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Consulting Engineers Ltd

Queen's University Belfast

Cold-formed steel portal frames in fire

STRUCTURES IN FIRE FORUM

5 September 2016, University of Edinburgh

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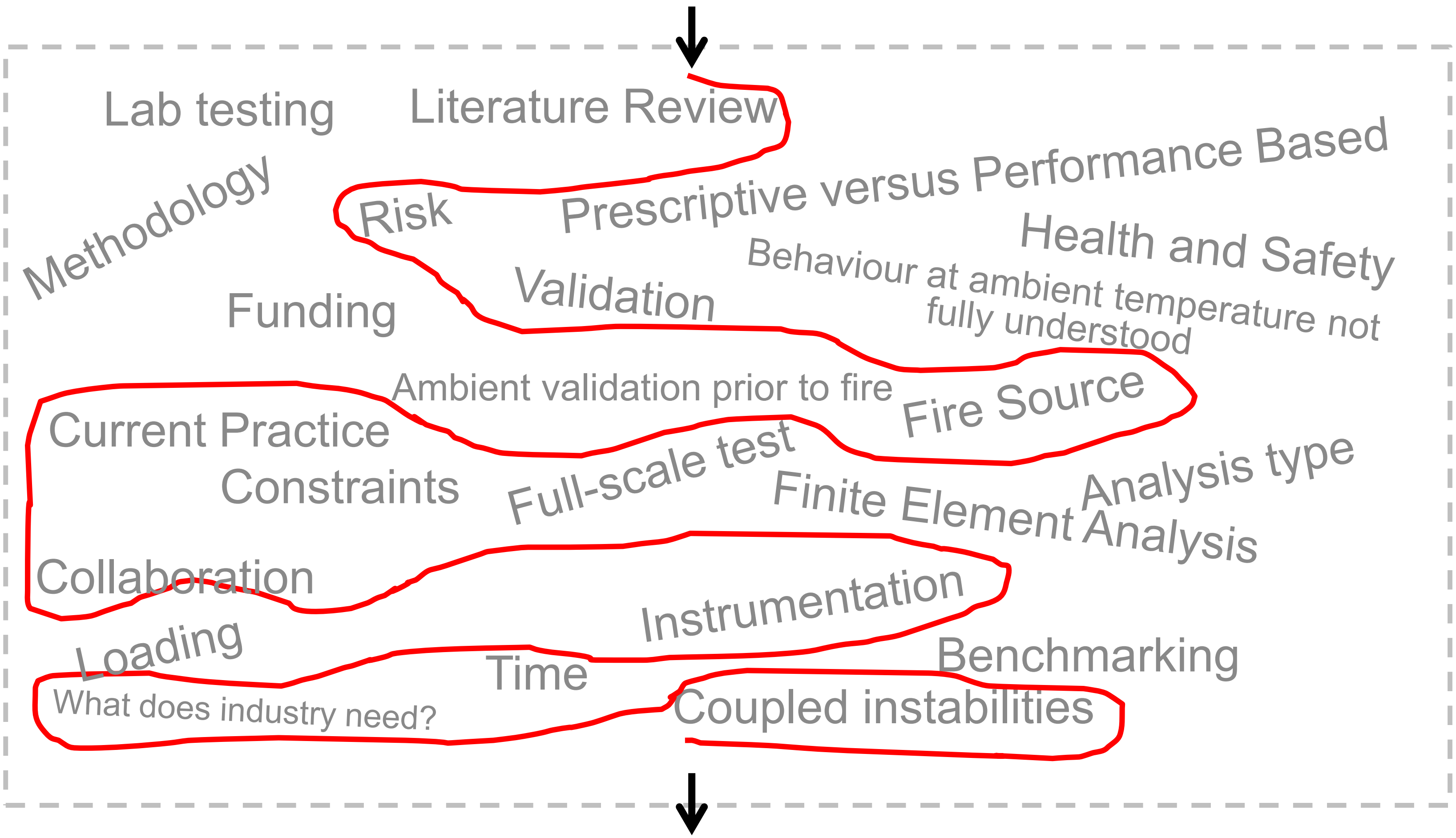
Determine the collapse behaviour of cold-formed steel portal frame structures at elevated temperatures (**fire**).

Provide guidance to **prevent** undesirable **outwards** collapse mechanism.

START: Simple Problem

COMPLEX



FINISH: Simple Solution

What is a cold-formed steel portal frame?

Viable alternative Sustainable Popular in Australia/NZ

Joints possess reduced capacity Limited research + guidance

Current Practice – portal frames in fire boundary conditions

Only available for hot rolled steel portal frames. Based on SCI P313 Guidance Document. No such guidance for cold-formed steel portal frames.


SCI PUBLICATION P313

Single Storey Steel Framed Buildings in Fire Boundary Conditions

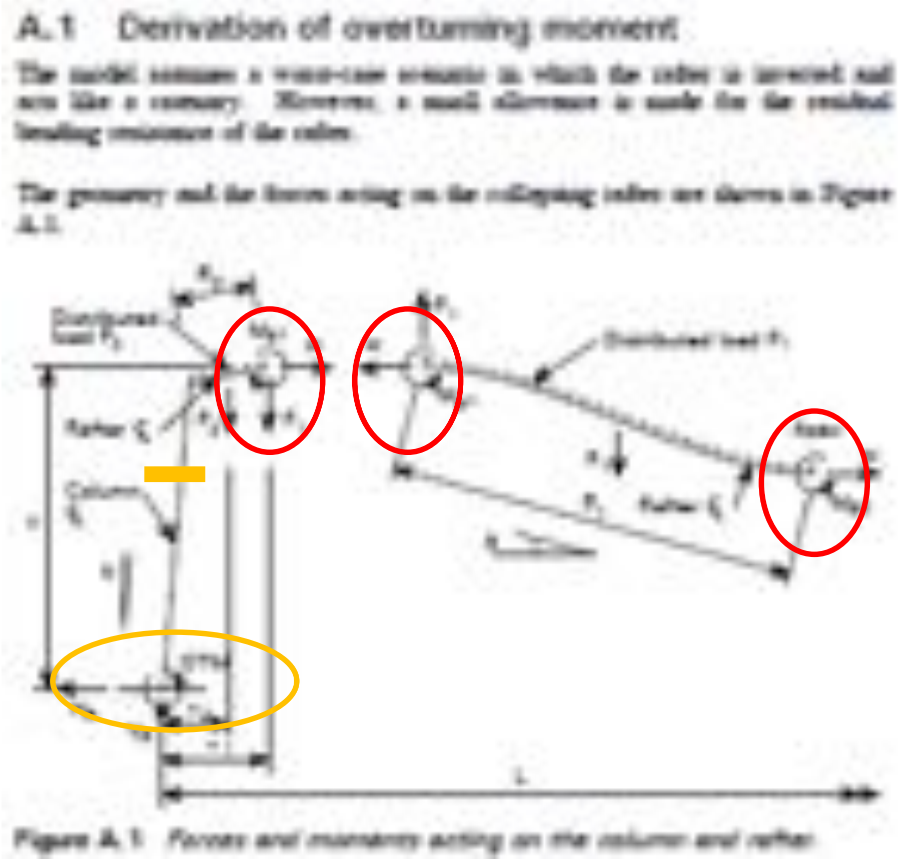
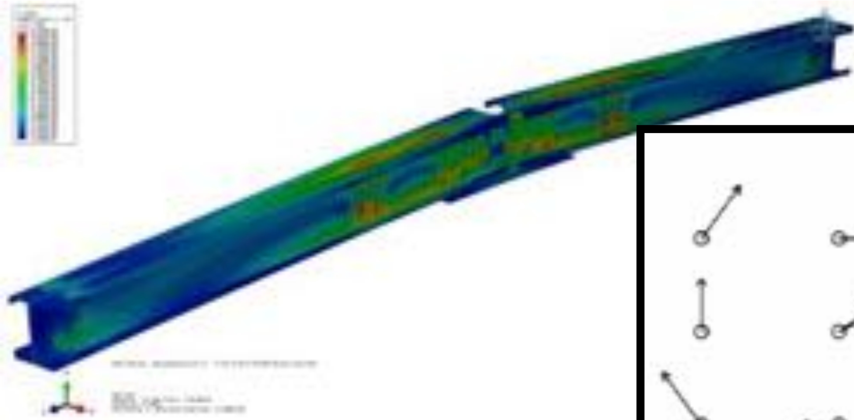
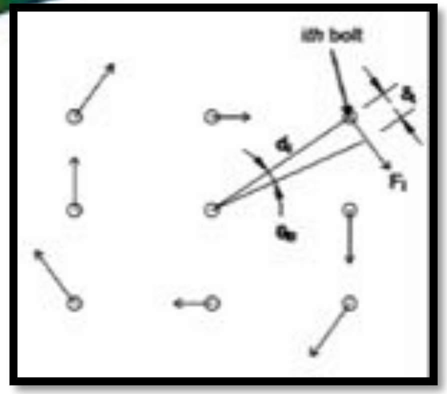
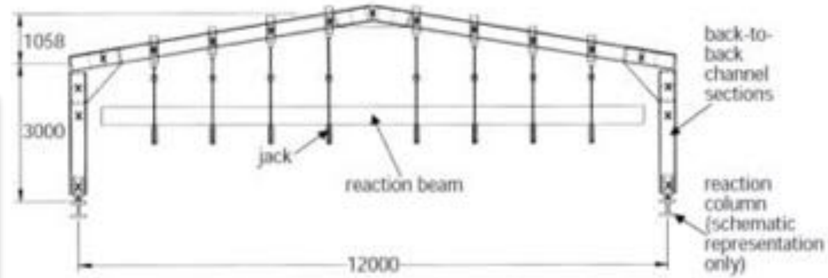

A.1 Derivation of overturning moment

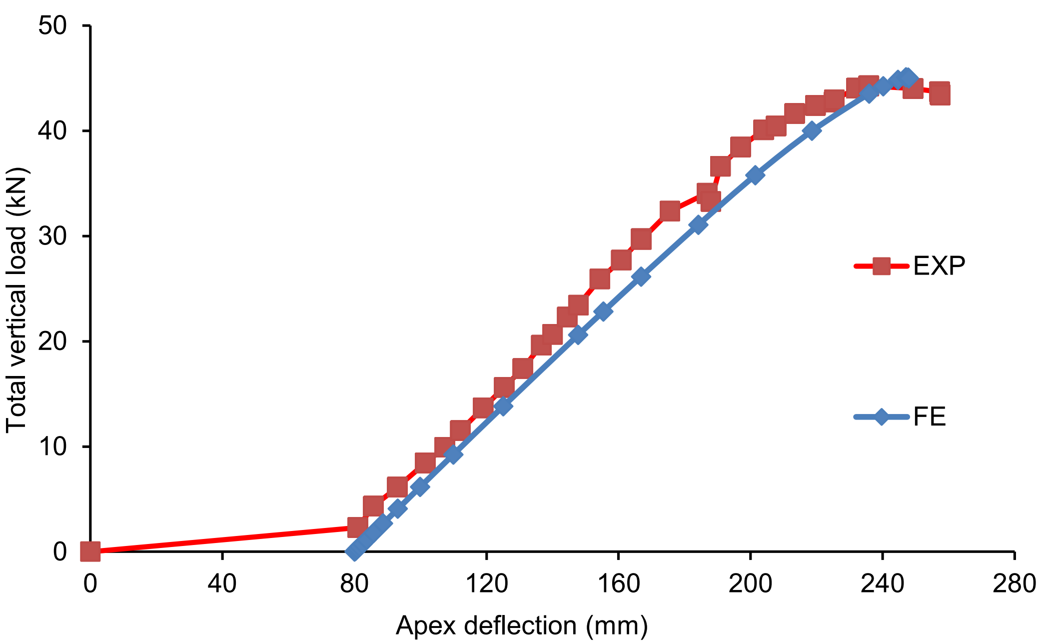
Figure A.1 Forces and moments acting on the column and rafter

