Design and Detailing for Resilience and Sustainability of Concrete Structures

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ABSTRACT: With the increasing regularity and severity of natural disasters such as floods, fires, cyclones, severe storms, hail, heatwaves, coastal inundation and earthquakes, the importance of providing a resilient built environment is becoming an essential part of design for Engineers. Resiliency could be defined as the need to design so that buildings can return to full functionality after such extreme events, ideally with no damage, but certainly so that it is repairable after a design event, without causing severe economic and social costs.

Reinforced concrete has been used in Australia since 1895 because of the many benefits that it continues to offer in terms of resilience against fire, termites, water and hot and cold weather, as well as long life, low maintenance and sustainability. Requirements to provide robustness against earthquakes was first included in the Standards in 1979, and the revision of AS 3600 in 2018 included design requirements to further improve the resilience of buildings based on the lessons learnt from the Christchurch earthquake in 2011.

Designs that provide long life with minimum maintenance makes them inherently sustainable. The recent focus on reducing embodied carbon through material minimisation appears to have introduced conflicting requirements, as this approach may reduce the resilience and long-term sustainability through inadequate detailing. This paper considers some important design and detailing issues for designing reinforced concrete for resilience, and from a low embodied carbon perspective, addresses the issue of material minimisation.

KEYWORDS: robustness, resilience, sustainability, long life, low maintenance

INTRODUCTION

Resilience encapsulates our ability to not only survive disasters and extreme events such as bushfires, floods and earthquakes, but to also recover more quickly from them, with reduced impact on not only peoples' lives, but also in many cases, their livelihoods. Robustness on the other hand, is defined in the NCC [1] as "designing to sustain local damage, with the structural system as a whole remaining stable and not being damaged to an extent disproportionate to the original local damage". While natural disasters (paticularly earthquakes) may cause local damage, robustness will ensure the buidling survives and provides life safety, and resilience is the ability to recover from the event, including repairing damage.

A special report by Deloitte [2] estimates that by 2060, natural disasters will cost Australia $73 billion annually under a low emissions senario, or one which limits CO_2 emissions and hence climate change caused by global warming and the resultatnt increased frequency of severe weather events and natural hazards. Natural hazards include events such as flooding, bushfires, tropical cyclones, severe storms, hail, heatwaves, earthquakes, coastal inundation and tsunamis. "Disaster occurs when natural hazards intersect with people and things of value, and when the impacts of hazards exceed our ability to avoid, cope or recover from them" [3]. The Deloitte report was commissioned to better understand the costs associated with these events (**Figure 1**), to allow better decision making regarding investments in resilience, mitigation and post-disaster recovery.

In comparison to natural hazards such as floods, severe storms and cyclones which occur on a regular basis, the losses attributed to earthquakes are comparatively small. This is because in Australia we are considered to have low to moderate seismicity compared to other countries such as New Zealand, and earthquakes tend to occur in remote areas. However, when an earthquake occurs in a major city, the impacts can be devastating. Consider Christchurch, New Zealand, where a Magnitude 6.2 earthquake destroyed 95% of the CBD area (**Figure 2**). In comparison, the new Royal Adelaide Hospital in Australia, which has a post disaster function, was designed for a Magnitude 7.5 earthquake, demonstrating that major earthquakes are expected here in Australia. Fortunately, only a few major cities have experienced earthquakes in the past in Australia, including Adelaide in 1954 (Magnitude 5.5), Meckering in Western Australia in 1968 (Magnitude 6.9), and Newcastle in 1989 (Magnitude 5.6). It was fortunate that both Meckering and Newcastle events occurred on public holidays, limiting the number of people exposed in the city centres.

The Adelaide event resulted in 3,000 buildings being damaged and 30,000 insurance claims. The Meckering event damaged or completely destroyed most structures and resulted in a 37 km long fault line scarp (**Figure 3**). The Newcastle event is considered one of Australia's worst natural disasters with damage extending over a 9,000 square kilometre area with movement up to 800 kilometres away (**Figure 4**). Aside from the estimated $4 billion of damage (at the time) to 35,000 homes, 147 schools and 3,000 buildings, the real tragedy was the 13 people that were killed, and further 160 that were hospitalised.

