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FINITE ELEMENT ANALYSES OF HIGH STRENGTH COLD-FORMED SUPACEE® SECTIONS IN SHEAR

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***Abstract**. The paper will describe finite element analyses using the program ABAQUS of SupaCee® Sections in Shear. These high strength (450 MPa) C-profile steel sections contain additional return lips and web stiffeners which enhance the bending and shear capacity of the sections. They are used widely in Australia as purlins in roof and wall systems. The results of nonlinear analyses by the finite element method (FEM) depend heavily on the imperfections assumed for the analysis of the thin-walled members. Different buckling modes (Mode 1 Anti-Symmetric and Mode 2 Symmetric) are assumed with different magnitude levels of imperfection as proposed by Camotim in Portugal and Schafer in the USA. The paper summarises the results of the finite element nonlinear simulations of the shear tests on SupaCee® sections performed at the University of Sydney and described in a separate paper. The FEM results are compared with the tests to calibrate the imperfection magnitudes and modes against the tests. Conclusions regarding the size and type of imperfection are made in the paper.*

1 INTRODUCTION

Numerical simulation using the Finite Element Method (FEM) of thin-walled cold-formed steel sections undergoing buckling depends substantially on assumption regarding boundary condition, initial geometric imperfection, element mesh and type. For high strength sections in compression [1], accurate simulations have been achieved by using ABAQUS [2]. For sections in bending, Yu [3] provided complete details of the finite element models consisting of shell elements to investigate the influence of the test setup on the buckling modes of cold-formed steel members in bending and additional nonlinear analysis is also included. For sections in shear, and combined bending and shear, an accurate simulation [4] has been recently reported to calibrate against tests of an experimental investigation on normal C-section steel purlins performed at the University of Sydney [5]. As sections become more complex with additional multiple longitudinal web stiffeners and return lips as designed on SupaCee® sections [6], the computation of the effective widths becomes more complex. In order to further understand the behavior high strength cold-formed channel sections in shear, another experimental program has been recently performed at the University of Sydney for SupaCee® sections. The tests, which are described as predominantly shear test series (*V*-series) in this paper, consist of two different commercially available depths and three different thicknesses of SupaCee® sections.

This paper presents the modeling and analysis of the experimental specimens of *V* test series by using the Finite Element Method (FEM) program ABAQUS. The effect of initial geometric imperfection has been investigated. Experimental data from [7] was utilized to evaluate the performance of the FE model. The accurate results of the numerical simulation show that the finite element analysis can be utilized to predict the ultimate loads which include the post-buckling behavior of cold-formed purlin in shear.

2 FINITE-ELEMENT SIMULATION

2.1 General

A detailed FE model has been developed to study the structural behavior of high strength cold-formed SupaCee® sections in shear. In order to obtain realistic models, for the finite element non-linear analysis, plastic strains are included. Tensile coupons were tested to determine the stress-strain curves and the plastic strain data of the sections tested by Pham and Hancock [7].

The commercially available software package ABAQUS/Standard [2] version 6.8-2 was used to develop the FE models. The simulation consists of two steps. In the first step, an elastic buckling analysis, called a Linear Perturbation analysis, was performed on a perfect purlin to obtain its buckling modes (eigenmodes). This shows the possible buckling modes of the structure. The second step was a non-linear analysis using the modified Riks method. Material plasticity strains and geometric imperfection based on the eigenmodes are included in the analysis to obtain the ultimate failure loads and failure modes of purlins in shear. Although, the channel section members were symmetrically tested in pairs with flanges facing inwards and with a gap between them to ensure inside assembly was possible, only one channel beam was modeled in order to save computational time.

2.2 Material Properties

In the non-linear analysis, ABAQUS requires the input of the material stress-strain curves in the form of true stress σ_{true} versus true plastic strain ε_t. The true stress (σ_{true}) and true plastic strain (ε_{true}) were converted from the engineering stresses (σ) and engineering strains (ε) as follows:

$$\sigma_{true} = \sigma(1+\varepsilon) \tag{1}$$

$$\varepsilon_{true} = \ln(1+\varepsilon) - \frac{\sigma_{true}}{E} \tag{2}$$

where E is the Young's modulus, σ and ε are engineering stress and strain respectively [2]. The measured stress and strain curves were based on tensile coupon tests conducted by Pham and Hancock [7] for each of the section sizes tested. The yield stress f_y was obtained by using the 0.2 % nominal proof stress.

