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Experimental investigation on the structural behavior of cold formed lean duplex stainless steel hollow oval section columns

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ABSTRACT

This paper deals with the investigation on behavior of Cold-formed stainless steel oval hollow columns subjected to axial compression. The finite element analysis software ABAQUS has been used to create the numerical model for the hollow oval columns. The accuracy of the numerical model has been verified against the Experimental results reported in the Literature. The failure modes of material yielding, local buckling and flexural buckling as well as interaction of local and flexural buckling were found in this study. The Parametric study was carried out by varying the cross sectional dimensions and overall member slenderness ratio. Sectional properties and local buckling load factor were obtained from CUFSM software by performing elastic buckling analysis. The overall slenderness ratio of the columns is varied from 0.25 to 2.25 with different cross section geometries. Totally 120 analysis were done in the parametric study. The ends of the columns are considered as Fixed-Fixed. Theoretical Analysis was conducted by using Direct Strength Method (DSM), American Specification (ASCE-8-02), and Australian/New Zealand and European specifications for cold-formed steel structures and compared with the Numerical results. Based on the comparison, the structural response and strength of hollow oval columns are discussed.

Keywords: Cold-formed steel; Direct Strength Method; Hollow oval column; Buckling.

INTRODUCTION

Since the industrial revolution, carbon steels dominated the construction industry for various advantages such as low cost, long experience, well developed design rules etc. An improvement over carbon steels came with the introduction of stainless steels. Stainless steel offers several advantages that include high corrosion resistance, high strength, smooth and uniform surface, aesthetic appearance, high ductility, impact resistance and ease of maintenance. Among stainless steels, austenitic steel grades are used visibly, however, with ever increasing nickel prices (nickel content is of 8% to 11% in austenitic stainless steel) there is an apparent jump in the demand for lean duplex stainless steel (LDSS) such as grade EN1.4162, with low nickel content of 1.5% and twice the mechanical strength of austenitic and ferrite stainless steel. The higher strength of EN1.4162 enables reduction of member section sizes leading to higher strength to weight ratio. The objective of this project is to study the structural performance of cold-formed lean duplex stainless steel oval hollow columns. A total number of 120 columns were analyzed and numerical results obtained from the parametric study in this project and the available numerical data, were compared with the ASCE-8-02[3], Australian/New Zealand Standard [2], EN-3 [8] as

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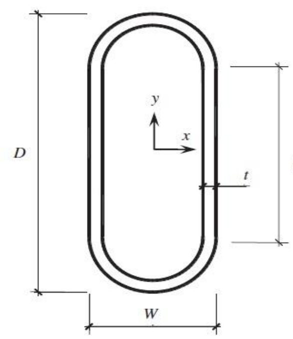
well as the Direct Strength Method (DSM)[1]. Besides, it has the advantage of different major and minor axes properties. Gardner and Ministro [10] reported some applications of oval hollow sections in structural engineering projects.

SELECTION OF SECTIONS

Design of Section

The section dimensions were selected based on AS/NZ Specification for the design of cold-formed steel structural member. The typical geometry of selected section for this study is shown in Figure 1.1.



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D - Overall depth, W-Width of column, t - Thickness of column

Figure 1.1– Geometric Dimensions

Labeling of specimen

The labeling of the specimens is done in such a way to self-describe about the specimen. The Labeling is illustrated in Fig. 1.2.

For example specimen 150x75x1.5 – 0.25

150X75X1.5 - 0.25

Column dimension Slenderness ratio

Figure 1.2 Labeling of Specimen

150x75x1.5- The First terms indicates the overall depth of column, second term indicates the width of column and third term indicates the thickness of the column 0.25 - The term indicates the slenderness ratio as 0.25, Totally 24 sections were selected for the study.