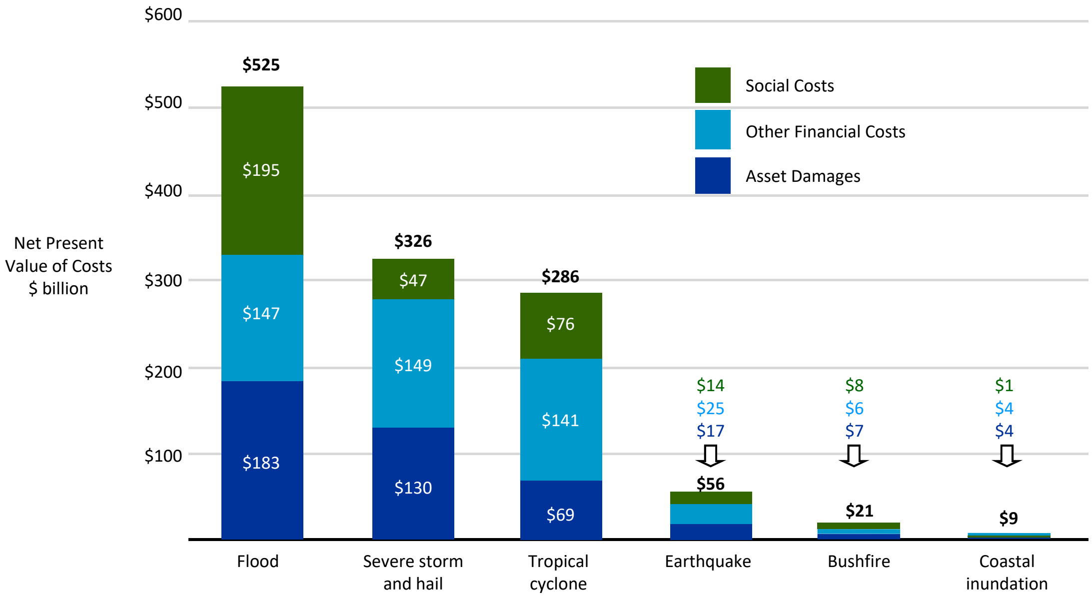


Figure 1 Predicted present value of economic costs and the components of costs under low emissions scenario by type of natural disaster over the next 40 years (from Deloitte Access Economics 2021[2])

The Woods Point earthquake, some 130 kilometres east of Melbourne in September 2021, was a Magnitude 5.9 event that was felt as far as 750 kilometres away and resulted in some 120 buildings being damaged, some of which were located in Melbourne. The south east region of Australia is considered one of the more seismically active regions in Australia.

In Christchurch, New Zealand's second largest city and the largest on the south island, the economic asset loss was approximately $55 billion, not to mention the social and other financial costs associated with the many thousands of displaced residents and businesses that could no longer operate. This is virtually the same as the projected cost by Deloitte over the next 40 years in Australia (**Figure 1**), and demonstrates that while earthquakes are considered a low incidence event in Australia, they are also a high consequence event. Christchurch only had a population of about 370,000 at the time, compared to the loss that would result in one of our major urban areas with a population many times that of Christchurch. According to the Bushfire and Natural Hazards CRC [4], "the international reinsurance industry recognises that a moderate earthquake in Sydney is in their top-10 financial risks". It goes on to state that "there is a perception in the Australian construction industry that design for earthquakes is a poor use of money due to the low likelihood of a strong earthquake in Australia". Fortunately to date, many of the major earthquakes experienced in Australia have been in remote outback areas that are sparsely populated, possibly explaining the low estimated cost of earthquake damage in **Figure 1**. However, as previous earthquakes have demonstrated, dispite the probability of an earthquake being low in our major cities, they are not immune as stated by Geosciences Australia [5].

Geosciences Australia [5] expects that Australia will experience:

- 1 shallow earthquake of Magnitude 6.0 or more once every 10 years, which is almost equivalent to the 2011 Magnitude 6.2 Christchurch earthquake.
- 1 shallow earthquake of Magnitude 5 or more every two years, which is equivalent to those in Newcastle and Adelaide.
- 2 Magnitude 5 earthquakes every year.

Figure 2 CBD area of Christchurch, New Zealand following demolition of the majority of damaged buildings after the 2011 Magnitude 6.2 earthquake.