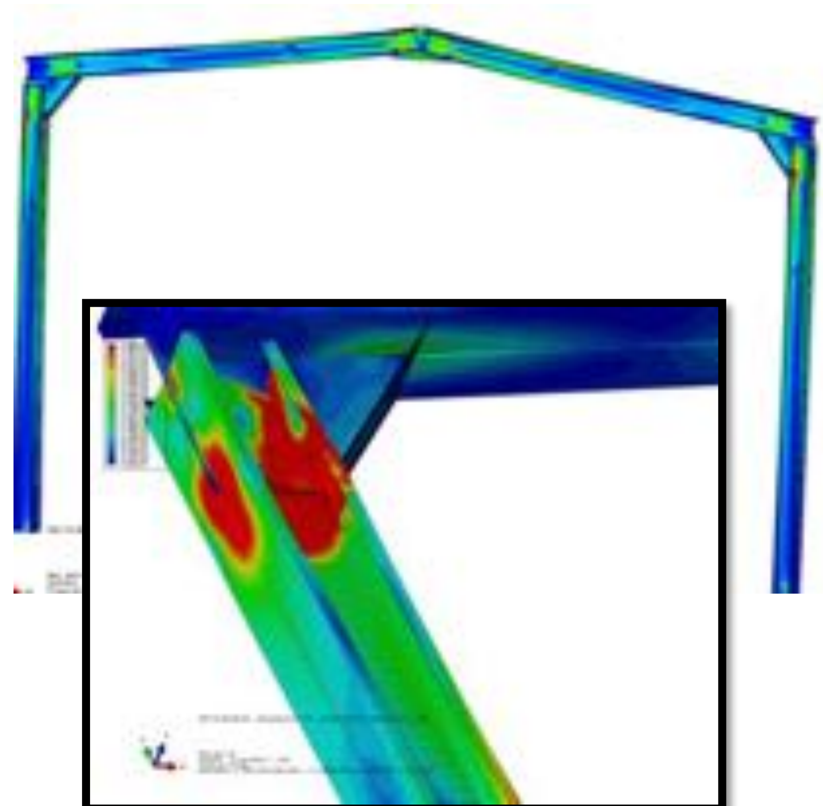
Potentially unsafe to use this for cold-formed steel portal frames. Require a prominent amendment to cover cold-formed steel frames.











OUTPUT:- JOINT RIGIDITY + AMBIENT VALIDATION

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Queen's University Belfast

University of Strathclyde Glasgow

People

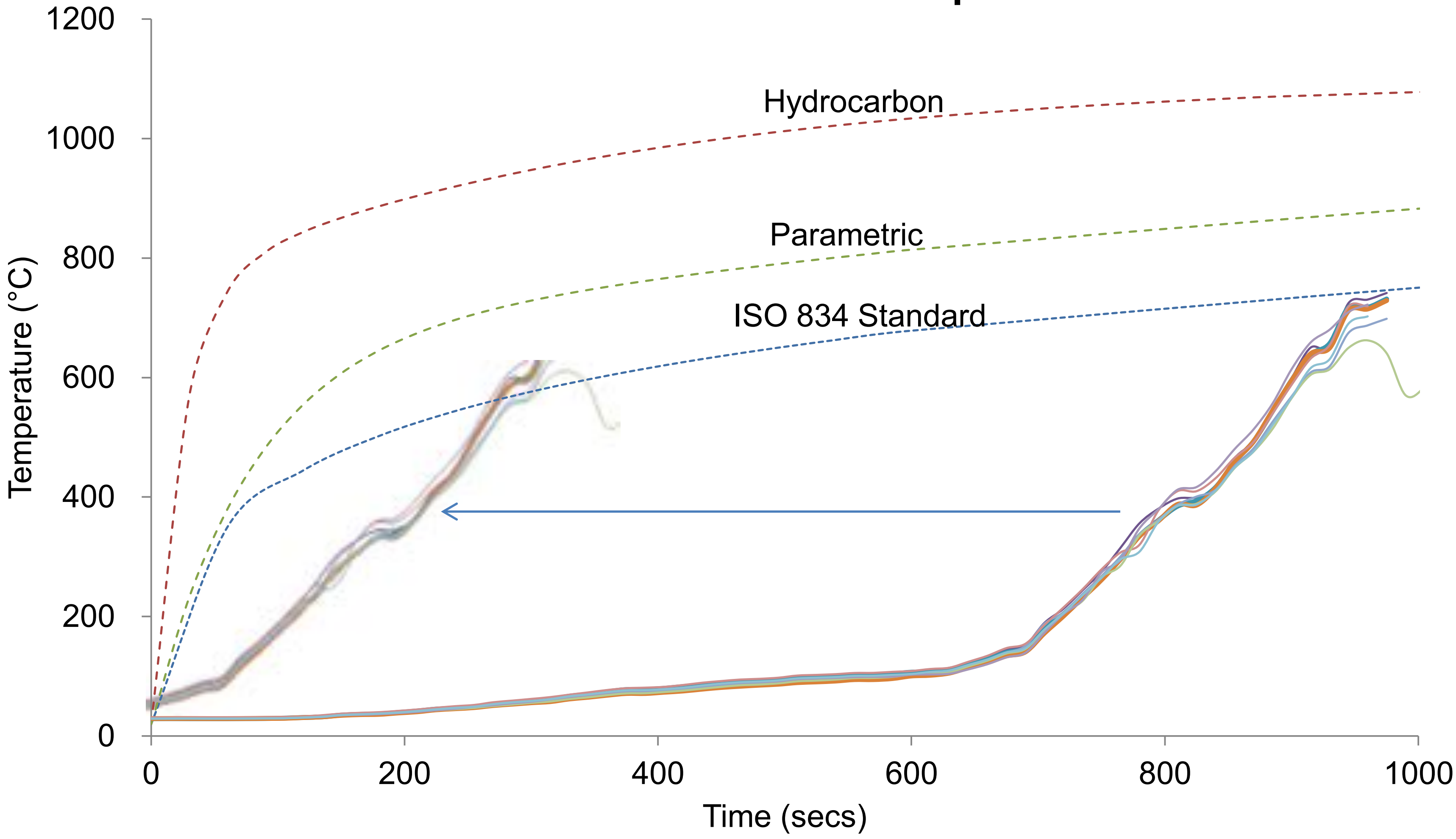
The Institution of Structural Engineers

ice Institution of Civil Engineers

EcoSteel

Curtin University Sarawak Malaysia

Site Test Results - temperature



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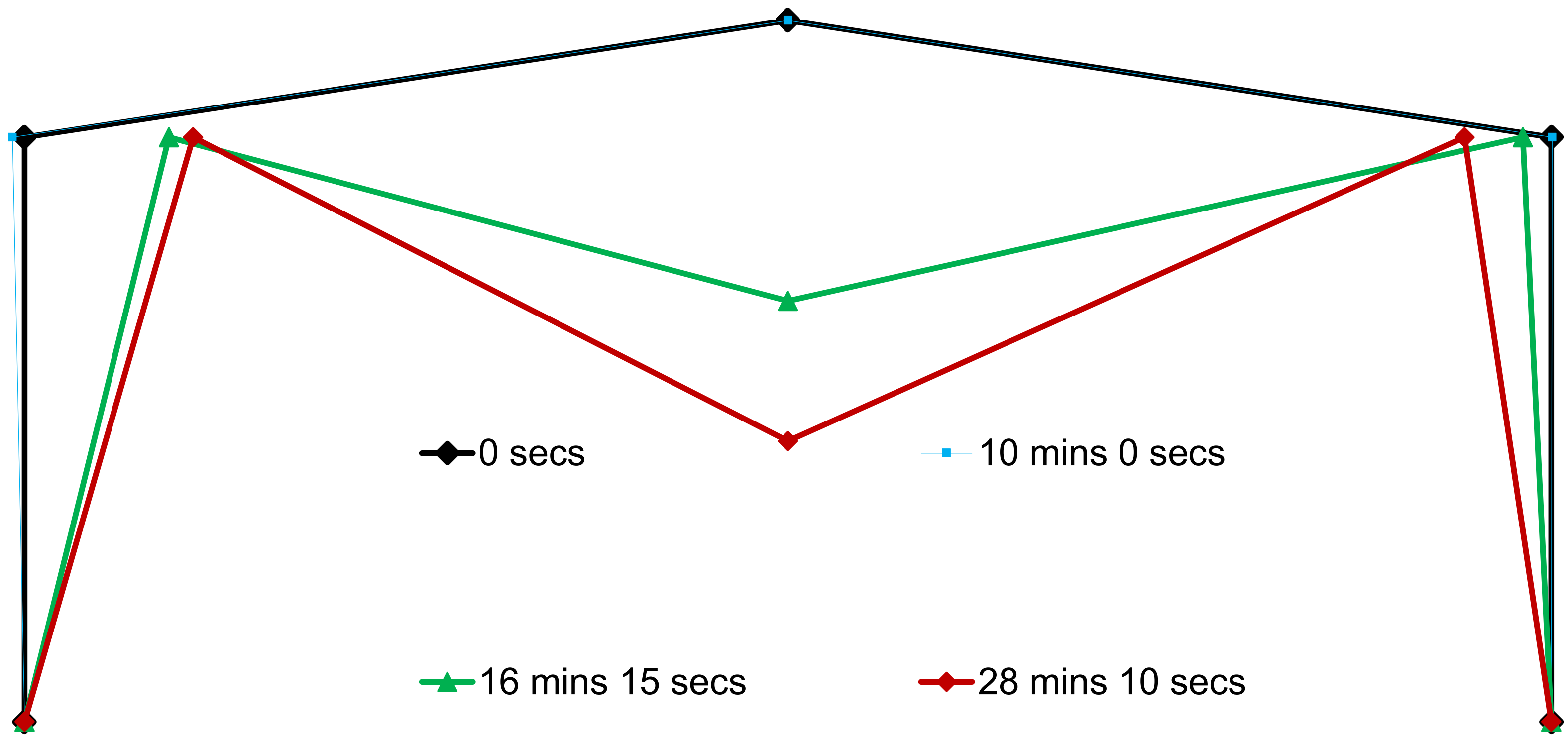
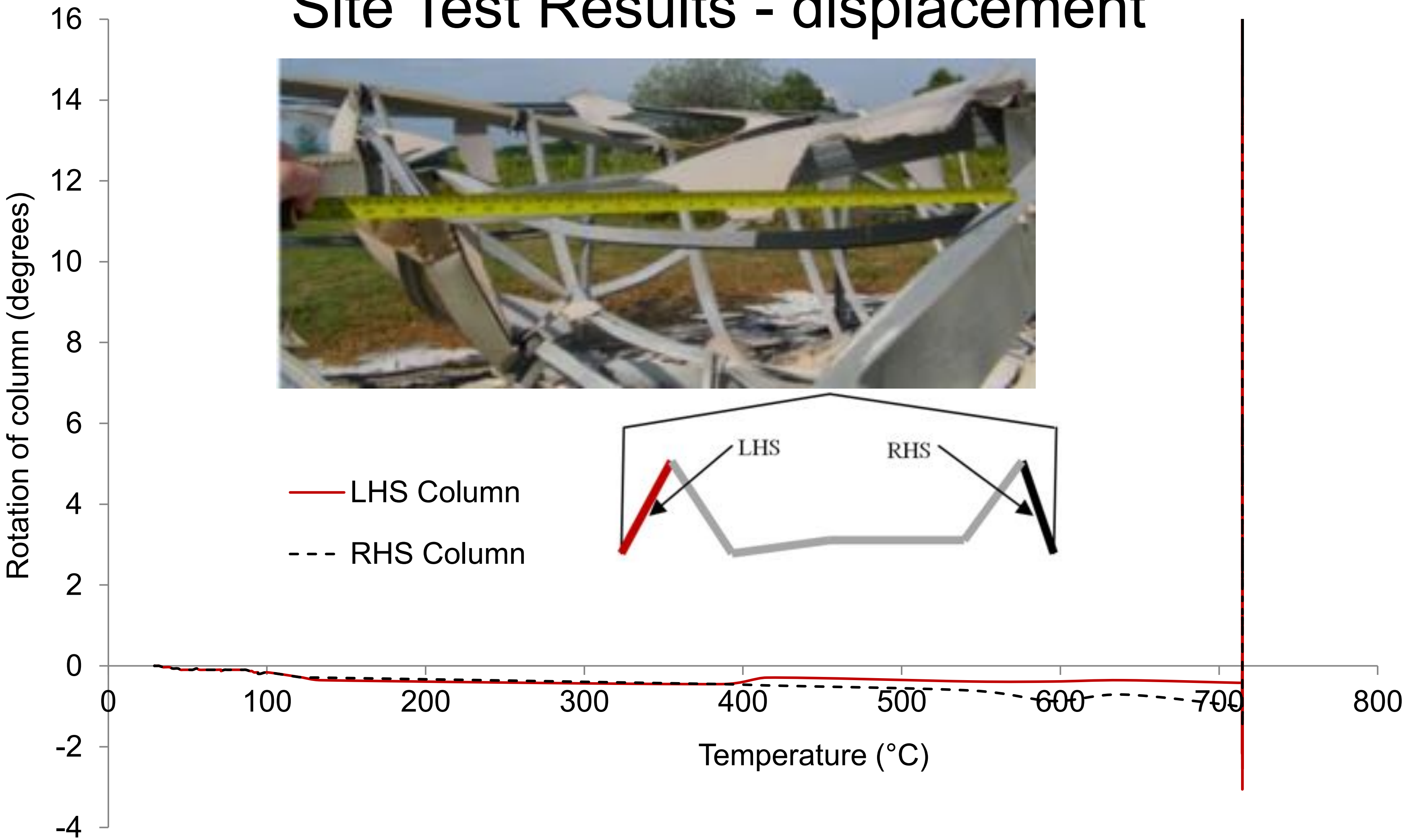
Site Test Results - displacement



