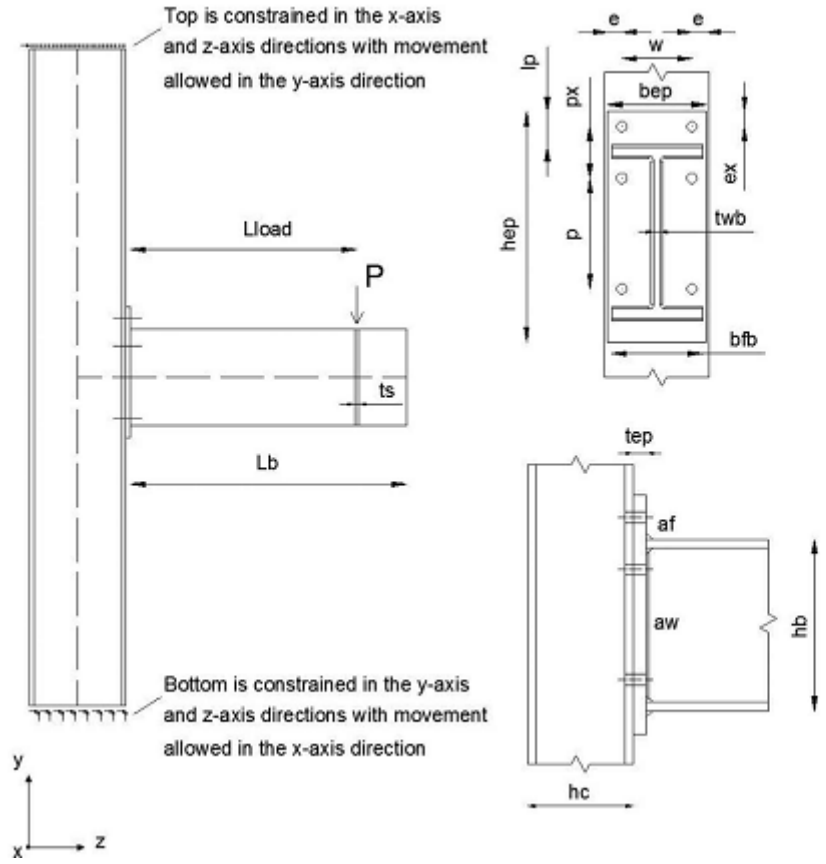
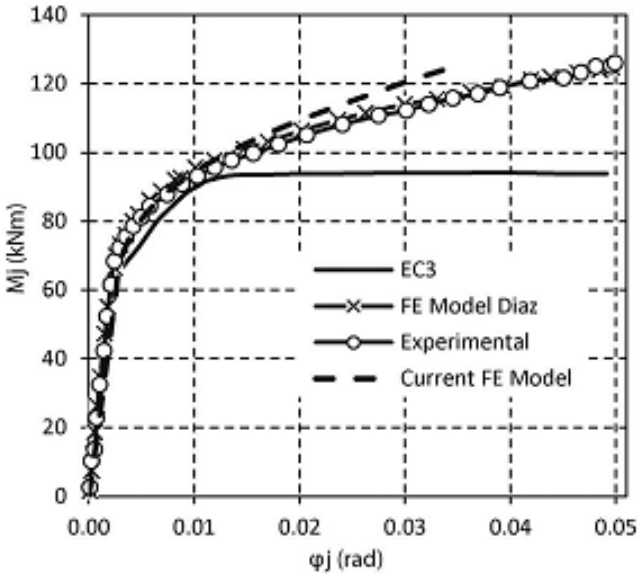
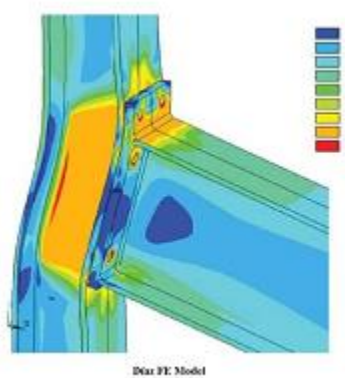
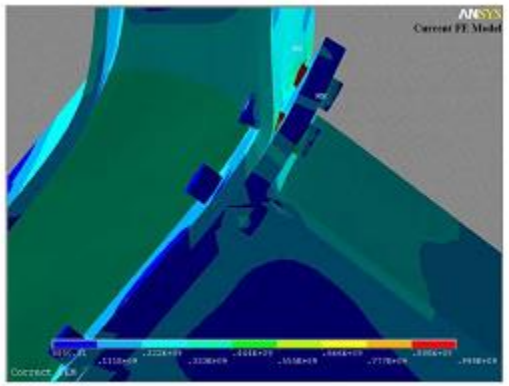






