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Plastic design of hot-finished high strength steel continuous beams

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ABSTRACT

High strength steels (HSS) are increasingly used in structural engineering applications owing to their high strength to weight ratio. Due to the inferior ductility and strain-hardening characteristics of HSS and the lack of relevant structural performance data, plastic design is currently not permitted for HSS indeterminate structures. To this end, the present paper aims to generate structural performance data and to assess the applicability of plastic design to hot-finished HSS continuous beams. Upon a summary of previously drawn conclusions regarding the applicability of European design provisions to S460 and S690 hot-finished square and rectangular hollow sections, a gap on the response and design of indeterminate structures is identified. Validated numerical models of two-span HSS continuous beams are subsequently used for the generation of a wide range of structural performance data by developing a broad parametric studies numerical program. The effect of key parameters such as the cross-section slenderness, the cross-section aspect ratio and the steel grade on the structural response of continuous beams is assessed. The obtained results are discussed and the possibility of plastic design for high strength steel indeterminate structures is evaluated, whilst reliability of the elastic and plastic design methods is also verified according to Annex D of EN 1990.

1. Introduction

Structural steels with yield strengths over 460 N/mm^2, known as high strength steels (HSS) in building sector, can be achieved by appropriate heat treatments that improve its material and mechanical properties. Normalising (N), quenching and tempering (QT) and thermomechanical controlled rolling process (TMCP) are the most common heat treatments applied for the development of high strength steels. N produces rolled sections of moderate strength up to 460 N/mm^2, QT results in very high strength steel plates up to 1100 N/mm^2, whilst TMCP sections can have a yield strength up to 690 N/mm^2. QT steel plates are commonly known as ultra or very high strength steel plates, while TMCP generally produces rolled steel with high toughness properties and better weldability than ordinary steel.

HSS applications can potentially lead to lighter structures, considerable sustainability gains and more economic design. In order to maximise these benefits and increase the usage of HSS in the construction industry, appropriate design guidance in line with the observed structural response needs to be available. The European provisions for HSS structural design are set out in EN 1993-1-12 [1] and in most cases adopt the design provisions codified in EN 1993-1-1 [2] for conventional steel structures. Despite the significant differences 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 requires assessment.

Towards this direction, numerous experimental and numerical programmes have been conducted in order to determine the structural response of HSS cross-sections, individual members and structures, and estimate the suitability of design specifications to HSS. In particular, research studies on HSS long columns [3–6], stub columns [7,8] and beams [9–11] have been carried out. It is noteworthy that studies on the behaviour of HSS members with a nominal yield strength exceeding 1000 N/mm^2 have also been reported [12,13]. Most of the aforementioned studies have focused on the performance of cold-formed and welded HSS sections, leaving the performance of hot-finished cross-sections relatively unexplored. The fact that focus has been placed on cold-formed and welded HSS sections is mainly related to the residual stresses that could be significant in those cases, affecting the ultimate performance. However, as demonstrated in past studies [14–16], the ultimate structural performance is related to the ratio of the residual stresses to the yield strength and not the magnitude of the residual stresses themselves, which appear similar for mild and high strength steels. Therefore, the influence of the residual stresses is expected to

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decrease for increasing steel grades, while the effect of the reduced strain-hardening and ductility of higher steel grades remains. The latter means that the effect of the material response of HSS needs to be considered also for hot-finished sections, where the final processing is performed using high temperature thermal treatment, resulting in lower residual stresses. Hence, the investigation of the structural performance of HSS hot-finished hollow sections is warranted.

To this end, an extensive experimental programme [17–22] has been recently carried out in order to evaluate the ultimate performance of structures employing square and rectangular hot-finished hollow sections in S460 and S690 steel grades. The present paper initially summarises the conclusions and design recommendations regarding the applicability of European design provisions to HSS hot-finished hollow sections resulting from this recent research programme. A knowledge gap regarding the response and design of HSS indeterminate structures is thus identified. Aiming to address the lack of design guidance and structural performance data for HSS indeterminate structures, a comprehensive finite element (FE) parametric study on HSS continuous beams is reported herein. It is noteworthy that even though the structural performance of continuous beams made from mild steel [23,24], aluminium alloys [25–27] and stainless steels [28–30] has been studied, research on high strength steel continuous beams has not been reported yet. Thus upon numerical analyses execution, the possibility to extend conventional plastic design rules to high strength steel indeterminate structures is discussed.

