# STRENGTH AND DUCTILITY OF HIGH-STRENGTH CONCRETE COLUMNS REINFORCED WITH HIGH-STRENGTH STEEL

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## Abstract:

The demand for high-strength reinforcing materials has been steadily increasing. In 2001, AS3600 for the first time incorporated 500 MPa grade reinforcing steels, which represented a 20 per-cent increase in strength over the 400 MPa grade steel of the previous standard. In 2018 the Australian Concrete Structures Standard AS3600–2018 was released, allowing for high strength steel (HSS) to 600 MPa for longitudinal reinforcement and 800 MPa for column ties. A major application for HSS is in columns for high rise construction. Such improvement in the performance of materials can lead to more efficient, smaller, sections with lower carbon footprints and lower costs. This paper reports of tests undertaken at UNSW Sydney on high-strength concrete columns with 670 MPa reinforcing steel for the longitudinal reinforcement, and 810 MPa steel for tie reinforcement. The columns had a cross sections 200 × 200 mm and 150 × 250 mm were tested under different loading eccentricities. The test results are compared with the design models of AS3600–2018 and the models are shown to predict the performance well.

**Keywords**: Column, confinement, ductility, high-strength concrete, high-strength steel.

## 1 Introduction

Over the past few decades, there has been increasing demand for high strength steel (HSS) reinforcement in concrete structures (yield strength over 550 MPa). Generally, HSS material could reduce the required volume of steel in different structural components (Shahrooz et al., 2011), leading to smaller cross sections in different structural elements, reduction of congestion in heavily reinforced sections, improved concrete placement, savings in the cost of labour, reduction in construction time and, in some cases, enhanced resistance to corrosion.

Having the same modulus of elasticity as conventional strength steels, HSS requires a greater strain to yield and may be beyond the crushing strain of unconfined concrete in compression. Therefore, there is a concern that longitudinal reinforcement made of HSS may not reach its full potential before crushing of concrete in columns (Mirza & Lacroix, 2002). Accordingly, different codes have limited the maximum yield strength of longitudinal reinforcing steel in columns.

In 2001, the Australian Standard for Concrete Structures AS3600 introduced 500 MPa reinforcing steel, which was a 20 per-cent increase over that of the previous Standard. In 2018, the strength of steel for bar reinforcement was further increased to an upper limit of 600 MPa generally and 800 MPa steel for ties in high-strength concrete (HSC) columns. In the case of column ties, confinement of the core must be provided at critical sections, which can be best achieved by using efficient tie configurations and optimised by opting for a high strength material. This paper reports on testing of five HSC columns containing HSS longitudinal reinforcement, together with HSS ties, under concentric and eccentrically applied axial loads.

## 2 Theoretical Background

*2.1 Ultimate strength*

The ultimate strength of a column section may be defined in terms of its axial force-bending moment interaction diagram tracing the locus of all combinations of the ultimate axial force $N_u$ and bending moment $M_u$. AS3600–3600 gives the squash load ($N_{uo}$) as:

$$N_{uo} = \alpha_1 f_c' \left(A_g - A_s\right) + A_s f_{sy} \tag{1}$$

$$0.72 \leq \alpha_1 = 1.0 - 0.003 f_c' \leq 0.85 \tag{2}$$

where $f_c'$ is the compressive strength of the concrete, $A_g$ is the gross area of the section and $A_s$ are $f_{sy}$ are the total area and yield strength of the longitudinal reinforcement, respectively. The *M–N* interaction curve between the point of decompression through to pure bending is determined by fixing the extreme compressive strain as 0.003 and with a rectangular stress block of height of $\alpha_2 f_c'$ and depth of $\gamma d_n$, where:

$$\alpha_2 = 0.85 - 0.0015 f_c \geq 0.67 \tag{3}$$

$$\gamma = 0.85 - 0.0025 f_c' \geq 0.67 \tag{4}$$

and $d_n$ is the depth of the neutral axis.

