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Composite steel-concrete beams and columns fabricated with high strength steel (HSS) plate

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COMPOSITE STEEL-CONCRETE BEAMS AND COLUMNS FABRICATED WITH HIGH STRENGTH STEEL(HSS) PLATE

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ABSTRACT

High strength quenched and tempered structural steel has seen widespread implementation in heavily loaded columns in multistorey building construction. However, many current international codes do not cater for the use of high strength steel and thus much needed research is required to give structural engineers the confidence to use this new and innovative material in a safe and efficient manner in construction. Herein, experiments and analytical studies on composite steel-concrete composite beams and recommendations for modified design procedures will be summarised. This paper will also provide a comprehensive summary of experimental results on the uses of high strength structural steel in composite columns specifically for multistorey building construction. Calibration of these experiments with theoretical models and the Eurocode 4 approach have highlighted some of the differences that need to be implemented in order to design building structures safely with this material. Suggested design recommendations as well as further research will therefore be addressed in this paper.

1 INTRODUCTION

The newly released European Standard commonly known as "Eurocode 4" has an implied delineation point of 460 N/mm^2 to distinguish between mild and high strength steel, [1]. Furthermore, the draft Hong Kong Standard defines high strength steels as having a nominal yield stress between 460 and 690 N/mm^2, [2]. This standard will also have provisions for ultra high strength steel which have nominal yield stresses exceeding 690 N/mm^2. In the USA the ASTM standard specifies a nominal yield stress of 690 N/mm^2 for quenched and tempered steel which is the equivalent high strength steel used in plate form, [3]. High strength structural steel in Australia is defined as a steel material which currently exceeds the maximum yield stress of 450 N/mm^2, [4].

High strength quenched and tempered structural steel which is manufactured as steel plate in Australia currently has a nominal yield stress of 690 N/mm^2. This material is made from mild steel plate known as "green feed" and it possesses a nominal yield stress of 300 N/mm^2. This material is rapidly heated and quenched in a cooling bath, a process which provides the steel with its high strength characteristics. At this stage the steel has martensite present in it's microstructure, which provides high strength, but also leads to brittle type failure when elongated. The plate is therefore reheated into the austenitic range and is then allowed to slowly cool (a process known as tempering), which then allows the steel to redevelop its ductile nature.

2 PREVIOUS BUILDING APPLICATIONS

This section will highlight previous building applications, which have been completed and planned, and are summarised in Table 1. This list identifies the scope and size of the projects which have used high strength steel in construction. In particular, this table reflects tall or large building projects in Australia and Japan where high strength steels have been used. In the design of Star City, Sydney (illustrated in Figure 1) the largest building project in Sydney since the Sydney Opera House, the major benefits derived from the use of high strength steel were in providing additional car spaces in the basement levels of the building. This was a mandatory requirement for the project specified by the Sydney City Council, [5]. The use of high strength steel in the other Australian buildings was justified by the reduction in column cross-section sizes and excavation costs and thus providing additional available floor area and car park spaces in the completed building envelope. This was also used on projects in Sydney, Melbourne and Perth in notable buildings such as Grosvenor Place, 300 Latrobe Street and Central Park, (Structural Steel Development Group [6] and [7]). The Dai-Ichi building in Osaka, Japan, was designed utilising high strength steel box columns in the perimeter frames. High strength steel was used to ensure that the structure remained in the elastic range under severe earthquake loading. The Shimizu Super High Rise (SSHR), which is a proposed project in Tokyo, Japan, will use high strength steel in box columns for the exterior spandrel frame, (Council on Tall Buildings and Urban Habitat, [8]). Figure 1 illustrates the most recent project in Australia to take advantage of the use of high strength structural steel. The Latitude building in Sydney used concrete filled high strength steel box sections in the transfer trusses above street level.