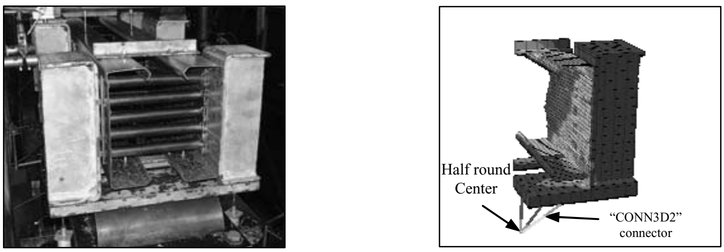
2.3 Test Rig Configuration and Specimen Boundary Conditions

The experimental program comprised a total of twelve tests conducted in the J. W. Roderick Laboratory for Materials and Structures at the University of Sydney. The basic design of the test rig was developed by LaBoube and Yu [8]. All tests were performed in the 2000 kN capacity DARTEC testing machine, using a servo-controlled hydraulic ram. Two different commercially available SupaCee® sections of 150 mm and 200 mm depths were chosen with three different thicknesses of 1.2 mm, 1.5 mm and 2.4 mm. A photo of the test set-up is shown in Fig. 1 for the *V*-series with the ratio of span to depth of 1:1. The channel section members were tested in pairs with flanges facing inwards and with a gap between them to ensure inside assembly was possible.

At the supports, the test two beam specimens were bolted through the webs by vertical rows of M12 high tensile bolts. These rows of bolts were connected to two channel sections 250x90x6CC with stiffeners. Steel plates of 20 mm thickness were used as load transfer plates which were also bolted through the flanges of the channel sections 250x90x6CC with stiffeners. These load bearing plates rested on the half rounds of the DARTEC supports to simulate a set of simple supports as shown in Fig. 2(a).

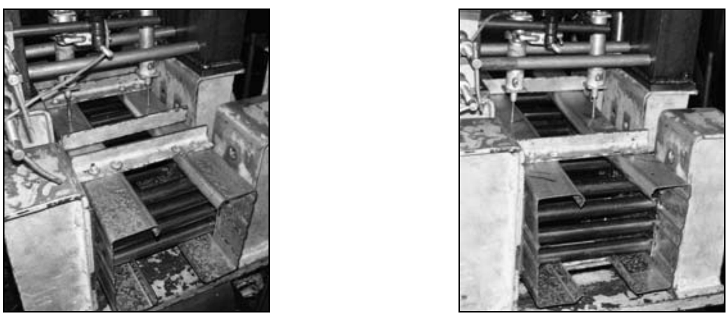
At the loading point at mid-span, the DARTEC loading ram has a spherical head to ensure that the load is applied uniformly on the bearing plate. The load was transferred to two channel sections 250x90x6CC with stiffeners which were connected to the test beam specimens by two vertical rows of M12 high tensile bolts. For the 150 mm section, four bolts were used at each support and eight at the load point, and for the 200 mm deep section, five and ten bolts were used respectively.

Figure 1. *V* - Series Configuration (Dimensions for 150 mm Deep Section)



(a) Test (b) FE Model

Figure 2. Specimen and ABAQUS Boundary Conditions (Dimensions for 200 mm Deep Section)



(a) With Straps (b) Without Straps

Figure 3. *V* - Series Configuration with and without Straps adjacent Loading Point

For the predominantly shear *(V)* test series, six of the twelve tests had four 25x25x5EA straps connected by self-tapping screws on each of the top and bottom flanges adjacent to the loading point and reactions as shown in Fig. 3(a). Six remaining tests were tested without the two 25x25x5EA straps adjacent to the loading points on the top flange as shown in Fig. 3(b). The purpose of these two straps is to prevent distortion of the top flanges under compression caused by bending moment. The distortion may be a consequence of unbalanced shear flow or distortional buckling.

This test rig is modelled explicitly by using 3D deformable solid members which were made using normal steel properties. All M12 high tensile bolts of 830 MPa for Grade 8.8 were pretensioned up to 90 kNm torque to prevent slip under initial loading. In order to model these contacts, the "tie" constraints were used to model contacts between the specimens and rigs where the the channels were the slave surfaces and the rigs were the master surfaces.

At the supports, the simply supported boundary conditions of the loading bearing plates resting on the half rounds of DARTEC supports were simulated in ABAQUS model as shown in Fig. 2(b). "CONN3D2" connector elements were used to connect the bearing plates to the centre of the half round. Both ends of connector elements are hinges and the length of the shortest connector member is the radius of half round. At the loading point at mid-span, in the ABAQUS model, loads were directly applied at the bolt positions to simulate the load transfering from the loading ram to the channel section via the 250x90x6CC channel sections.