*2.2 Confinement of the core for HSC columns*

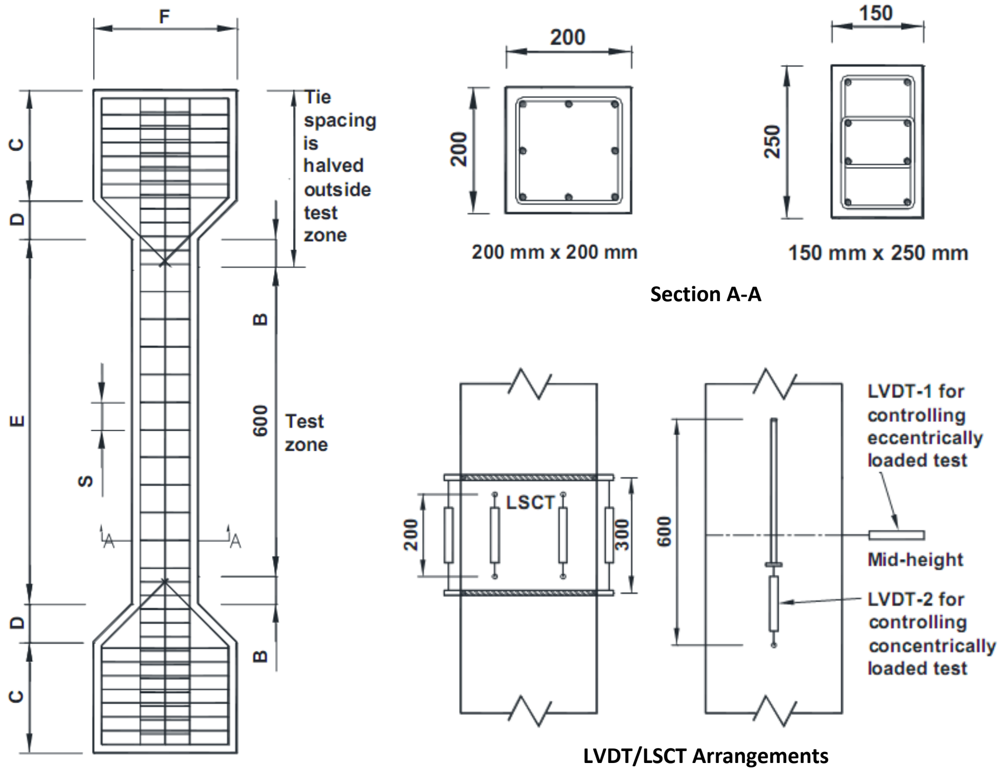
Robustness and ductility are important considerations when it comes to the detailing of all concrete members. However, due to its more brittle nature, extra lateral reinforcements are required for HSC columns. Ductility in columns is derived from confinement provided by the tie reinforcement to the core and is a function of the yield strength of the ties, the concrete strength, the volumetric ratio of the tie reinforcement, and the arrangement of the ties. At high overload the cover concrete spalls from the section and, as such, only the core concrete is considered in the calculation for ductility, where the core is defined as the section bounded by the centre-line of the outermost ties.

To ensure sufficient ductility in HSC columns, AS3600 requires the lateral reinforcing bars to provide at least a minimum confinement level within identified special confinement regions. In these regions, the minimum effective confining pressure provided at the time of yielding of the ties is $0.01 f_c'$. Other detailing measures are also enforced; specifically, spacing of lateral reinforcing bars is not to exceed the lesser of $0.6D_c$ and 300 mm, where $D_c$ is the smaller sectional dimension of a rectangular cross section. The background to calculating the effective confining pressure is given in Foster and Attard (2001) and Foster (2009).

## 3 Experimental tests

*3.1 Selection of variables and specimen details*

In this study three 200 × 200 mm square and two 250 × 150 mm rectangular section columns were tested using a nominal concrete compressive strength of 100 MPa and a maximum aggregate size of 10 mm (the actual concrete strength at the time of testing was 110 MPa). The columns were reinforced longitudinally with 8 by 10.7 mm diameter bars of 670 MPa yield strength, giving reinforcement ratios of 1.8% and 1.9% for the square and rectangular section specimens, respectively. The tie reinforcement consisted of 5.5 mm diameter bars of 810 MPa yield strength and spaced at 70 mm and 100 mm for the square and rectangular sections, respectively; the maximum spacing allowed by AS3600 for the given tie arrangement. The column ends were haunched to apply the eccentric loading and to limit failure within the intended test zone in the middle 600 mm along the columns' length (Foster & Attard, 1997). Details of column dimensions and reinforcement agreements are given in **Fig. 1**.




| Column Size | C (mm) | D (mm) | E (mm) | F (mm) | Overall Length (mm) |
|---|---|---|---|---|---|
| 200 x 200 mm | 350 | 100 | 900 | 400 | 1800 |
| 250 x 150 mm | 400 | 150 | 1000 | 480 | 2100 |

