ON THE RESPONSE AND DESIGN OF HIGH STRENGTH STEEL STRUCTURES EMPLOYING SQUARE AND RECTANGULAR HOT-FINISHED HOLLOW SECTIONS

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Abstract

The application of high strength steels (HSS) in the construction industry can allow for lighter structures, more economic design and profound sustainability benefits. Even though most international structural design codes have included HSS within their contents, many of the recommended rules are widely based on assumed analogies with mild steel, rendering necessary the investigation of their applicability to HSS. To this end, the present paper provides an overview of a series of comprehensive studies investigating the performance of structures employing square and rectangular hot-finished hollow sections in S460 and S690 steel grades. Meticulously generated finite element models are validated against test data and subsequently used for the generation of additional structural performance data through the execution of parametric studies. Implementing the aforementioned methodology, the structural response of individual structural components, namely concentric and eccentric stub columns and beams, is examined. Focus is also placed upon the structural performance of HSS prestressed trusses. Based on the obtained results, the applicability of current codified design methods to HSS is assessed and appropriate design recommendations are made.

Περίληψη

Η εφαρμογή χαλύβων υψηλής αντοχής (XYA) στον κατασκευαστικό κλάδο μπορεί να οδηγήσει σε ελαφρύτερες κατασκευές, οικονομικότερο και βιώσιμο σχεδιασμό. Παρά το γεγονός ότι οι περισσότεροι διεθνείς κώδικες σχεδιασμού έχουν συμπεριλάβει τους XYA, πολλοί από τους προτεινόμενους κανόνες βασίζονται σε υποθέσεις για μαλακούς χάλυβες, καθιστώντας αναγκαία τη διερεύνηση της εφαρμοσιμότητάς τους σε XYA. Σε αυτή την κατεύθυνση, η παρούσα εργασία διερευνά τη συμπεριφορά κατασκευών από τετράγωνες και ορθογωνικές κοιλοδοκούς θερμής κατεργασίας, σε ποιότητες χάλυβα S460 και S690. Σχολαστικά μοντέλα πεπερασμένων στοιχείων επικυρώνονται με αποτελέσματα πειραματικών δοκιμών και στη συνέχεια χρησιμοποιούνται για τη δημιουργία επιπρόσθετων δεδομένων, μέσω της εκτέλεσης παραμετρικών μελετών. Ακολουθώντας την προαναφερθείσα μεθοδολογία, εξετάζεται η απόκριση μεμονωμένων δομικών στοιχείων και συγκεκριμένα κοντών υποστυλωμάτων υπό κεντρική και έκκεντρη θλίψη και δοκών. Έμφαση δίνεται επίσης στην απόκριση προεντεταμένων δικτυωμάτων από XYA. Με βάση τα αποτελέσματα, αξιολογείται η εφαρμοσιμότητα των υφιστάμενων μεθόδων σχεδιασμού σε XYA και γίνονται κατάλληλες σχεδιαστικές προτάσεις.

1. INTRODUCTION

Structural steels with yield strengths over 460 N/mm², widely known as high strength steels (HSS), can potentially lead to lighter structures, considerable sustainability gains and more economic design. The aforementioned benefits have attracted growing attention from structural engineers. The European provisions for HSS structural design are set out in EN 1993-1-12 [1] with a large reference on EN 1993-1-1 [2]. Despite the identified difference in material ductility and strain-hardening characteristics between high strength and mild steel, HSS design provisions are largely based on test data for mild steel. Hence, the suitability of current design provisions to HSS needs assessment. To this end, the present paper summarises recently obtained results [3-8] examining the performance of structures employing square and rectangular hot-finished hollow sections in S460 and S690 steel grades.

2. METHODOLOGY

The methodology adopted for this research is shown in Fig. 1 and the steps followed are presented hereafter:

- 1. Brief description of the experimental tests, which are subsequently used for the validation of the numerical models.
- 2. Development of the finite element models, together with a detailed description of the modelling assumptions, including the applied element type, material model, mesh size, boundary conditions and analysis techniques.
- 3. Validation of the finite element models against the test results, based on the comparison of the experimentally and numerically obtained initial stiffness, ultimate capacity, failure mode and load-deformation response.
- 4. Execution of parametric studies in order to examine the effect of key parameters on the structural performance.
- 5. Analysis of the results and assessment of relevant design methods.



Fig. 1: Methodology.

For the finite element modelling (steps 2-4), the general purpose software Abaqus [9] has been used and the following assumptions were made:

The material properties were based on tensile coupon tests [4], while the von Mises yield criterion with isotropic hardening was applied. The general purpose four-noded shells with reduced integration and finite membrane strains, suitable for large-strain analysis, have been mainly used for the discretisation of the structural components. Quadrilateral elements have been chosen, whereas the average element size was set equal to the section's thickness, thus allowing efficient computational times. The effect of the supports was simulated through appropriate boundary conditions and constraints. Initial geometric imperfections were incorporated in the numerical models in form of the lowest elastic buckling mode shapes. Riks, an arc-length method, was applied to carry out geometrically and materially nonlinear analysis with imperfections included.