Table 1. Projects utilising high strength structural steel

Building	City	Year completed	Number of storeys	Column type	Steel grade (N/mm^2)
Grosvenor Place	Sydney	1988	50	Encased	690
Central Park	Perth	1989	50	Encased	690
300 Latrobe St.	Melbourne	1990	30	Encased	690
Star City	Sydney	1997	20	Encased	690
Dai-Ichi	Osaka	Unknown	20	Filled	600
Post-Tower	Bonn	Unknown	41	Filled/Geilinger	Unknown
Latitude	Sydney	2005	55	Filled	690
Shimizu SSHR	Tokyo	Proposed	120	Filled	600

Fig. 1: Star City and Latitude, Sydney

3 BEHAVIOUR OF COMPOSITE STEEL-CONCRETE MEMBERS WITH HSS

3.1 Composite steel-concrete beams

Figure 2 provides an illustration of a simply supported composite steel-concrete beam fabricated with a welded high strength steel section. The use of high strength steel in simply supported composite tee beams is ideal since local buckling is improved by the restraint provided by the concrete slab for the top flange in compression. Furthermore, flexural-torsional buckling is restrained by the presence of closely spaced lateral restraints in the form of shear connectors between the concrete slab and steel beam. Also, deflections are generally not a controlling factor in composite beam design since propped construction can be utilised in buildings and pre-cambered girders are often used for dead loads in building and bridge construction. Thus the use of high strength steel in composite beams has the advantage of reducing the structural depth and weight when designing a beam for strength. Uy and Sloane [9] conducted a comprehensive experimental and theoretical research program utilising welded high strength steel sections with a composite concrete slab connected through headed shear studs. The main findings of this study were that full depth yielding of the steel was unable to be achieved as strain limitations in the concrete slab in compression governed the failure of the member.

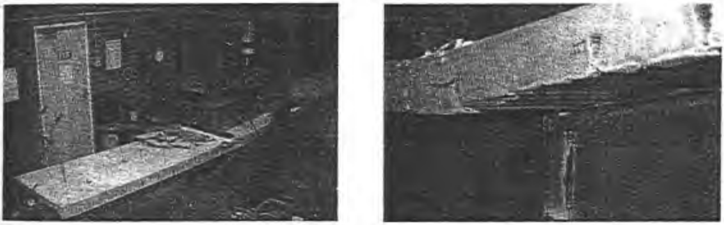


Fig. 2: Composite steel-concrete beams, (Uy and Sloane [9]).

3.2 Composite steel-concrete columns

Uy [10] presented the results of steel and composite sections using high strength structural steel of nominal yield stress of 690 N/mm^2. These sections constructed as stubby columns were subjected to concentric axial compression. A theoretical model to predict the axial strength of these columns was provided and was shown to be in good agreement with the models suggested by Eurocode 4, [1].

Bergmann and Puthli [11] conducted an extensive experimental programme on short and slender high strength steel encased sections of 460 N/mm^2 grade steel subjected to combined compression and bending. These tests were then compared with the Eurocode 4 approach, which was found to be suitable for predicting the ultimate load for short columns. However, the results of the slender column tests proved to be inconclusive.

Uy [12] conducted an extensive experimental programme on short concrete filled steel box columns, which incorporated high strength structural steel of nominal grade 690 N/mm^2. The experiments were then used to calibrate a refined cross-sectional analysis method, which considered both the non-linear material properties of the steel and concrete coupled with the measured residual stress distributions in the steel. The model and experiments were then compared with the existing approach of Eurocode 4 and it was found that certain modifications were necessary. The Eurocode 4 approach, which employs the rigid plastic analysis method, was found to over predict the strength of the cross-sections. A modified technique known as a mixed analysis was therefore developed and found to be in good agreement with both the test results and the refined analysis procedure. This model considers the concrete to be plastic and the steel to be elastic-plastic and provides a much more realistic design approach for sections utilising high strength structural steel, particularly when large flexural loads are present.