**Fig. 1** Column details.

The stress-strain curves for the reinforcing bars are shown in Fig. 2. The 10.7 mm diameter bars had a cross-sectional area of 90 mm$^2$, a yield strength ($f_{sy}$) of 670 MPa and an ultimate strength ($f_u$) of 780 MPa ($f_u/f_{sy} = 1.16$). The 5.5 mm diameter bars had a cross-sectional area of 31 mm$^2$, $f_{sy} = 810$ MPa and $f_u = 930$ MPa ($f_u/f_{sy} = 1.15$). The elastic modulus ($E_s$) for both bar sizes was 210 GPa. The concrete strength gain in time is shown in Fig. 2, with each marker representing the average of three 200 mm high by 100 mm diameter cylinders tested at 20 MPa/min.

The test program is outlined in Table 1. The columns are identified with a series of numbers and letters that represent the longitudinal steel ratio, the type of concrete, initial load eccentricity, tie spacing, and the type of reinforcing steel used for ties. For example, in column 1.8H20-70S-HS, the ratio of longitudinal reinforcement to cross sectional area of column is 1.8%, "H" identifies HSC, the initial load eccentricity is 20 mm, the centre-to-centre spacing of ties is 70 mm, "S" denotes the type of ties, indicating square or rectangular and "HS" represents a column with HSS longitudinal bars.

*3.2 Instrumentation*

The specimens were instrumented to record strain in the longitudinal reinforcing bars, ties, and axial direction of the columns. Strains in longitudinal bars were measured using 5 mm-electrical resistance strain gauges attached to four corner longitudinal bars at their mid-level. Four to six strain gauges were also attached on the tie located at the mid-level. To measure the axial strain of the concrete, six linear strain conversion transducers (LSCTs) were installed with gauge lengths of 200 and 300 mm. Lateral deflections were measured by linear variable displacement transducers (LVDT) and laser transducers. LVDT-1 and LVDT-2 controlled the loading rate for eccentrically and concentrically loaded tests, respectively (Fig. 1).

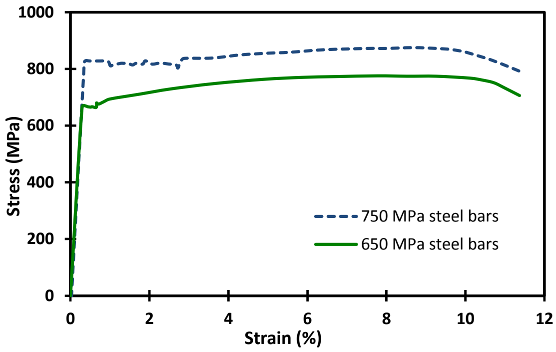



**Fig. 2** Stress-strain curve for 670 and 810 MPa bars of 10.7 mm and 5.5 mm diameter, respectively.

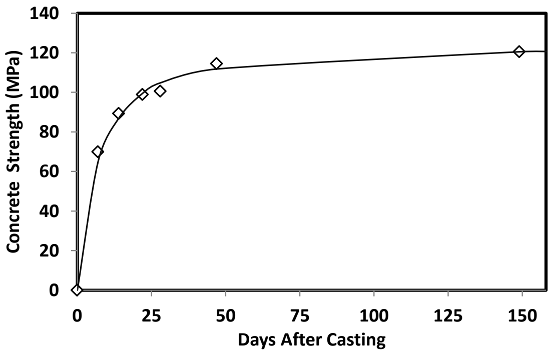



**Fig. 3** Concrete compressive strength versus days after casting.

**Table 1. Details of test specimens.**

| Specimen Designation | Cross Section (mm x mm) | Concrete Strength (MPa) | Initial Load Eccentricity (mm) | Yield Strength of Long. Bars (MPa) | Ratio of Long. Bars (%) | Yield Strength of Ties (MPa) | Tie Spacing (mm) |
|---|---|---|---|---|---|---|---|
| 1.8H0-70S-HS | 200 x 200 | 110 | 0 | 670 | 1.8 | 810 | 70 |
| 1.8H10-70S-HS | 200 x 200 | 110 | 10 | 670 | 1.8 | 810 | 70 |
| 1.8H20-70S-HS | 200 x 200 | 110 | 20 | 670 | 1.8 | 810 | 70 |
| 1.9H12.5-100R-HS | 150 x 250 | 110 | 12.5 | 670 | 1.9 | 810 | 100 |
| 1.9H25-100R-HS | 150 x 250 | 110 | 25 | 670 | 1.9 | 810 | 100 |