As shown in Fig. 2, the structures studied can be divided in two main categories: 1) individual structural components which aimed to investigate the cross-sectional behaviour by examining the response of concentric stub columns, 3-point and 4-point beams and

eccentrically loaded short columns; 2) vertically loaded trusses. For all the structures, two steel grades, namely S460 and S690, were considered. Regarding the study on trusses, it should be noted that even though the yield stress increases together with the steel grade, the Young's modulus remains unchanged, rendering buckling phenomena and second order effects potentially critical for HSS's structural design. To overcome the latter issue, the application of prestress has been successfully implemented in carbon steel structures [10]. On this basis, the possibility of adding prestress to the bottom chords of high strength steel trusses in order to enhance the overall response has also been investigated herein.



Fig. 2: S460 and S690 structures.

3. **DEVELOPMENT AND VALIDATION OF THE FINITE ELEMENT MODELS**

In order to establish the accuracy of the numerical results, the developed finite element models were validated against test data. In total, the experimental results of 11 stub column tests [3], 22 beams [4], 12 stub columns under eccentric compression [5] and 4 tubular trusses under different prestress levels [7] have been used for the calibration of the numerical models presented herein. The FE models were calibrated assuming different imperfection magnitudes for the initial geometric imperfections. The imperfection sensitivity analysis performed during the validation of the FE models is shown in tabulated form in Fig. 3 and comprised six and ten cases for the models investigating the crosssectional response and for the trusses, respectively. Based on the comparison ratios of the experimental to numerical ultimate loads [8], it was concluded that for the HSS hotfinished square and rectangular cross-sections, initial local geometric imperfections with t/50 magnitude, where t the section's thickness, overall resulted in excellent agreement with the test results, whilst for the trusses, the magnitudes L/750 and L/1500 for the out-ofplane and in-plane initial geometric imperfections respectively, where L the length of the buckled member, led to an accurate replication of the overall test response. Note that for the modelling of the trusses, in addition to the geometric imperfections, numerous parameters needed to be initially calibrated, as thoroughly described in [7].

Individual structural components [3-6]			Trusses [7, 8]		
Stub columns	3-point and 4-point beams	Eccentrically loaded short columns		Out-of-plane	In-plane
 no imperfection 1% of the section wall thickness t (i.e.t/100) 2% of the section wall thickness t (i.e. t/50) 10% of the section wall thickness t (i.e. t/10) the maximum measured imperfections w₀ w_{DW} an imperfection value evaluated from the predictive model of Dawson and Walker [11] 			1) 2) 3) 4) 5) 6) 7) 8) 9)	L / 1000 L / 2000 L / 1000 L / 1500 L / 750 L / 1000 0 L / 2000 L / 2000	L / 1000 L / 1000 L / 2000 L / 750 L / 1500 0 L / 1000 L / 2000 L / 750
			10) L 1	L / 1500 ength of buckled mer	L / 1500 nber

Fig. 3: Imperfection sensitivity analysis.

Figs. 4(a)-7(a) show the developed FE models along with the assigned boundary conditions, while Figs. 4(b)-7(b) illustrate the successfully replicated failure modes. Typical graphs of the load-deformation response for the different considered models and the various assumed imperfection magnitudes are given in Fig. 8.



a) FE model

b) Replicated failure modes [3]





a) FE model

4-point beam

b) Replicated failure modes [4]

Fig. 5: 3-point and 4-point beams - FE models.



Fig. 6: Eccentric stub columns - FE models.





Fig. 8: Typical comparisons of experimental and FE load-deformation curves.

4. PARAMETRIC STUDIES

For the present study, the validated models were utilised for the generation of additional structural performance data. It is worth noting that the individual structural components were expected to fail by local buckling (i.e. the buckling mode which occurs at cross-section level and its occurrence could limit the exploitation of the material's yield strength). In order to treat local buckling, all modern structural design codes make use of the cross-section classification procedure. Based on the comparison of the width-to-thickness ratio (c/t) to codified slenderness limits (c/t ϵ), where c is the compressed flat width, t is the plate thickness and $\epsilon = (235/f_y)^{0.5}$ with fy being the material yield strength, the constituent plate elements comprising a cross-section can be classified in four classes [1, 2]. Therefore, one critical parameter considered for the individual structural components is the cross-section slenderness. The matrix of all the parametric studies performed is given in Fig. 9. Within the scope of the present research study, 2850 additional nonlinear static

analyses were performed in order to obtain the response of S460 and S690 members and structures.

