EFFECT OF GEOMETRIC PARAMETERS ON TORSIONAL BEHAVIOUR OF LEAN DUPLEX STAINLESS STEEL SEMI-ELLIPTICAL HOLLOW SECTION MEMBERS

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This paper investigates the torsional effects on the structural behavior of Lean Duplex Stainless Steel (LDSS) semi-elliptical hollow section (SEHS) members, via numerical modeling using the commercial FE software Abaqus. The effects of cross section geometric parameters viz. curve length, aspect ratio, on torsional response of lean duplex stainless steel semi-elliptical section stub members, were assessed. The effect of curve length of section was examined by considering semi-elliptical sections of constant flat length and varying curve length. Sections with higher curve length were found to have comparatively higher torsional capacity. On the other hand, increasing curve length was observed to lead to earlier initiation of failure. A near linear increase in torsional capacity was seen with increase in curve length. To check the effect of aspect ratio, cross sectional aspect ratio was varied by keeping cross sectional area constant (thus ensuring same material consumption). Section having higher aspect ratio was observed to have higher torsional capacity. The rate of increase in torsional capacity with section aspect ratio was seen to be higher for stocky cross sections as compared to slender ones.

Keywords: Torsion, lean duplex stainless steel, semi-elliptical hollow section, finite element modeling.

1 Introduction

Torsion in structural members can occur in cases of eccentric members and irregular structures under action of earthquake load (Nie et al. 2012), tall members under lateral loading (Han et al. 2007) etc. In general, torsion can result when load is applied away from the shear center. However, unlike compression and bending, limited research on torsional loading has been reported. However, due to the increasing demand of innovative architecturally attractive structural elements (especially steel tubular members), it has become pertinent to study the effects of torsional forces, that may arise due to eccentric loading. Again, it may be noted that closed hollow sections have the advantage of high torsional rigidity over open sections and hence, are efficient torsion supporting member. Variety of closed section shapes are commercially available including new and interesting shapes such as elliptical, semi-elliptical, tunnel shaped etc. Due to its recent introduction in the construction industry, these new section shapes are relatively under-studied. Studies on torsion of structural tubular members have been reported by Donnell (1933), Mahendran and Murray (1990), Ridley-Ellis (2000), Beck and Kiyomiya (2003), Aisyah Mohd Zaifuddin et al. (2017) etc. Further, it may be worthwhile to

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mention that, there is a lack of codified provisions for torsional design, especially for tubular steel structures.

Among currently available structural stainless steel grades, lean duplex stainless steel (LDSS) is one of the promising economical grades, owing to its relatively low initial cost (due to low nickel content ~ 1.5%); along with additional benefits of higher strength than commonly adopted austenitic stainless steel, good corrosion resistance and fracture toughness (Baddoo 2008, Theofanous and Gardner 2009). Increased interest in LDSS among architects and engineers have been seen in the last two decades. Investigations have been reported on LDSS member under compression by Theofanous & Gardner (2009), Anbarasu and Ashraf (2016) etc. and flexural behavior by Huang & Young (2013), Zhao et al. (2015) etc. However, study on torsional behavior of LDSS closed hollow section member has not been reported yet.

Hence, an attempt to investigate torsional behavior of cold-formed LDSS semi-elliptical hollow section (SEHS) member subjected to torsion using finite element (FE) software, Abaqus has been made, in this paper. SEHS is a closed hollow section having a unique cross-section combination of flat and curve elements; and relatively less information on its structural behavior is available in the public domain. Effect of cross-section geometrical parameters such as curve length, aspect ratio and cross-section thickness on torsional response was studied.

2 Experimental investigation

Experimental investigation was carried out initially, with an aim to generate torsion test results which can be used to validate FE models to be used in parametric study. Since, neither LDSS nor SEHS are readily available in Indian market, experiments were carried out on cold-formed YSt 210 steel square hollow section (SHS) member (a widely adopted steel in India) manufactured by Tata steel. Tensile coupon test and member torsion tests on YSt 210 SHS were conducted.

