High Strength Reinforcing Steels: The Benefits and How They Are Delivered

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Abstract

Changes in 2018 to AS 3600 - Concrete Structures and in 2019 to AS/NZS 4671 - Steel for the reinforcement of concrete, have provided the reinforced concrete industry the opportunity to explore the benefits offered by higher strength, ductile reinforcing steels. The design models in AS 3600:2018 now apply for reinforcing steels with yield strengths up to 800 MPa for column fitments and up to 600 MPa for all other elements.

An Australian steel reinforcing manufacturer has identified that they can utilise these changes to offer innovative products in non-standard diameters. These products are in comparison more sustainable, with the potential to reduce the safety risk and the total project cost of a concrete structure.

This paper details the changes to the two Standards referenced and how higher strength steels up to 750 MPa grade in non-standard diameters can be simply substituted for existing 500 MPa grade reinforcing steel to capture the benefits offered. It also outlines the research work undertaken and to be undertaken to support and drive the changes to the Standards and the design information that is available.
CHANGES TO AUSTRALIAN STANDARDS

Drivers for Change

Australian Standards are modified from time to time to reflect the changing needs of the stakeholders of a product or service. The changes to the maximum allowable characteristic yield strength (hereafter referred to as yield strength) in the two key Australian Standards for reinforced concrete construction, AS 3600 – Concrete structures and AS/NZS 4671 – Steel for the reinforcement of concrete, driven by researchers has allowed manufacturers greater scope to develop innovative reinforcing products that offer benefits to the consumers and improves the sustainability of construction projects.

Research undertaken (Parvez et. al, 2017) at the University of New South Wales as part of an Australian Research Council (ARC) Linkage Grant with partner organisation OneSteel (now InfraBuild) has underpinned the inclusion of high strength steels in AS 3600:2018 and AS/NZ 4671:2019. These changes follow the trend around the world for manufacturers to develop and offer higher strength materials that provide a significant benefit to the construction industry.

Changes in Detail

The changes to AS 3600:2018 in relation to increased yield strengths are relatively straight forward. The yield strength applicable for designs, which was previously 500 MPa, has been generally raised to 600 MPa and 800 MPa for column fitments in the current edition of the Standard.

AS 3600:2018, Clause 1.1.2 Application, provides the following:

This standard applies to structures and members in which the materials conform to the following:

(d) Higher reinforcing grades > 500 MPa to 800 MPa meeting the requirements of Table 3.2.1. For Ultimate limit states the strength of the reinforcement in design model shall be not taken as greater than 600 MPa unless noted otherwise.

Whilst AS 3600:2009 Clause 10.7.3.3, allowed column fitments to be designed with yield strengths of up to 800 MPa, this could not be exercised given that AS/NZS 4671:2001 only allowed steels with yield strengths up to 500 MPa and AS 3600 required steels to conform to that Standard. AS 3600:2018 provided an interim solution by adding the strength, ductility and weldability requirements to Table 3.2.1, as shown in Figure 1, until the release of AS/NZS 4671:2019 which introduced higher grades of steel up to 750 MPa but did not preclude higher strengths. Prior to this, designers were unable to utilise the provision in AS 3600 which was present, but ineffective for over a decade.

The changes to AS/NZS 4671 were a little more complex given it was not just the strength of the reinforcing material that needs consideration but also its ductility and weldability. Research (Gilbert and Sakka 2007) identifying the brittle nature of a slab with low ductility mesh highlighted the importance for safety by requiring high strength steels to have Normal Ductility (Class N). The penalty in AS 3600:2018 of requiring a phi factor which is 24% lower for a Low Ductility (Class L) reinforcing bar compared to a Class N reinforcing bar means there is little to no economic value in producing a Class L high strength bar. A Class L bar is not be permitted by AS 3600 to resist significantly higher loads than a 500N reinforcing bar, therefore the new higher grades of reinforcing bars in AS/NZS 4671:2019 are all Class N steels.

The other critical parameter for a reinforcing bar is its weldability or carbon equivalent value (CEV). In Australia it is relatively common practice to weld reinforcing bar particularly for manufacturing a prefabricated reinforcing cage in a factory, for transport to site. A factory offers conditions where there is greater protection from the environment and better facilities for production control compared with a construction site. Weldability is also important where lapping of bars is not possible or practical, or where a bar requires welding as a remedial action on site. AS/NZS 4671:2019 recognised the importance of the weldability requirements to local industry by requiring the new higher strength steels to the same maximum CEV limit that was in the previous edition of the Standard; specifically, CEV
equal to 0.49 for a cast analysis and 0.51 for a product analysis. Two new tables were added to AS/NZS 4671:2019 to provide the limiting mechanical properties (Figure 2a) and chemical compositions (Figure 2b) for steels greater than 500 MPa.

