Citation: Tsavdaridis, K. D. and D'Mello, C. (2011). Finite Element Investigation on Web-Post Buckling of Perforated Steel Beams with Various Web Opening Shapes subjected under different shear-moment interaction. Paper presented at the 6th European Conference on Steel and Composite Structures, 31-08-2011 - 02-09-2011, Budapest, Hungary.

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FE MODELLING TECHNIQUES FOR WEB-POST BUCKLING RESPONSE
Perforated Steel Beams with Closely Spaced Web Openings of Various Shapes

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INTRODUCTION

The current method of assessment is based on FE models which still lack computational efficiency and are restricted by a number of limitations. Therefore, this work aims at the feasibility of developing FE models which are applicable to deformation and strength prediction of full scale perforated steel beams. The main area of interest is the stability of the web-post under the combined effect of shear and compression, especially at the edge of the web openings, where the stabilizing effect of tension field action is less than that at the centre of the web-post.

1 WEB-POST BUCKLING

1.1 Structural behaviour

Web-post buckling is one of the major and more complex failure mechanisms for perforated beams with closely spaced web openings (i.e. those usually manufactured with the profile cutting procedure). Slender web-posts in combination with deep I-sections induce instability into such structural forms. The result is a very complex failure mechanism where the axial force due to global moment, the shear force due to the global shear force and the local Vierendeel moments due to the transfer of shear force across the web opening length, act simultaneously and in combination with the local actions of the two adjacent web openings. The mechanism depends on a number of parameters, including the spacing between openings. Additional vertical deflections as well as out-of-plane displacements due to the presence of multiple web openings are considered.

1.2 Method of study

FE analyses can be used as a tool to analyse buckling phenomenon. Linear buckling is a useful first step which gives an idea of buckling mode shapes. However, the buckling loads found through linear buckling analyses are highly non-conservative and should therefore be used with caution. The FE analyses presented here makes use of ANSYS v11.0, which includes material non-linearity (i.e. plastic behaviour) and geometrical non-linearity (buckling). An extensive parametric FE local study is included in which a number of geometric parameters are varied. Further relevant work can be found in [1], in which experimental tests are presented and compared with FE analyses. Also, non-standard innovative web opening shapes have been included as they have a number of advantages, including the structural behaviour, the economic design and the ease of fabrication [2].

In applying any non-linear FE analysis, it is essential to validate generic results preferably by comparison with tests, or alternatively by comparing them with the results of similar analyses with known closed form solutions. However, there are not any closed form solutions for the design of perforated steel beams and particularly for web-post buckling. The movement of the stress concentration (i.e. plastic hinges) in the vicinity of the web openings is still under question. Consequently, an analytical comparison between the experimental tests conducted in the literature [1,3] is carried out to validate the FE method. Finally, a parametric FE study with four different web opening shapes is conducted to demonstrate the divergence of the results.

1.3 Non-linear buckling as a design tool

The inherent difficulty in solving non-linear FE buckling problems is due to the fact that in solving these types of problems in a static framework, at the point of geometric instability the stiffness matrix may be singular and so prevent a solution from being obtained.

1.4 Eigen-value buckling analysis

Similar to dynamic analyses, a linear analysis should always be performed in advance of solving the non-linear problem. Eigen-value buckling is part of a typical solution for a non-linear buckling problem. The eigen-value buckling analysis predicts the theoretical buckling strength of an ideal elastic structure. It computes the structural eigen-values for the given system loading and constraints taking into consideration the secondary effects (i.e. geometric non-linearity). This is known as “classical Euler buckling analysis”. Any buckling mode from a linear buckling analysis can be used to generate ‘imperfections’ on the model for use in a non-linear buckling analysis (material and geometric non-linearity).