2.4 Initial Geometrical Imperfection

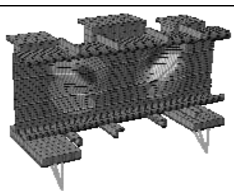
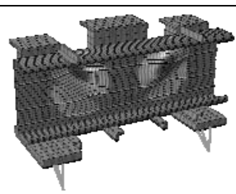
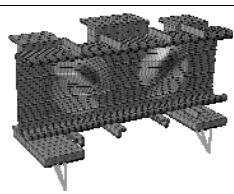
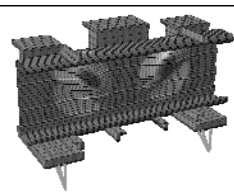
In the non-linear analysis, imperfections are usually introduced by perturbations in the geometry. Initial geometrical imperfections are added onto the "perfect" model to create out-of-plane deformations of the plate elements. In the ABAQUS model, there are three methods to define the geometric imperfections. Firstly, the geometric imperfections can be defined by the linear superposition of buckling eigenmodes. Secondly, specifying the node number and imperfection values directly on the data lines gives a method of direct entry. The final method is defined by the displacements from an initial *STATIC analysis, which may consist of the application of a "dead" load.

In this paper, the first method employing the linear superposition of buckling modes is used. An initial analysis is carried out on a perfect mesh using the elastic buckling analysis to generate the possible buckling modes and nodal displacements of these modes. The imperfections are introduced to the perfect mesh by means of linearly superimposing the elastic buckling modes onto the mesh. The lowest buckling modes are usually the critical modes and these are, therefore, used to generate the imperfections. The coordinates of the eigenmodes obtained from this analysis are by default stored in a file with extension *.fil and can subsequently be used as input for the *IMPERFECTION command in the actual simulation with different scaling factors with respect to the thickness of the channel. The imperfection magnitudes were based on two scaling factors of 0.15t and 0.64t with both positive and negative signs where t is the thickness of channel section. These two factors were proposed by Camotim and Silvestre [9] and Schafer and Pekoz [10] respectively.

2.5 Eigenvalue Buckling Analysis Prediction and Post-buckling Analysis

Eigenvalue buckling analysis is generally used to estimate the critical buckling loads of a stiff structure. ABAQUS uses the subspace iteration eigensolver when the *BUCKLE analysis is carried out. Eigenvalues, also known as load multipliers, are extracted in this analysis and the lowest values are important. The buckling mode shapes are the most useful outcome in the eigenvalue analysis, since they predict the likely failure mode of the structure.In the analysis in this paper, two buckling mode shapes were chosen. The first mode is normally an antisymmetric buckling shape whereas the second is normally symmetric. Buckling modes with both positive and negative signs are also considered in this paper. Tables 1 shows the buckling modes shapes of: *V*-predominantly shear test series. Modes 1 are generally anti-symmetric about the centerline of the member, and Modes 2 are generally symmetric.

Table 1. Buckling Modes of *V* –Shear Test Series

Mode 1		**Mode 2**	
With Straps	**Without Straps**	**With Straps**	**Without Straps**
			

A structure which has material and geometrically nonlinearity or unstable postbuckling response requires a load-displacement analysis to be performed. This analysis is known as the “Modified Riks Method” and generally used to predict unstable, geometrically nonlinear collapse of a structure. The Riks method uses the load magnitude as an additional unknown; it solves simultaneously for loads and displacements. ABAQUS uses the “arc length” along the static equilibrium path in load-displacement space to measure the progress of solution. This method provides solutions regardless of whether the response is stable or unstable. Riks [11, 12] proposed an incremental approach to deal with the buckling and snapping problems. The Riks method works well in snap-through problems in which the equilibrium path in load-displacement space is smooth and does not branch. The Riks method can also be used to solve post-buckling problems both with stable and unstable post-buckling behaviour. However, the exact post-buckling problem cannot be analysed directly due to the discontinuous response at the point of buckling. To analyse this problem, the model has to have a continuous response instead of bifurcation. This effect can be accomplished by adding initial imperfections to create a perturbed mesh. There is therefore some response in the buckling mode before the critical load is reached. Herein, the *STATIC, RIKS procedure was used to perform the collapse or post-buckling analysis.