Figure 1: AS 3600:2018, Table 3.2.1 allowing steel $>500$ MPa $\leq 800$ MPa
Standards and Innovation

Australian Standards can inhibit innovation because they are documents that set out specifications and procedures designed to ensure products are safe, reliable and consistently perform the way they are intended to (Standards Australia 2019). Where the requirements are prescriptive it is difficult for manufacturers to innovate. The design Standard AS 3600 and the product Standard AS/NZS 4671 pre 2018 together limited manufacturers to produce reinforcing steels with a maximum yield strength of 500 MPa. If we compare this with steel fibres, where there is neither an Australian design standard nor a product standard, manufacturers are free to innovate, producing fibres with strengths in excess of 1200 MPa, with very little ductility. Though this flexibility comes at a cost, as there is a reliance on the integrity of the manufacturer’s product specification and their assessment of reliability and expected performance; furthermore, there is no independent authority to set the minimum standard expected.

The solution to the lack of flexibility is a revision to the standard to bring it into line with community expectations, new research and current technology. The community expects that products today are more sustainable; designers want to deliver this; construction workers and logistics companies want a material that is easier, faster or more efficient to transport and handle. Researchers and manufacturers can develop lighter, stronger or more durable materials to address these needs but can be bound by strict and in some cases out-dated requirements until the key stakeholders revise the requirements of a standard. This reflects what has happened with the AS 3600 and AS/NZS 4671 Standards.

THE INNOVATIVE PRODUCT

750 MPa Steel

Australian steel manufacturer, InfraBuild (formerly OneSteel), has released into the market an innovative, patented product meeting the requirements of AS/NZS 4671:2019, that is a Grade 750 MPa Class N and weldable bar with a CEV of less than 0.49. The production of a 750 MPa steel is not new or innovative, however what is new is that the strength is achieved without any reduction in ductility or weldability. Additional, strength in steels is usually achieved by work hardening which decreases the ductility or adding
alloying elements which decreases the weldability. The 750 MPa steel called Viribar®750 has generally better ductility than its 500 MPa Class N equivalent and a similar chemistry, making it just as easy to weld. Figure 3 below shows a typical stress-strain diagram for Viribar®750 compared to a standard 500 MPa Class N bar. Table 1 shows the typical chemistry range for these 750 MPa reinforcing steels.

![Stress Strain Curve Comparison](image)

**Table 1: 750 MPa Steel (Viribar®750) – Typical Chemistries and CEV**

<table>
<thead>
<tr>
<th>Element</th>
<th>C</th>
<th>P</th>
<th>Mn</th>
<th>Si</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Cu</th>
<th>V</th>
<th>CEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max %</td>
<td>0.19</td>
<td>0.040</td>
<td>1.45</td>
<td>0.33</td>
<td>0.040</td>
<td>0.35</td>
<td>0.25</td>
<td>0.10</td>
<td>0.35</td>
<td>0.100</td>
<td>0.44</td>
</tr>
<tr>
<td>Min %</td>
<td>0.14</td>
<td>-</td>
<td>1.10</td>
<td>0.23</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.060</td>
<td>-</td>
</tr>
</tbody>
</table>

**750 MPa in Equivalent Force Capacity Diameters**

Instead of being manufactured in the 500 MPa standard diameters of 10, 12 and 16 mm the 750 MPa bars are available in what is termed equivalent force capacity diameters. The diameters available and their force capacities for the 750 MPa bars are as shown in Table 2.

<table>
<thead>
<tr>
<th>Diameter (mm)</th>
<th>Min. Design Capacity (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{sy,f} = 500$ MPa</td>
<td>$f_{sy,f} = 750$ MPa</td>
</tr>
<tr>
<td>$A_{h,fit} \times f_{sy,f}$</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>8.2</td>
</tr>
<tr>
<td>12</td>
<td>9.8</td>
</tr>
<tr>
<td>16</td>
<td>13.1</td>
</tr>
</tbody>
</table>

