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Analysis of Flexural Behaviour of Hybrid Stainless Steel I-Beams

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ABSTRACT

This study presents a comprehensive numerical investigation into the flexural behavior of Hybrid Stainless Steel (HSS) I-beams using the finite element software ABAQUS. The hybrid sections incorporate Duplex Stainless Steel (DSS) and Lean Duplex Stainless Steel (LDSS), aiming to balance strength, ductility, and cost efficiency. The research validates the finite element (FE) models against experimental results from literature and evaluates the influence of geometric parameters such as flange and web slenderness on moment capacity and failure modes. Parametric studies reveal that hybridization significantly enhances moment resistance while mitigating local buckling. The study further compares numerical results with predictions from the European Standard EN 1993-1-4 and the Direct Strength Method (DSM). Findings demonstrate that DSM provides more accurate and conservative predictions for hybrid sections, making it a viable design approach for HSS beams. The results contribute to a deeper understanding of the flexural performance of hybrid stainless steel beams and support the development of efficient and reliable design methods for stainless steel structural members.

Keywords: *Hybrid Stainless Steel Beams; Flexural Behavior; Duplex Stainless Steel (DSS); Lean Duplex Stainless Steel (LDSS); Finite Element Analysis; ABAQUS; Local Buckling; Direct Strength Method (DSM); EN 1993-1-4; Structural Design.*

1. INTRODUCTION

In building civil engineering structures with large spans such as bridges, steel buildings, etc welded I-sections are commonly adopted. Also, considering the benefits and advantages of using stainless steel as a structural material (Gardner, 2005; Baddoo, 2008; SCI-P413, 2017), nowadays studies have been carried out on the flexural behaviour of stainless steel I-sections (e.g. (Yamada. and Kato, 1988; Carvalho et al., 1990; Kouhi et al., 2000; Olsson, 2001; Real and Mirambell, 2005b; Real et al., 2007; Saliba and Gardner, 2013a; 2013b)). Fabricated sections akin to welded I-section are built up sections made by welding (e.g. laser welding (Gardner et al., 2016), shielded metal arc welding (SMAW) (Gardner and Cruise, 2009; Yuan et al., 2014a)) together hot-rolled plates.

In addition to the family of homogenous steel I-section which are traditionally used in the construction industries, newer Hybrid steel I-section are being explored both in research and construction (e.g. (Frost and Schilling, 1964; Greco and Earls, 2003; Azizinamini et al., 2007; Shokouhian and Shi, 2014, 2015; Shokouhian et al., 2016)). Hybrid steel I-sections are fabricated sections having high strength steel flanges and relatively lower strength steel web. Flexural resistance of a beam is primarily attributed by the flanges, and hence for a member under pure bending, the concept of hybrid provides more economical and efficient design (Shokouhian and Shi, 2014). This concept is true since the longitudinal flexural stress are more critical than the shear stress in typical I-section beams under constant moment loading (Greco, 2000). Furthermore, it has been reported that use of hybrid steel sections can result in cost savings up to ~15% as compared to homogenous steel girders (Veljkovic and Johansson, 2004).