Mursi and Uy [13] conducted further research on high strength steel box columns filled with concrete. This study consisted of three short columns and three slender columns to consider both the strength and stability aspects of high strength steel-concrete composite columns. The results of this study, showed that further refinement or adjustments need to be made to the Eurocode 4 approach, to allow for the effects of high strength steel particularly when large flexural loads are present. More recently, Mursi et al. [14] completed an experimental program on short steel sections and concrete filled high strength steel columns subjected to biaxial bending. The experiments were compared with the existing Australian, European and American Standards and found to be in good agreement.

Fig. 3: Composite steel-concrete columns, (Uy [12], Mursi and Uy [13] and Mursi et al. [14])

Bergmann and Hanswille [15] recently considered the effects of using high strength steel billets inside a concrete filled steel tube, which has been used in projects like the Post-Tower in Bonn. This type of column, known as a Geilinger column has quite a few issues which need to be addressed and as the authors noted, is not able to be currently covered in Eurocode 4. Firstly, residual stresses across the billet sections are quite large and render the stability approaches for slender columns unconservative. Secondly, the high strength billet sections essentially need to be considered elastically as full depth yielding can not occur within the section.

4 SUGGESTED DESIGN PROCEDURES OF COMPOSITE MEMBERS WITH HSS

4.1 Composite steel-concrete beams

Composite steel-concrete beams composed of high strength structural steel which utilise headed shear studs need to be designed with a considerable degree of caution. Research by Uy and Sloane [9] showed that the full plastic moment as illustrated in Figure 4 (a) and outlined in Eurocode 4, [1] and AS2327.1-1996 [16] could not be achieved. The reasons for this were that the concrete starts to crush and unload at strains in the order of about 3000 $\mu\varepsilon$ (microstrain). With the yield strain of the steel at about 3500 $\mu\varepsilon$, this almost always results in the concrete crushing, prior to full yielding occurring throughout the depth of the steel section. Thus, it is suggested that a mixed analysis approach be used, whereby the concrete is essentially crushed and the steel is assumed to be only yielded in the bottom flange. The remainder of the steel beam can be considered to be in the elastic range as illustrated in Figure 4 (b). This would provide a convenient approach, but also conservative approach when estimating the capacity of such cross-sections.

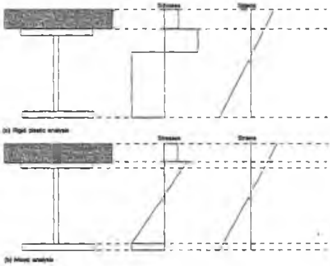
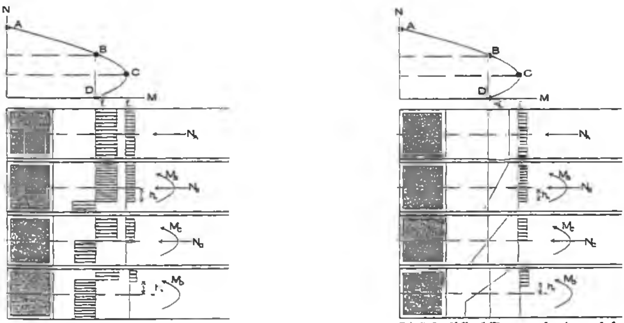


Fig. 4: Various stress distributions for high strength steel-concrete composite beams

4.2 Composite steel-concrete columns

Extensive experiments have been carried out by Uy [12] on the behaviour and design of short concrete filled steel box columns. In addition to the experiments, a cross-sectional analysis procedure was developed with fully non-linear material characteristics. The model also incorporated the effects of residual stresses, together with local and post-local buckling. The experiments and model were compared with the Eurocode 4 rigid plastic model which is illustrated in Figure 5 (a). The comparisons showed that the Eurocode 4 model was unconservative in it's prediction of the strength of the columns, particularly when large amounts of bending moment were present. The reasons for the unconservative strength estimation were considered to be due to the infill concrete crushing prior to the steel yielding throughout the depth. In order to provide a conservative design approach, Uy [12] therefore developed a modified Eurocode 4 approach which is illustrated in Figure 5 (b). This approach was found to be conservative in its prediction of the strengths of the column sections and thus considered to be acceptable as a design approach for short composite columns composed of high strength structural steel.