1.5 Non-linear static buckling analysis

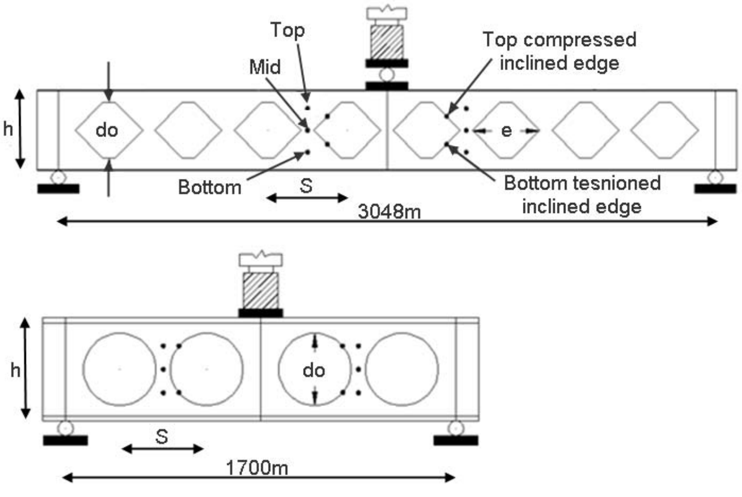
To determine the critical load (but not the post-buckling response), a typical non-linear static solution can be run. A non-linear buckling analysis is more accurate than an eigen-value buckling analysis because it employs non-linear, large-deflection static analysis to predict buckling loads. The true non-linear nature of this analysis permits the modelling of geometric imperfections, load perturbations, material non-linearities and gaps.

For this type of analysis, small eccentric loads or imperfections are needed to initiate the desired buckling mode on a ‘perfect’ FE model. The common method is to create a small imperfection in the mesh for use in non-linear buckling analyses. Similar techniques involve application of small point loads on certain areas transverse to the web, inducing buckling. The post-buckling behaviour is not of interest in this paper.

2 MODELLING THE EXPERIMENTAL WORK

2.1 Beam models

The two perforated beams shown in *Fig. 1* have been modelled. One is a non-composite castellated beam with mid-depth hexagonal web openings and the other a mid-range perforated beam with one web-post at each size and circular web openings. Experimental details can be found in [1,2,3]. In the experimental work it was ensured that the load was transferred via a bearing plate, as an eccentric load could cause local buckling at the edges of the web openings close to the point load. *Table 1* below summarises the experimental and FE results.



Castellated: h=376.4mm, b_f=70.6mm, t_f=4.45mm, t_w=3.61mm, d_o=0.7h=263.48mm, S=1.4d_o=368.3mm, e=311.9mm
Element type: SHELL181
Element size: 15-20mm (in total 8,980 elements)
Web: f_y=357MPa, f_u=501MPa
Flange/Stiffener: f_y=342MPa, f_u=505MPa
E=200GPa, v=0.3, Tang. Modulus=2000MPa (=E/100)

Cellular (UB457x152x52): h=449.8mm, b_f=152.4mm, t_f=10.9mm, t_w=7.6mm, d_o=0.7h=315mm, S=1.2d_o=410.22mm, $t_{mid\text{-}stiffener}$=20mm
Element type: SHELL181
Element size: 15-20mm (in total 3,445 elements)
Web: f_y=375.3MPa, f_u=492.7MPa
Flange/Stiffner: f_y=359.7MPa, f_u=480.9MPa
E=200GPa, v=0.3, Tang. Modulus=2000MPa (=E/100)

Fig. 1. Testing arrangements, section properties and material properties

2.2 Eigen buckling

A point load is applied at the mid-span and four eigen-modes are extracted based on the ‘Block Lanczos’ method to verify whether or not there is a possibility of multiple buckling mode shapes being triggered (two of them are shown in *Fig. 2*) following the linear static analysis.

