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Behaviour and design of high strength steel-concrete filled columns

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ABSTRACT

This paper considers the behaviour and design of high strength steel-concrete composite columns used in major infrastructure engineering systems. The paper will highlight the major applications where high strength steel has been used in Australia and internationally. Current codes of practice will then be considered, highlighting the latest developments in Australian and International Standards for the use of high strength steel and high strength concrete in composite structural forms of construction. This paper also presents the results of an experimental study of the use of high strength steel-concrete composite columns which evaluates the in-plane residual stresses. This study uses high strength steel with nominal yield stress of 690 MPa coupled with high strength concrete of characteristic compressive strength of 100 MPa. The concrete used in this study adopts a reduction of 30% of the use of cement content by using high volume fly ash. The use of both of these high strength materials satisfies the Green Building Council of Australia objectives to reduce materials and the impact of construction materials on carbon emissions. This paper focuses on a number of the technical aspects which the combination of these two materials allows. The improved local buckling resistance of the use of steel in contact with concrete is taken into account. Furthermore, the effect of increased confining effect due to the larger elastic range of steel is also considered.

1. INTRODUCTION

This paper will consider the development of high strength steel sections filled with concrete that will provide an improved method of sustainable construction for columns and axial load carrying members in a wide variety of applications for the construction sector. This method involves the use of an innovative construction method using novel sustainable structural materials which have the ability to make significant improvements to Australia's construction industry. The Australian construction industry accounts for about $160 billion of activity, which represents 7% of Australia's Gross Domestic Product and includes approximately 9% of the Australian workforce, (Australian Bureau

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of Statistics, 2010). Buildings also have a significant impact on the environment, consuming 32% of the world's resources and up to 40% of its energy whilst accounting for 40% of waste to landfill, (Green Building Council of Australia, 2009). Thus, methods that attempt to reduce the effects on the environment by reducing material produced by high energy means are of great value to the construction industry. Recent advances in building construction in Australia to promote this sustainability drive have seen the introduction of a green star rating system, (Green Building Council of Australia, 2009). The two most widely used construction materials, concrete and steel can have a significant effect on sustainability in buildings by adopting two simple measures, which include (i) the use of higher strength steels (*ie* Quenched and Tempered (QT), f_y > 450 MPa) and (ii) the use of concrete with reduced amounts of Ordinary Portland Cement (OPC) < 40% compared with normal concretes, (Green Building Council of Australia, 2010a, Green Building Council of Australia, 2010b and American Society of Civil Engineers, 2010). This paper will therefore consider the behaviour of concrete filled steel columns using higher strength steels (QT) with higher strength concrete incorporating low percentages of OPC typically using high volume fly ash (HVFA). Composite columns composed of a steel outer tube casing and an inner concrete core are increasingly becoming a very attractive form of construction for multi-storey buildings throughout the world.

Previous building projects which have been completed in Australia, are summarised in Table 1. This list identifies the type of projects and the potential benefits achieved from the use of high strength steel. In particular, this table reflects tall building projects in Australia where high strength steel has been used. In the design of Star City, Sydney 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 space in the basement levels of the building. This was a mandatory requirement for the project specified by the Sydney City Council, (Davie, 1997). The use of high strength steel in other Australian buildings has been justified in reducing column sizes and excavation costs and thus providing additional floor area and car park spaces in the building as shown in Figure 1. This was also used on projects in Sydney, Melbourne and Perth in notable buildings such as Grosvenor Place shown in Figure 2, 300 Latrobe Street and Central Park, (Structural Steel Development Group 1990,1989). Figure 3 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 as shown in Figure 3. Figure 4 also illustrates the cross-sections utilised for the columns in each project.