Figure 3 Fault line scarp from the Meckering, Western Australia 1968, Magnitude 6.9 earthquake.

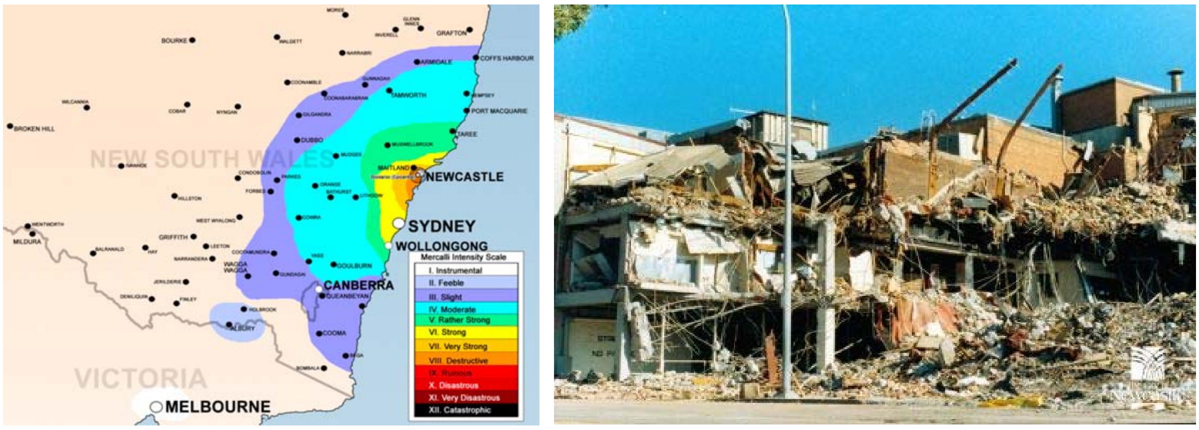


Figure 4 Influence of the Newcastle earthquake and damage to the Newcastle Workers Club, which was subsequently demolished and rebuilt (Photo Courtesy Newcastle Library).

RESILIENCE AND SUSTAINABILITY OF REINFORCED CONCRETE BUILDINGS

Reinforced concrete has numerous properties that contribute to the resilence of buildings. In 1913 in a presentation to the Institute of Engineers in Queensland, European Engineer L. Massy was reported by the Brisbane Courier as highlighting the rapid acceptance and widespread use of reinforced concrete because of its many benefits, which he stated included "(1) fireproof, (2) antproof, (3) waterproof, (4) easy to build, (5) no skilled labour needed, (6) lowest cost of insurance, (7) substantiality, (8) light construction, (9) good, aesthetic, and attractive appearance, (10) impermeable, (11) unaffected by hot or cold weather, (12) or by sea water, (13) durability, (14) soundproof, (15) decreased maintenance, &c., &c." These benefits have not changed and still provide reinforced concrete with the resilience to survive natural disasters.

FM Global [6], one of America's large insurance companies considers resilience to be a choice, and works with their clients to assess risks and offers advice regarding the resilience of their client's buildings to minimise potential losses from not only natural hazards, but also events such as building fires. To assist clients, they have released a Worldwide Earthquake Map to determine the probability of earthquake damage. However, fire is highlighted as the most significant risk exposure. Strategies to improve resilience against fires include retrofitting of solid (concrete) floors and replacing combustible wall panels with fire-retardent ones, reinforced concrete also satisfying this criteria. In terms of resilience against damage from flooding, quicker recovery after the event is possible with concrete floors and waterproof walls of solid (concrete) construction, possibly tiled as well.

Regarding earthquakes, the damage caused to buildings in Christchurch, not adequately designed and detailed for earthquakes, was a real wake up call for designers. The lessons learnt from how buildings performed in that disaster formed the basis of the 2018 revision of our Concrete Structures Standard AS 3600 [7], in order to make our future reinforced concrete buildings more resilient and provide greater life safety to people that may be trapped inside during a seismic event. In fact, the devastation in Christchurch has resulted in the New Zealand Government changing the design requirements so that every new building must be able to be repaired after the design earthquake event, to prevent such economic loss and community disruption again. So it is not just about making our built environment more resilient to these events, it also involves better preparing communities and businesses to recover from such events. To this end, our focus on disaster resilience has led to the establishment of the Sydney Resilient Office, to consider potential disasters that may occur in Sydney, and to help build community resilience to cope with such events. The task requires the involvement of all levels of Government, businesses and the community.