250x125x1.5	150x75x1.5
250x125x2.5	150x75x2.5
250x125x4.0	150x75x4.0
250x83.33x1.5	150x50x1.5

250x83.33x2.5	150x50x2.5
250x83.33x4.0	150x50x4.0
250x62.5x1.5	150x37.5x1.5
250x62.5x2.5	150x37.5x2.5
250x62.5x4.0	150x37.5x4.0
250x50x1.5	150x30x1.5
250x50x2.5	150x30x2.5
250x50x4.0	150x30x4.0

Finite strip method-CUFSM

Engineers must consider buckling of the thin walls of the cross-section in addition to global (e.g., flexural or lateral torsional) buckling of the member. Classical hand solutions to these instabilities become unduly cumbersome for more complex buckling modes, such as distortional buckling; and may ignore critical mechanical features, such as inter element equilibrium and compatibility.

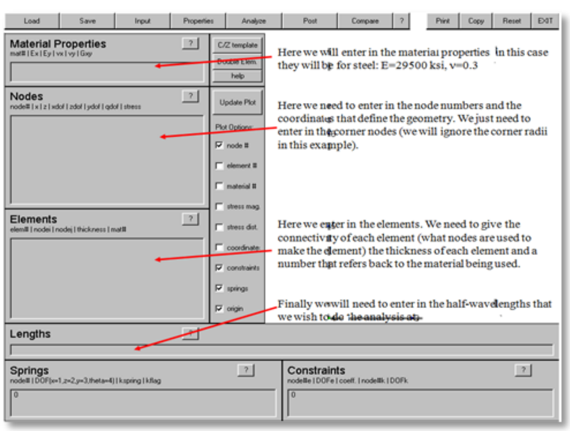
To remedy this, the engineer may turn to numerical solutions such as the finite strip method (FSM). Conventional FSM provides a means to examine all the possible instabilities in a cold-formed steel member under longitudinal stresses (axial, bending, or combinations).

CUFSM is Free, open source, software that allows you to explore the elastic buckling of any cold-formed steel cross-section using the finite strip analysis.

CUFSM properties

CUFSM is freely available Software for exploring elastic buckling behaviour developed by Schafer.

- CUFSM calculates the buckling stress and buckling mode of arbitrarily shaped, simply supported, thin-walled members.
- Using this software we can easily predict where the Local, Distortional buckling and Global buckling occurs. The corresponding load factors are predicted with help of that curve. This load factors are incorporated in design procedure.
- It also used to calculate cross-section properties Area, Moment of Inertia Warping Constant, Shear Centre, Venant's Constant, and Centre of gravity.



The Figure 3.3 shows the input parameter window for CUFSM software.

Figure 1. 3 The input parameter window for CUFSM software

The Figure 1.4 shows the parameter input window of CUFSM in which material properties, nodes, elements, constraints, boundary conditions for a section, whose section properties and buckling behavior has to be determined, are given as input

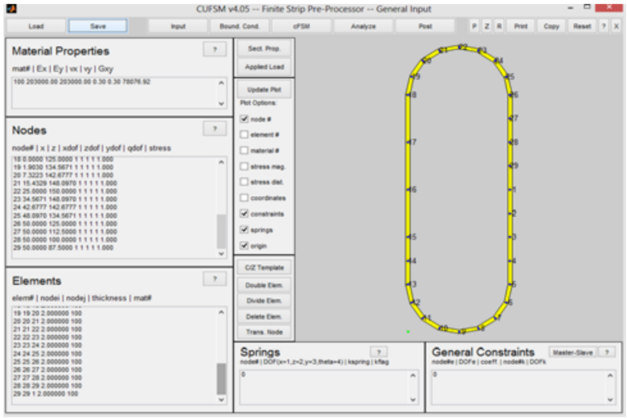


Figure 1.4 Cross section of member for given input

Figure 1.5 shows the properties of cross section such as area, moment of inertia, centre of gravity, shear centre, warping constant, torsional, etc.,