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
Latitude	Sydney	2005	55	Filled	690

Fig. 1 Star City, Sydney

Fig. 2 Grosvenor Place, Sydney

Fig. 3 Latitude building, Sydney

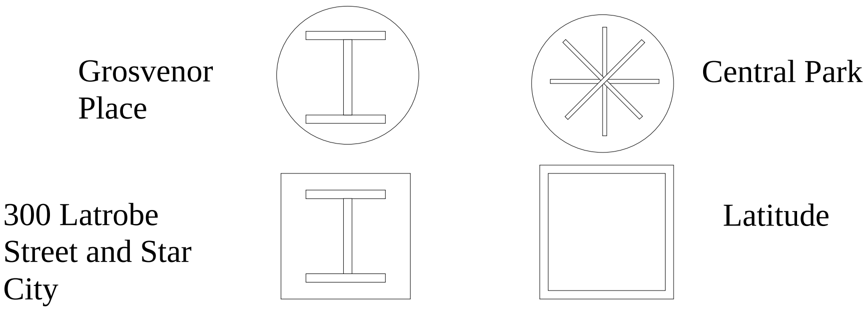


Fig. 4 High strength steel sections

Some significant international examples of the use of high strength steel include the proposed redesign of the columns of the Lotte World Tower in Seoul, Korea using HSA800 steel, which has a yield strength range between 650-700 MPa and tensile strength between 800-950 MPa (Kim et al. 2012). Completed and proposed projects in Japan included the Dai-Ichi and Shimizu Super High Rise in Osaka and Tokyo respectively, each designed with columns composed of a 600 MPa yield stress, (Council on Tall Building and Urban Habitat, 1993). The world's tallest building upon completion, Taipei 101 in Taipei, Taiwan and illustrated in Figure 5 was composed of concrete filled mega columns of 3 metre width using a steel grade of 570 MPa and 70 MPa concrete strength, (Shieh et al., 2003).

Fig. 5 Taipei 101

2. INTERNATIONAL CODES OF PRACTICE

The use of various high strength materials is currently limited by international codes of practice and further research is required to inform and update these standards. The American Institute of Steel Construction (American Institute of Steel Construction, 2010) limits the maximum yield stress of steel to 525 MPa and the compressive strengths of concrete to 70 MPa. The Eurocode 4 document (CEN-European Committee for Standardization, 2005) limits the maximum yield stress of steel to 460 MPa and compressive strengths of concrete to 60 MPa. The Chinese Standards also limit the maximum yield stress of steel to 420 MPa and compressive strength to 80 MPa, (National Standard of the People's Republic of China, 2002 and 2003). Recent advances in Australia now allow concrete cylinder compressive strengths up to 100 MPa (Standards Australia, 2009) and the steel standards have approved the introduction of the use of high strength steel up to 690 MPa yield stress, (Standards Australia, 1998). This is in line with the internationally leading Hong Kong Steel Code which has also recently introduced the use of high strength steel up to 690 MPa, (Hong Kong Buildings Department, 2011). The Australian/New Zealand standard for composite bridges and buildings is currently being revised and will allow for the use of concrete filled steel columns with a concrete compressive strength of 100 MPa and steel yield strength of 690 MPa, (Standards Australia 2014a and Standards Australia 2014b).

3. BEHAVIOUR OF HIGH STRENGTH STEEL AND HIGH STRENGTH COMPOSITE COLUMNS

3.1 High strength steel columns

Rosier and Croll (1987) considered the benefits of high strength quenched and tempered steel being applied in structures such as bridges, buildings and silos. This study included consideration of the economics of the material over conventional mild structural steel and showed the significant advantages that could be derived from its use. Rasmussen and Hancock (1992 and 1995) conducted tests on both high strength steel fabricated I-sections and box sections with nominal yield stress of 690 MPa. These tests established local buckling slenderness limits for these high strength steel sections. Furthermore, slender columns were tested and the behaviour of these was compared with the slender column curves of the existing Australian Standard AS 4100-1998 (Standards Australia, 1998). It was found that providing the local buckling slenderness limits were adhered to, then the slender column behaviour could be described using this standard developed specifically for mild structural steel.

Hagiwara et al. (1995) and Mochizuki et al. (1995) considered the behaviour of high strength structural steel for the application in super high-rise buildings in Japan. Sivakumaran and Yuan (1998) considered slenderness limits and ductility of steel sections fabricated with high strength steel with nominal yield stresses between 300 and 700 MPa respectively. Recent Korean research on both box and H sections has also been carried out on HSA800 steel to evaluate the compressive strength characteristics, (Yoo et al. 2012 and Lee et al. 2013). HSA800 has a typical yield stress ranging between 650-770 MPa and ultimate tensile strength ranging between 800-950 MPa.