(a) $M_{j,u}$ = 124.1kNm



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

Parametric Study on Circular Openings

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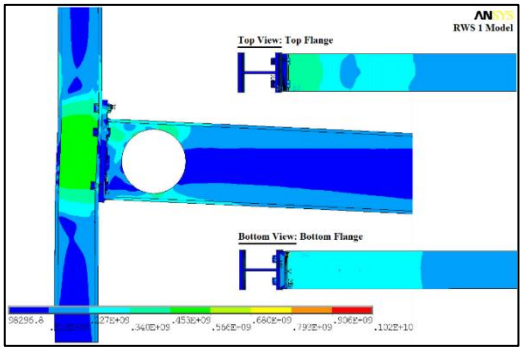

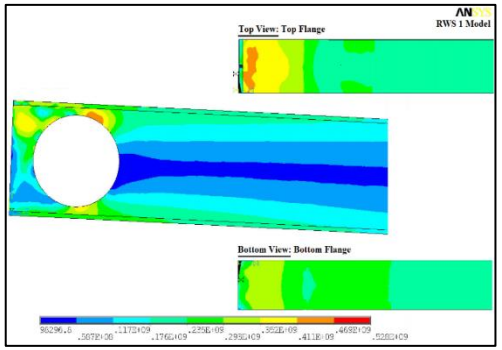

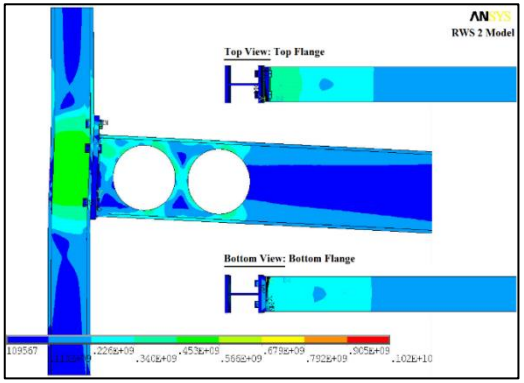

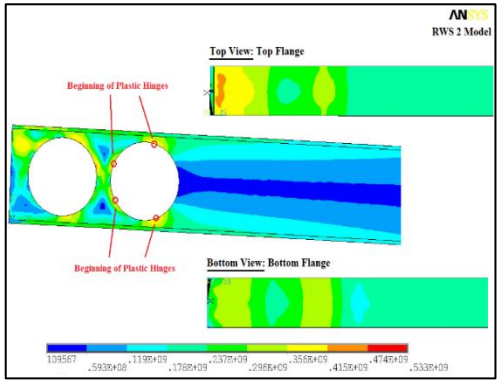

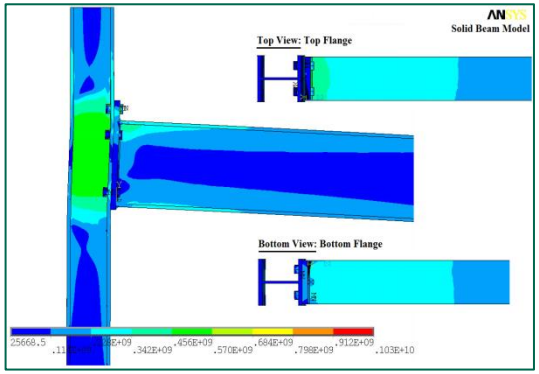

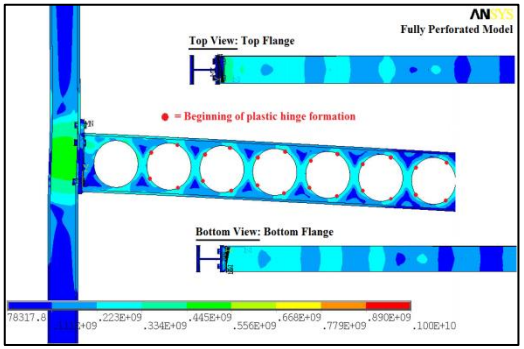

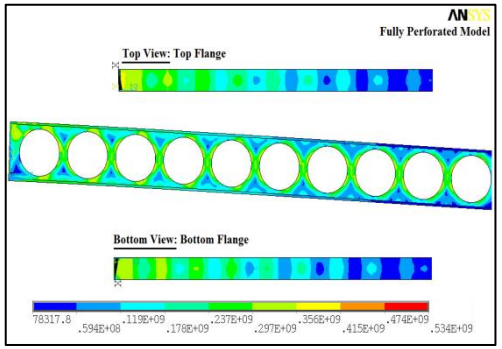

Comparison

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Specimen	Number of Circular Perforations	Yied Moment M_y (kNm)	Ultimate Moment M_u (kNm)	Yield Rotation φ_y (rad)	Ultimate Rotation φ_u (rad)