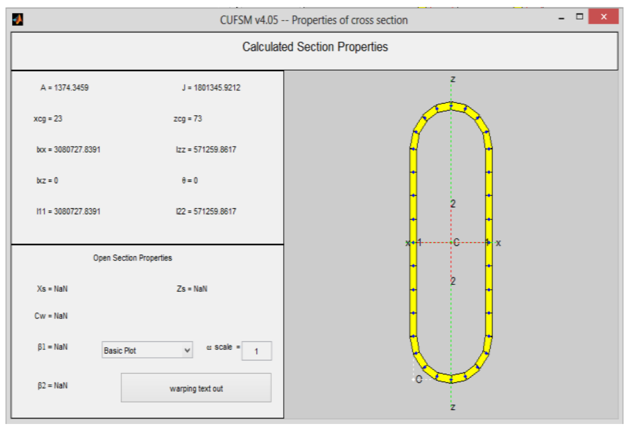


Figure 1.5 Section properties window

Fig 3.6 and 3.7 shows the buckling plot for the specimen 150x50x4 series for local and flexural buckling modes. From this the buckling mode shapes and corresponding load factor value can be obtained. This load factor is incorporated in the design standards for computing the Local and flexural buckling strength.

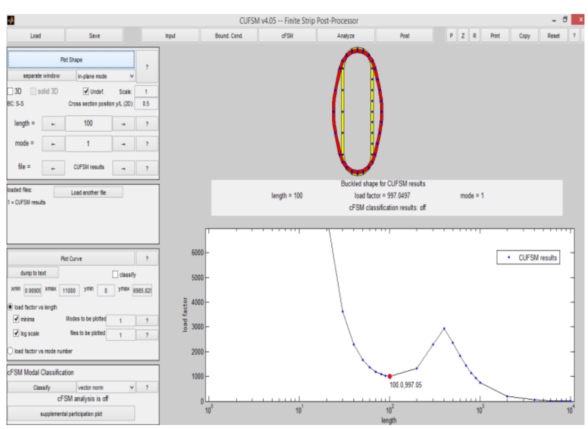


Figure 1.6 Buckling plot for 150x50x4

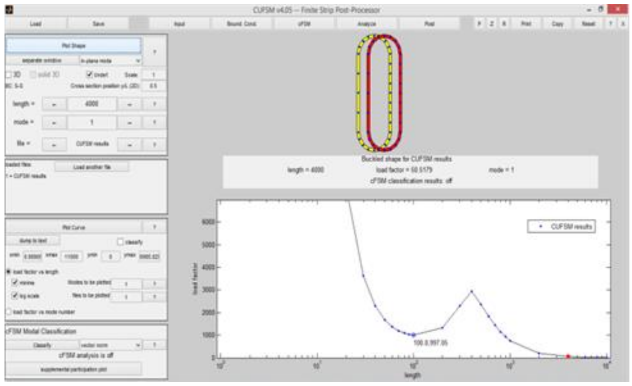


Figure 1.7 Buckling plot for 150x50x4

Numerical analysis

Validation of results

Fine element method (ABAQUS) procedure is validated through the literature "Cold-Formed-Steel Oval Hollow Sections under Axial Compression" reported by Zhu JH and Young B [17]. The Table 2.1 shows the geometric details of the section.

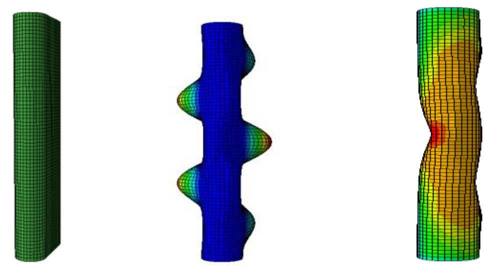
Table 2.1 Geometric Details of the Section

Specimen	Length L (mm)	Depth D (mm)	Width W (mm)	Thickness t (mm)
A360	361.2	120.4	47.7	1.94
A360#	359.7	120.3	47.8	1.99
A600	597.4	120.4	47.8	1.96
A1200	1199	120.3	48	1.95
A1200#	1197.5	120.3	47.7	1.93
A1800	1799.5	120.4	47.9	1.95
A2400	2400.1	120.2	48.3	1.94
A3000	3001.2	120.2	48.2	1.94