3.2 High strength composite columns

Uy (1999) and Uy (2001a) presented the results of steel and composite sections using high strength structural steel of nominal yield stress 690 MPa and normal strength concrete of 20 MPa. These sections were constructed as stubby columns and were subjected to concentric axial compression. A theoretical model to predict the axial strength of these columns was provided and shown to be in good agreement with the models suggested by Eurocode 4, (CEN-European Committee for Standardization, 2005). Uy (2001b) conducted an extensive experimental programme on short concrete filled steel box columns, which incorporated high strength structural steel of Grade 690 MPa. 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 utilizing high strength structural steel, particularly when large flexural loads are present. Uy et al. (2002) 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 steel-concrete composite high strength 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. Mursi and Uy (2004, 2006a and 2006b) carried out further experimental work on high strength steel slender columns loaded uniaxially and biaxially and looked at the applicability of existing codes of practice to deal with high strength steel and normal strength concrete. Their findings showed that existing codes of practice were quite conservative with dealing with these structural forms, however due to limitations in test equipment capacity this could not be extended to the use of high strength concrete. This is one of the central tenets of this paper to study the behaviour of composite columns composed of high strength steel and high strength concrete.

Kilpatrick and Rangan (1999) considered concrete filled steel columns with compressive concrete strengths up to 96 MPa, however these sections had an upper limit of steel yield strength of about 450MPa being characteristic of cold formed mild structural steel tubes which are currently accepted by Australian Standards. Liew and Xiong (2010) also recently conducted a very comprehensive study on ultra high strength concrete up to 200MPa compressive strength of concrete with steel tubes of yield strength of about 450 MPa.

The major benefits of using high strength steel coupled with high strength concrete are that the structural steel is optimised by the presence of the concrete restraint to delay local and post-local buckling, (Uy and Bradford (1996) and Uy (1998 and 2000)). Furthermore, the use of high strength steel has the ability to permit elastic behaviour to exist for much larger strain regimes which has the ability to improve the effects of concrete confinement. The representative stress-strain diagrams in Figure 6 best illustrates the advantages that can be achieved by the coupling of high strength steel and high strength concrete. The representative stress-strain curves shown are for Mild Steel (MS), High Strength Steel (HSS), Normal Strength Concrete (NSC) and High Strength Concrete (HSC). Typically the yield and compressive strength values for MS is from 250 to 450 MPa (N/mm^2), HSS is approximately 700 MPa (N/mm^2), Normal Strength Concrete is up to 50 MPa (N/mm^2) and HSC is up to 100 MPa (N/mm^2). The benefits of using HSS in combination with HSC, is through the ability of the HSS shell or casing to allow confinement to occur. Since the steel shell or casing is still in the elastic range when the concrete reaches its unconfined compressive strength, the steel shell should allow the concrete to be appropriately confined and follow the alternative paths shown, thus allowing optimisation of both materials in compression.