### *3.3 Testing Procedure*

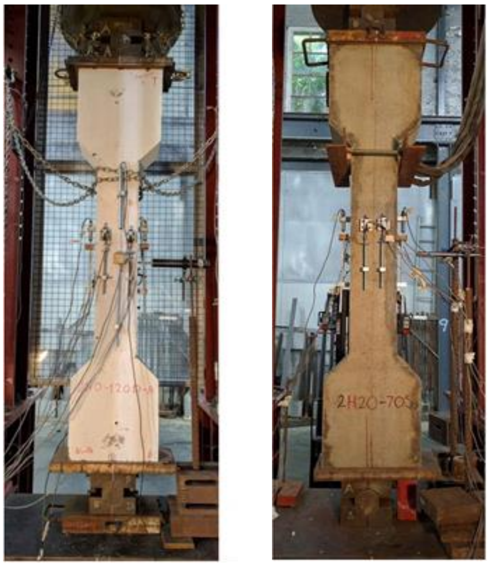
Each column was tested vertically in a 5 MN stiff testing frame (**Fig. 4**). High strength steel pins and bearing plates were placed at the desired nominal eccentricity at each column end to allow free rotation to the ends and to distribute the load. A thin 4 mm Masonite board was placed between the specimen and the steel end plates to reduce any effect of unevenness at the ends.

Testing was undertaken in a closed loop servo control system. At the initial stage of tests, loadings were controlled by ram displacement. At 40% of the estimated peak load, control was changed over to externally measured displacement. For the eccentrically loaded specimens, control was on the lateral LVDT; for the concentrically loaded specimens, axial strain was used as the control, with the strain measured over the 600 mm test zone (monitored by a LVDT placed vertically and shown in **Fig. 4**a). The peak load was normally associated first spalling of the cover.

## 4 Testing Results and Observations

### *4.1 Ultimate strength*

The loads versus lateral deflections for the columns tested in this study are presented in Fig. 5. One of the objectives of this study was to investigate the ultimate strength capacity of HSC columns reinforced with 500 MPa grade steel and HSS confined with HSS ties placed at maximum spacing according to AS3600. The results of the tests conducted by Parvez et al. (2017), in which nominal 500 MPa grade longitudinal reinforcement was used, are included in the following comparisons.



(a) (b)

**Fig. 4** Testing arrangements: (a) concentric and (b) eccentric test set up.

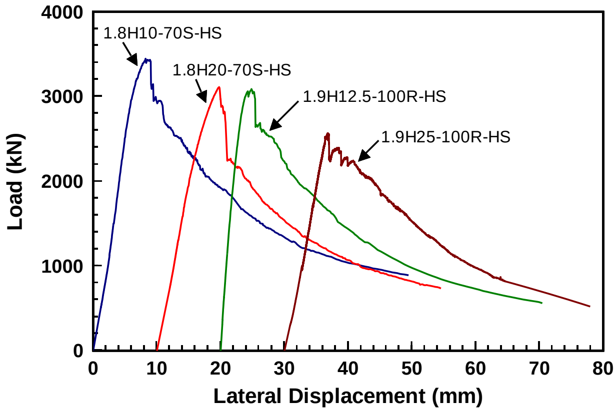



**Fig. 5** Load versus lateral deflection for HSC-HSS columns tested in this study.

Table 2 provides a summary of the main results, including peak loads, measured (actual) initial eccentricities, lateral displacement at the peak load and the corresponding bending moments and the calculated ductility index, where available. In Fig 6 the ultimate loads and corresponding bending moments, are plotted against the predicted interaction diagram, defined by Eqs. 1 to 4, together with those from Parvez et al. (2017). The results show that AS3600–2018 provides a conservative estimate of the capacity of HSC-HSS columns.

*4.2 Column ductility*

The second objective of this study was to investigate the ductility of HSC columns confined by HSS ties, while the ties were placed at the maximum spacing according to AS3600. There are different methods in the literature to indicate the ductility level of reinforced concrete columns. In this study ductility is measured following the method of Foster and Attard (1997), as outlined in Parvez et al., (2017).