(a) Eurocode 4 model (b) Modified Eurocode 4 model

Fig. 5: Design models for the interaction of axial force and bending moment of short columns

To determine the global stability behaviour of concrete filled columns utilising high strength steel an extensive experimental and theoretical program of research has been carried out by Mursi and Uy [13]. The research was carried out on three sets of specimen sizes, all with different plate slenderness ratios. Six slender columns were tested under various eccentricities to try and ascertain the interaction between local and overall buckling. The experimental research program was also coupled with the development of a numerical model which was capable of capturing the interaction between local and global effects. In addition to this, the results of the experiments were compared with the model and the suggested model for slender column behaviour presently existent in Eurocode 4. This model which is illustrated in Figure 6 allows one to determine the overall capacity of a column, knowing the plastic resistance of the section, N_{plRd} as well as the critical load of the column N_{cr}. This method commonly known as the column curve approach assumes that certain forms of fabrication produce different residual stress patterns and initial geometric imperfections in a column. Thus, members which are heavily welded typically obey column curve *c*, whilst members which are hot rolled obey curve *b*. Columns which are annealed generally obey curve *a* in Figure 6. Furthermore, the presence of concrete infill can inhibit geometric imperfections from growing and curve *a* would be most appropriate. The study by Mursi and Uy [13] showed that curve *a* is the most suitable approach to be used for high strength steel composite columns as the level of residual stress as a function of the yield stress, means that the residual stress neutral curve is appropriate for design. Furthermore, the presence of concrete infill ensures that the growth of imperfections is minimised.

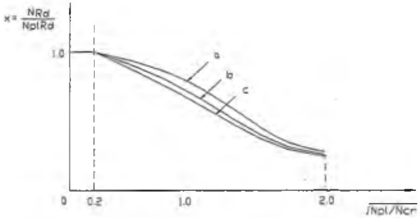


Fig. 6: Column curves for slender composite columns as in Eurocode 4, (Uy and Liew [17])

4 CONCLUSIONS AND FURTHER RESEARCH

This paper has provided a definition of the material of "high strength" or "high performance" steel as outlined in the European, Hong Kong, USA and Australian design contexts. An extensive background of the previous applications to buildings has been presented and the niche applications where the material is applicable have been highlighted. A very comprehensive summary of previous research into the behaviour of composite steel-concrete beams and columns has been carried out. Furthermore, this paper has also provided guidance for the design of composite steel-concrete composite beams and columns utilising high strength structural steel. This has involved highlighting the differences and nuances that need to be considered when using existing international standards with this material.

It should however be borne in mind, that the research highlighted and summarised in this paper has been predominately conducted on columns and specimens which were tested in laboratory conditions. In particular the cross-sections were of very moderate geometrical dimensions, with typical nominal plate thicknesses of 5 mm being used. In these cases the component plates and the welding methods used are generally characteristic of lightly welded conditions. In most of the building applications summarised in this paper, the column sizes and the component plates used were generally extremely large (thicknesses >50 mm) and thus for fabrication heavily welded conditions would be more representative. It is thus important to highlight that the designers utilising the results of such studies are made aware of the limitations of the research programs conducted herein. In order to be conservative it would be more appropriate to assume "heavily welded" conditions for the majority of practical applications of "high strength" or "high performance" steel when trying to estimate the effects of residual stresses in as built structures.

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NOTATION

f_c	concrete compressive strength
f_y	steel yield strength
χ	ratio of slender column strength to short column plastic resistance, $0<\chi<1.0$

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KEYWORDS

composite construction, composite columns, composite beams, high strength steel, tall buildings