Site Test Results - displacement



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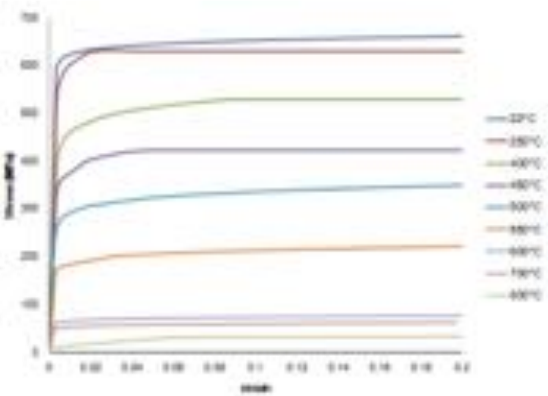
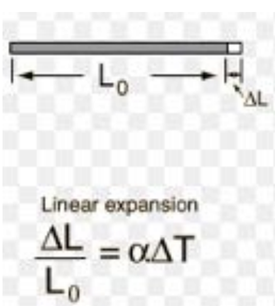
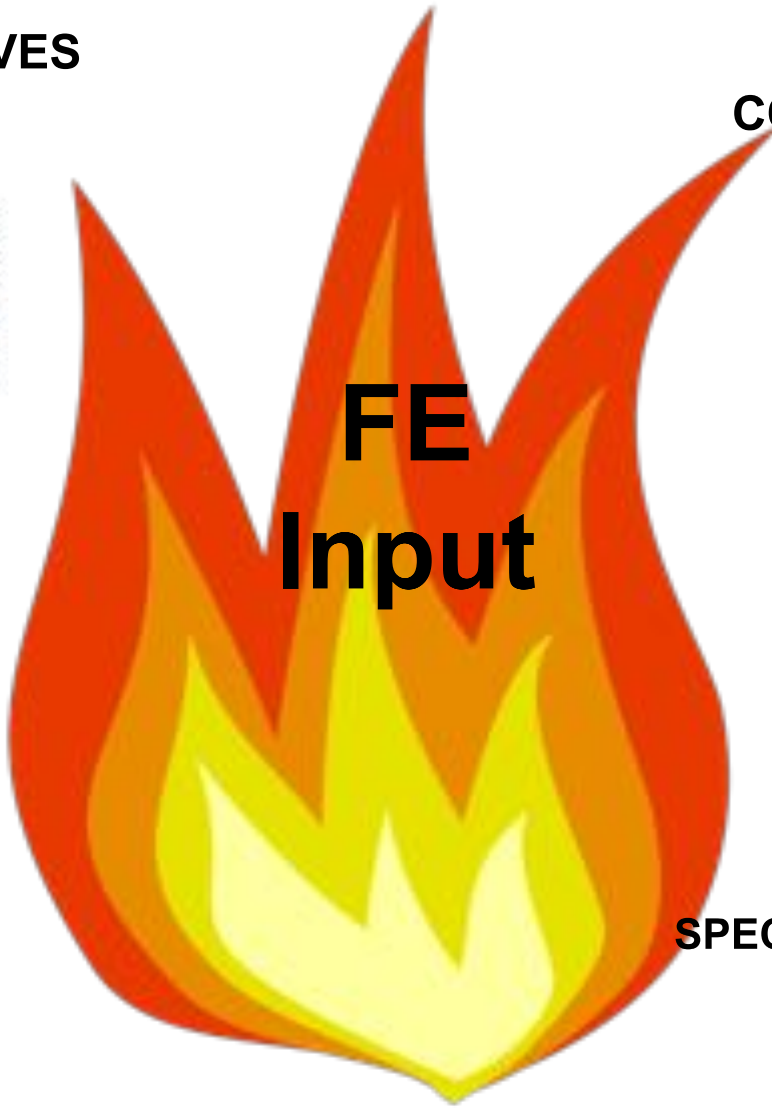
STRESS STRAIN CURVES



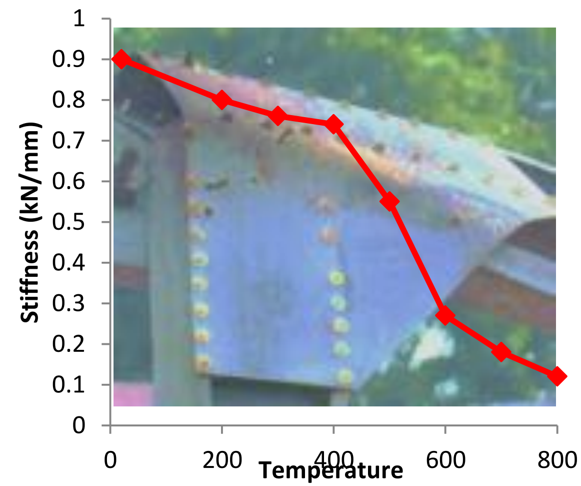
EXPANSION





FE Input

CONNECTION STIFFNESS



YOUNG'S MODULUS

CONDUCTIVITY

SPECIFIC HEAT

Verification (i)