The specimen is modeled, meshed and linear and non-linear analysis was carried out in ABAQUS is shown in Figure 2.1. The properties of the material used for validation is shown in Table 2.2

Table 2.2 Material Properties

Coupon	E (Gpa)	$\sigma_{0.2}$ (MPa)	σ_u (MPa)
A (flat)	201.9	358.6	402.8
A(curved)	206.4	379.2	415.4



a) Meshed **b) Linear Analysis** **c) Non-Linear Analysis**

Figure. 2.1 –Finite Element Model

Comparison of Test Load with FEA Load

The comparison between the ultimate load of the tested specimens, and those computed by the finite element analysis are presented in Table 2.3 and showed a reasonable agreement between the finite element results and test results. FEM procedure has been validated.

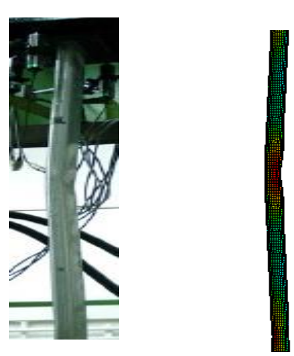
Table 2.3 Comparison of Load from FEA and Test

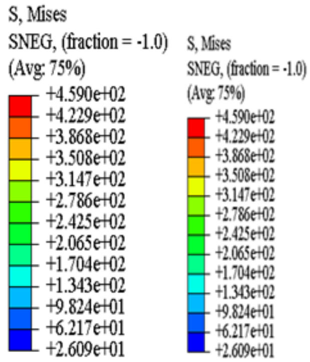
SPECIMEN	P_{TEST}	P_{FEA}	P_{TEST}/P_{FEA}
A360	181.2	182.3	0.99
A360#	185.9	183	1.15
A600	196	194.87	1.005
A1200	190.3	187.27	1.01
A1200#	188.5	190.16	0.99
A1800	183.9	182.5	1.007
A2400	173.1	171.8	1.007
A3000	157.7	159.1	0.99
MEAN			1.017
Std. Dev.			0.054

The mean and standard deviation of the Test to FEA ultimate loads for are 1.017 and 0.054 respectively.

Comparison of Failure Modes and Results

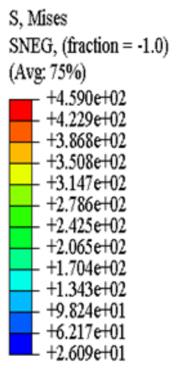
Figure 2.2 (a) are presented the characteristic failure modes for experimentally tested and numerically simulated specimens. The comparison of the experimental and finite element analysis failure mode of specimen A360 is chosen in Figure 2.2 (b). It is observed that reasonable agreement has been achieved between both results





a) Experimental failure b)Abaqus Failure c)Value of stress mode

Figure. 2.2 – Comparison of Failure Modes



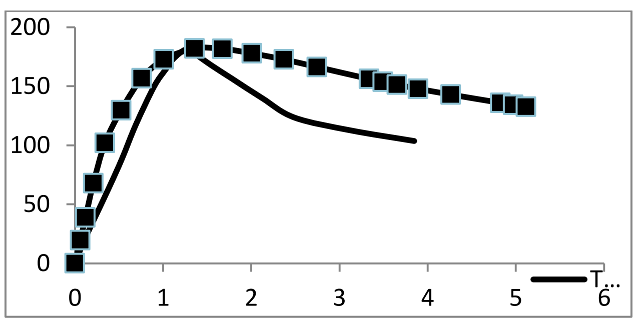


Figure 2.3 Load Vs Axial shortening curve for A360

The variation of load with axial displacement of the oval hollow column is presented in Figure 2.3. It can be seen from Figure 2.3 shows that Gardner-Ashraf closer to ultimate load and axial displacement at peak load. Hence for all the subsequent parametric analysis the material model proposed by Gardner-Ashraf is used.