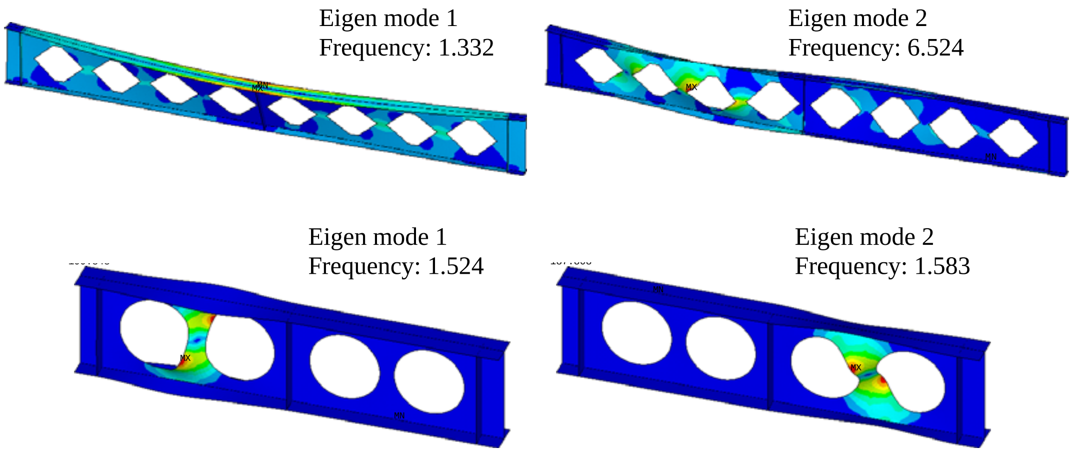


Fig. 2. Four Buckling Modes Extracted by ‘Block Lanczos’ Method

From other work carried out by the authors, the best representation of the real structural behaviour is obtained by using the first eigen-mode and a scaled factor equal to $t_w/200$. However, while the failure mode and the web-post profile is similar to the tested specimen’s, *Fig. 3* and *Fig. 4* show that the amplitude of the out-of-plane displacements in the FE analysis is lower than that from the test. This difference in overall stiffness is due to the existence of manufacturing imperfections and experimental uncertainties, as well as the lack of information on the material properties of the steel.

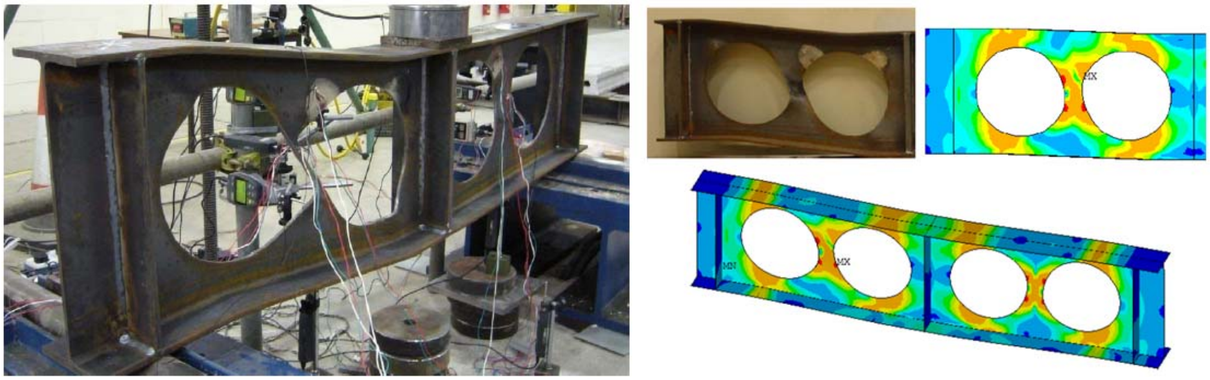


Fig. 3. Tested cellular beam compared with FE model (Von-Mises stresses)

The predicted mode of buckling includes some flange rotation, which is also observed in the test beam. In most of the FE analyses, an early out-of-plane web movement is observed due to the applied lateral force. The latter can be a trigger load, an imperfection or the eigen-vectors. As the load is increased the web starts to return to its original position. At higher load levels the web starts becoming unstable which is the onset of buckling. Increasing the load results in the web deforming plastically (buckling), while in some cases a jump in the opposite direction is observed (*Fig. 5a*). In the current study, the ‘*critical buckling load*’ is assumed to be the onset of buckling. This is realistic although somewhat conservative approach.