2.5 Element Mesh

The element sizes were 8 mm. The 4-node shell element with reduced integration, type S4R, was selected from the ABAQUS element library. This element uses three translation and three rotational degrees of freedom at each node. The element accounts for finite membrane strains and arbitrarily large rotations. Therefore, it is suitable for large-strain analyses and geometrically nonlinear problems. The other elements with five degrees of freedom such as S4R5 can be more computationally economical. However, they cannot be used in finite-strain applications. According to the Simpson rule, reduced integration was carried out by using five integration points through the shell thickness. Since S4R is a linear element, the hourglass control settings needed to be activated.

3 COMPARISONS OF TEST LOADS WITH FINITE-ELEMENT MODELING

The results of the test and ABAQUS ultimate loads are given and reproduced in Table 2 for the *V* – shear test series. As can be seen in Fig. 4, the test loads with straps are comparable with ABAQUS results over both geometric imperfections of amplitude 0.15t and 0.64t. The differences in the results between ABAQUS and the tests are less than approximately 10%. In the case of the symmetric Mode 2 with magnitude 0.15t and -0.64t, the ABAQUS results are in the best agreement with the test results.

Table 2. *V* – Shear Test Series and ABAQUS Results

Section	Test (P_T)	P_T/ABAQUS Load								
			Mode 1	Mode 1	Mode 1	Mode 1	Mode 2	Mode 2	Mode 2	Mode 2
V-Series	**(kN)**	**Imp=0**	**0.15t**	**0.64t**	**-0.15t**	**-0.64t**	**0.15t**	**0.64t**	**-0.15t**	**-0.64t**
SC15012	168.539	0.908	0.920	0.938	0.919	0.938	0.925	0.943	0.892	0.941
SC15012w	157.307	0.928	0.963	1.000	0.968	1.061	0.941	0.958	0.961	1.012
SC15015	222.317	0.966	0.985	1.017	0.980	1.018	1.006	1.032	0.943	1.008
SC15015w	207.484	0.973	1.001	1.075	0.999	1.054	1.054	1.024	1.017	1.069
SC15024	354.291	0.890	0.897	0.975	0.897	0.940	0.903	0.951	0.907	0.947
SC15024w	355.512	0.968	0.974	1.008	0.976	1.008	0.962	0.962	0.980	1.026
SC20012	185.936	0.946	0.950	0.956	0.945	0.958	0.947	0.942	0.952	0.962
SC20012w	182.212	1.011	1.042	1.056	1.041	1.064	0.964	0.973	1.057	1.074
SC20015	248.260	0.980	0.989	0.993	0.987	0.996	0.984	0.987	0.979	0.980
SC20015w	246.612	1.017	1.061	1.082	1.069	1.084	1.016	1.018	1.057	1.085
SC20024	496.826	1.039	1.068	1.101	1.068	1.101	1.058	1.093	1.013	1.053
SC20024w	469.235	1.037	1.076	1.117	1.069	1.142	1.045	1.081	1.068	1.126

Fig. 5 shows similar comparisons to Fig. 4 except that it applies to the tests without the straps. The results are generally less accurate and more variable than the tests with the straps especially with imperfection magnitude of 0.64t. It appears that the imperfection of the top flange adjacent to the loading points obtained by buckling analysis causes the reduction of the ABAQUS results especially with a large imperfection magnitude of 0.64t. As can be seen in Fig. 5, the ABAQUS results with antisymmetric Mode 1 and imperfection magnitude of 0.15t give the best predictions on average in comparison with the tests.

The load-vertical displacement curve for the *V* – shear test series with straps of the SC20015 sections and ABAQUS results are illustrated in Figs. 6. When the load increases up to about 120 kN, the load increases linearly and matches with that of the ABAQUS model. The explanation is due to the contacts between the channel members and the test rig. In the test, two beam specimens were bolted through the webs by vertical rows of M12 high tensile bolts. Further displacement when the load exceeds 120 kN is due to the slip between the beam specimens and the test rig.

After the peak load in the ABAQUS model, the curves with Mode 1 imperfection where the buckling mode is antisymmetric drop more sharply than those with Mode 2 symmetric imperfection. It can be explained by the stress redistribution at only one span of the *V* – shear test which causes failure mode in 1 span only. Fig. 8(a) shows the corresponding failure mode shapes of *V* – shear test with straps of the SC20015 section for the test and ABAQUS model. The failure modes are identical and symmetrical for both test and ABAQUS. As can also be seen in Fig. 6, soon after the peak load, the load-vertical displacement curves of the test are of the same shape as the ABAQUS curves with Mode 2 symmetric imperfection.