**Fig. 7** compares the ductility index ($I_{10}$) calculated using the test results of Foster & Attard (1997), Saatcioglu and Razvi (1998), Foster and Attard (2001), Ghazi (2001), and Parvez et al. (2017) together with the results from this study. It is observed that the columns tied with HSS steel performed equally well, or better, than the HSC columns with conventional strength ties from the earlier studies. It is concluded that HSS ties provide the confinement needed to meet the established ductility requirements.

**Table 2. Summary of results.**

| Specimen ID | Measured initial load eccentricity (mm) | Deflection at peak load (mm) | Peak load, $N_u$ (kN) | Moment at peak load, $M_u$ (kNm) | Ductility Index, $I_{10}$ |
|---|---|---|---|---|---|
| 1.8H0-70S-HS | 0 | 0 | 4271 | 0 | – |
| 1.8H10-70S-HS | 10 | 8.2 | 3447 | 62.8 | – |
| 1.8H20-70S-HS | 20 | 9.6 | 3112 | 92.1 | 6.2 |
| 1.9H12.5-100R-HS | 14 | 4.8 | 3089 | 58.1 | – |
| 1.9H25-100R-HS | 24 | 6.6 | 2567 | 78.5 | 7.0 |

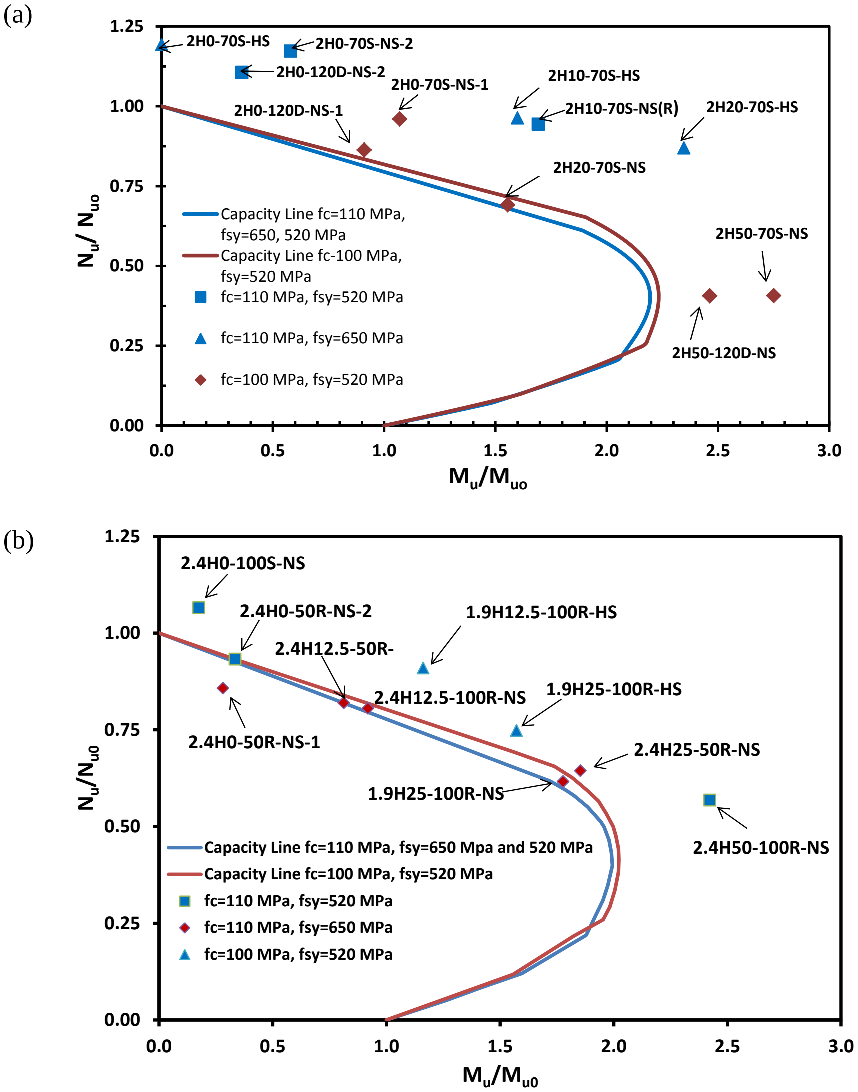



**Fig. 6** Column capacities compared to AS3600–2018 interaction diagram: (a) 200 × 200 mm section; (b) 250 × 150 mm section (tested in this study and that of Parvez et al., 2017).