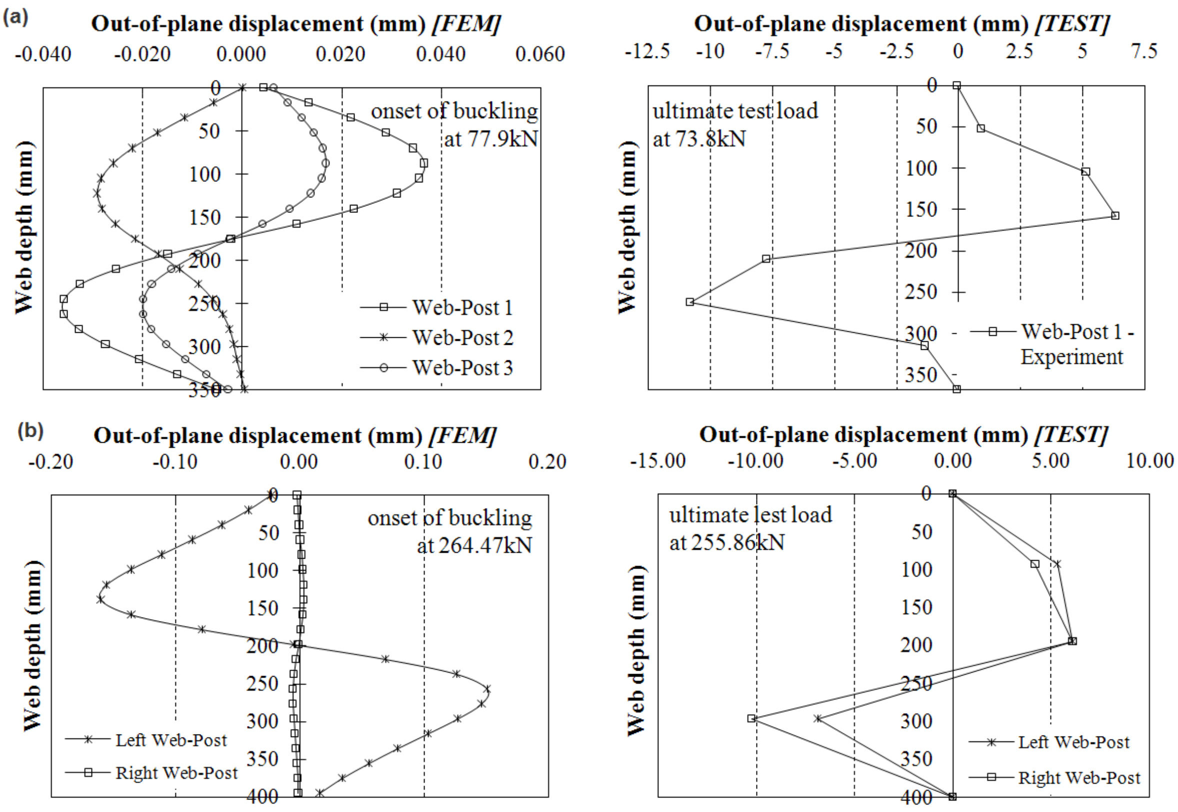


Fig. 4. Out-of-plane displ. vs Web depth (a) castellated and (b) cellular beam [Eigen buckling]

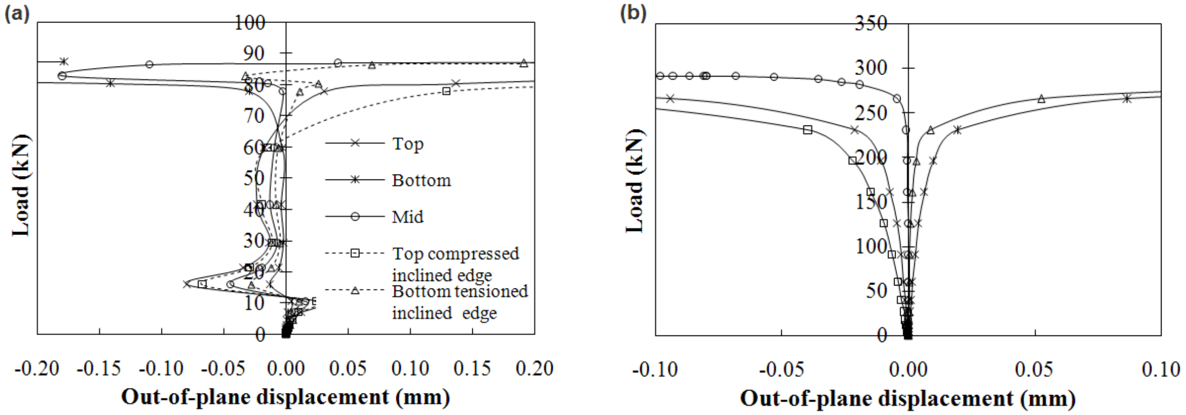


Fig. 5. Out-of-plane displ. at web-post 1 (a) castellated (b) cellular beam [Eigen buckling]