Numerous studies on the flexural behaviour of homogeneous steel I-sections have been carried out (e.g. (Haaijer, 1957; Haaijer and Thürlimann, 1958; McDermott, 1969; Kemp, 1985; Schilling, 1988; Kuhlmann, 1989; Barth and White, 1998; Green et al.,2002; Wilkerson, 2005; Topkaya, 2006; White and Jung, 2007)). Despite the advantages and benefits of utilizing hybrid steel I-sections, relatively lesser work has been carried out as compared to homogeneous sections. Studies on the structural performance of hybrid sections include investigations by Frost and Schilling (1964), Greco and Earls (2003), Azizinamini et al., (2007), Shokouhian and Shi (2014, 2015), Shokouhian et al., (2016). According to the author's knowledge, study on structural behaviour of hybrid I-beams using stainless steel materials have not been conducted. Therefore, in the light of expanding the knowledge of structural behaviour of hybrid I- beams, study is initiated on the flexural performance of Hybrid Stainless Steel (HSS) I- beams utilizing Duplex Stainless Steel (DSS) and Lean Duplex Stainless Steel (LDSS) on the flanges and web respectively based on parametric study of flange and web slenderness. Furthermore, for the purpose of direct comparison with HSS I-beams, similar study will also be carried out in homogenous section such as LDSS I-beams following Saliba and Gardner (2013a) and DSS I-beams for the same section. The FE bending strength (Mu) results are also compared with those predicted by European code (EN 1993-1-4:2006 + A1, 2015) and Direct Strength Method (DSM) (Becque et al., 2008; Rossi and Rasmussen, 2012; Arrayago et al., 2017), in order to assess their applicability. Finally, attempts are made to modify both the European code and DSM design equations, for a possible improvement in the design predictions, for HSS I- beams.

2. NUMERICAL MODELLING

Numerical study was carried out utilizing the commercial finite element software, Abaqus (2009) by employing similar modelling procedure adopted in a number of previous studies (e.g. (Theofanous and Gardner, 2009; Patton and Singh, 2012; Hassanein and Silvestre, 2013; Huang and Young, 2013; Saliba and Gardner, 2013a; Sonu and Singh, 2017)) and are known to provide accurate results. Initially, the experimental results: 3-point bending (3PB) and 4-point bending (4PB) tests on LDSS welded I-beams (Saliba and Gardner, 2013a) and 4PB tests on hybrid high-strength steel (Gr.Q345 and Gr.Q460) welded I-beams (Shokouhian et al., 2016) are used for validating the FE models. Hence, the validated FE models are further utilized for parametric studies to cover a wide range of slenderness study on LDSS, HSS and DSS I-beams.

Geometry

The cross-sectional geometry of the I-beam, where bf, tf, hw and tw are the flange width, flange thickness, web height and web thickness respectively. The specimen designation system is given by section type, followed by web height × flange width × flange thickness × web thickness. The schematic diagram of 3PB and 4PB specimens of constant length (L= 2800 mm).

FE modelling

The finite element type S4R, reduced integration four-noded doubly curved shell element with six degrees of freedom per node (three displacements and three rotations per node) was adopted in the current investigation to discretize FE models as shown in 2. This element is reported sui for modelling a wide range of shell thickness and was successfully used in similar type of investigations conducted in thin walled structures (e.g. (Ellobody and Young, 2005; Patton and Singh, 2012; Saliba and Gardner, 2013a; Sonu and Singh, 2017)). FE elements with aspect ratio of S4R element equal to ~1.0 were adopted. Element size of ~10 mm × 10 mm has been chosen based on mesh convergence study (by performing linear elastic eigen value buckling analysis). The number of S4R elements used in the current study ranges from ~ 12,000 to 25,000. Boundary conditions for bending tests were chosen to match up the experimental test conducted by Saliba and Gardner (2013a). Vertical and lateral displacements were restrained at both the support ends (bottom flange) similar to simply supported condition and lateral displacement was restrained at mid span where vertical concentrated load is applied (top flange) in order to avoid lateral torsional buckling following Saliba and Gardner (2013a). The loads were applied as static uniform loads in increments at the loaded points using the modified RIKS method, which is reported to be sui for static and non-linear analysis (Hassanein, 2011). Intermediate stiffeners and end posts are also provided at the loaded points and supports the following Saliba and Gardner (2013a) in order to prevent local buckling of web and flanges particularly at loaded points and supports due to heavy concentrated loads.

3. LITERATURE REVIEW

Hybrid stainless steel I-beams, which integrate different steel grades (e.g., austenitic, duplex, ferritic, carbon steel) within a single cross-section, aim to balance cost-efficiency with superior mechanical performance. Research into the flexural behavior of such hybrid beams remains relatively limited compared to their homogeneous counterparts but is gaining momentum due to the increasing demand for corrosion resistance and strength optimization.