2.1 *Tensile coupon test*

Tensile coupon tests were conducted to characterize the basic mechanical properties of cold-formed YSt 210 steel. Coupons were extracted from flat and corner region of SHS having outer section width (B) and thickness (t) of 50 mm and 2.9 mm respectively (designated herein as SHS 50 × 50 × 2.9). The tensile coupons were prepared as per ASTM (ASTM 2015). Coupons were then tested using procedure recommended by Huang and Young (2014). Table 1 provides the basic mechanical properties of YSt 210 flat and corner coupons.

Table 1: Basic mechanical properties of YSt 210 obtained from coupon test

Section	E (MPa)	$\sigma_{0.2}$ (MPa)	σ_u (MPa)
50×50×2.9-flat	1,97,311	354.17	368.48
50×50×2.9-corner	1,83,393	450.13	510.48

2.2 *Member test*

Two SHS members of cold-formed YSt 210 steel were prepared in laboratory for torsion testing. Test specimens were cut from the same SHS tube used for tensile coupon testing. The specimens were cut to achieve a nominal length of 600 mm. Additional support fixtures were designed to fasten the specimen in the testing machine. Torsional testing arrangement of test specimen is shown in Figure 1. Solid metal blocks were inserted at each end of hollow SHS tube to avoid local buckling in the interior of supports. The specimen ends were then inserted in a metal fixture having a cuboidal cut out of depth 72.5 mm. Metal fixture, SHS sample and metal block insert were bolted together using four bolts to restrict movement during testing. This whole arrangement was then mounted on the testing machine, aligned, bolted and tightened. With all support fixtures attached to specimen tubes, an effective length of ~ 455 mm is available which is free to twist.

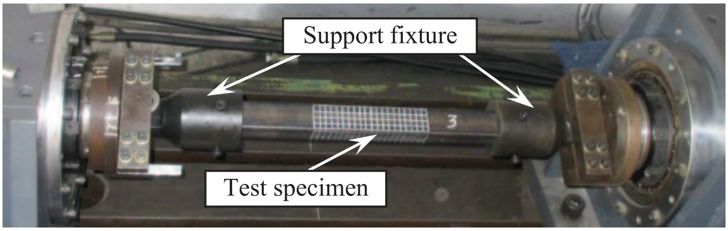

Figure 1: Torsion testing arrangement of test specimens

Testing was then carried out in a servo hydraulic torsion testing machine with a load cell capacity of 10 kNm and having a rotating actuator of stroke ± 50 degrees. One end of test specimen was fixed (all degrees of freedom constrained) and twist was applied at the other end (all degrees of freedom constrained except rotation about axial axis) at a rate of ~ 9.68×10^{-4} radian/sec as in literature (Ridley-Ellis 2000). Resulted Torque (T) - twist (θ) responses of test specimens are provided in Figure 2. In the present case, SHS 50 × 50 × 2.9 - R is a repeat test of SHS 50 × 50 × 2.9.

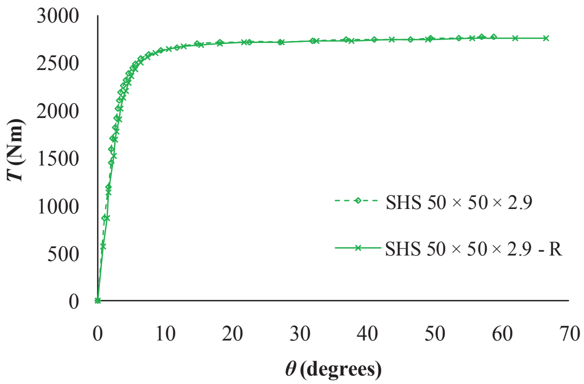

Figure 2: T- θ response of tested SHS specimens

3 Numerical modeling

Finite element (FE) models were generated for the parametric study using FE software Abaqus (Abaqus 2009). This section details the modeling procedure adopted to develop the FE models. A fairly standard procedure available in literature (Ridley-Ellis 2000, Theofanous and Gardner 2009) which is widely accepted for modeling for thin-walled members has been adopted in this study. The developed FE models were validated using experimental results presented in this study. The sectional dimensions mentioned in Section 2 were adopted for the FE validation.