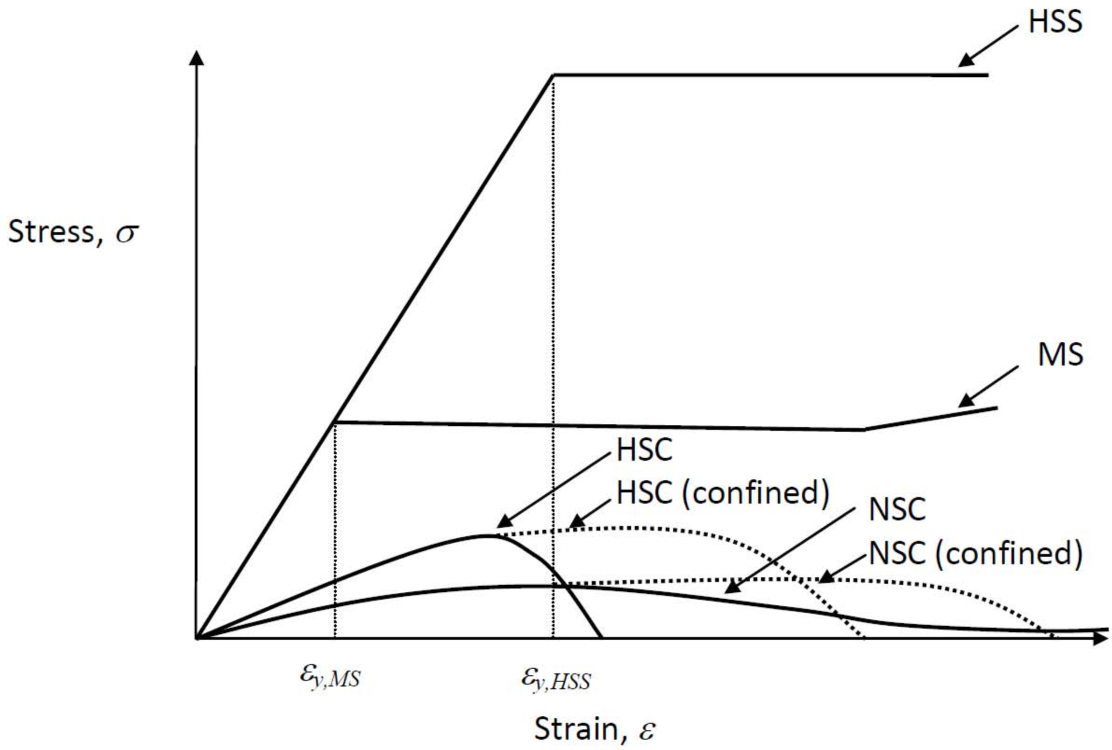


Fig. 6 Representative stress-strain diagrams for concrete and steel

4. DESIGN OF HIGH STRENGTH STEEL AND HIGH STRENGTH COMPOSITE COLUMNS

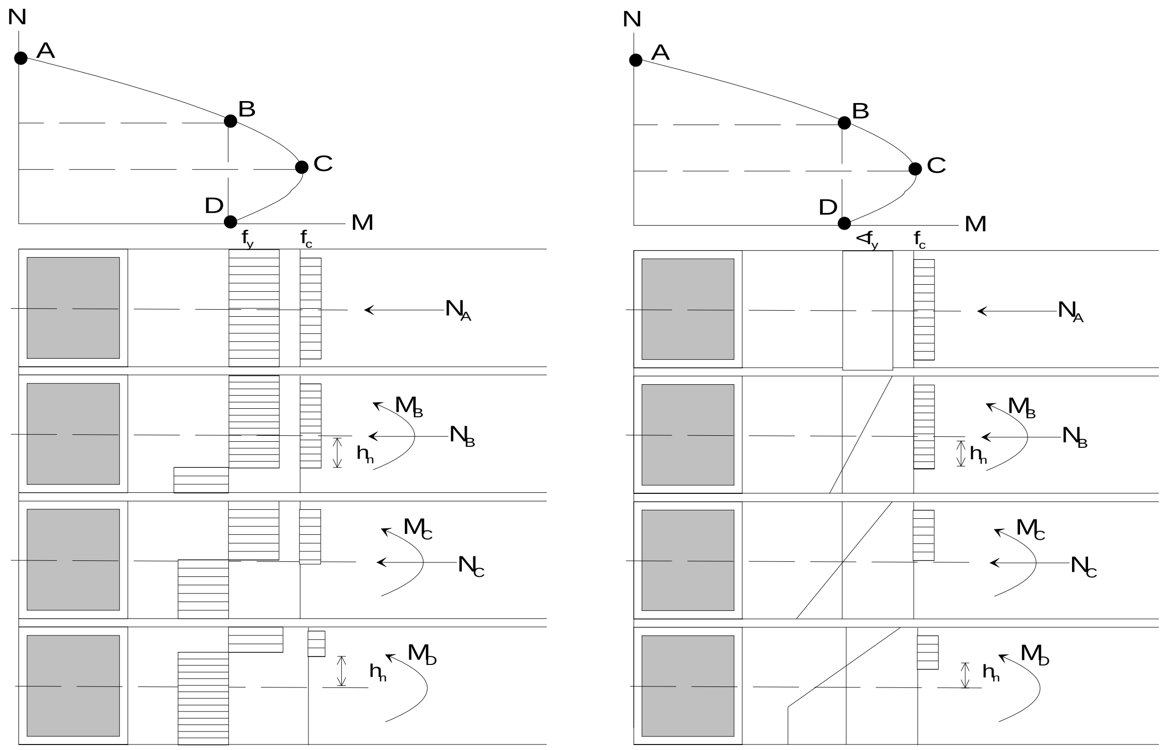
4.1 High strength steel columns

Previous research by Rasmussen and Hancock (1992) and Sivakumaran and Yuan (1998) established the slenderness limits for the component plates of both I section and box sections composed of high strength structural steel and subjected to concentric axial load. Rasmussen and Hancock (1995) then considered the behaviour of I section and box section columns for global slenderness effects. They found that the column curves suggested in the Australian Standard, AS4100-1998 (Standards Australia, 1998) were appropriate for use and that the effects of residual stresses and geometric imperfections were generally lower than for mild steel columns.