Theoritical analysis

General

Many design codes and manual are available for the design of cold formed stainless steel such as European (EN1993-1-4) Code[8], American Society for Civil Engineers (ASCE-8-02) Standard[3], Australian/New Zealand Standard (AS/NZS4673)[2], Direct Strength Method (DSM)[1] (here after referred to as 'codal'), but none have design provisions for structural columns with flat oval sections. However, it may be worth mentioning that ASCE-8-02 provides design guidance i.e. consideration of effective areas, for elemental local buckling interaction of curve and flat panels. The calculations of effective width/length (and hence effective area) are necessary for slender flat plates. ASCE 8-02 and AS/NZS 4673 specifications are similar, with flat plate buckling coefficient k taken as 4. Zhu and Young considered semicircular curve portion of the section to be fully effective (i.e. gross area of the semicircular curved section is considered for load calculation) as the local buckling resistance of portions is relatively higher than that of the flat plates; whilst only effective area has been considered for the flat portions as per the provisions of the code. Similar assumptions are made for the present study. The calculations as per DSM, ASCE8-02, AS/NZS4673 and EN1993-1-4 are briefly described below:

Direct strength method (DSM)

The direct strength method (DSM) was proposed by Schafer and Pekoz for the design of cold formed steel members undergoing local, global and distortional buckling. DSM does not rely on effective width but it requires the estimation of elastic buckling load in local, global and distortional buckling modes. The elastic buckling load can be determined by using existing numerical or FEM (finite element method).

The design procedure of DSM has been given in details in Appendix1 of NAS. In DSM, the slenderness ratio of the full cross-section is employed instead of the most slender constituent elements .The column design equations of DSM for cold formed steel are shown in Eqs. (3.1) – (3.3). The nominal axial strength, PDSM is given by Eq. (3.1).

$$P_{DSM} = \min(P_{ne}, P_{nl}) \quad (3.1)$$

Where

$$P_{ne} = \begin{cases} (0.658\lambda_c^2)P_y \ for\ \lambda_c \leq 1.5, \\ \left(\frac{0.877}{\lambda_c^2}\right)P_y \ for\ \lambda_c \leq 1.5\,. \end{cases} \quad (3.2)$$

$$P_{nl} = \begin{cases} P_{ne} & for\ \lambda_l \leq 0.776. \\ \left[1 - 0.15\left(\frac{P_{crl}}{P_{ne}}\right)^{0.4}\right]\left(\frac{P_{crl}}{P_{ne}}\right)^{0.4} P_{ne} & for\ \lambda_l > 0.776. \end{cases} \quad (3.3)$$

$$Where\ P_y = f_y A\,;\ \lambda_c = \sqrt{P_y/P_{crl}}\ ;\ \lambda_l = \sqrt{P_{ne}/P_{crl}}\,,$$

$$where\ P_{cre}(= \pi^2 EA\,/(l_e/r_y)^2.$$

Pcrl, ry, and Pnl are the critical elastic buckling load in flexural buckling, critical elastic local buckling load, and radius of gyration of gross cross-section about the minor axis of buckling, and nominal axial strength for local buckling as well as interaction of local and overall/global buckling respectively.

AS/NZ code recommendation

As per ASCE8-02 [15] and AS/NZS4673 [16], the member capacity is calculated based on the effective width given by Eqs. (3.4)–(3.6). The effective width (b_e) is dependent on the value of cross sectional slenderness ratio, λ.

$$FOR\ \lambda \leq 0.673, b_e = b \quad (3.4)$$

$$For\ \lambda > 0.673, b_e = \rho b \quad (3.5)$$

Where $\rho = \frac{\left(1 - \frac{0.22}{\lambda}\right)}{\lambda} \leq 1.0; \lambda = \left(\frac{1.052}{\sqrt{k}}\right)\left(\frac{b}{t}\right)\left(\sqrt{\frac{f}{E}}\right)$ where f = (σ_{cr}) is the critical stress for unstiffened compression element. The value of k is conservatively taken as 4.0. The member capacity is then computed.