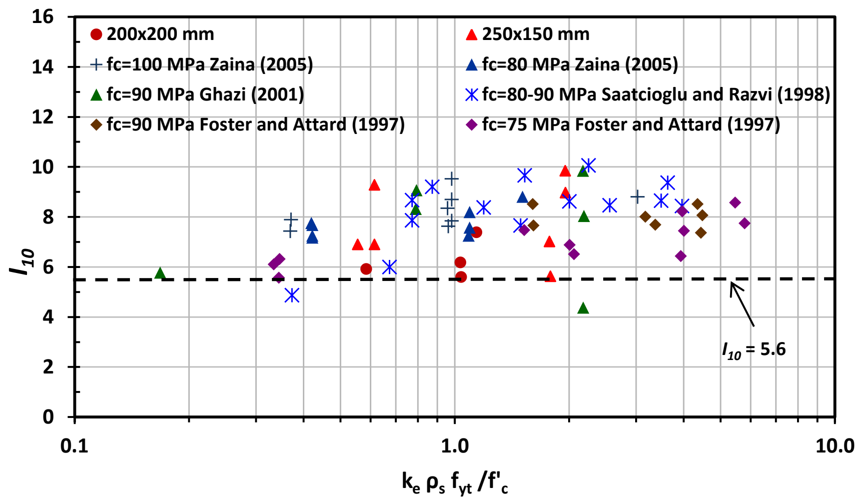



**Fig. 7** Ductility index of $I_{10}$ versus the confinement parameter $k_e \rho_s f_{yt} \,/\, f_c'$.

*4.6 Yielding of 670 MPa longitudinal reinforcement*

One of the objectives of this study was to investigate whether HSS longitudinal bars can reach their yield strain before the crushing of concrete, or not. The load versus strain of the most compressed longitudinal bar are plotted in **Fig. 8**. According to these figures for a certain amount of load, longitudinal bars in the compressive zones of the columns with greater eccentricities, undergo greater strains. Some longitudinal bars in some of the columns yielded before the peak load or shortly after the peak. This is consistent with previous experimental results, (Liu et al. 2000), in which it was reported that the longitudinal reinforcement reaches yield point at the spalling load, however the tie steel does not reach the yield point at the time of cover spalling. The yielding of longitudinal bars ascertains the full usage of steel material. This indicates that by using HSC with proper confinement provided by HSS ties, HSS longitudinal bars could show their full yielding strength before crushing of the concrete.

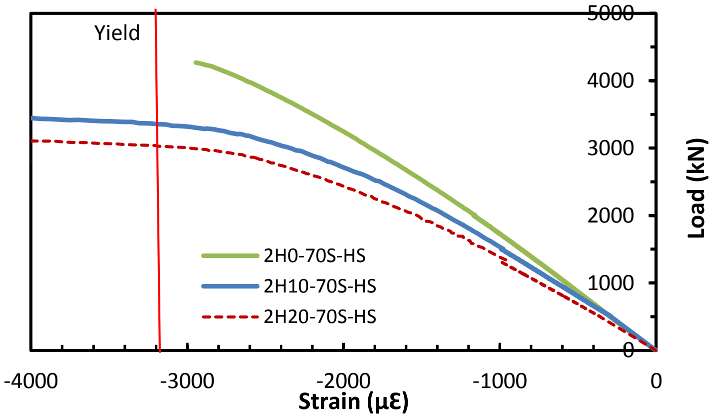



**Fig. 8** Load versus steel strain of 670 MPa longitudinal bar: (a) 200 × 200 and (b) 250 × 150 mm section.

## 5 Conclusions

In this study, 5 end-haunched HSC-HSS columns were tested to investigate the strength and ductility with reference to AS3600–2018. The yield strength of longitudinal reinforcement and ties were 670 MPa and 810 MPa, respectively. The test results were also compared with those for HSC and conventional strength longitudinal bars tested by Parvez et al. (2017). The following conclusions are drawn from this study:

- The tested columns demonstrated ultimate strength well above that required by AS3600–2018.
- The 810 MPa grade ties (nominal strength of 750 MPa) provided the same level of ductility as 500 MPa grade ties with 33% less tie reinforcement and a saving of about 25% in greenhouse gas emissions.
- Monitoring of strain in HSS longitudinal bars showed that for columns with minimum code eccentricities, and greater, the 670 MPa bars yielded and the concentrically loaded specimen achieved a strain of 0.003 at peak (stress of 600 MPa).

## Acknowledgements

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