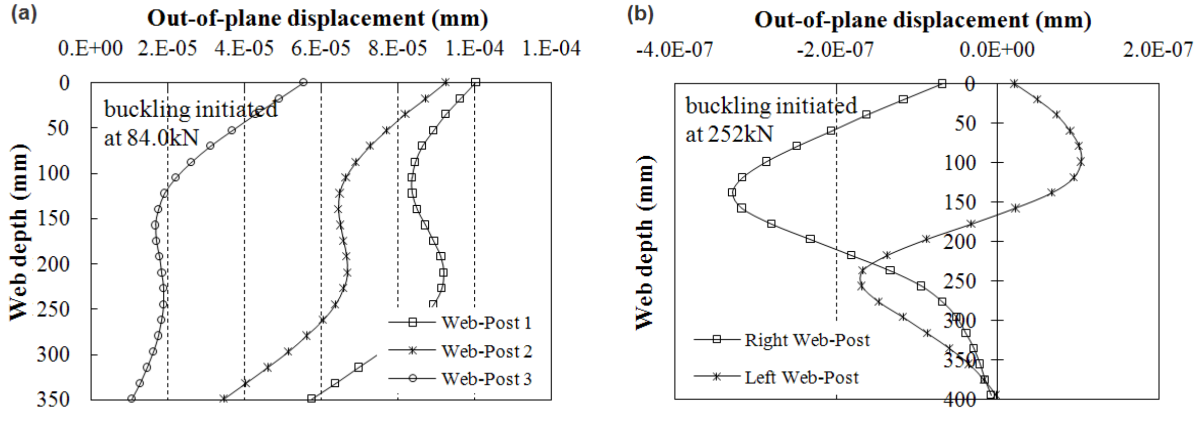


Fig. 6. Out-of-plane displ. vs Web depth (a) castellated and (b) cellular beam [Non-linear buckling]

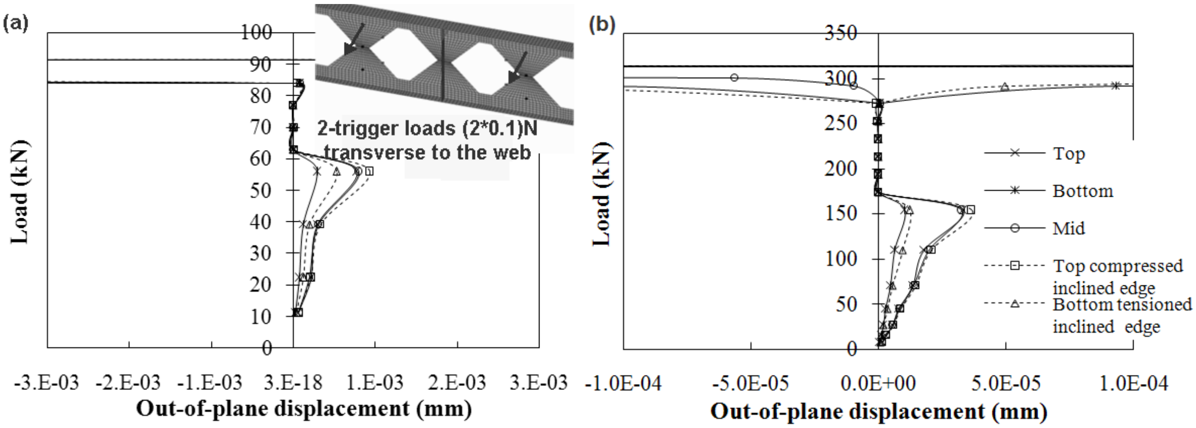


Fig. 7. Out-of-plane displ. at web-post 1 (a) castellated and (b) cellular beam [Non-linear buckling]

2.3 Non-linear buckling

Two load steps were used in this analysis. Load-step 1 was used to load the beam up to 154kN and then load-step 2 to gradually increase the load from 154kN to 350kN, past the expected buckling load. A small out-of-plane load transverse to web was also applied during load-step 1. Following an investigation into the optimum position and the magnitude of the trigger load, a 2- point load of just 0.1N was applied at the middle of the top half of the web-post 1 (*Fig. 7a*).

2.4 Comparisons and results

Table 1. Test loads and predicted strengths

Model	$P_{y(test)}$ (kN)	$P_{cr(test)}$ (kN)	$P_{ult(test)}$ (kN)	$P_{y(FEM)}$ (kN)	$P_{cr(FEM)}$ (kN)	$P_{ult(FEM)}$ (kN)	$\frac{P_{cr(FEM)}}{P_{cr(test/theory)}}$	$\frac{P_{ult(FEM)}}{P_{ult(test)}}$
Castellated	*Theoretical:* 75.62	*Theoretical:* 68.95	73.84	**1:** 70.00	**1:** 77.90	**1:** 87.40	**1:** 1.129	**1:** 1.184
				2: 70.00	**2:** 84.00	**2:** 91.04	**2:** 1.218	**2:** 1.233
Cellular	185.5	219.24	255.86	**1:** 195.5	**1:** 265.5	**1:** 315.0	**1:** 1.211	**1:** 1.231
				2: 193.2	**2:** 252.0	**2:** 330.0	**2:** 1.149	**2:** 1.289