4.2 High strength composite columns

An extensive experimental and theoretical program of research has been carried out by Uy (2001b) on the behaviour and design of concrete filled steel box columns. In addition to the experiments, a cross-sectional analysis procedure was developed with full 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 (CEN-European Committee for

Standardization, 2005) rigid plastic model which is illustrated in Figure 7 (a). The comparisons showed that the EC4 model was unconservative in its 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 (2001b) therefore developed a modified Eurocode 4 approach which is illustrated in Figure 7 (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. 7 Models for the interaction of axial force and bending moment of short columns

In addressing 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 (2004). 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 8 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 8. 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 (2004) 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. This result was consistent with the findings of Rasmussen and Hancock (1995) for the behaviour of slender high strength steel columns.

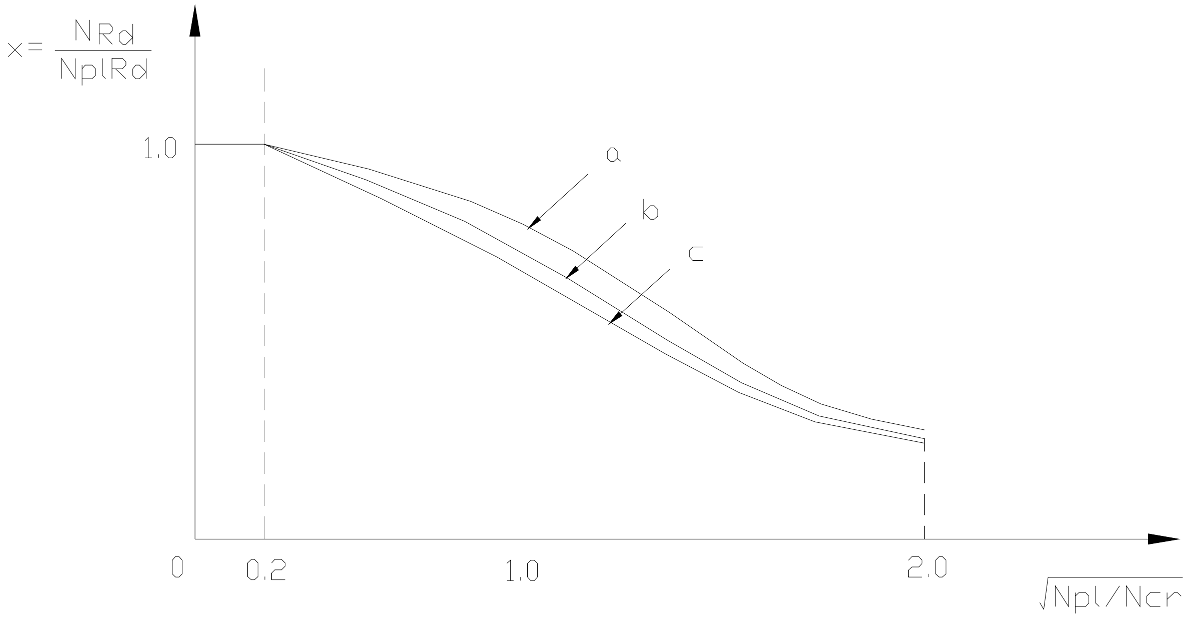


Fig. 8 Column curves columns as in AS5100: 6 and Eurocode 4, (Uy and Liew, 2002)

4.3 Practical design considerations for high strength steel and composite columns

It should be borne in mind that for both the high strength steel and high strength composite members, experimental tests were carried out on sections with fairly small plate thicknesses, namely nominal plate thicknesses of 5 mm. Fabrication for these types of sections would typically require single pass welding and thus would be typically on the lightly welded side of fabrication. Some of the building applications discussed previously in this paper used fabricated sections of up to 50 mm plate thicknesses. These sections would typically need multiple weld passes in their fabrication and would thus affect the residual stresses generated through the manufacturing process. It is more likely that these types of sections would fall near the heavily welded section type as outlined in the Australian Standard for Steel Structures, (Standards Australia, 1998). This issue is subject to future research and investigation and is of great significance in the widespread applicability of high strength steel in major infrastructure.