The member was discretised with shell element S4R (Abaqus, 2009) which is widely adopted for thin-walled members. Aspect ratio of all elements was maintained ~ 1. Number of discretised elements along member length is $L/32$. Finer local mesh was adopted in the corner region of SHS, with ~ $2t$ number of elements. Boundary conditions were applied through two reference points, each at bottom (RP-1) and top (RP-2) positioned at centroid of section (similar to the arrangement followed in Bian et al. 2016) to which all degrees of freedom were coupled through kinematic coupling (available in Abaqus 2009). To mimic the boundary condition of test specimen, bottom end of member was held fixed while rotational degree of freedom was released at the loaded top end. Twist was applied at RP-2 at the same rate as in the experimental investigation. Full range stress-strain curve was developed using modified Ramberg-Osgood stress-strain model (Ramberg and Osgood 1943,Gardner and Ashraf 2006) adopting material properties provided in Table 1. Flat coupon material property was applied in the flat region while corner coupon property was limited only to corner region of SHS. To define plastic property in Abaqus (Abaqus 2009), the stress-strain curve was then converted to true stress and true plastic strain.

3.1 *Validation of FE models*

The modeling procedure adopted in this study has been assessed for its adequacy in capturing the overall torsional response of member. Torsional response and deformed shapes obtained from FE models were compared with test results from the experimental investigation in the present study. Comparison of experimental and FE results is shown in Figure 3. Good agreement was observed in overall T - θ response, with very close match in ultimate torque (T_u), initial elastic stiffness of T - θ curve, deformed shapes etc. The FE models were also checked for different values of initial geometric imperfection, *viz*. $t/10$, $t/50$ and $t/100$. Effect of initial geometric imperfection was found less significant on member response. Hence, an imperfection value of $t/100$ was adopted for FE models as reported suitable for modeling thin walled hollow sections (Theofanous and Gardner 2009). Residual stress was not explicitly included in the models as it was reported not to have significant effect as stated in earlier studies (Huang and Young 2013, Theofanous and Gardner 2009). These modeling steps can then be considered fairly accurate for developing thin-walled hollow steel sections under torsion and hence are adopted for parametric study.

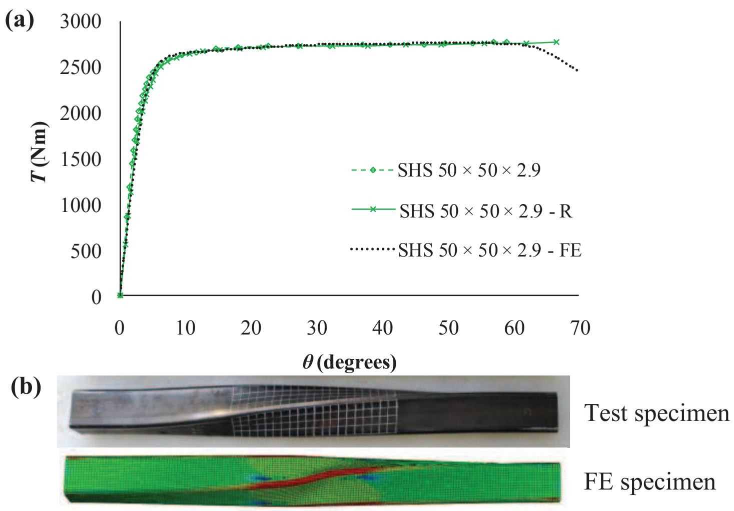

Figure 3: Comparison of experimental and FE (a) T - θ responses and (b) deformed shapes for SHS 50 × 50 × 2.9 specimens

4 Parametric study

A parametric study has been carried out to investigate effect of geometrical parameters of LDSS semi-elliptical hollow section member *viz*. curve length (l_c) and aspect ratio (h/b) of cross-section, on its torsional capacity. Typical cross section geometry of SEHS is provided in Figure 4. A range of cross-section thickness (t) was considered (t = 1 - 30 mm). Length of the member was equal to three times the flat length (l_f) of cross-section. To study effect of l_c of SEHS section, l_f was kept fixed and l_c varied from 270 - 540 mm. Effect of h/b on torsional capacity of member was investigated by varying h/b from 0.5 - 2 while keeping the cross-sectional area constant, thus ensuring same material consumption for same value of t. All degrees of freedom were restrained at bottom end while longitudinal displacement and rotational degree of freedom were released at the loaded top end. Such boundary conditions are widely adopted in the literature for torsional study (e.g. Aisyah Mohd Zaifuddin et al. 2017, Shen et al. 2018). Using displacement control, rotation about longitudinal axis was applied through top reference point. Material property of LDSS adopted for the parametric study was taken from coupon test results by Theofanous and Gardner (2009) (Table 2).