Reinforced concrete structures offer inherent resilience to natural disasters, and their longer service life, without needing replacement provides improved sustainability. The current focus on reducing embodied carbon through minimising the materials within structures has to be balanced against the ability of the structure to be both durable, resilient and sustainable over time. As an example of this, Dr Chris Bridges of Aurecon stated in Engineers Australia Create Magazine, September 2022, that “With my sustainability hat, I want to be using less material, less carbon. And then with my resilence hat, I am trying to protect the infrastructure for the next 100 years”. Australian Standards have recently introduced higher grade reinforcing steels to allow less materials but still achieving performance requirements. This will minimise materials and yet still deliver sustainability outcomes.

AS 3600 RESPONSE

Specifically regarding the design for robustness of new reinforced concrete buildings, the 2018 revision of AS 3600 incorporated new reinforcement design and detailing provisions to make our buildings more resilient to earthquake events.

This section focuses on clarifying two detailing areas that are critical to the resilience of buildings in extreme events such as earthquakes: structural integrity reinforcement and arrangement of fitments in beams, as some Engineers are misinterpreting these requirements released in 2018. The minimum reinforcement detailing provisions in the Standard are there for a reason and Engineers should be interpreting the provisions correctly and complying with them.

Structural Integrity Reinforcement

Structural integrity reinforcement consists of a few reinforcing bars passing through the confined core of the column, which is the section within the column reinforcement cage **Figure 5**. This is critical, as research and evidence from past earthquakes has shown that the unrestrained cover concrete can be lost as a result of the lateral displacement of the structure or building during an earthquake **Figure 6**.

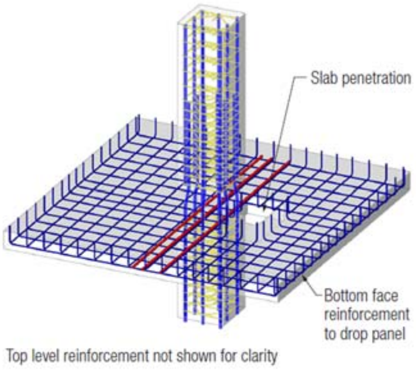


Figure 5 3D view of reinforcement at column-slab intersection showing structural integrity reinforcement in red (*detail courtesy of Wallbridge & Gilbert*)

Figure 6 Unrestrained cover concrete to column of Copthorne Hotel in Christchurch lost during 2011 seismic event (*photograph courtesy Peter McBean*)

This nominal amount of reinforcement was found to be very effective at preventing the collapse of slabs following punching shear failures in Christchurch, improving the life safety of the building **Figure 7**. The Newcastle Workers Club punching shear failure resulted from no structural integrity reinforcement being provided **Figure 8**. The benefits provided led the SRIA to include this aspect of detailing on the cover of the 2016 *Guide to Seismic Design and Detailing of Reinforced Concrete Buildings in Australia* [8], which is freely available as a pdf copy from the SRIA website. While the Guide includes guidance on structural integrity reinforcement, it has come to our attention that the provisions for slabs in Clause 9.2.2 of AS 3600 in 2018, are being misinterpreted. As a result, the SRIA has produced a new separate *Technical Note 8* [9] to clarify the requirements for structural integrity reinforcement for slabs.

The area of reinforcement required is covered in Clause 9.2.2 of AS 3600 [7]. Paragraph 1 states that: "The summation of the area of bottom reinforcement connecting the slab, drop panel, or slab band to the column or column capital on all faces of the periphery of a column or column capital shall be not less than,

$$A_{\text{s.min}} = \frac{2N^*}{\phi f_{\text{sy}}} \qquad \text{Equation 9.2.2}$$

in which N* is the column reaction from the floor slab at the ultimate limit state."

Figure 7 Punching shear failure with structural integrity reinforcement preventing collapse of slab, Hotel Grand Chancellor, Christchurch
(*photograph courtesy Peter McBean*)

Figure 8 Punching shear failure at Newcastle Workers Club during the 1989 Newcastle earthquake – no structural integrity reinforcement to prevent risk of collapse
(*photo courtesy Cultural Collections, the University of Newcastle, Australia*).