5. RECENT RESEARCH OF HIGH STRENGTH STEEL AND HIGH STRENGTH COMPOSITE SECTIONS

This section outlines the initial outcomes of an extensive experimental and theoretical study into the behaviour of high strength steel and composite columns. The first stage of this project involves considering welded box sections of nominal yield stress of 690 MPa in conjunction with high strength concrete with a nominal cylinder compressive strength of 100 MPa. These two values were chosen as they represent the extremities of the Australian Standards for concrete, steel, composite and bridge structures. The development of the high strength concrete in this project will involve using up to 40% Ordinary Portland Cement replacement by volume. In this initial stage of the project, the following issues will be outlined, residual strain and stress measurements and the interaction of concrete confinement with steel local buckling.

5.1 Residual stresses

One of the key issues that affects the behaviour of both hollow steel and concrete filled steel sections is the pattern of membrane (in-plane) residual stresses developed during the fabrication process. Residual stress patterns for high strength steel are not that well defined and often involve destructive techniques. Residual stress patterns in this project have been measured using the Kowari Strain Scanner system at the Australian Nuclear, Science and Technology Organisation, (ANSTO), Sydney. Strain scanning involves the use of neutron scanning and the advantage of using neutron scanning is it allows the strain measurements to be made through the thickness. Figures 9 and 10 illustrate schematically and in photograph the Kowari facility with a hollow steel section being analysed.