The Steel Construction Institute

Silwood Park, Ascot, Berks SL5 7QN
Telephone: (01344) 623345
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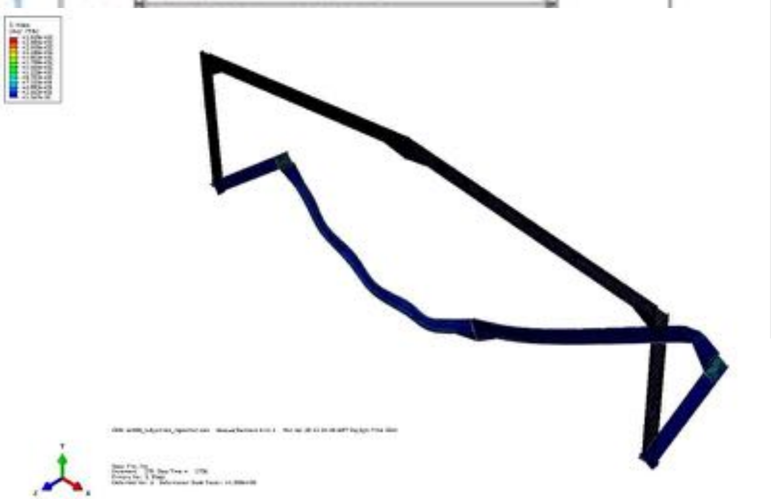
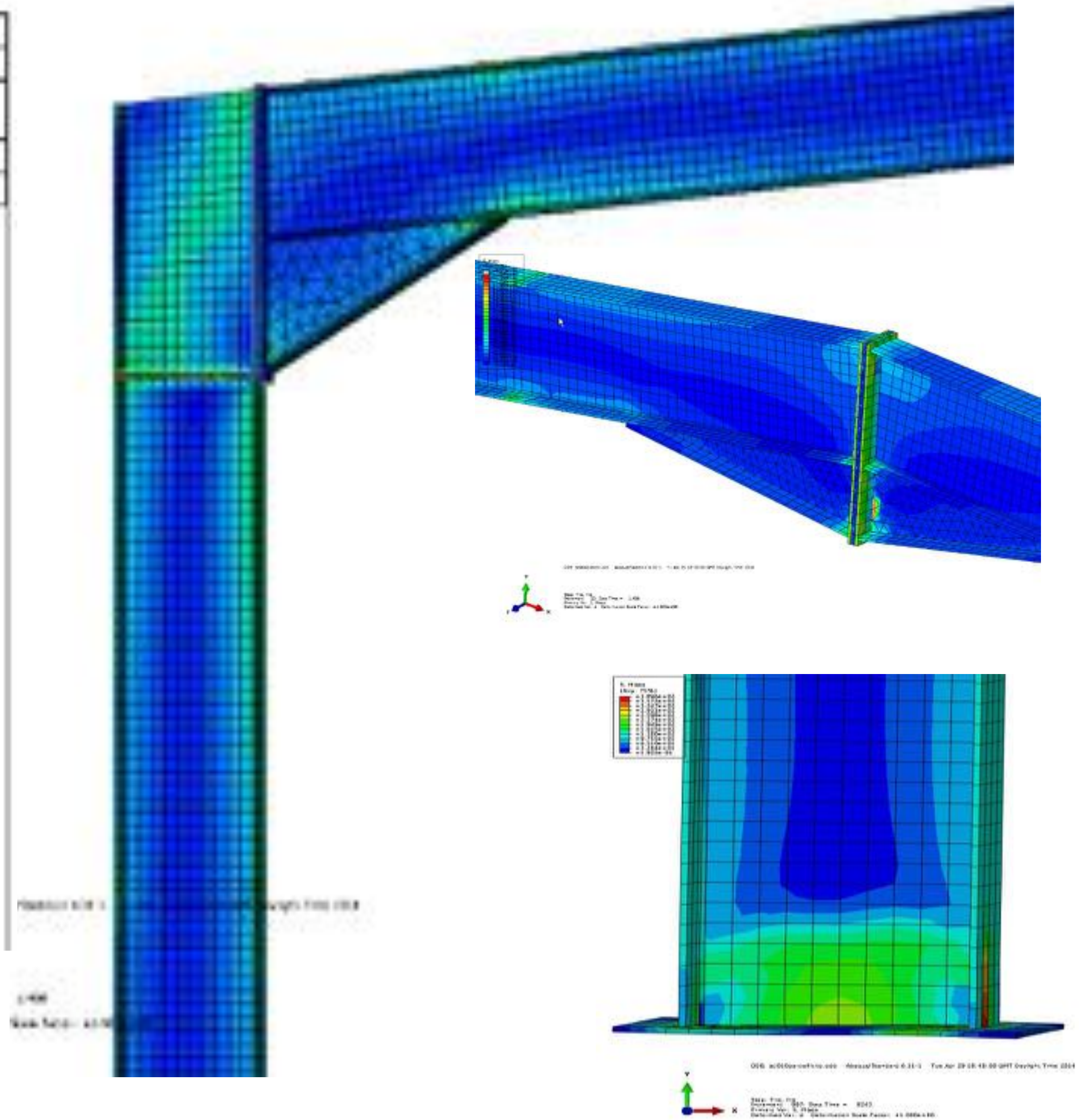
CALCULATION SHEET

Job No.	BCF 838	Sheet 1 of 3	Rev A
Job Title	Steel framed buildings in boundary conditions		
Subject	Worked Example 1: Single storey portal framed building with UB rafter		
Client SCI	Made by WIS	Date July 2002	
	Checked by GMH	Date July 2002	

2 BAY STEEL PORTAL FRAME WITH UNIVERSAL BEAM RAFTER

The building construction consists of a single span portal frame fabricated from UB sections, as shown in the following figure.





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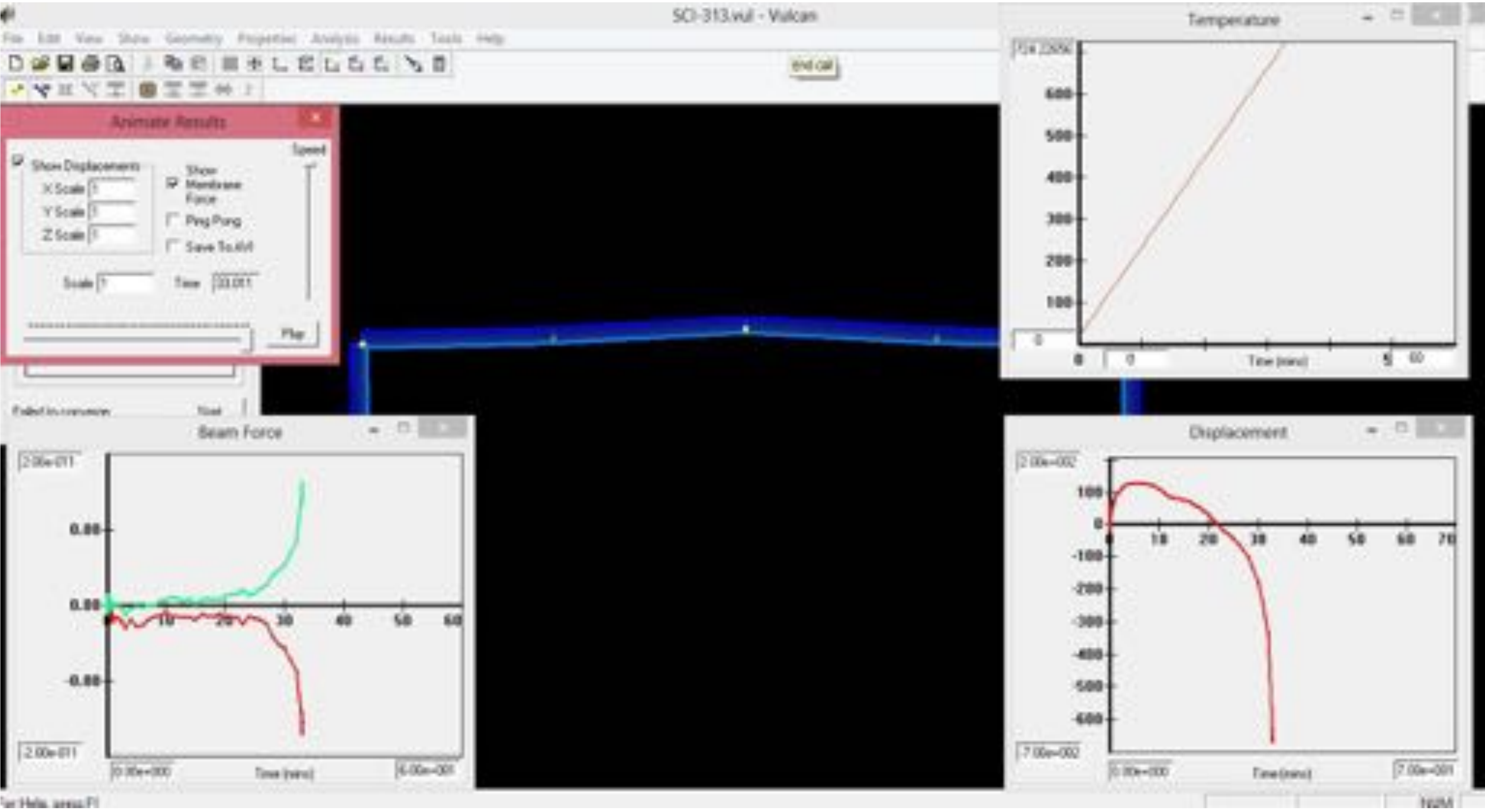
Benchmark - VULCAN