$$P_{ASCE}\ or\ P_{AS/NZS} = f_y A_e; where A_e = b_e t \quad (3.6)$$

European code recommendation

The present study of flat oval cross-sections comprises of Class 2(c/tεr26.7), Class3(c/tεr30.7) andClass4(c/tε430.7) sections as per EN1993-1-4[8], depending on the value of cross-section slenderness (c/tε, where c is the flat element length, t is the plate thickness and $\varepsilon = \left(\frac{235\ E}{f_y\ 210000}\right)^{0.5}$, f_y is the material yield stress). For Class 2 and 3 sections, no deductions in material cross-sectional area are made (i.e. gross area (Ag) is considered to be wholly effective) in the calculation of axial compressive strength. For Class 4 section, effective area (Ae) of cross section is considered to take into account of the effect of local buckling.

As per EN1993-1-4, the effective width (be) for Class4 (i.e. for slender cross sections) plated structural element, is based on a reduction factor (ρ; ρ = b/be where l = flat element width) parameter given by Eq. (3.7),

$$\rho = \frac{0.772}{\bar{\lambda}_p} - \frac{0.125}{\bar{\lambda}_p^2}; where\ \bar{\lambda}_p = \frac{\frac{b}{t}}{28.4\varepsilon\sqrt{k}} \qquad (3.7)$$

The effective area for Class4 flat oval section is calculated using Eq. (3.8)

$$A_e = A_g - (b - 2b_e)t \qquad (3.8)$$

The cross-sectional resistance as per EN1993-1-4 is in Eq. (3.9)

$$P_{EN} = f_y A \qquad (3.9)$$

Where A may be Ag or Ae depending on class type of the section under consideration.

Parametric study

Introduction

A total of 120 FE models with column lengths varying from 0.165–6.28 m, which provided a range of cross-sectional slenderness values (λs ~ from 0.64 to 3.54), five overall slenderness values (λ_0 = 0.25, 0.75, 1.25, 1.75 and 2.25) for thicknesses of 1.5 mm, 2.5mm and 4.0 mm, were analysed in the FE parametric studies of oval hollow columns.

The overall slenderness λ_0 of a stainless steel column is commonly defined as:

$$\lambda_0 = \sqrt{\sigma_{0.2\%}/\sigma_E} = \left(\frac{L_e}{r}\right)\sqrt{\frac{\sigma_{0.2\%}}{\pi^2 E_0}} \qquad (4.1)$$

Where, $\sigma_{0.2\%}$ = 0.2% proof stress, L_e = Effective length of column, r = radius of gyration, E_0 = initial modulus. The cross-sectional slenderness λ_s is defined as:

$$\lambda_s = \sqrt{\sigma_{0.2\%}/\sigma_{cr}} \qquad (4.2)$$

Table 4.1 and Table 4.2 shows the section properties of the selected sections

Table 4.1 Section properties of selected specimens

SPECIMEN ID	λs	A(mm2)	σcr(MPa)
150X75X1.5	1.48	569.14	300.85
150X75X2.5	0.95	940.76	721.43
150X75X4	0.64	1486.49	1609.55
150X50X1.5	1.89	527.09	183.14
150X50X2.5	1.19	870.67	467.49
150X50X4	0.80	1374.35	1026.37
150X37.5X1.5	2.08	506.06	151.62
150X37.5X2.5	0.95	835.63	373.54
150X37.5X4	0.86	1317.27	895.16

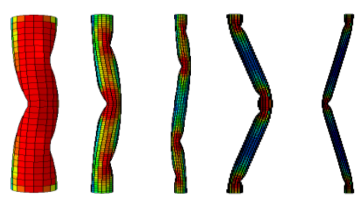
150X30X1.5	2.23	488.76	132.26
150X30X2.5	1.38	841.00	344.73
150X30X4	0.87	1284.63	371.54