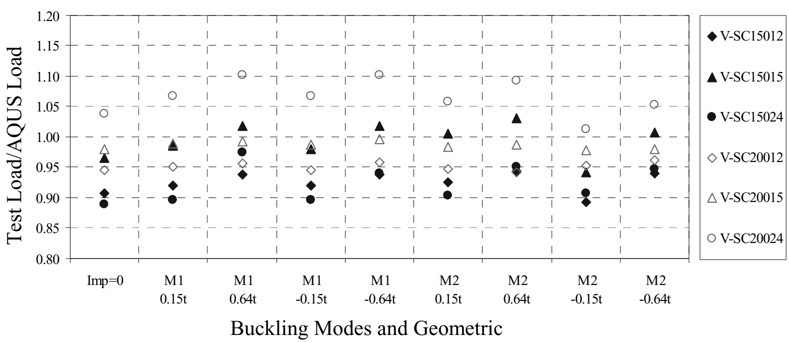


Figure 4. Comparison of Test and ABAQUS Loads – V Series – With Straps

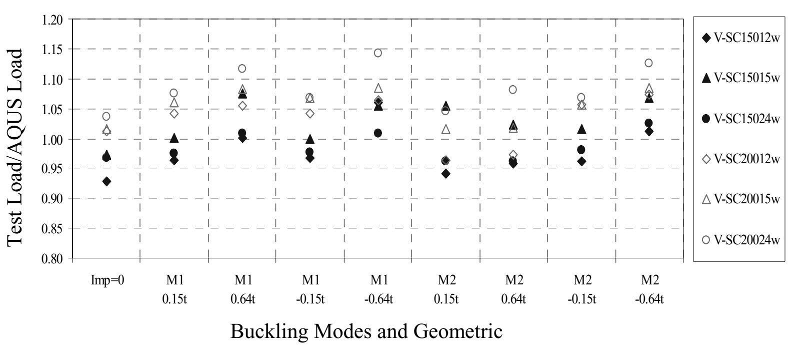


Figure 5. Comparison of Test and ABAQUS Loads – V Series – Without Straps

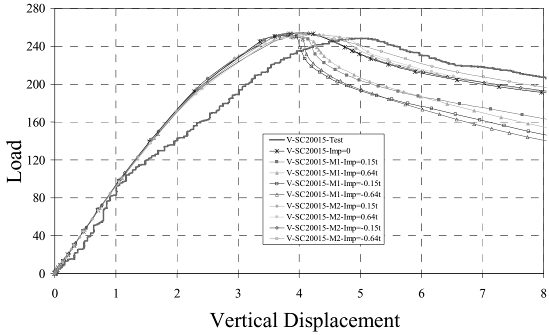


Figure 6. Load and Vertical Displacement Relations of V-SC20015 – With Straps

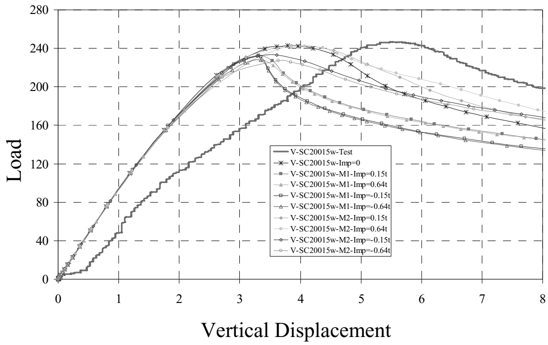
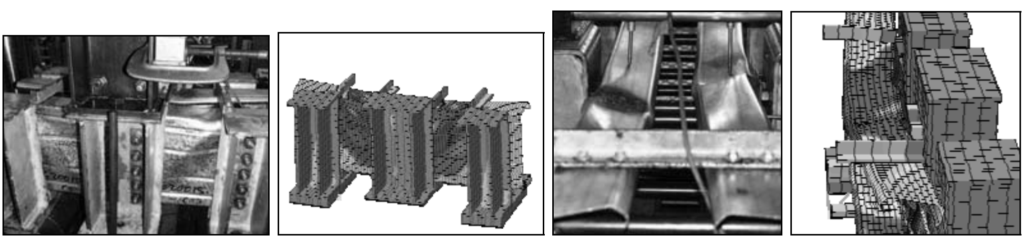


Figure 7. Load and Vertical Displacement Relations of V-SC20015w – Without Straps