Frost and Schilling (1964) pioneered research on hybrid steel beams by combining high-strength low-alloy steel (A514) with mild carbon steel. Their experimental findings indicated that strategic material placement—i.e., placing high-strength steel in flange regions and lower-grade steel in webs—resulted in improved moment capacity and economic steel usage. While their research did not focus on stainless steel specifically, it laid foundational principles for modern hybrid design.

Greco and Earls (2003) explored the flexural behavior of hybrid girders composed of A992 web and A572 flanges. Their finite element studies, complemented by experimental validation, demonstrated that hybrid sections exhibit stress redistribution under bending and can be effectively designed using modified plastic analysis techniques. These concepts were later adapted in stainless steel contexts to consider strain hardening and nonlinear stress-strain relationships.

Veljkovic and Johansson (2004) studied hybrid steel members with a focus on welded I-girders for bridges. Their work emphasized the importance of weld compatibility, residual stress effects, and potential for premature buckling due to strength mismatch. Though stainless steel was not used, this research highlighted the necessity of detailed numerical simulations for hybrid assemblies—an approach adopted in later stainless steel hybrid studies.

Azizinamini et al. (2007) investigated hybrid I-beams in composite steel–concrete structures, examining flange–web interactions and plastic hinge formation. While their focus was on seismic behavior, the methodologies of plastic moment capacity prediction and strain compatibility principles were transferable to hybrid stainless systems, particularly in assessing ultimate flexural strength.

4. MATERIALS AND METHODS

Materials

Three types of stainless steel were considered for the I-beam sections in this study:

- Low-Ductility Stainless Steel (LDSS)
- High-Strength Stainless Steel (HSS)
- Duplex Stainless Steel (DSS)

The mechanical properties of these materials were modeled based on existing experimental data and verified literature sources. The yield strength (σ0.2f), modulus of elasticity, and strain hardening characteristics were input into the FE model. LDSS, HSS, and DSS were selectively used in the flange and/or web of I-beams to evaluate the structural performance of monolithic and hybrid cross-sections. Material behavior was assumed to follow an elasto-plastic stress-strain relationship with isotropic hardening.

Output Parameters

The following response characteristics were evaluated:

- Normalized Moment (M/Mel, M/Mp): To compare actual moment capacity with elastic and plastic capacities.
- Rotation Capacity (R): Defined as the ratio θu/θy\theta_u / \theta_y, where θu\theta_u is the rotation at ultimate moment (Mu) and θy\theta_y at yield moment.
- Von-Mises Stress Contours: To assess yielding and plastic hinge (PH) formation.
- Buckling Patterns: Identification of local buckling (LB) and web buckling (WB) regions at critical stages.

Direct Strength Method (DSM) Evaluation

The applicability of the DSM approach was investigated for all beam configurations:

- Conventional DSM based on Becque et al. (2008)
- Modified DSM (DSM-RR) incorporating strain-hardening (Rossi & Rasmussen, 2012)