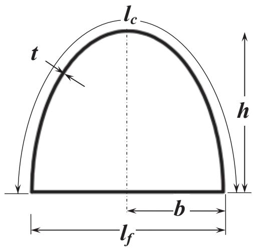

Figure 4: Typical cross-section geometry of semi-elliptical hollow section

Table 2: Compressive flat material property for LDSS (Theofanous and Gardner 2009)

Cross section	E (MPa)	$\sigma_{0.2}$ (MPa)	$\sigma_{1.0}$(MPa)	Compound R-O coefficient	
				n	$n'_{0.2,1.0}$
100 × 100 × 4	198200	560	642	8.3	2.6

5 Results and Discussion

Figure 5 shows torsional response of two different sections having different failure pattern. In the figure, T is normalized by T_y (yield torque) along y axis, to check capacity of section to achieve T_y. It can be seen from Figure 5a that the section (having t = 2.7 mm) fails before reaching T_y ($T/T_y < 1$ at failure). Failure was observed in this member by local buckling in flat element at a low value of θ. This type of failure was commonly seen in members having thinner cross-section. Such members which do not have the capacity to reach yield stress before failure are generally termed as slender section. Figure 5b shows torsional response of a thicker section (t = 17 mm) and it was observed that yield stress was achieved prior to failure ($T/T_y > 1$ at failure). It was found that the member fails at large value of θ, after significant yielding. Such sections are characteristic of a stocky section.

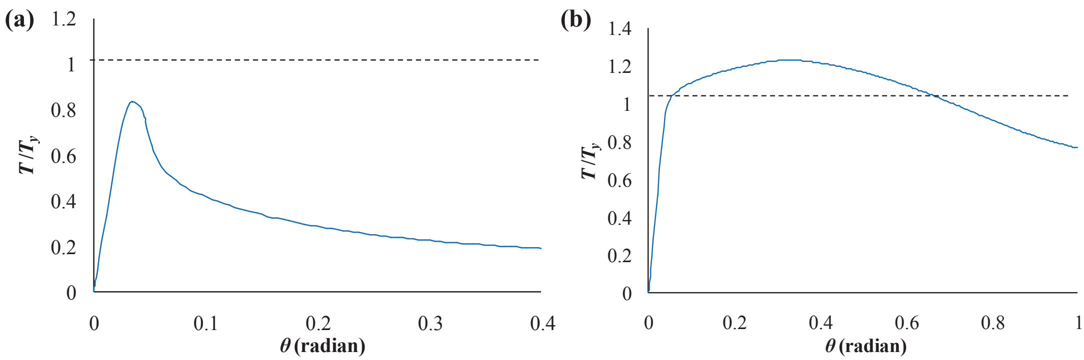

Figure 5: Typical T/T_y vs θ curve of (a) slender section (t = 2.7 mm) and (b) stocky section (t = 17 mm)

5.1 *Cross section classification*

Cross-section classification of stainless steel tubular sections under torsion has not been addressed yet to the best of authors' knowledge. However, a similar approach of classification as that of a web under shear force given in EN 1993-1-4:2006+A1 may be used since stress distribution is very similar with that of closed cross-section under uniform torsion (Trahair et al. 2007). As per EN 1993-1-4:2006+A1, a cross-section slenderness (λ) limit of 46.8 separates stocky and slender sections where $\lambda = \frac{h_w}{t}\sqrt{\frac{f_y}{235}\frac{210000}{E}}$, f_y is yield stress of material, h_w is clear distance between flanges ($h_w = l_f - 2t$ for SEHS in the present study). Figure 6 shows a plot of T_u/T_y versus λ (slenderness calculated based on flat element of SEHS). It was observed that a limit of 46.8 can be safely adopted for LDSS SEHS under torsion.