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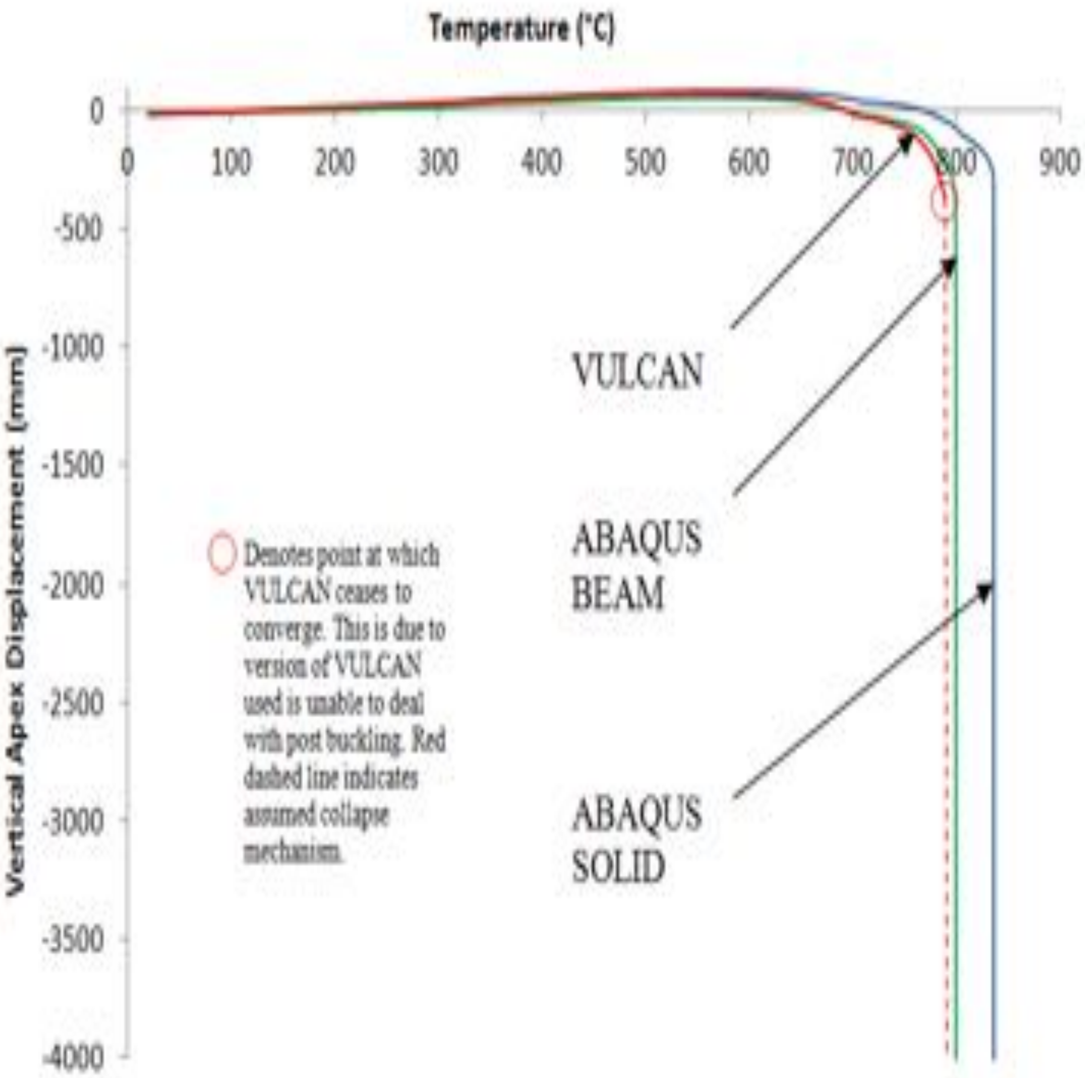
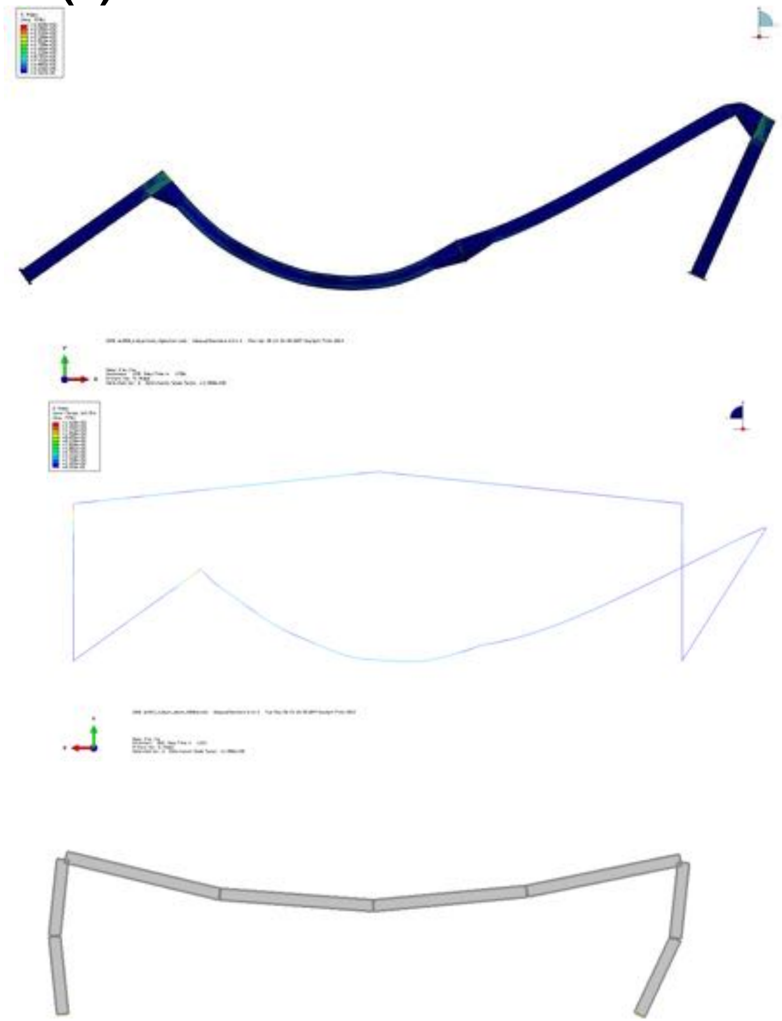
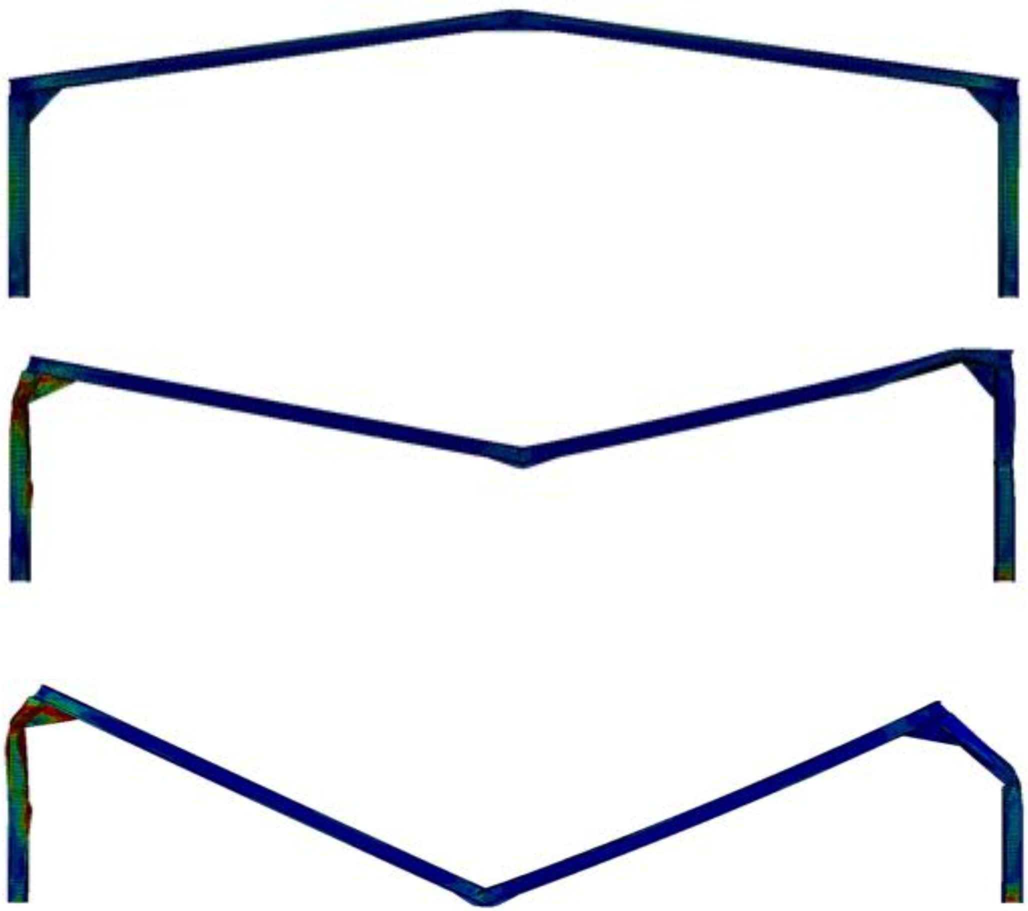
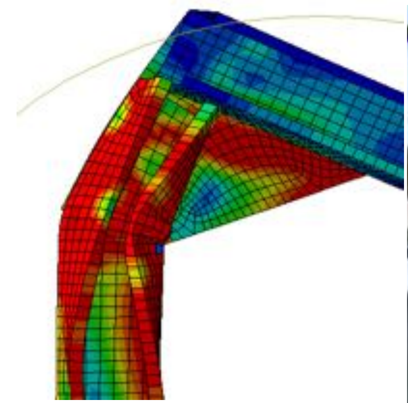
Verification (i)

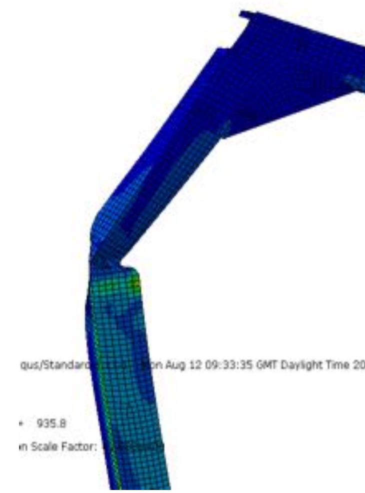




Site Test Results – finite element







Shell Finite Elements – more complex than beam but able to model accurate geometry and capture complex buckling modes of the thin walled structures

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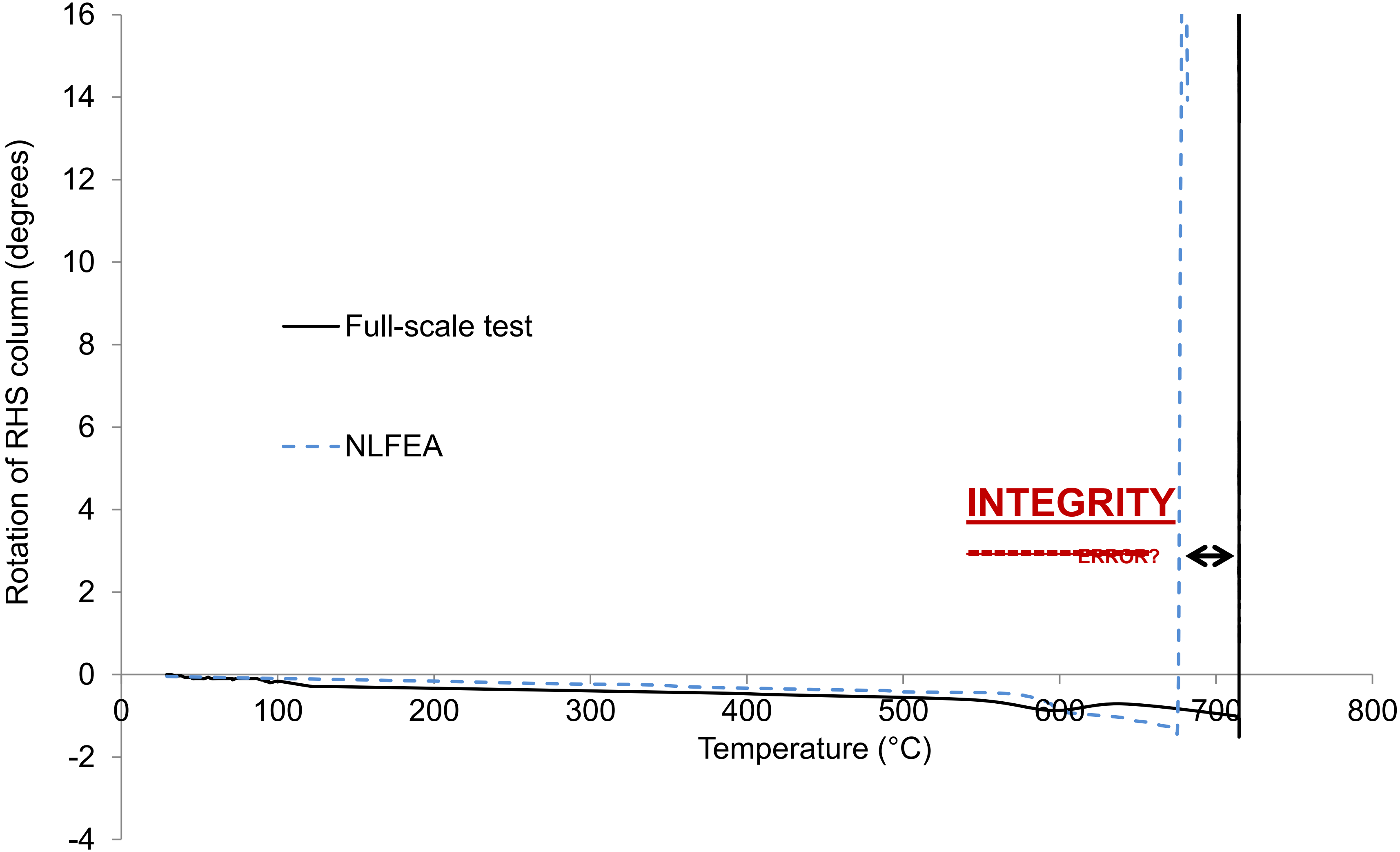
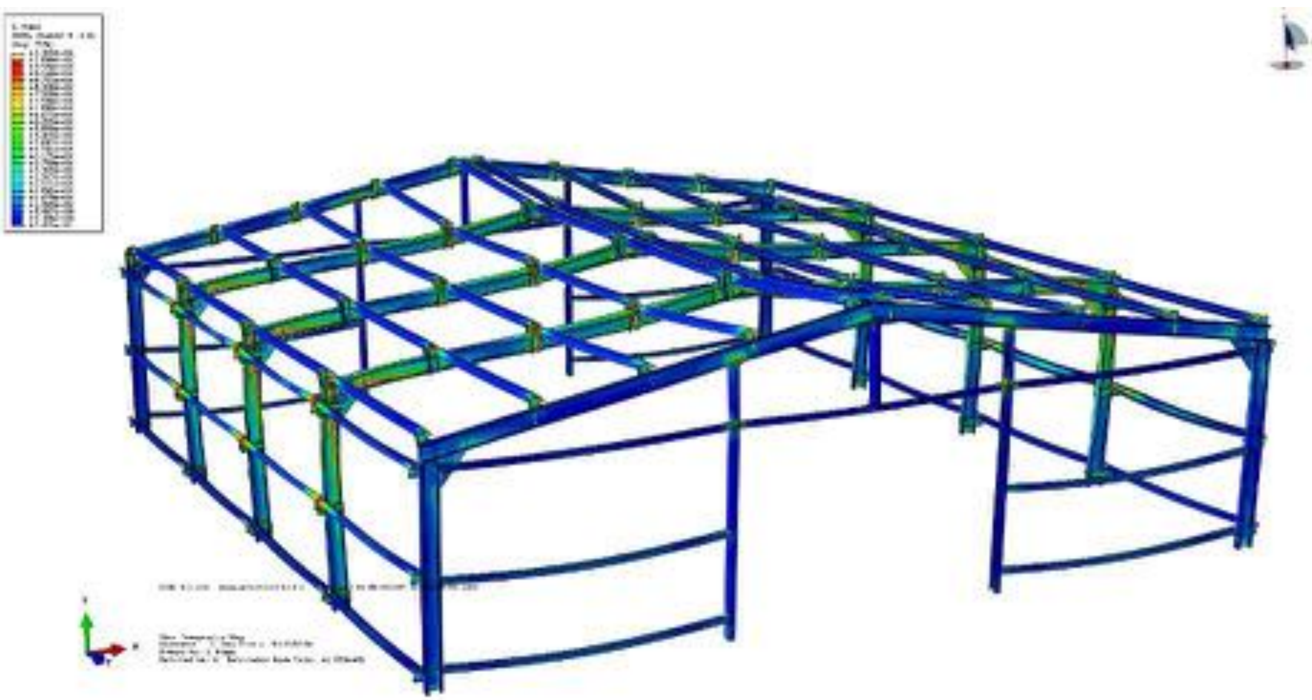
Site Test Results – finite element