5. RESULTS AND DISCUSSIONS

Flange-critical section

The results obtained from the FE models are categorized into three section types as discussed earlier LDSS, HSS and DSS I-beams subjected to 3PB and 4PB. 3.10 shows normalized moment-rotation (M-θ) curve for Class 1 section (i.e. cf /tfε ≤ 9) of flange slenderness ratios (cf /tf = 4.7) for LDSS, HSS and DSS I-beams in 3PB and 4PB. For 3PB specimen (see 3.10), it can be seen that rotation capacity (R) is maximum for LDSS I-beams, and a reduction of ~34% and ~48% can be seen from HSS and DSS I-beams respectively. Similar observations can also be seen for the case of 4PB specimen as compared to that of 3PB specimen with R being maximum for LDSS I-beams with a reduction of around ~36% and ~38% for HSS and DSS I-beams respectively (see .10). The increase of R clearly shows that LDSS I-beams have higher ductility as compared to HSS and DSS I-beams thus indicating that use of LDSS results in enhanced ductility. However, Mu is found to be minimum for LDSS I-beams. In comparison with LDSS I-beams, an increase of around ~22% and ~26% in case of 3PB specimen (s 3.4-3.6), and ~27% and ~31% in case of 4PB specimen (s 3.4-3.6) can be seen for HSS and DSS I-beams respectively. From this observation, significant increase in Mu can be seen in case of HSS I-beams although the proportion of DSS material is maintained in HSS I-beams. Though, it is known that incase of HSS I-beams, DSS material is used only in the flanges which are relatively of higher strength as compared to LDSS material and consistent with Mu being primarily contributed by the flanges for a member subjected to pure bending (Shokouhian and Shi, 2014). Von-Mises stress contours for HSS Class 1 section (cf /tf = 4.7) in 3PB and 4PB corresponding to θu (rotation at Mu) and 2θu. The values of Von-Mises stress (hereafter referred to as stress) ≥ 652 MPa (i.e. σ0.2f) are grey-coloured, in order to identify areas which have exceeded yield stress of flange (i.e. σ0.2f). The stress exceeding yield stress can be the effect of strain hardening. It can be observed from 3PB specimen (s 3.11a and b) that at θu, the top and bottom flanges in the mid span have yielded and further at 2θu the beam initiates to bend without any signs of plastic hinge (PH). In case of 4PB specimen (s 3.11c and d), relatively larger area compared to 3PB specimen at the top and bottom flanges near the mid span have yielded at θu. At 2θu, the beam initiates to bend with occurrence of PH on top flange near the mid span. In both cases (i.e. 3PB and 4PB specimens), shown in 3.10, it can be seen that 3PB specimen shows higher Mu as compared to 4PB specimen for Class 1 sections .This is a commonly observed phenomenon and the reason may be due to lesser possibility of occurrence of local buckling (LB) in case of 3PB specimen (Saliba and Gardner, 2013a).

Web-critical section

Normalized M-θ curve for Class 1 sections (cw/twε ≤ 72) of web slenderness ratios (cw/tw= 41.7) for LDSS, HSS and DSS I-beams in 3PB and 4PB are shown in 3.14. It can be observed that increasing the web slenderness (cw/tw) decreases the amount of R for the three cases considered (see 3.14) similar to the observations made by Shokouhian and Shi (2014). It can be seen that R is generally high for LDSS I- beams when compared with HSS and DSS I-beams in case of Class 1 sections (cw/tw = 41.7) similar to the case of flange-critical section (see Section 3.4.1). Reduction of~36% and ~39% can be seen for HSS and DSS I-beams respectively in 4PB. However, in contrast to 4PB specimen, opposite behaviour can be observed in the case of 3PB specimen. R is found to be maximum for DSS I-beams with a reduction of around ~6% and ~20% for HSS and LDSS I-beams respectively in 3PB. Normally, Mu is found to be minimum for LDSS I-beams with an increase of around ~31% and ~36% in case of 3PB specimens (s 3.4-3.6), and ~28% and ~31% in case of 4PB specimens (s 3.4-3.6) for HSS and DSS I-beams respectively. This comparison shows that the concept of using hybrid section has significantly improved Mu which was mentioned earlier in flange-critical section (see Section 3.4.1). 3.15 shows stress contours for HSS I-beams Class 1 sections (cw/tw = 41.7) in 3PB and 4PB corresponding to θu and 2θu. In case of 3PB specimens (s 3.15a and b), it can be seen that at θu, the top and bottom flanges around the mid span have yielded. At 2θu, bending can be seen without any signs of PH similar to the case observed in flange- critical section (see Section 3.4.1). However, in 4PB specimens (s 3.15c and d), it can be seen that a larger area compared with the case of 3PB specimens at the top and bottom flanges in the mid span have yielded at θu. At 2θu, initiation of bending can be seen due to buckling of web (WB) in the mid span which enhances occurrence of PH in the top flange around mid span.