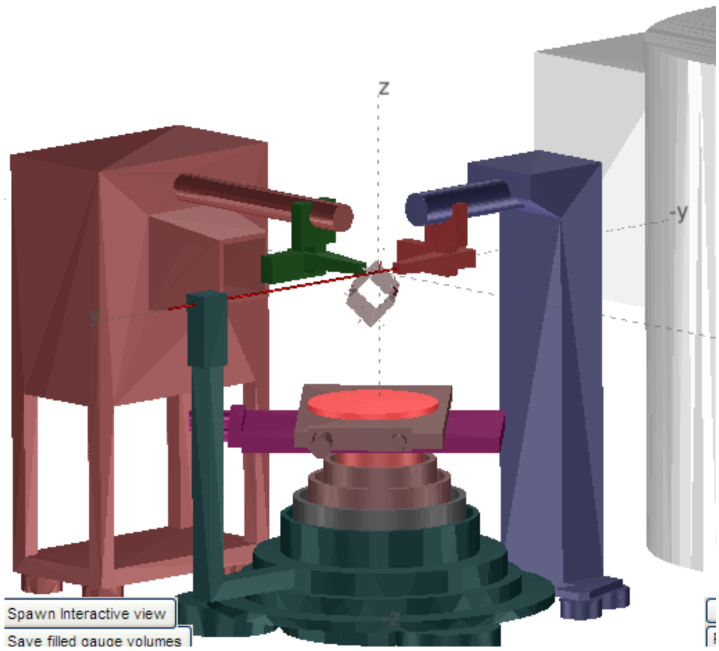


Fig. 9 Schematic of Kowari Strain Scanner at ANSTO, Sydney

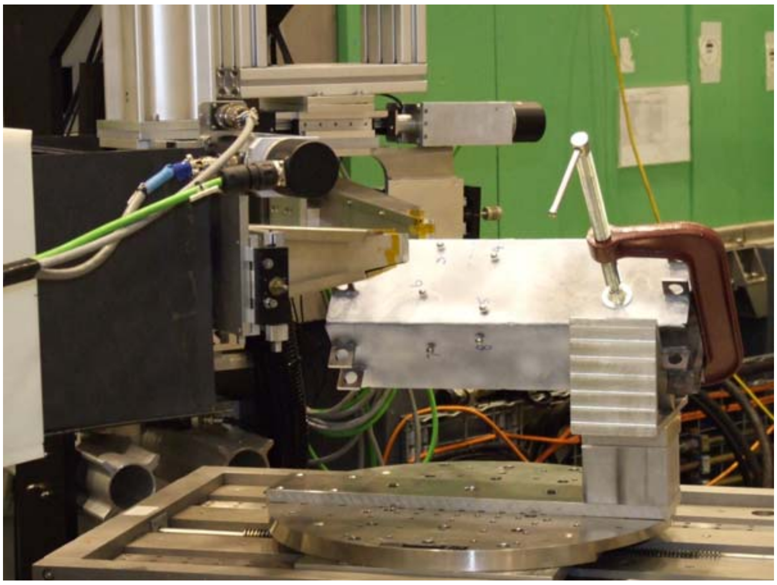


Fig. 10 Actual test specimen in Kowari Strain Scanner at ANSTO, Sydney

Residual strain and stress measurements were made and preliminary results are illustrated in Figure 11. This highlights that the maximum tensile residual stresses are about 70% of the yield stress (approximately 500 MPa) and the maximum compressive residual stress is about 30% of the yield stress (approximately 200 MPa), which is significantly higher than what has been previously reported for high strength steel.

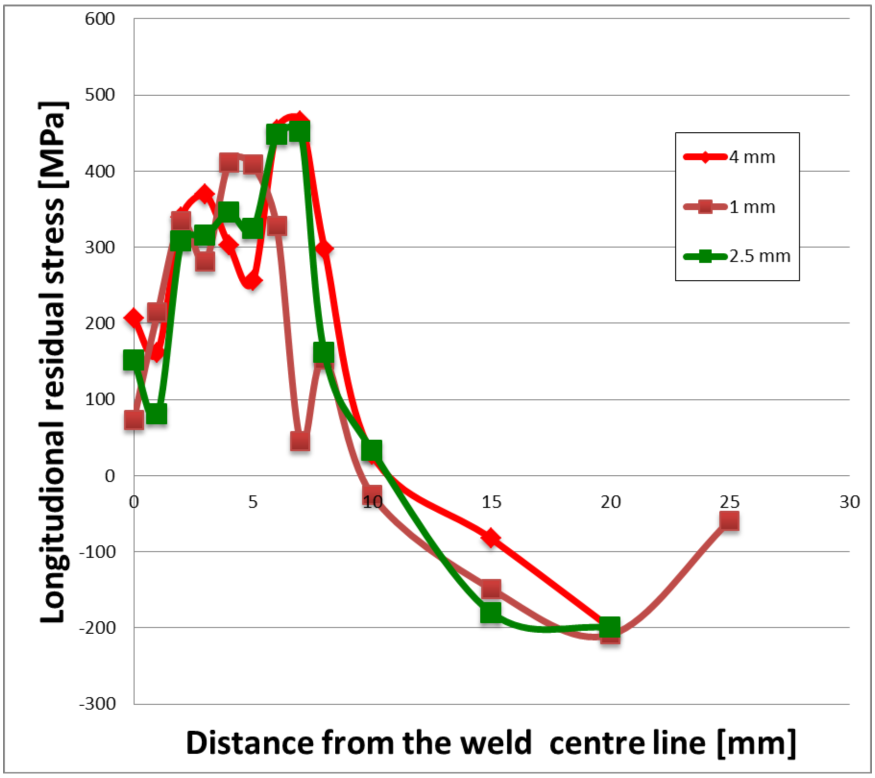


Fig. 11 Through thickness longitudinal residual stress distribution

5.2 Short column tests

This section presents the results of an experimental study on concentrically loaded high strength square short concrete filled steel tube (CFST) columns. The nominal yield strength of the steel sections of the columns was 690 MPa, and the unconfined compressive strength of the inner concrete section of the CFST columns had a range from 80MPa to 100 MPa. Forty short specimens, with a length to width (*L*/*b*) ratio of 3.5 and a width to thickness ratio (*b*/*t*) of 15 to 40 were subjected to monotonic loading to investigate the ultimate strength, the local buckling effects and the confinement effects of the high strength CFST columns. The loading condition in the experiments presented herein only involved loading of composite columns and hollow sections. The ultimate strengths of columns from the experiment were compared against the current Australian design standards which govern the design of steel and composite columns.