Solid Beam	-	74.59	128.58	0.009592	0.049989
RWS 1	1	71.14	112.19	0.009492	0.050025
RWS 2	2	64.41	117.23	0.009292	0.050025
Fully Perforated	10	62.44	105.77	0.008555	0.050004

Specimen	Rotational Ductility D_φ	Initial Rotational Stiffness K_i (kNm/rad)	Web Opening Area (mm^2)	Dissipated Energy E (kNm)(rad)
Solid Beam	5.21	10329.89	-	107.14
RWS 1	5.27	10240.98	44907.8	92.50
RWS 2	5.38	9167.77	44907.8	81.19
Fully Perforated	5.85	8097.76	44907.8	45.94

Additional Innovative Designs

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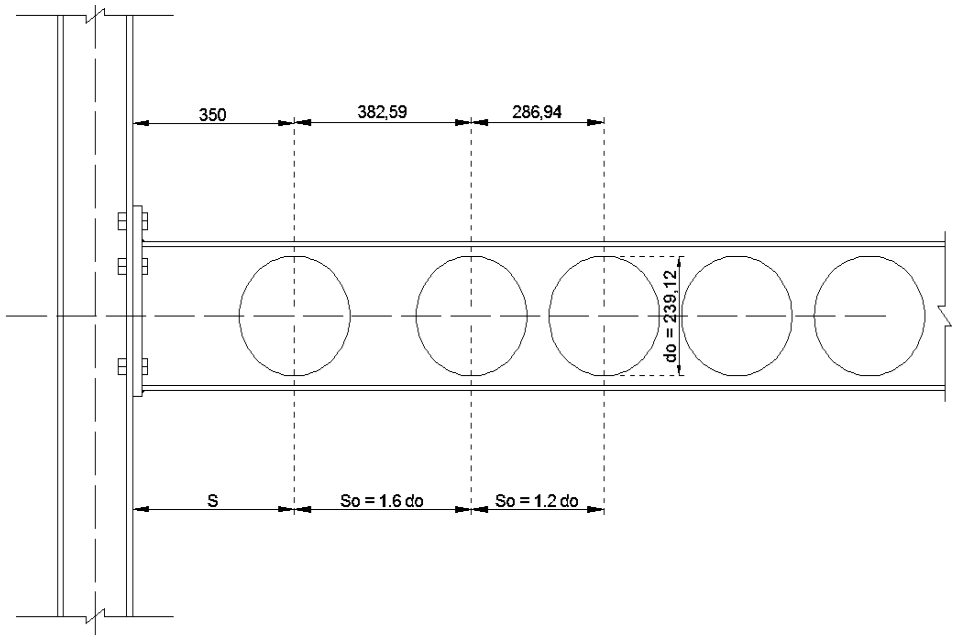