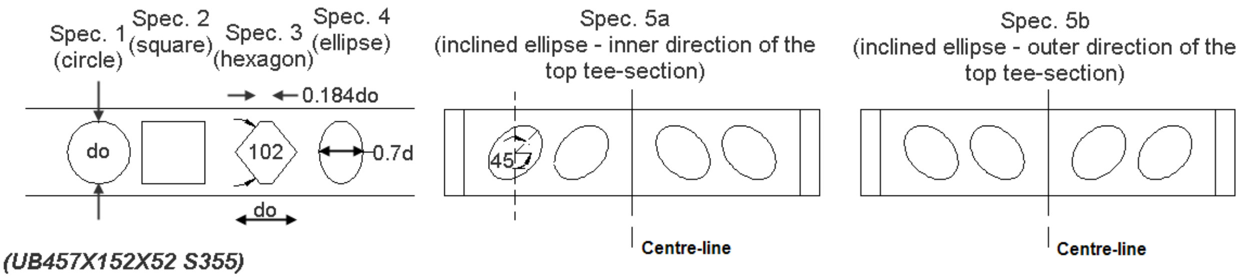
1: Eigen-mode is used to initiate buckling
2: Trigger load is applied to initiate buckling

The results show higher loads from the FE analysis. This overestimation of the FE model is due to the limited number of the nodes on each element (i.e. only four nodes), as well as the 'reduced integration points' function which is used to avoid numerical problems such as shear locking on shell elements.

3 PARAMETRIC FE STUDY

3.1 FE models

An eigen buckling analysis (based on the scaled frequency of mode 1) is used to predict the critical loads in the following parametric FE study. The main objective is to revise the existing design model for circular web openings for this complex failure mode and establish new models for other standard and non-standard web opening shapes [1,2,5]. The web opening diameter (i.e. depth) is the 70% of the beam's overall depth, whereas in the case of using inclined elliptical web openings (*Fig. 8*), the web opening depth is decreased to 60.4% of the beam depth. Various web opening spacing ratios are reported in this paper while the minimum web-post width is always kept to 63mm, which corresponds to a spacing of $1.2d_o$ for the standard circular web opening. In addition, three web thicknesses are examined giving d_o/t_w ratios which vary from 25.6 to 68.5.



(UB457X152X52 S355)
s=63mm, tmid-stiffener=10.9mm, Element type: SHELL181, Element size:15-20mm, Web/Flange/Stiffener: fy=355MPa, E=190GPa, v=0.3, Tang. Modulus=20<Pa (BKIN)

Fig. 8. Testing specimens and material properties

Table 2. Predicted strengths from the parametric FE study

	Web opening area (mm^2)	*S/d_o*	*$P_{cr(FEM)}$* (kN)						*$P_{ult(FEM)}$* (kN)		
			Onset of Buckling			*Buckling*			t_w (mm)		
			t_w (mm)			t_w (mm)					
			4.6	*7.6*	*10.6*	*4.6*	*7.6*	*10.6*	*4.6*	*7.6*	*10.6*
Specimen 1	76615.9	1.2	140	218	379	155	261	386	159	290	450
Specimen 2	99225	1.2	55	84	111	144	261	324	233	347	396
Specimen 3	58733.6	1.2	189	327	394	202	377	444	214	462	522
Specimen 4	54552	0.9	177	294	428	185	320	473	195	328	541
Specimen 5a	54552	1.23	164	318	497	196	347	517	289	367	531
Specimen 5b	54552	1.23	168	378	475	180	387	524	204	401	538

4 SUMMARY

FEA is a good solution choice when traditional buckling theory is difficult and there are no closed formed solutions. More importantly, all the factors affecting beam stability can be incorporated into a FE model and neither the effective length nor the uniform moment equivalent factor is needed. The contribution of FEA to prediction of the web-post buckling response has been clearly demonstrated by the eigen-value tracking method and perturbation by force imperfections transverse to the web. The FEA solutions were non-trivial, requiring non-linear geometric and material consideration. The FE models were correlated with benchmarked tests. Having adjusted the modelling technique to match the previously established benchmarks, solutions for new web opening shapes are generated. Further development of perforated steel beams can lead to economic design, using light members with high capacities. An established work is to be published by the authors where details of the FE techniques and a comprehensive parametric study, is carried out.

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