The area of reinforcement required by Equation 9.2.2 should be distributed evenly on all faces of the column (refer Figure 5 in *Technical Note 8* [9]). Note that this reinforcement must be placed in the bottom of the slab, slab band or drop panel, otherwise it will not be effective in providing tensile membrane action to resist the gravity actions and reduce the risk of collapse. Referring to **Figure 8**, it can be seen that the top cover was lost and the top reinforcement, which was left exposed, was not effective at preventing collapse.

The structural integrity reinforcing bars are either spliced with existing bottom reinforcement in the slab in accordance with Clause 13.2 of AS 3600, or are provided as separate bars, extending a distance of $2L_{\text{sy.tb}}$ past the face of the column or column capital. They should have hooked or cogged ends at discontinuous edges, including penetrations. Note that where a punching shear failure may result in the loss of bracing to a perimeter column, additional tie back reinforcement may also be required to control the buckling length of the external column.

Note that the first paragraph of Clause 9.2.2 of AS 3600 specifically includes the connection of a slab band to a column. Often, some nominal reinforcement is provided to slab bands within post-tensioned slabs (**Figure 9**), but slab bands are not considered as beams in terms of structural integrity reinforcement and the nominal reinforcement that may be provided will not satisfy structural integrity requirements based on the exemption given in Paragraph 2 of Clause 9.2.2 which states that: "Integrity reinforcement shall not be required if there are beams containing shear reinforcement and with at least two bottom bars continuous through the joint in all spans framing into the column." The reference to beams is intended to refer to members that cannot punch and are designed in accordance with Section 8 of AS 3600.

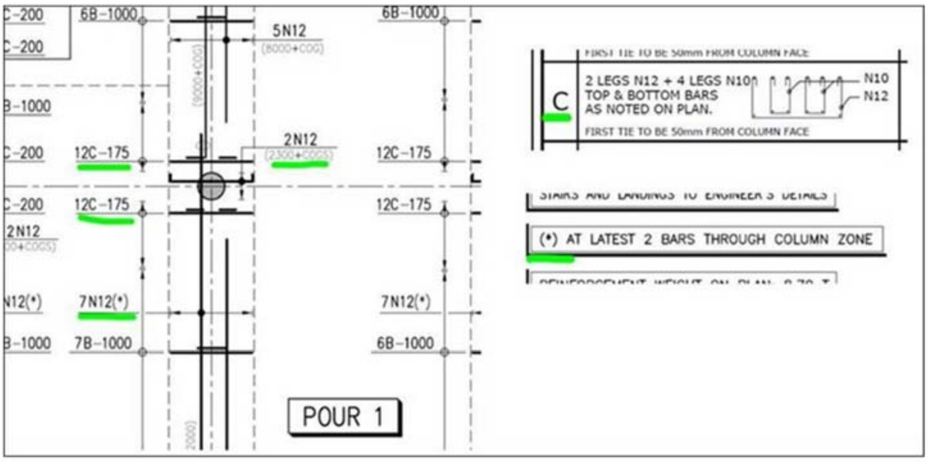


Figure 9 Example of nominal bottom reinforcement to a slab band of a post-tensioned slab (*from SRIA Technical Enquiry*)

Note that in the example shown in **Figure 9**, the 2N12 bottom bars in each direction can be included as part of required area of structural integrity reinforcement, $A_{s.min.}$.

Another issue that we come across is whether post-tensioning can be considered as structural integrity reinforcement. Referring to **Figure 10**, there is no structural integrity reinforcement in the bottom of the slab band over the column. Note that the area of the post-tensioned bonded tendons in the top of the slab and/or slab band at column locations cannot be taken as part of the required structural integrity reinforcement as they are in the top of the slab. The collapse of the Christchurch post-tensioned carpark slabs shown in **Figure 11** demonstrates the importance of providing the required structural integrity bottom reinforcement.

Where slabs are supported by beams, the structural integrity requirements for these are covered in Section 8 of AS 3600. While AS 3600 does not define what a beam is, the rule of thumb is that the depth is 1.5 to 2 times the width with shear reinforcement and cannot punch. Slab bands therefore can not be classified as beams, or wide beams, to avoid the provision of the required area of structural integrity reinforcement, $A_{s.min.}$.