**750 MPa Column Fitments**

The 750 MPa steel is manufactured for use as column fitments only, as AS 3600 limits the strength for all other reinforcing in concrete elements to 600 MPa. AS 3600:2018, Clauses 10.7.3 and 10.7.4 indicate that...
if the confining pressure and the restraint to the longitudinal bars provided by the fitments are not changed, then spacing requirements of the fitments are also not changed. Therefore one diameter fitment can be substituted by another diameter fitment provided they have the same or higher design capacity which is given by the product of the area of the fitment (A_{b,fr}) and the yield strength (f_{y,fr}) of the fitment. For example, in Table 1 above -

For a 500 MPa 10 mm fitment, the design capacity is

\[
\frac{\pi \times 10^2}{4} \times 500 = 39.3 \text{ kN}
\]

For a 750 MPa 8.2 mm fitment, the design capacity is:

\[
\frac{\pi \times 8.2^2}{4} \times 750 = 39.6 \text{ kN}
\]

Therefore, the 500 MPa 10 mm diameter fitment can be directly substituted with a 750 MPa 8.2 mm diameter fitment with the same spacing because it has the same or slightly higher design capacity of 39.6 kN.

**No Re-design Required for Column Fitments**

In general, where columns are not designed to carry earthquake actions as part of a moment resisting frame the 500 MPa fitment can be directly substituted with the equivalent force diameter 750 MPa fitment with no re-design required. For columns designed as part of an earthquake resisting frame, AS 3600:2018 Clause 14.5.4 (b) requires an additional spacing check which is arguably unnecessary given that the additional nominal spacing between fitments will be 3mm or less if the 750 MPa fitment is directly substituted for the equivalent 500 MPa fitment. Standards Australia has issued for public comment Amendment 1 to AS 3600:2018 which includes a change to this Clause. When this Amendment is published the 500 MPa fitment may be directly substituted with its 750 MPa equivalent without any redesign even when the column is to resists earthquake loads.

No re-design required for the product to be substituted into a project obviously offers a significant advantage. Columns designed with standard 500 MPa fitment can be substituted with 750 MPa fitments at any stage in the project without any time delays because of an engineer having to perform design checks. The substitution could begin anywhere along the construction supply chain or even during the construction stage of a project. Even if the lower floors were reinforced with 500 MPa fitments, the upper floors could still utilise 750 MPa fitments.

**600 MPa REINFORCING BAR**

**AS 3600 – Concrete structures**

AS 3600:2018 – *Concrete structures*, limits the yield strength of bars in the majority of reinforced concrete elements to 600 MPa, so this is the grade which should have the greatest applicability for designers and builders and is potentially easier to manufacture than the higher strength Grades. 600 MPa reinforcing bar can be produced by a combination of chemistry, controlled rolling and quenching and still be within the limits of chemistry and ductility required by AS/NZS 4671:2019.

If it is a larger market and easier to produce, then why have manufacturers not focused on producing a 600 MPa reinforcing steel and why are designers not demanding it? The reason is not obvious until you start looking at the individual clauses in AS 3600 and applying them to a design using 600 MPa reinforcing steel. If we consider columns, predominately in compression, there are no issues with deflection and a higher strength reinforcing bar intuitively should result in a higher load capacity if the bar is a higher strength and the same area of steel is provided. Testing conducted at the University of New South Wales (Khalajestani et al 2018) using nominal 600 MPa longitudinal bars and 750 MPa fitments confirms that this is the case.
When the standard grade of reinforcing steel went from 400 MPa to 500 MPa the force - moment interaction diagram showed typical increases in capacity of 6% for axial load to 21% as shown in Figure 4. This leads to an expectation there would be a similar improvement when steel strengths are raised from 500 to 600 MPa.

However, applying AS 3600:2018 Clause10.6 shows there is little benefit in using 600 MPa steels for increasing axial capacity as shown in Figure 4. Clause 10.6.2.2 limits the strain under squash loads to 0.0025 while Clauses 10.6.2.3 which limits the strain in the extreme compressive fibre of concrete to 0.003 means that the full 600 MPa capacity of the reinforcing bar cannot be utilised. This is best explained with reference to Figure 5 which shows the idealised stress/strain curves referred to in AS 3600 for 500 and 600 MPa steels and 50 MPa concrete.
Figure 5: Idealised Stress-Strain Curves to AS 3600:2018

AS 3600, Clause 10.6.2.2 and compatibility, represented in the idealised stress strain-strain curve in Figure 5a means that the maximum stress in the concrete is assumed to be reached when the strain is 0.0025. Figure 5b showing the idealised stress-strain curves for 500 and 600 MPa, this indicates that at a strain of 0.0025 the stress in the steel is 500 MPa. The squash load for a column in accordance with this Clause is:

\[
\text{Squash load} = \text{Concrete Stress} \times \text{Concrete Area} + \text{Steel Stress} \times \text{Steel Area}
\]

Given the steel stress is limited by the strain to 500 MPa, the calculated squash load using AS3600 is the same whether 500 or 600 MPa steel is used. For the capacity of 600 MPa steels to be fully utilised the concrete strain under squash load would need to be increased to 0.003. Furthermore, Clauses 10.6.2.3 and 10.6.2.5, used to determine the decompression point in the axial load-moment diagram require:

a) the extreme compression fibre in the concrete to have a limit of 0.003 strain; with

b) the extreme tension fibre in the steel to have a value equal to zero.