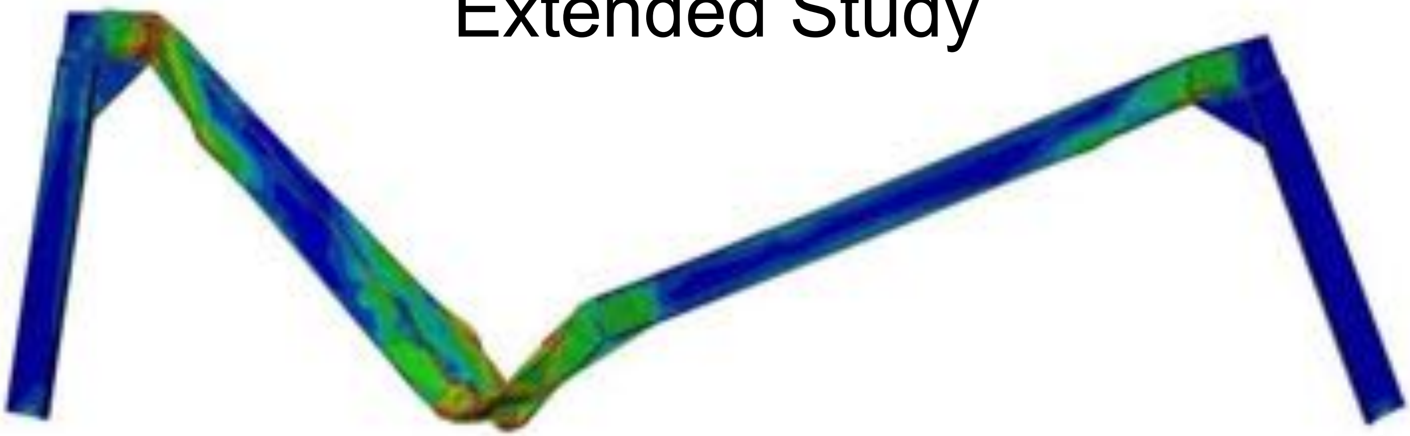
Variance in FE and EXP due to beneficial effect of purlins, side-rails and cladding? Single portal frame model not able to accurately model this, need a multi-bay portal frame arrangement.

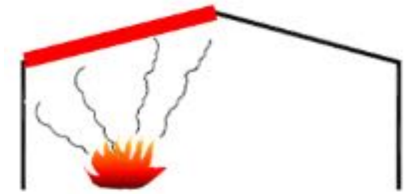
Full building geometry model

Model Type	Failure Temperature (°C)	Variance with EXP (%)
Full-scale test	714	n/a
NLFEA shell single	682	4.48
NLFEA shell full building geometry	704	1.40



Extended Study





Further investigations to determine influence of SCI guidance, sensitivity of connection stiffness, *<u>in-plane restraint</u>* and a realistic design scenario.

Collapse phase for model one (with perfect geometry): 6 m span frame

Imperfections

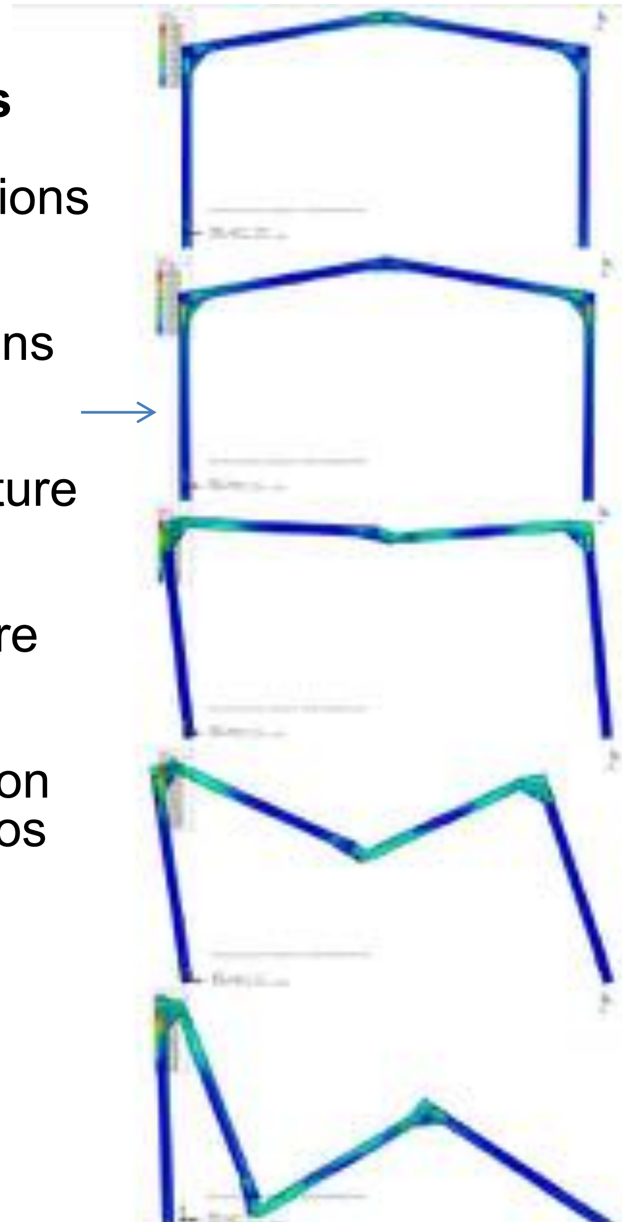
Without imperfections
665 degrees

With imperfections
662 degrees

Minimal temperature
difference

Change in failure
mechanism

Effects depend on
span/height ratios



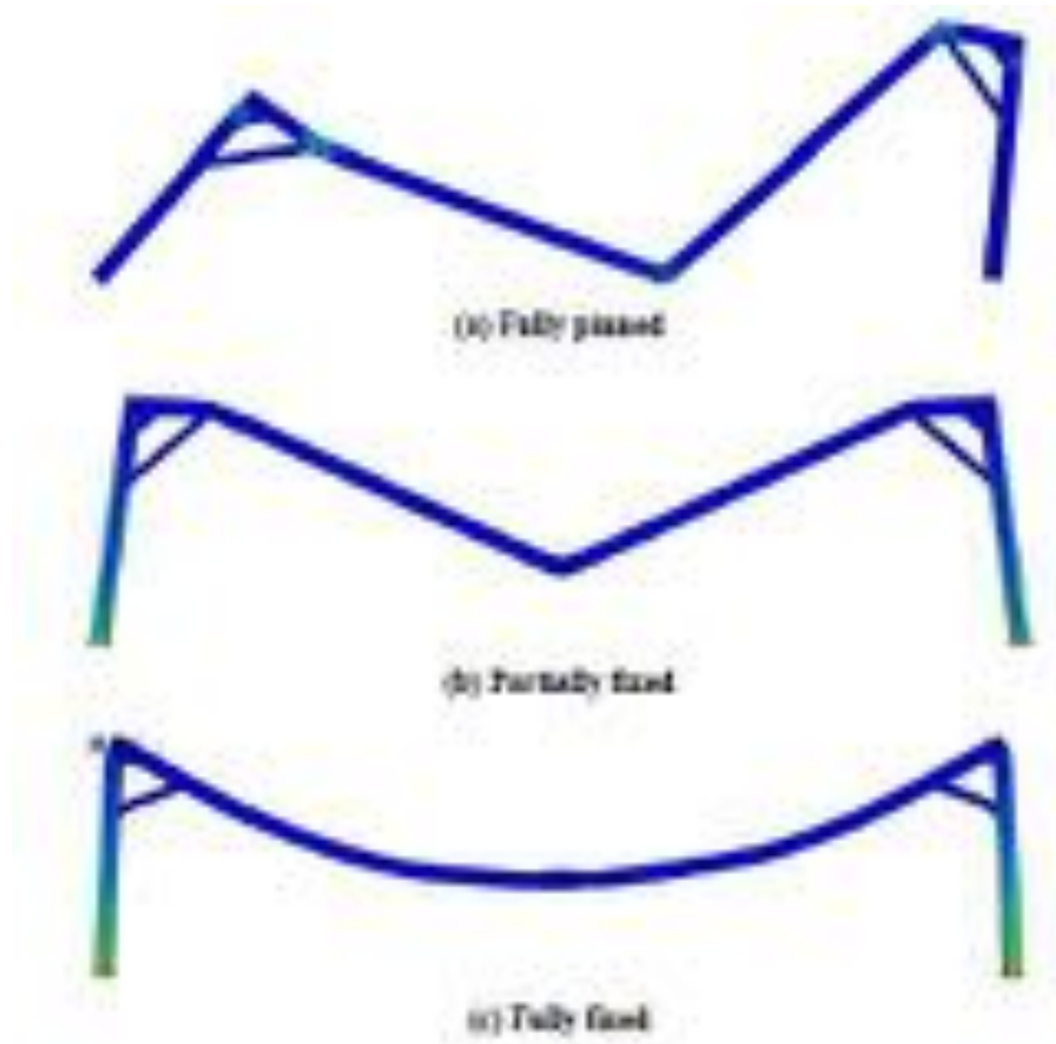
.3 Collapse phase for model two (with imperfect geometry): 6 m span

Potential for Application of Results

- NLFEA model to predict collapse behavior
- Practical design guidance for engineers
- Base for further research into the behaviour of such structures at elevated temperatures.