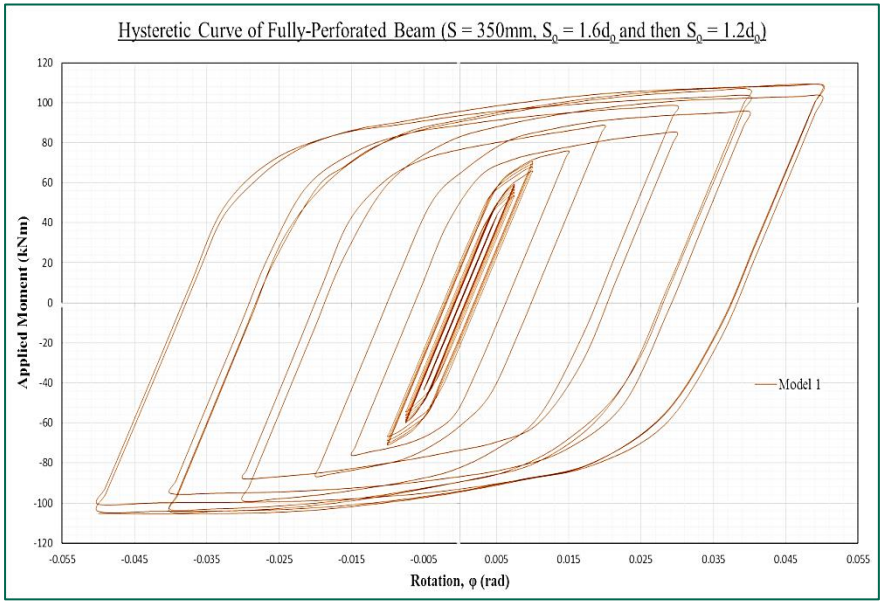

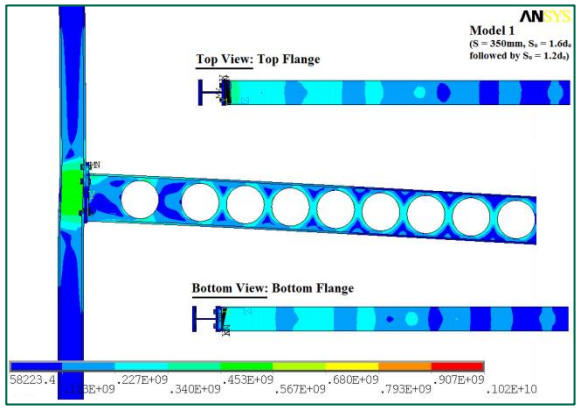

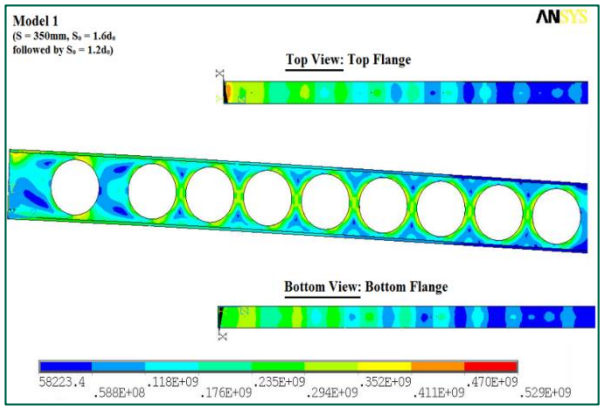

Further Concluding Remarks

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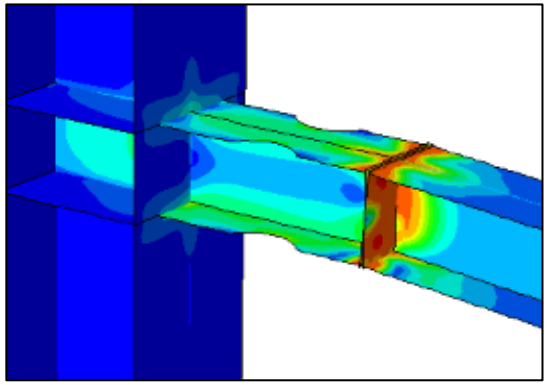
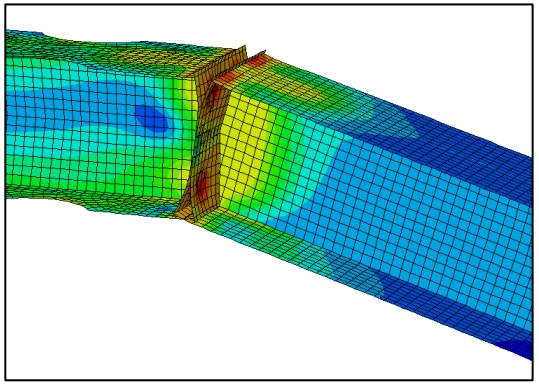
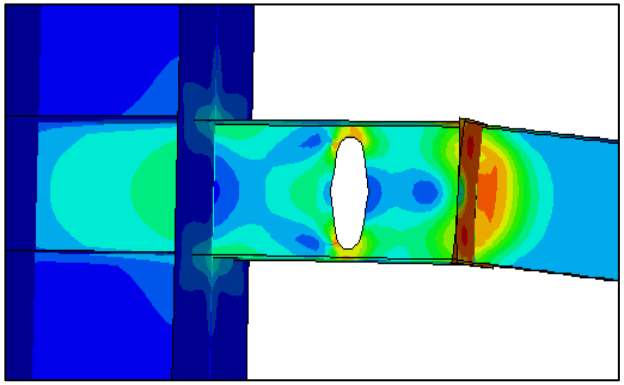
- The position of the first from the support web opening is again critical.
- Providing there are not web openings close to the supports, there is no mobilisation of the high stresses from the shear panel zone.
- The concept of the "fuse mechanism" with controlled damage and replacement can be realised.