Figure 6 provides an example to show how Clauses 10.6.2.3 and 10.6.2.5 limit the compression in 600 MPa steels below its capacity; by comparison the 500 MPa reinforcing steel is allowed to reach its full capacity. The example considers a 600 x 600 mm column as noted in Figures 6a and 6b. A compressive load and a moment are applied to determine the decompression point. The strains are shown in Figure 6a for each layer of reinforcement S1, S2, S3 and S4. Using the two strains specified in the AS 3600 at the decompression point, the strain at the 3 other layers of reinforcing bars \(\varepsilon_{52}, \varepsilon_{53},\) and \(\varepsilon_{54},\) can be determined and are tabulated in Figure 6d. Using these values of strain at each layer, the stress in the 500 and 600 MPa bars can be determined using the idealised stress strain diagrams in Figure 6c or by using the recognised simplified equations:

a) For 500 MPa steels – Stress = Min (\(\varepsilon \times 2 \times 10^5\), 500)

b) For 600 MPa steels – Stress = Min (\(\varepsilon \times 2 \times 10^5\), 600)
The results of the stress at each layer have been determined using equations a) and b) and are tabulated in Figure 6d for the two steels.

The stress values in layer 1 for 500 MPa steels shows that the capacity of the bars in this layer are fully utilised compared with layer 1 for 600 MPa steels which shows only 89% of the capacity is utilised. To
enable the 600 MPa steels to be fully utilised, the strain in the extreme compression fibre in the concrete would need to be raised to 0.0035 in line with research conducted by (Parvez et al 2017), Eurocode 2 (British Standards Institution, 2008) and the fib model concrete code (Walraven and Bigaj-van Vliet, 2010).

Similar calculations can be performed from the decompression point to the balance point on the axial force-moment interaction curve to get the full diagram shown in Figure 5. However, until the values for concrete strain are reviewed in AS 3600:2018 for columns there is little value in specifying 600 MPa for longitudinal column bars, even though they are permitted by the AS 3600:2018 design models.

**ADVANTAGES OF HIGH STRENGTH STEELS**

There are numerous benefits that high strength steels offer both the construction industry and the community more generally. A higher strength product generally means less material is required to carry the same load or perform the same function. The lighter product leads to a significant list of benefits including:

- Improving the sustainability credentials for a project
- Reduced transport, handling and fixing costs
- Improved safety through lighter manual lifts on site
- Less space is required for site storage

**Specifying 750 MPa Fitments**

Anecdotal evidence has shown that construction companies are the drivers for 750 MPa fitments because of the benefits they offer. Structural Engineers are specifying them because of the ease with which they can be substituted for fitments originally designed in 500 MPa standard diameters. Changes to AS 3600:2018 allow the 750 MPa fitments in equivalent force capacity diameter as listed in Table 2 to be substituted without redesign. Engineers can specify either 500 MPa or 750 MPa fitments and allow the equivalent bar in the different yield strengths to be substituted. The manufacturers of the 750 MPa fitments have also produced product and technical information including design calculations to AS 3600:2018 demonstrating how conformance is achieved (InfraBuild 2020).

The 750 MPa steel’s conformance to AS/NZS 4671:2019 and AS 3600:2018 means that it is deemed to comply with the Building Code of Australia and the National Construction Code. Test certificates with mandatory minimum information requirements introduced in the latest version of the AS/NZS 4671 would give builders and certifiers additional confidence of the material’s conformance to meet the regulatory authorities’ requirements.

**Benefits of 750 MPa Fitments**

The 750 MPa steel used as a fitment has 33% less mass and uses less energy to manufacture, transport and handle, than its equivalent 500 MPa fitment meaning it is a more sustainable option. This reduction in raw material and energy use enhances resource conservation and leads to a potential embodied energy and greenhouse warming savings of approximately 30%

It is widely recognised that specifying a steel product improves sustainability in construction as it is considered the most recycled building material in the world.