The cross-sections were fabricated with a single pass of weld along each fillet with one continuous run to fabricate the square box sections. Steel square sections were fabricated with a nominal thickness of 5 mm plate using BISALLOY 80 steel. Tensile coupon tests provided an average yield stress of 760 MPa, and ultimate tensile yield stress of 812 MPa. The infill materials of the composite columns consisted of high strength concrete (HSC), consisting of SL cement with 7.5% mineral addition, fly ash, a water:cement ratio of approximately 0.25, 10 mm Dunmore aggregate and Nepean Coarse sand. An average compressive strength of 95 MPa and 111 MPa was achieved from compressive cylinder tests after 28 days and 56 days respectively. The test specimens were loaded concentrically with fixed ends using a universal testing machine. Depending on capacities and heights of the test specimens, three universal testing machines with capacities of 3000 kN, 5000 kN and 10,000 kN, were used. Displacement transducers were installed at the top and bottom of test specimens to measure the axial shortening of columns. In addition, longitudinal and bi-directional strain gauges were also installed in the middle section of all sides of columns to monitor the strains of the steel. Figure 12 illustrates a typical short column failure from the test series. Tables 2 and 3 summarises the peak loads of the hollow and composite sections from tests respectively.

Fig. 12 Typical short column failure from test series

Table 2: Experimental peak loads for hollow sections and comparisons with AS4100

Specimen	***b/t***	***Nu***	***be/b***	***Ns***	***Nu/Ns***
HS15-SH (A)	15	1204	1	1035	1.16
HS15-SH (B)	15	1213	1	1035	1.17
HS20-SH(A)	20	NA	NA	NA	NA
HS20-SH (B)	20	1544	1	1380	1.12
HS25-SH(A)	25	1750	0.84	1454	1.2
HS25-SH(B)	25	1740	0.84	1454	1.2
HS30 -SH (A)	30	1811	0.7	1454	1.25
HS30-SH (B)	30	1820	0.7	1454	1.25
HS40-SH (A)	40	1718	0.53	1454	1.18
HS40-SH (B)	40	1728	0.53	1454	1.19
				Mean	1.19

Table 3: Experimental peak loads for filled sections and comparisons with AS5100

Specimen	***b/t***	***fc***	***Nu***	***Ns***	***Nu/ Ns***
CB15 - SH (A)	15	80	1634	1485	1.1
CB15 - SH (B)	15	80	1756	1485	1.18
CB20 - SH (A)	20	80	2524	2180	1.16
CB20 - SH (B)	20	80	2632	2180	1.21
CB 25 - SH (A)	25	80	3024	2975	1.02
CB 25 - SH (B)	25	80	2971	2975	1
CB 30 - SH (A)	30	95	4115	4208	0.98
CB 30 - SH (B)	30	95	3968	4208	0.94
CB 40 - SH (A)	40	98	5184	6362	0.81
CB 40 - SH (B)	40	98	5604	6362	0.88
				Mean	1.03

5.3 Comparison of test strengths with AS4100 and AS5100.6

The test results N_u were compared with the section capacity results, N_s of AS4100 and AS5100: Part 6 respectively. One can see from Tables 2 and 3 that the mean result shows that the model for steel and composite capacity is on the conservative side with a mean ratio of 19 and 3 % higher than the theoretical model. These results illustrate that the model for steel and composite columns for high strength steel and composite columns in AS4100 and AS5100 Part 6 is conservative.

6. CONCLUSIONS AND FURTHER RESEARCH

This paper has highlighted the state of the art in the use of high strength steel and high strength composite sections in building applications. The paper has summarised the current international trends in international codes of practice. The paper has also provided a summary of the behaviour and design of both high strength steel and high strength composite sections. Current research into the residual stress effects and the interactions between local buckling and concrete confinement has also been highlighted in this paper. Significant further research is necessary to further elucidate the use of high strength steel and high strength concrete in building applications.

A test programme on high strength hollow sections and composite sections, fabricated from high strength steel and high strength concrete were undertaken. Test strengths for hollow sections were compared against AS4100 and test strengths for composite sections were compared against AS5100.6 and these were shown to be conservative for the majority of cases. Further research is being carried out as part of this project to consider numerical and parametric studies and to study the slender column behaviour using high strength steel and high strength concrete.

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