To provide the necessary robustness and resilience to buildings and structures to enable them to survive extreme events such as earthquakes, it is essential that the required structural integrity reinforcement for slabs is provided in accordance with AS 3600.

Figure 10 Post-tensioned slab band (*from SRIA technical enquiry*)

Figure 11 Remains of post-tensioned carpark floor at Christchurch, New Zealand showing punching shear failure at columns (*photograph courtesy Peter McBean*)

Fitments in Beams

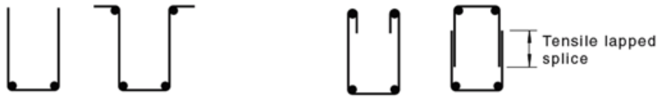
Typically, fitments in beams will consist of closed fitments as defined in Clause 1.6.3.12 of AS 3600 ie continuous around the perimeter and anchored at the ends using 135 degree hooks around a longitudinal bar.

However, Clause 8.3.2.4 of AS 3600 provides four options for anchoring fitments:

- A hook or cog complying with Clause 13.1.2.7 ie a closed fitment, or
- By welding of the fitment to a longitudinal bar, or
- By a welded splice, or
- By lapped splices.

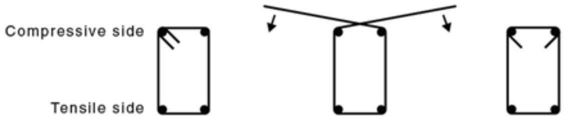
We would not recommend site welding because of its general poor quality, and placing sufficient good quality weld material between a fitment and longitudinal bar for anchorage may not be possible. Using two 'U' bars forming a lapped splice on each side of the beam may be satisfactory for very deep infrastructure type sections, but for the typical beams used in buildings, the plastic deformation during seismic events, and resultant possibility that the unrestrained cover concrete will be lost, is an unsatisfactory solution as it will not develop the required tensile lap capacity.

When the Commentary to AS 3600 [10] was published in March 2022, **Figure 12** was included to advise Engineers of satisfactory methods of providing anchorage to fitments. Every Engineer should have a copy of the Commentary and refer to it for additional background information and clarification of clauses. According to the Commentary to AS 3600, the open fitments shown in **Figure 12** "do not provide confinement for the concrete in the compression zone and is undesirable in heavily reinforced beams where confinement of the compressive concrete may be required to improve ductility of the member."



(a) Incorrect

(b) Undesirable



(c) Satisfactory

Figure 12 Anchorage of fitments in beams (Figure C8.3.2.4(B) of AS 3600 Commentary [10])

Another issue with open fitments such as shown in **Figure 13**, is that the compression reinforcement may not be adequately restrained. Hooks to anchor fitments (as shown at top of beam):

- Do not form a closed fitment – refer Clause 1.6.3.12 of AS 3600.
- Are not satisfactory as torsional reinforcement, which requires closed fitments according to Clause 8.3.3(a) of AS 3600.
- Clause 8.3.1.6 of AS 3600 states that: "Compressive reinforcement required for strength in beams shall be adequately restrained by fitments in accordance with Clause 10.7.4". Note that if perimeter beams are being used as chord members in the design of diaphragms, they should also be designed as columns to cater for the compression loads.

Interestingly, the Americam Concrete Institute in ACI 318M-19 [11], requires a closing tie at the top of the beam if open ties with hooks at the top are used **Figure 14**. Clause 9.7.7.1 of ACI 318M-19 [11] requires closed fitments (or open fitments with a cap tie having the 90 degree bend on the slab side for better confinement) for all perimeter beams. Lap spliced 'U' fitments are not allowed in perimeter beams, and there are specific requirements for these in other situations, as they are considered as undesirable (refer **Figure 12**).

The spacing of fitments is another area that needs to be considered. Clause 8.3.2.2 of AS 3600 dealing with detailing of shear reinforcement states that: "In members not greater than 1.2 metres in depth, the maximum longitudinal spacing shall not exceed the lesser of 300 mm and 0.5*D*; otherwise, the longitudinal spacing shall not exceed 600 mm." However, what should be provided where shear reinforcement is not required? Clause 8.2.1.6 of AS 3600 states that shear reinforcement is only required where: $V^* > \phi(V_{uc} + P_v)$, or $T^* > 0.25\phi T_{cr}$, or the overall depth of the member $D \geq 750$ mm.