The Waste Hierarchy (Figure 7), a fundamental guide to managing our diminishing resources, demonstrates
the 33% reduction in mass provided by specifying a 750 MPa fitments is even more valuable for sustainability than its recyclability credentials.

The sustainability credentials of 750 MPa column fitments are specifically recognised by the Green Building Council of Australia which automatically awards 1 Green Star point in their Green Star rating tool, if they are used on a project. Similarly, the Infrastructure Sustainability Council of Australia’s rating tool recognises in their material calculator the benefits of using less steel product and rewards it accordingly.

Transport, handling and fixing costs are all potentially reduced because of the lighter fitment. The savings in transport will generally be a benefit to the manufacturer as they are charged a rate based on the mass of product transported. Reduced crane costs, as less lifts are required, and reduced fixing costs, which are charged by the tonne, represent a saving for the builder.

A lighter fitment not only leads to potential productivity improvements but also reduces the safety risk associated with lifting heavy construction materials. Consider the fitments in the example shown in Figure 6. The external set of fitments if they were 500 MPa, N12 at 350 mm centres for a 4 m high column would weigh 24 kg; by contrast 750 MPa, 9.8 mm fitments would weigh just 16 kg. Steel fixers will typically try to move the whole bundle from its storage location to where it is needed to be fixed in a column. While 25 kg is the OH&S limit for a man, the 16 kg bundle of fitment would be easier to lift and be a lesser risk of causing back injuries.

The 750 MPa smaller diameter bars with equivalent capacity means that congestion of reinforcement using traditional 500 MPa fitments can be reduced allowing faster fixing times and better concrete flow. This is of particular benefit for design in seismic regions where a high concentration of column fitments is required for concrete confinement to enable the column to behave in a more ductile manner under extreme loads. Figure 8 shows an example from the US (CKC 2020) of the reduction in congestion by using high strength steel fitments.

Figure 8 - High strength ties in foreground, standard grade ties in background

A further benefit offered specifically by Viribar®750 is that rather than being deformed bar it is a smooth bar. This gives a larger effective area for strength, reduces friction between bars which is of particular benefit to steel fixers as it reduces the interference between bars and also reduces resistance to concrete flow during placement.

Projects

The real measure of the benefit that higher strength steels offer, is whether the potential opportunities can be realised for a tangible gain. At this early stage it appears that at least one Tier 1 construction company in Australia has achieved a that gain. This construction company first used 750 MPa fitments on a residential care facility in Five Dock, NSW. The original structural engineering documents specified 500 MPa N12 fitments, but the engineers were satisfied that AS 3600:2018 allowed these to be substituted with equivalent capacity 750 MPa 9.8 mm (Viribar®750 - V9.8) fitments. The five storey building had a total of just under 9 tonnes of N12 fitments substituted by less than 6 tonnes of V9.8 fitments. The success of the 750 MPa fitments in the residential care facility led the construction company to advise their structural engineering consultant to specify 750 MPa fitments on all major projects. Subsequently, supply of 750 MPa V9.8 fitments for a building in excess of 70 storeys on Sydney Harbour commenced in August 2020 with numerous other buildings to follow.
CONCLUSIONS AND FUTURE WORK

Conclusions
A significant amount of research and development has enabled 750 MPa equivalent force capacity fitments to be directly substituted for standard diameter 500 MPa fitments. University tests have confirmed the theory, which is now reflected in the Australian Standards, for high strength steel fitments. Product manufacturers have responded with an innovative approach to manufacture 750 MPa bars in diameters that are equivalent in force capacity to 500 MPa diameter bars. These 750 MPa, Class N, non-standard diameter bars are readily weldable and make design and/or direct substitution of the product for standard 500 MPa fitments more practical and easier, delivering a range of benefits for the project and the community via its greater environmental credentials.

Further Research and Development
This paper has also highlighted that more R & D work is required for high strength longitudinal bars in columns to yield a similar benefit as high strength fitments in columns. While laboratory test at the University of New South Wales has shown that 600 MPa longitudinal reinforcement offers a significant increase in column capacity it is not reflected in the design Standard AS 3600:2018 – Concrete structures. Work by Australian Standards committees to continually revise AS 3600 as they recognise these tests and the equivalent concrete design Standards from other jurisdictions will drive manufacturers to produce more innovative products.

Significantly more work can be done to explore the benefits high strength steels has for flexural members and those currently governed by serviceability requirements. InfraBuild continues to drive research, standards and their own manufacturing facilities to innovate.

REFERENCES