- **Design Procedure**
- **Critical Temperature**
- **Influence of purlins/side rails**
- **Effect of fire scenario**
- **Base fixity and Overturning moment**

22 m span frame – Like for Like comparison with SCI P313 guidance



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22 m span frame – Like for Like comparison with SCI P313 guidance

Fig. 8.6 NLFEA shell model of 22 m span frame: displacement and buckling under applied vertical load at ambient temperature

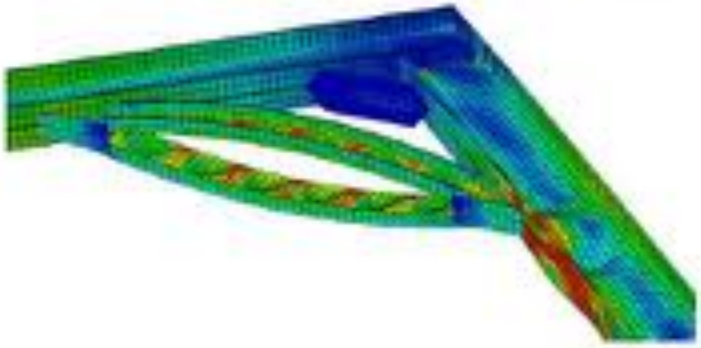
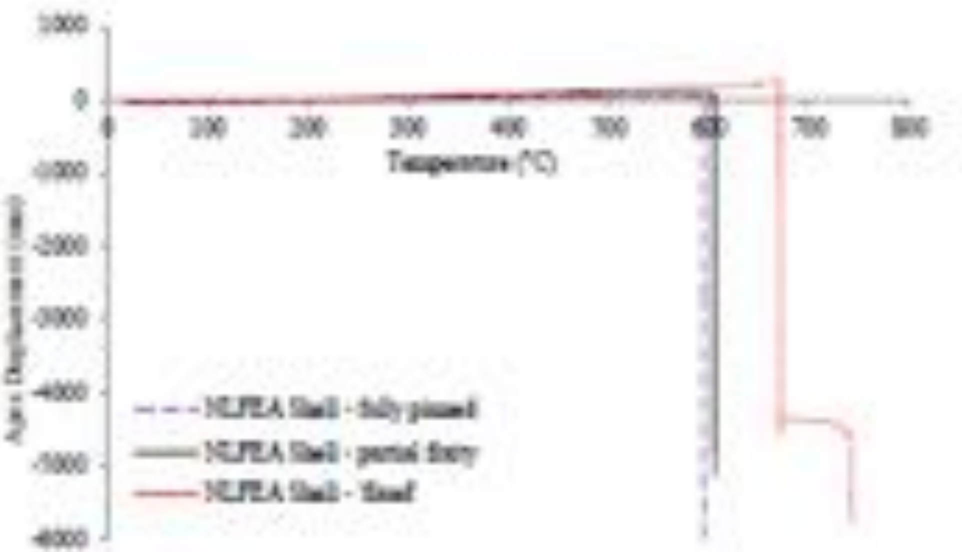
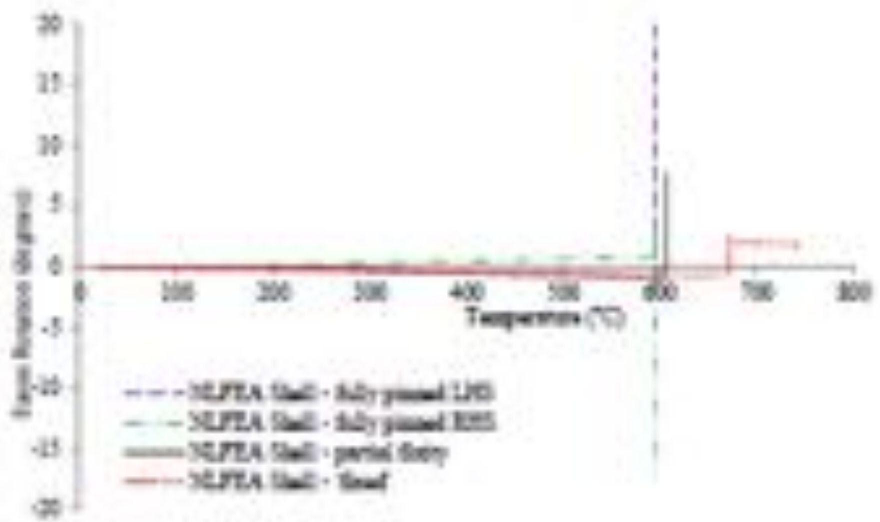


Fig. 8.7 NLFEA shell model of 22 m span frame: local and flexural buckling of the knee brace member

22 m span frame – Like for Like comparison with SCI P313 guidance



(a) Variation of apex displacement against temperature (-ve displacement denotes downwards movement)



(b) Variation of eaves rotation against temperature (-ve rotation denotes outwards movement)

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22 m span frame – Like for Like comparison with SCI P313 guidance

- As expected, models with fully pinned bases resulted in an outwards sway failure when idealised in-plane restraint is not provided. Therefore fully pinned bases should not be used in fire boundary conditions.
- If in-plane restraint is not provided, NLFEA models of cold-formed frames were susceptible to outwards sway collapse mechanism under varying fire scenarios. Therefore, adequate provision should be made to ensure continued in-plane restraint from the side-rails and fire rating cladding.
- Initial geometric imperfections have minimal effect on the failure temperature, but can affect the type of collapse mechanism in some instances, when the fully pinned condition was used.
- Different fire scenarios should be considered to allow for conservative design.

Proposed amendment to design guidance

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9.3.4 Suggested mathematical model for cold-formed steel portal frames

The suggested mathematical model for cold-formed steel portal frames in fire boundary conditions is demonstrated in Fig. 9.1. The spring stiffness, idealised from the in-plane restraint from the steel cladding and protected side-rail should limit outward displacement to 1 degree, to keep consistent with the guidance for hot-rolled steel portal frames in fire (Simms and Newman, 2002).

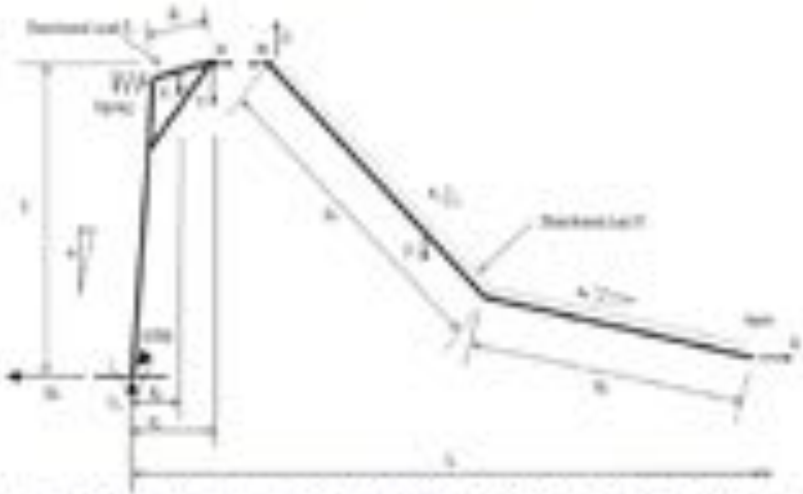

Fig. 9.1 Proposed mathematical model for cold-formed steel portal frames in fire boundary conditions

Considering vertical equilibrium, the vertical reaction on the column base is given as follows:

$$V_B = F_1 + F_2 \quad \text{Eqn. 9.1}$$

Considering horizontal equilibrium, the horizontal reaction on the column base is given as follows:

$$H = F_1 R_a \cos\theta_a + F_2 R_b \cos\theta_b \quad \text{Eqn. 9.2}$$

And

$$H_B = H \quad \text{Eqn. 9.3}$$

For column equilibrium, the base overturning moment is given by:

$$OTM = HY + F_1 X_1 + F_2 X_2 \quad \text{Eqn. 9.4}$$

Where

R_r is the rafter length from end of the knee brace to apex including allowance for elongation, where $R_r = R_a + R_b$

R_1 is the length of rafter to knee brace connection from centre line of column

R_a is equal to 0.7 * R_r

R_b is equal to 0.3 * R_r

Y is the height of end haunch (can be considered equal to 1.15 * R_1)

L_s is the span

H_c is the column height

X_1 is the horizontal distance from column base to end of knee brace connection along rafter