Table 4.2 Section properties of selected specimens

SPECIMEN ID	λs	A(mm2)	σcr(MPa)
250x125x1.5	2.36	953.25	118.26
250x125x2.5	1.51	1580.94	289.08
250x125x4	1.01	2510.78	550.43
250x83.33x1.5	3.02	883.15	72.27
250x83.33x2.5	1.92	1461.12	177.39
250x83.33x4	1.25	2323.86	420.48
250x62.5x1.5	3.33	848.11	59.13
250x62.5x2.5	2.13	1405.72	144.54
250x62.5x4	1.40	2230.42	335.07
250x50x1.5	3.54	827.09	52.56
250x50x2.5	2.29	1370.67	124.83
250x50x4	1.46	2174.35	308.79

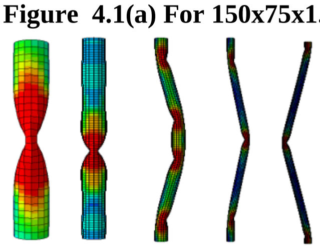
Final failure mode shapes and results

The Figure 4.1 and Figure 4.2 shows the deformation shape for the sections 150x75x1.5, 150x75x2.5, 150x75x4 and 150x50x1.5.



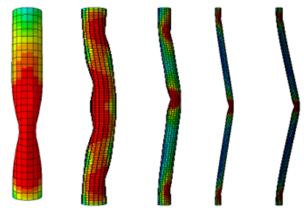
0.25 0.75 1.25 1.75 2.25

Figure 4.1(a) For 150x75x1.5



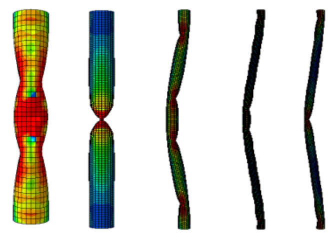
0.25 0.75 1.25 1.75 2.25

Figure 4.1 (b) For 150x75x1.5



0.25 0.75 1.25 1.75 2.25

Figure 4.1 (c) For 150x75x1.5



0.25 0.75 1.25 1.75 2.25

Figure 4.1 (d) For 150x75x1.5

RESULT AND DISCUSSION

The column strengths are compared with the unfactored design strengths determined by the ASCE-8-02 specification, DSM method, AS/NZ specification and EN 1993-1-4 specification. The design strengths predicted by the ASCE specifications are generally unconservative, with the load ratios P_{FEA}/P_{ASCE} of 0.94 and the corresponding standard deviation of 0.13. The design strengths predicted by the DSM,AS/NZ and EN specifications are generally conservative, with the load ratios P_{FEA}/P_{DSM}, $P_{FEA}/P_{AS/NZ}$ & P_{FEA}/P_{EN} of 1.04, 1.07, and 1.01, and the corresponding standard deviation of 0.13, 0.170, and 0.160 respectively. The AS/NZ specifications are generally overly conservative.

CONCLUSION

The fixed ended cold-formed lean duplex stainless steel oval hollow column has been investigated. A finite element model was developed and compared well with test results. The validated FE models were used for parametric study. The results of parametric study together with 120 available numerical data of lean duplex stainless steel oval hollow columns were compared with the design strengths calculated from Direct Strength Method (DSM), ASCE-8-02, AS/NZ and EN-3 code specifications for cold-formed steel structures. The design strengths predicted by the DSM method, AS/NZ and EN-3 code specifications were conservative and reliable. The design strength predicted by the ASCE-8-02 specification is unconservative and is not in the safer side. It is demonstrated that the column design rules in the DSM, AS/NZ and EN-3 code specifications for cold-formed stainless steel structures can be used for oval hollow sections. DSM is more conservative and reliable than AS/NZ and EN-3 code specifications.

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