Comparison of FE results with European code

The FE results of LDSS, HSS and DSS I-beams in 3PB and 4PB are collected and plotted for the various response characteristics such as Mu/Mel, Mu/Mp and R vs the flange slenderness (cf/tfε) for the flange-critical section and web slenderness (cw/twε) for the web-critical section shown in s 3.18-3.23. First considering the case for flange-critical section shown in s 3.18-3.20, it can be seen that 3PB specimens give more resistance to bending as compared to 4PB specimens for the same cross- section and class similar to the observation seen in (Saliba and Gardner, 2013a). The flange slenderness limits (cf /tfε) such as Class 3 limits (14), Class 2 limits (10) and

Direct strength method

This section evaluates the applicability of DSM for the design of LDSS, HSS and DSS I-beams. First the DSM formulation (DSM) developed for stainless steel section (Becque et al., 2008) shown in Equation 3.13 has been plotted for all the three sections and it can be seen that the results predicted are too conservative particularly for stocky sections since the DSM flexural capacity (Mv) is limited to Mel. The values of mean (Pm), coefficient of variance (Vp) and reliability index (β) for LDSS, HSS and DSS I-beams are found to be 1.17, 0.09, 3.09; 1.14, 0.09, 3.00; and 1.18, 0.09, 3.06 respectively (see s 3.4-3.6). From the results of reliability analysis, the values of β is found to be greater than the target reliability index (βo=2.5) and hence reliable.

Furthermore, the modified DSM incorporating the beneficial strain hardening effect proposed by Rossi and Rasmussen (DSM-RR) (2012) given in Equation 3.14 was plotted and it can be observed that the predicted results are overly-conservative particularly for HSS and DSS I-beams. However, the formulation given in Equation 3.14 predicted accurate results and can be adopted for LDSS I-beams. The values of Pm, Vp and β for LDSS, HSS and DSS I-beams are found to be 1.06, 0.06, 2.80; 1.07, 0.07, 2.81; and 1.11, 0.07, 2.90 respectively (see s 3.4-3.6). The values of β is also found to be greater than the target reliability index (βo =2.5), and in comparison with the DSM formulation (DSM) given in Equation 3.13, the modified DSM formulation (DSM-RR) given in Equation 3.14 predicts more accurate results for all three sections and hence reliable.

Proposed Direct strength method

A new DSM formulation for HSS I-beams is proposed based on the full-range DSM formulation for carbon steel given by Arrayago et al., (2017), in which the ultimate stress (σu) and the yield stress (σ0.2) given in Equation 3.17 are replaced by their weighted average values which are given in Equations 3.18 and 3.19 respectively. After incorporating these weighted average values in Equation 3.17, a simplified equation is obtained and is given in Equation 3.20 which was found to predict conservative results. The proposed modified DSM formulation (Mv,P) for HSS I- beams is given in Equation 3.20 and they predicted accurate results.

6. CONCLUSION

Numerical study investigating the flexural behaviour of HSS I-beams along with LDSS and DSS I-beams for both flange-critical and web-critical section were conducted in this paper, through a parametric study. Furthermore, the FE results were used to evaluate the applicability of existing design approaches predicted by European code (EN 1993-1-4:2006 + A1, 2015) and Direct Strength Method (DSM) (Becque et al., 2008; Rossi and Rasmussen, 2012; Arrayago et al., 2017). The conclusions drawn from the numerical investigations are presented below:

1) For both Class 1 flange-critical section of cf /tf = 4.7 (cf /tfε = 7.86) and web- critical section of cw /tw= 41.7 (cw /twε = 62.52), it can be observed that LDSS I- beams has a higher R as compared to HSS and DSS I-beams.

2) Significant increase in Mu can be seen in case of HSS I-beams although the proportion of DSS material is maintained in HSS I-beams. Also, 3PB specimens show higher Mu as compared to 4PB specimens.

3) An increase in flange slenderness (cf /tfε) and web slenderness (cw /twε) decreases the amount of R for all sections.

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