X_2 is equal to X_1 * 0.5

α is the column deflection angle

θ_a is the rafter sag angle for portion R_a

where: $\theta_a = \cos^{-1}[(L_s - 2X_1)/(2.5R_r)]$

θ_b is the rafter sag angle for portion R_b

where: $\theta_b = \theta_a/2$

F_1 is the distributed vertical load on the rafter length R_a

F_2 is the distributed vertical load on the rafter length R_b

V_B is the vertical reaction on the column base

H_B is the horizontal reaction on the column base

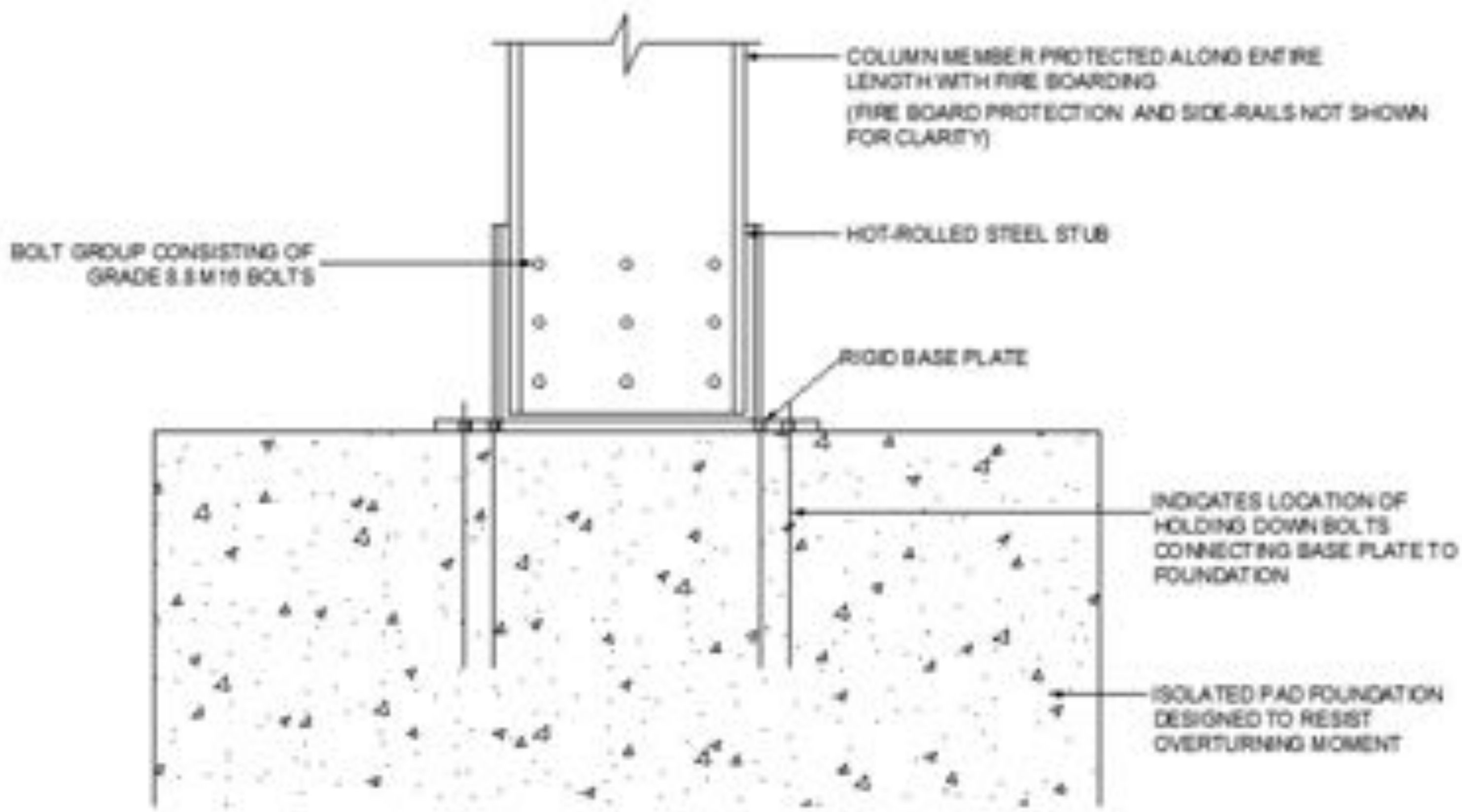

Fig. 9.3 Side view of proposed column base detail

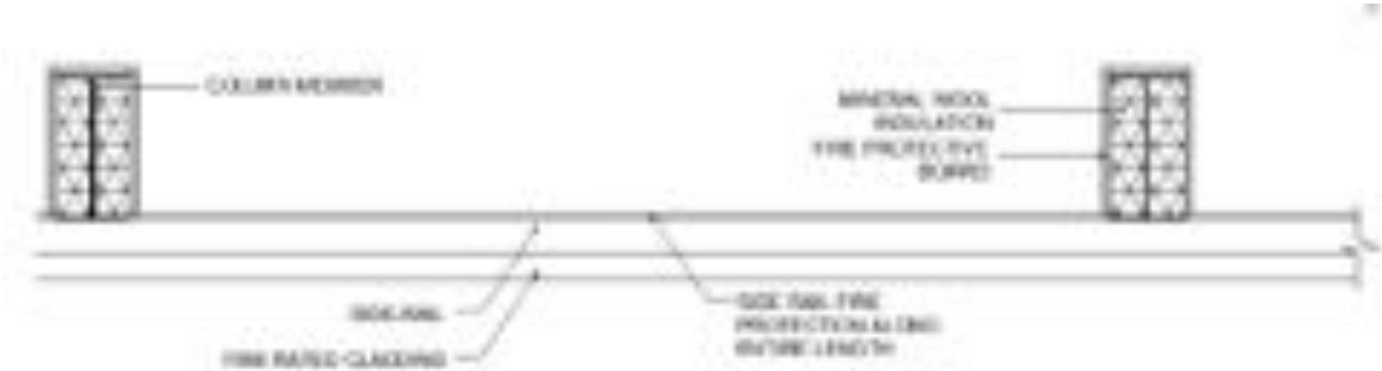

Fig. 9.4 Plan view of proposed column and side-rail fire protection

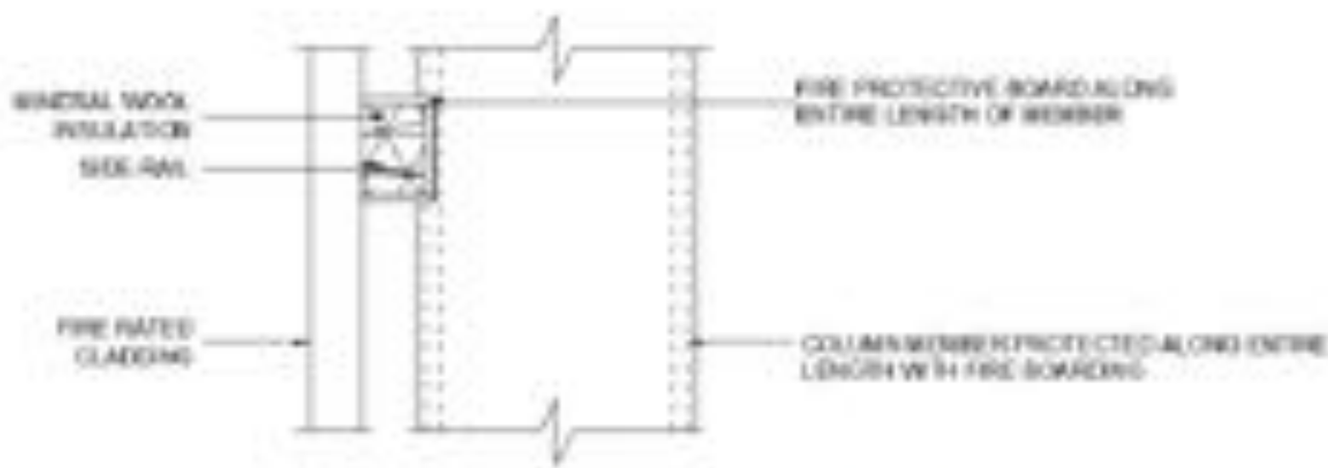

Fig. 9.5 Proposed column and side-rail fire protection

Fire Boundary Conditions

Base fixity and in-plane restraint from side-rails have a beneficial effect in preventing premature collapse and un-desirable collapse mechanisms.

As the fixity of cold-formed steel portal frame bases cannot be correctly quantified or regulated, it is recommended that side-rails are protected along their entire length along the fire boundary to prevent sway failure. (Top side rail gives largest lever arm!)

Model fire boundary frames using validated NLFEA to predict behaviour of frame

Current Work

Benchmark with SAFIR

Université de Liège

University of Liege – Fire Safety Engineering

SAFIR®

ACKNOWLEDGEMENTS

- **Hanna + Hutchinson Consulting Engineers**
- **Queen's University Belfast School of Planning, Architecture & Civil Engineering. Dr James Lim, Dr Mohammed Sonebi, Professor Cecil Armstrong**
- **IStructE, ICE & EcoSteel**
- **DEL Funding Body**
- **COST European Network: Integrated Fire Engineering and Response**

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Cold-formed steel portal frames in fire: full-scale testing and finite element analysis

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Synopsis
A full-scale, non-uniform natural fire test on a cold-formed steel portal frame building is described. The results of the fire test are used to validate a non-linear, elasto-plastic, finite element shell idealisation, for the purposes of later forming the basis of a performance-based design approach for cold-formed steel portal frames at elevated temperatures. The test building had a span of 8m, height-to-eaves of 2.2m, length of 10m, with a frame spacing of 2.5m. The member and connections of the frame were constructed entirely from cold-formed steel and the eaves and apex joints were classified as semi-rigid. In order to reduce the influence of diaphragm action, the cladding was detailed to act independently from the frames. The frame collapsed with an eventual inwards asymmetrical collapse mechanism at 714°C, with collapse being due to member buckling rather than failure of the screws or joints. The collapse temperature predicted using the shell idealisation was 682°C, with a deformed shape similar to that observed in the fire test.

Introduction
Cold-formed steel portal frames (Figure 1) can be a viable alternative to conventional hot-rolled steel portal frames for light industrial, sports and agricultural buildings. Lim and Nethercot[1-4], Chung and Lau[5], Mills and LaBoube[6], Dubina et al[7] and Rhodes and Burns[8] have all independently conducted tests on the joints of such frames. A full literature review of this and other work has been described by Wrzesien et al[9] However, despite the increasing popularity of cold-formed steel portal frames, there is limited research on their collapse behaviour at elevated temperatures. Ideally, an eventual inward – as opposed to outward – collapse mechanism should take place (O'Meagher et al[10]). This is in order to prevent fire spread as well as to protect the safety of occupants escaping and firefighters who may be in

Journal papers

1. **Johnston, R. P. D.**, Lim, J. B. P., Lau, H. H., Xu, Y., Sonebi, M., Armstrong, C. G., Switzer, C. & Mei, C. C., 2014. Cold-formed steel portal frames in fire: Full-scale test and finite element analysis. *The Structural Engineer*, 92(10), pp. 44-50.
2. **Johnston, R. P. D.**, Wrzesien, A. M., Lim, J. B. P., Sonebi, M. & Armstrong, C. G., 2013. The effect of semi-rigid joints on the design of cold-formed portal frame structures. *Journal of Civil and Environmental Engineering*, 3, pp. 1-5.
3. **Johnston, R. P. D.**, Sonebi, M., Lim, J. B. P., Armstrong, C. G., Wrzesien, A. M., Abdelal, G. & Hu, Y., 2015. The collapse behaviour of cold-formed steel portal frames at elevated temperatures. *Journal of Structural Fire Engineering (In press - Issue 2, 2015)*.
4. **Johnston, R. P. D.**, Lim, J. B. P., Xu, Y., Lau, H. H., Mei, C. C., Sonebi, M. & Armstrong, C. G. Finite element investigation of cold-formed steel portal frames in fire. *The Proceedings of the ICE - Buildings and Structures (Accepted for Publication)*.

Conference proceedings

1. **Johnston, R. P. D.**, Lim, J. B. P., Sonebi, M., Armstrong, C., Lau, H. H., Xu, Y., Switzer, C. & Mei, C. C., 2014. Cold-formed steel portal frames in fire: Full-scale test and finite element analysis. In: *ICTWS 2014, 7th International Conference on Thin Walled Structures*, Busan, Korea, Sept 2014, pp. 1509-1-8.
2. **Johnston, R. P. D.**, 2014. Cold-formed steel portal frame structures in fire: Full scale testing and numerical modelling. In: *16th International IStructE Young Researchers Conference*, London, UK, March 2014, pp. 43-44.
3. **Johnston, R. P. D.**, Wrzesien, A. M., Lim, J. B. P., Sonebi, M. & Armstrong, C. G., 2012. The effect of semi-rigid joints on the design of cold-formed portal frame structures. In: *The International Congress on Materials & Structural Stability*, Rabat, Morocco, November 2012, pp. 405.
4. **Johnston, R. P. D.**, Wrzesien, A. M., Lim, J. B. P., Sonebi, M. & Armstrong, C. G., 2013. The effect of joint rigidity upon the performance of cold-formed portal frame structures. In: *SBE 2013, The International Conference on Sustainable Built Environment for Now and the Future*, Hanoi, Vietnam, March 2013, pp. 399-406.
5. **Johnston, R. P. D.**, Lim, J. B. P., Sonebi, M., Wrzesien, A. M., Armstrong, C. G., 2013. The structural behaviour in fire of a cold-formed steel portal

Thank you. Questions?

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LinkedIn

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