2. Research programme on hot-finished hollow section members

2.1. Overview of the research programme [17–22]

A series of experimental and numerical studies have been performed to investigate the structural response of HSS structures. Two steel grades, namely S460 and S690 on square and rectangular hollow sections, were examined. The sections were hot-rolled, seamlessly fabricated from continuously cast round ingots and hollowed out in a piercing mill to their final section shape. The high strength of the sections in grade S460 was achieved with the normalising process, whilst for the S690 sections the quenching and tempering processes were used. The research programme is summarised in Table 1, where the structural components studied, the number of experiments and the number of FE analyses performed along with the parameters investigated are listed.

It is worth noting that the structural components studied in [17–21] were expected to fail by local buckling. In order to treat local buckling, Eurocode -as most modern structural design codes- makes use of the cross-section classification procedure. Based on the comparison of their width-to-thickness ratio (i.e. $c/t\varepsilon$, where c is the compressed flat width, t is the plate thickness and $\varepsilon = (235/f_y)^{0.5}$ with f_y being the material yield strength) against codified slenderness limits, the constituent plated elements comprising the cross-sections are placed in one of four behavioural groups termed classes, and the cross-section is classified as its least favourably classified element [2]. Therefore, one critical parameter considered for the individual structural components is the cross-section slenderness. Details on related research are provided in [17–22].

2.2. Eurocode assessment on the basis of the results

The obtained results of the research programme [17–22] were used to assess the applicability of Eurocode design specifications [1,2] to HSS. A summary of the Eurocode assessment is presented in Table 2 and explained briefly hereafter.

In [18] it was shown that the application of the Eurocode effective width equations [31] led to rather conservative strength estimations for rectangular hollow sections with high aspect ratios. To overcome this issue, the effective cross-section method was presented. The new approach suggests a reduction factor applied to the whole cross-sectional area (and not to each constituent plate element) and yields safe yet economic design estimations for hollow sections with different aspect ratios.

In order to assess the Eurocode provisions for the cross section capacity under interactive bending and compression, the test or FE to the predicted capacity ratio ($R_{test/FE}/R_{pred}$) was used in [20,21]. Points outside the boundary of the design curve (or surface) correspond to capacities higher than the predicted one (i.e. utilisation ratio higher than unity) and lead to safe predictions. The comparison displayed generally sufficiently accurate predictions.

The results of [22] were used to assess the applicability of flexural buckling formulae to HSS. A reliability analysis revealed that current European specifications are suitable for hot-finished S460 and S690 SHS and RHS columns as long as a safety factor γ_{M1} equal to 1.1 applies.

In order to assess the applicability of the Eurocode Class 2 and Class 3 limits for internal elements in compression to HSS, the relationship

Table 1
Summary of research programme [17–22].

Structure	No of experiments	No of FE parametric studies	Parameters
Stub columns under concentric compression [17,18]	11	180	• Fifteen cross-section slendernesses • Six cross-section aspect ratios • Two steel grades
Beams loaded in the three-point and four-point bending configuration [19]	22	216	• Twelve cross-section slendernesses • Three cross-section aspect ratios • 3-point with L/h = 10, 3-point with L/h = 20, 4-point with L/h = 20 • Two steel grades
Stub columns under combined compression and uniaxial bending [20]	12	720	• Eight cross-section slendernesses • Three cross-section aspect ratios • Nine loading eccentricities • Two bending axes for the rectangular hollow sections • Two steel grades
Stub columns under combined compression and biaxial bending [21]	–	1376	• Eight cross-section slenderness • Two cross-section aspect ratios • Forty-three loading eccentricities - bending about both axes • Two steel grades
Long columns under concentric compression [22]	30	144	• Three cross-section slendernesses • Two cross-section aspect ratios • Eight column slendernesses • Two buckling axes • Two steel grades