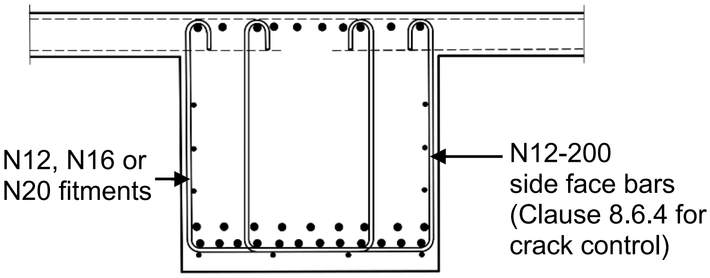


Figure 13 Example of open fitments to transfer beam

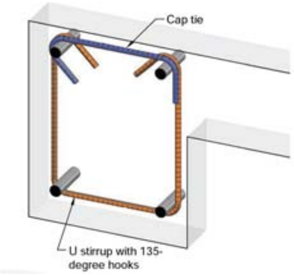


Figure 14 Cap tie (or closing fitment) for open fitments (Figure R9.7.7.1 from ACI 318M-19 [11])

Therefore, when $V^* \le \phi(V_{\text{uc}} + P_{\text{v}})$ and $T^* \le 0.25\phi T_{\text{cr}}$ and the overall depth of the member D < 750 mm, there is no requirement for shear reinforcement. However, some fitments still need to be provided to allow assembly of the reinforcement and hold it securely during construction and placement of the concrete, and will also assist if the beam is subjected to any overloads **Figure 15**.

Some Engineers may reduce the fitments to say R10 at 600 mm centres to minimise the reinforcement, but good detailing practice would be to keep them the same size as that required for shear, and simply adjust the spacing. Again, keeping the number of different spacing to a minimum is also good detailing practice. The maximum spacing of 600 mm consistent with Clause 8.3.2.2 of AS 3600 is considered a reasonable spacing in these areas. To assist in this area, the SRIA has produced a new *Technical Note 9* [12] dealing with the requirements for fitments.

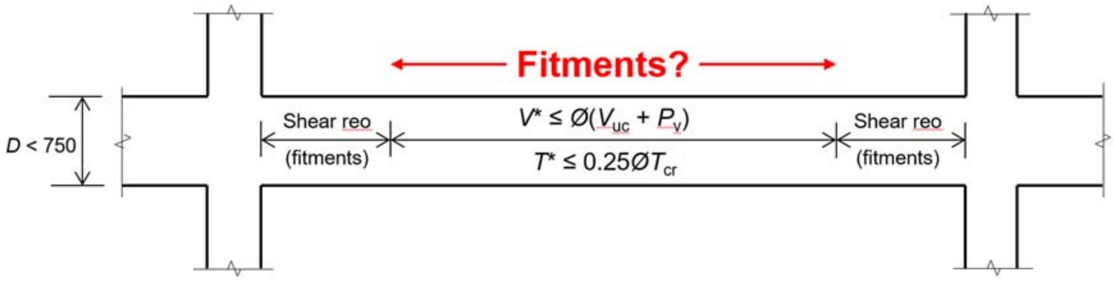


Figure 15 Length where no requirement exists for spacing of fitments

CONCLUSIONS

This paper highlights the benefits of reinforced concrete to provide both robust and resilient structures that are durable enough to provide extended service life which makes them more sustainable. Material minimisation to reduce embodied carbon can still be achieved through the use of higher strength reinforcing steels without the need to comprimise the performance requirements of the structure, and hence its improved sustainability. While there is limited guidance on what constitutes resilient design, providing at least the minimum reinforcement detailing in AS 3600 will ensure sufficient ductilty of the structure, important life safety in seismic events and minimise disruption to the community and associated social costs.

This paper has also highlighted the need to consider the important reinforcement detailing provisions incorporated into the 2018 revision of AS 3600 to address the issue of resilience against the expected risk of earthquake events in our major built up areas, and in particular those relating to structural integrity reinforcement and fitments.

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