- Completing the experimental campaign on RWS will lead us to the incorporation of such connections to EC8 and other design guidelines.

Aknowledgments (funding & technical support)

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COMMONWEALTH SCHOLARSHIPS

SCI

ASD metal services

klöckner & co multi metal distribution

The Institution of Structural Engineers

Westok

StructuralAwards2013

www.structuralawards.org

EPSRC

Engineering and Physical Sciences Research Council

TATA STEEL

GKT

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Tsavdaridis, K.D. and Pilbin, C. FE Parametric Study of WUF-B Moment Connections with Single Mixed Shape Beam Web Openings under Monotonic and Cyclic Loading. **International Journal of Steel Structures**. 2016

Tsavdaridis, K.D. and Papadopoulos, T. A FE Parametric Study of RWS Beam-to-Column Bolted Connections with Cellular Beams. ***Journal of Constructional Steel Research**, Vol. 116, 2016, pp. 92-113*

Tsavdaridis, K.D. Strengthening Techniques: Code-Deficient Steel Buildings, to the section: Structural Engineering - Structural Design, **Encyclopedia of Earthquake Engineering**, Springer Verlag, 2014, pp. 1-26

*Tsavdaridis, K.D., Faghih, F. and Nikitas, N. Assessment of Perforated Steel Beam-to-Column Connections Subjected to Cyclic Loading. **Journal of Earthquake Engineering**, Vol. 18, Issue 8, 2014, pp. 1302-1325*

Dilemma…

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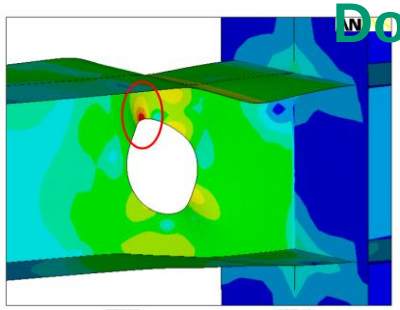
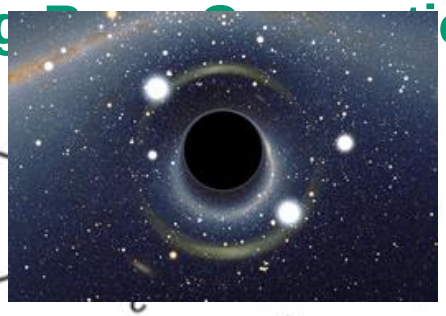
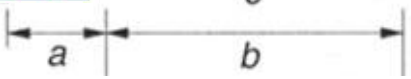
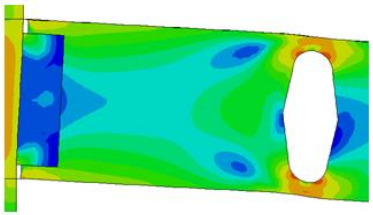
Dog Bone Connection

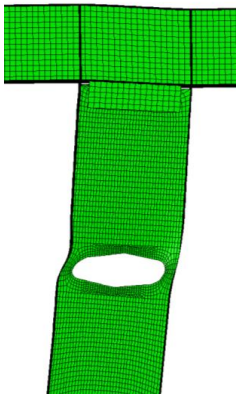


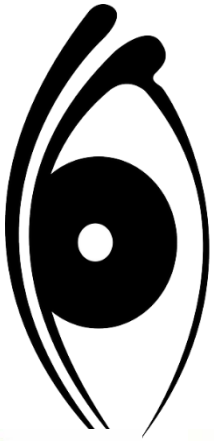




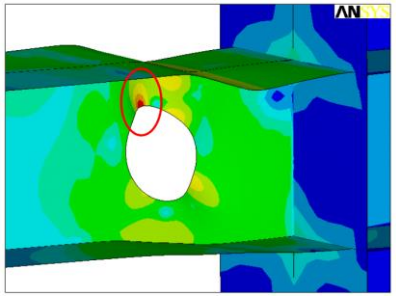
Black (White) Hole Connection?







Eye connection?



Donut Connection?