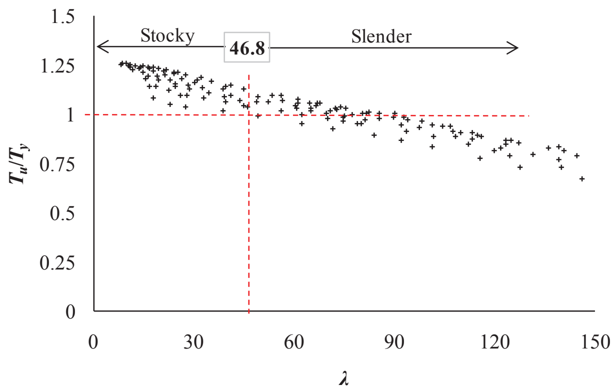

Figure 6: T_u/T_y vs cross section slenderness (λ)

5.2 *Effect of curve length* (l_c) *and aspect ratio* (h/b)

Figure 7a shows variation of T_u with l_c for t = 3-20 mm. For all cross-section thickness considered, a near linear increase in T_u was observed with increase in l_c. This may be explained by membrane analogy for thin-walled closed hollow sections. As l_c increases, volume enclosed by the membrane becomes larger and hence attributed to improvement in T_u. This improvement was seen to be higher in thicker sections (~ 373% for t = 3 mm and ~ 453% for t = 12 mm as l_c increases from 270 to 540 mm). On the other hand, increasing l_c was seen leading to earlier failure of both slender and stocky sections. Initial elastic stiffness of $T - \theta$ curve was observed to be higher in members of longer l_c. Figure 7b shows variation of T_u with h/b ratio for sections of different thickness. It can be seen that for same cross sectional area, torsional capacity was found to be higher for higher h/b ratio. Moreover, rate of increase in T_u with increase in h/b ratio was found to be more in case of thicker section. Increase in T_u of corresponding sections with different thickness was observed to be more in sections of higher h/b ratio. On contrary to T_u, twist at failure (θ_u) was not improved by increase in h/b. Elastic stiffness of $T - \theta$ curve was seen to be significantly affected by cross-section h/b ratio.

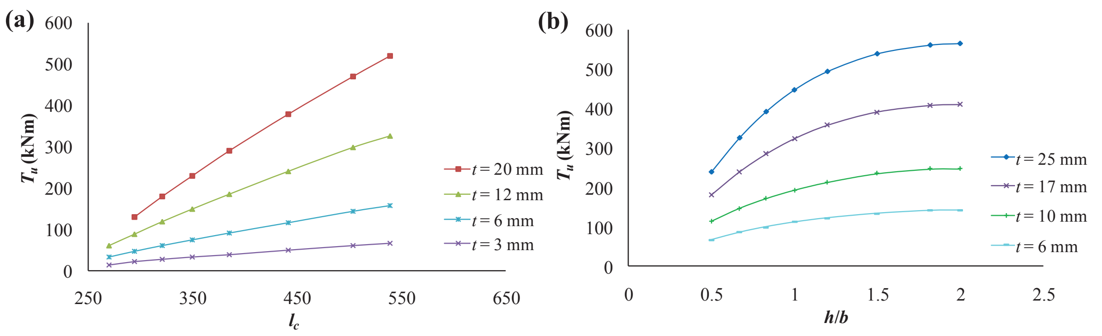

Figure 7: Variation of (a) T_u with l_c and (b) T_u with h/b

6 Conclusion

A parametric study has been carried out on lean duplex stainless steel semi-elliptical hollow section member subjected to torsion. Effect of cross-section geometrical parameters on torsional response was investigated. Based on the study, following conclusions have been made:

- Torsional capacity was found to increase in a near linear fashion with increasing curve length of semi-elliptical hollow section.
- Sections of higher aspect ratio were found to have higher torsional capacity.
- Rate of increase in torsional capacity was found to be higher in case of stocky sections.
- Elastic stiffness of torque-twist curve was observed to be significantly affected by both cross-section aspect ratio and curve length. While torsional capacity was seen to be improved by increase in aspect ratio and curve length, it was the opposite in case of twist at failure.

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