Fig. 7 shows the load-vertical displacement curves for the V – shear test series without the straps for the SC20015 section and the ABAQUS results. For the test, there are additional deflections up to about 5 kN compared with ABAQUS. The reason is due to the test assembly. The two load transfer plates did not rest evenly on the half rounds because of slight twist after assembly. The load is then fairly matched with ABAQUS up to 100 kN. After this point up to peak load, the bolts start to slip and lead to the further increase in the displacements of test in comparison with that of ABAQUS. The explanation is the same as above due to slip and local bearing failure. As can be seen in Fig. 8(b) which shows the corresponding failure mode shapes of the V – shear test without the straps of the SC20015w section for the test and ABAQUS model, the failure mode is Mode 1 antisymmetric imperfection. The load-vertical displacement curve of the test after peak load is similar to the ABAQUS model with Mode 1 anti symmetric buckling mode.



(a) With Straps (b) Without Straps

Figure 8. Mode Shapes of Test and ABAQUS Model of V-SC20015-With Straps

3 CONCLUSION

A series of ABAQUS simulations was carried out on high strength C-section cold-formed steel purlins. The simulations are compared with and calibrated against predominantly shear *(V)* test series on high strength cold-formed C-section purlins. The FE study was conducted for different effects of initial geometric imperfection. Two scaling factors of 0.15t and 0.64t with both positive and negative signs where t is the thickness of channel section were used for initial geometric imperfection input. The use of the FE program ABAQUS for simulating the behavior of high strength C-section cold-formed purlins is successful since the ABAQUS results were generally in good agreement with experimental values. FE results show that the effect of initial geometric imperfection is not significantly sensitive for *V*-predominantly shear. ABAQUS can therefore be used for further investigation to design and optimize thin-walled sections of high strength steel.

REFERENCES

[1] Yang, D., and Hancock, G. J., "Numerical Simulation of High-Strength Steel Box-Shaped Columns Failing in Local and Overall Buckling Modes." *Journal of Structural Engineering*, American Society of Civil Engineers, Vol. 132, Issue 4, 541-549, 2006.

[2] *ABAQUS/Standard Version 6.8-2; Abaqus/CAE User's Manual*, Dassault Systèmes Simulia Corp., Providence, RI, USA, 2008.

[3] Yu, C., "Distortional Buckling of Cold-Formed Steel Members in Bending." *Ph.D. Dissertation*, Johns Hopkins Univ., Baltimore, 2005.

[4] Pham, C. H., and Hancock, G. J., "Numerical Simulation of High-Strength Cold-Formed Purlins in Combined Bending and Shear", *Research Report No R904*, School of Civil Engineering, The University of Sydney, NSW, Australia, October, 2009.

[5] Pham, C. H., and Hancock, G. J., "Experimental Investigation of High Strength Cold-Formed C-Section in Combined Bending and Shear", *Research Report No R894*, School of Civil Engineering, The University of Sydney, NSW, Australia, April, 2009.

[6] Lysaght., "NSW SupaCee® is trademark of Bluescope Steel Limited." *Bluescope Steel Limited trading as Bluescope Lysaght*, 2003.

[7] Pham, C. H., and Hancock, G. J., "Experimental Investigation of High Strength Cold-Formed SupaCee® Sections in Combined Bending and Shear", *Research Report No R907*, School of Civil Engineering, The University of Sydney, NSW, Australia, December, 2009.

[8] LaBoube, R. A., and Yu, W. W., "Cold-Formed Steel Web Elements under Combined Bending and Shear." *Proc., 4th Int. Specialty Conf. on Cold-Formed Steel Structures*, University of Missouri-Rolla, St Louis, Missouri, U.S.A, 1978.

[9] Camotim, D. and Silvestre, N., "GBT-based Analysis of The Distortional Postbuckling Behaviour of Cold-formed Steel Z-section Columns and Beams." *Proc., 4th Int. Conf. on Thin-Walled Structures*, Loughborough, 243-250, 2004.

[10] Schafer, B. W. and Peköz, T., "Computational modeling of cold-formed steel: characterizing geometric imperfections and residual stresses." *Journal of Constructional Steel Research*, Vol 47, 193-210, 1998.

[11] Riks, E., "The Application of Newton's Method to The Problem of Elastic Stability." *Journal of Applied Mechanics*, Vol 39, 1060-1066, 1972.

[12] Riks, E., "An Incremental approach to The Solution of Snapping and Buckling Problems." *International Journal of Solids Structures*, Vol 15, 529-551, 1979.