Individual structural components [3-6]			Trusses [7, 8]		
Stub	3-point and	Eccentrically loaded	applied prestress load		
columns	4-point beams	short columns	truss configuration/shape		
cross-section slenderness (from stocky to slender)			steel grade of the truss elements		
cross-section aspect ratio			curvature of the truss chords		
-	moment gradient	-	cross-section sizes of the truss chords		
-	-	load eccentricity			

Fig. 9: Matrix of parametric studies.

5. DESIGN RECOMMENDATIONS

The results have been used for the assessment of current structural code specifications and the provision of design recommendations. Among others [8], the conclusions presented in this section have been drawn.

5.1 Concentric stub columns

The results have been used to assess Eurocode specifications and in particular the effective width method for the design of slender cross-sections [12]. In order to evaluate the applicability of the obtained results to Eurocode effective width equations, the actual reduction factors ρ_w are plotted against the critical web slenderness λ_w in Fig. 10(a), where the Eurocode design curve is also included. Although the Eurocode effective width equations are generally capable of predicting safe values, a trend of more conservative estimations for hollow sections with increasing aspect ratio is evident. This owes to the fact that the constituent plate element interaction effects that influence the onset of local buckling are neglected by Eurocode. To take this phenomenon into account, a new method, as shown in Fig. 10(b), has been presented [3]. The method recommends a reduction factor ρ_{cs} , expressed as a function of the plate slenderness λ_p and the cross-section aspect ratio h/b, applied to the whole gross cross-sectional area.



Fig. 10: Assessment of design specifications for slender cross-sections in compression.

5.2 Beams

The Eurocode slenderness limits for internal elements in compression can be assessed on the basis of the results on HSS beams. Even though plastic design is not permitted by Eurocode for high strength steels [1], the results on HSS hollow section beams have been used for the assessment of Class 1 limit, considering deformation capacity requirement R=3 and slenderness limit of 33, which are applied for normal strength steel [2]. As can be observed in 11(a), where the attained rotation capacity is plotted against the c/tɛ, the limit of 33 [2] appears questionable. Even though the previously proposed limit of 28 [4, 13] seems more appropriate, some results still remain below the rotation capacity requirement, while the Class 1 limit of 15 would allow for safe predictions for all of the S460 and S690 sections studied herein [8]. The ultimate moment capacity obtained from the tests and the FE analyses [4] are normalised with the plastic moment resistance are plotted against the cross-section slenderness c/te in Fig 11(b). As can be seen, the current Eurocode Class 2 limit of 38 seems unsafe for high strength steel hollow sections, especially for sections with higher aspect ratio, whilst the lower proposed limit of 34 follows closer the tests and FE results [4].



Fig. 11: Assessment of the Eurocode slenderness limits.

5.3 Eccentric stub columns

Both the cases of uniaxial bending and compression and of biaxial bending and compression have been studied for the eccentric stub columns. Normalising the ultimate load and moment capacity with the respective Eurocode resistances [2], Fig. 12 illustrates a typical interaction failure surface [6]. Similar surfaces have been generated for each of the 32 studied cross-sections [8]. For Class 3 cross-sections, the Eurocode predictions for linear interaction surface led to largely uneconomic estimations. However, the adoption of a linear transition from M_{pl} to M_{el} for the bending moment resistance, as proposed in [13] and shown in Fig. 12(b), allowed for more accurate resistance predictions, compared to those of Eurocode.



a) Interaction failure surface [6]

b) Design interaction surfaces [2, 13]

Fig. 12: Response and design of cross-sections under eccentric compression.

5.4 Trusses

A series of studies was performed with the aim to investigate the influence of key parameters on the gains in strength and the reduction of the mid-span displacement at failure load, due to prestress. It was shown that by applying the optimal prestress force P_{opt} [7] to trusses of various structural configurations, the ultimate load increases and the corresponding mid-span deflection decreases. On the basis of the results, a set of simplified checks for the design of prestressed steel trusses has been proposed [8]. Applying the aforementioned checks in Warren type trusses, it was found that a significant reduction in the structural weight, with an average value of 35%, can be achieved with the application of steel grade S460 instead of S235.

6. CONCLUSIONS AND FUTURE RECOMMENDATIONS

An extensive study on the structural performance of members and structures employing hot-finished square and rectangular hollow sections in S460 and S690 steel grades has been carried out. The obtained results were analysed and relevant design specifications were evaluated, extending the pool of available structural performance HSS data, thus contributing to the development of more advanced design specifications for HSS and hopefully leading to an increased usage of HSS in the construction sector. The possibility of applying prestress, as a means of increasing the strength and stiffness of HSS long span structures, was investigated. Future research can focus on the feasibility of plastic design for HSS structures, the structural performance of HSS connections and the behaviour of different kind of HSS prestressed structures like domes or spatial arches.

ACKNOWLEDGMENTS

The research leading to these results has received funding from the Research Fund for Coal and Steel (RFCS) under grant agreement No. RFSR CT 2012-00028.

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