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Critical Reinforcement Design and Detailing for Resilience and Preservation of Concrete Structures

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ABSTRACT

Reinforced concrete is the most common and versatile construction system used for buildings and structures worldwide. Ensuring these assets are resilient enough to survive extreme loads and can be maintained and preserved for future generations to use without the need for demolition and replacement, inherently improves the sustainability of our built environment. Australian reinforced concrete buildings have been demonstrated to last in excess of 100 years, however, investigation into building performance following the Christchurch earthquake, identified areas of reinforcement design and detailing that limited the resilience of buildings to survive the earthquake. As a result, 90% of the CBD was subsequently demolished and the building Codes and Standards were changed to ensure future buildings were resilient enough to allow repair following the design earthquake. AS 3600 was subsequently revised in 2018 based on the lessons learnt, to improve the resilience and robustness of building so that the majority of future buildings will survive for many generations to come and continue to provide a sustainable solution.

Knowing what critical reinforcement design and detailing to focus on, and the essential tools to support this design and assessment process, will deliver the resilience to support a more sustainable future. This paper examines critical reinforcement design and detailing performance issues and reviews simple reinforcement details that provide life safety and resilience to buildings and structures. Designing critical transfer elements and slabs inelastically to avoid failure of the structural system, subdivision of unsymmetrical floor plates and secondary services are all examples of essential areas that must be considered.

The Steel Reinforcement Institute of Australia (SRIA) has developed key resources to support engineering challenges in seismic design and detailing and assessment of historical reinforced concrete buildings. These provide the necessary technical information to improve the resilience of buildings and facilitate their preservation and hence improve sustainability.

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.

A special report by Deloitte [1] 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" [2]. 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.

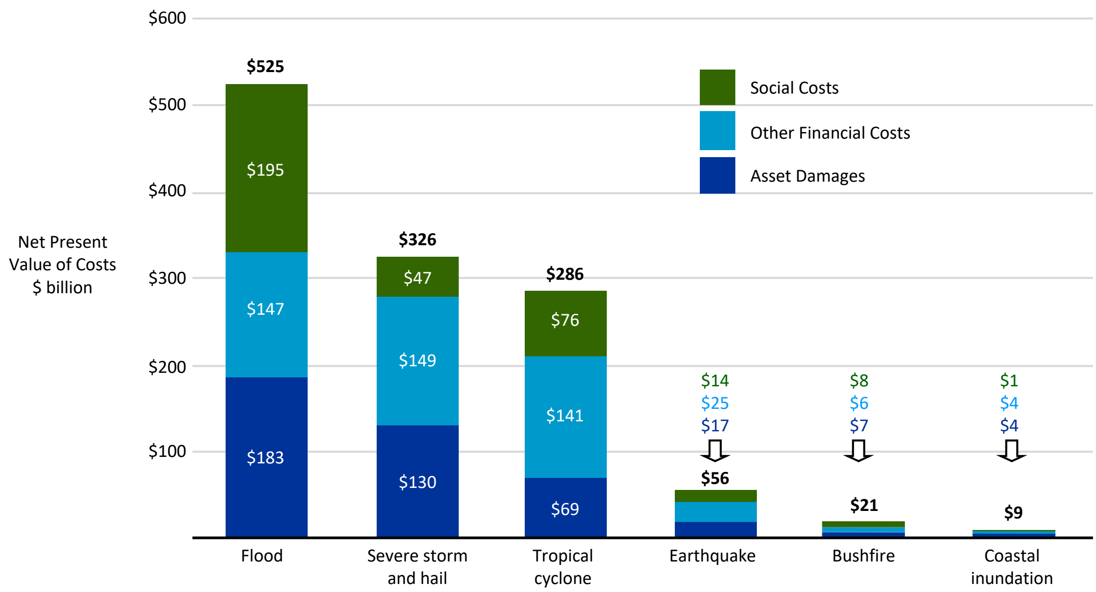


Figure 1 Predicted present value of economic costs and the components of costs under low emissions scenario by type of natural disaster over the next 40 years (from Deloitte Access Economics 2021[1])

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 be rare events, with a recurrence interval of perhaps one in 500 to 2,500 years. 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 earthquake 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 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.

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. As a result, we understand that earthquakes are considered the largest reinsurance risk in Australia. Fortunately to date, many of the major earthquakes experienced in Australia have been in remote outback areas that are sparsely populated.

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.

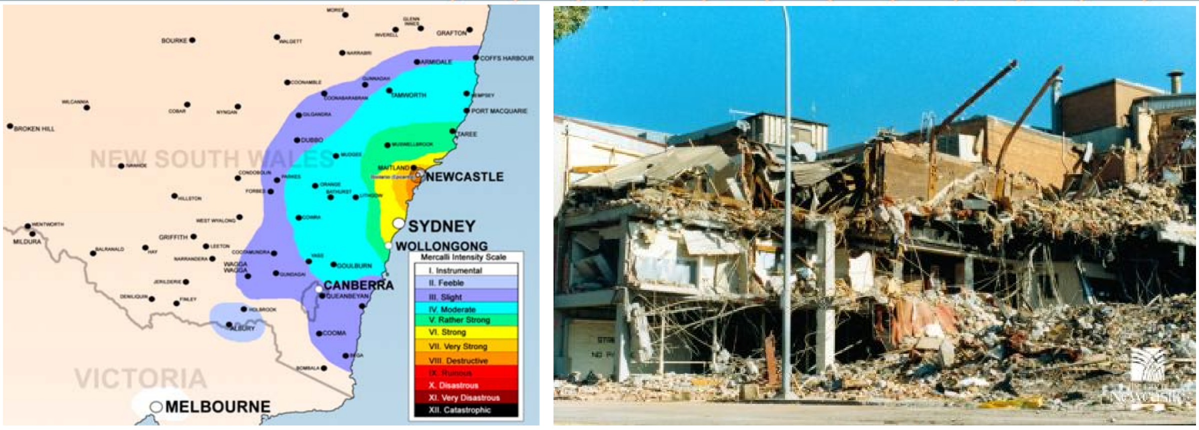


Figure 4 Influence of the Newcastle earthquake and damage to the Newcastle Workers Club, which was subsequently demolished and rebuilt (Photo Courtesy Newcastle Library).

So it is evident that Australia is not immune to major earthquake events. In fact, based on recent earthquake events, Geosciences Australia 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.

RESILIENCE OF REINFORCED CONCRETE BUILDINGS

Reinforced concrete has numerous properties that contribute to the resilence of buildings. FM Global [FM Global Annual Report 2021], 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 from the earthquake event, was a real wake up call for designers, and the lessons learnt from how buildings performed in that disaster formed the basis of the 2018 revision of our Concrete Structures Standard AS 3600 [3], 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, as they never want to see 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, and the role of the Chief resilience officer, Beck Dawson, is 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.

AS 3600 RESPONSE

Specifically regarding the design of new reinforced concrete buildings, the 2018 revision of AS 3600 was essentially to incorporate new reinforcement design and detailing provisions to make our buildings more resilient to earthquake events. However, Engineers are apparently still coming to terms with the new requirements, so this paper will focus on a few key areas that need to be clarified in terms of the way that certain clauses are being interpreted within the Standard. We understand that to produce more sustainable designs, there is a process of material minimisation being adopted, but 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.

The two areas that are the focus of this paper, are two aspects of reinforcement detailing that some Engineers are misinterpreting and yet are critical to the resilience of buildings in extreme events such as earthquakes. These are structural integrity reinforcement and arrangement of fitments in beams.

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**.

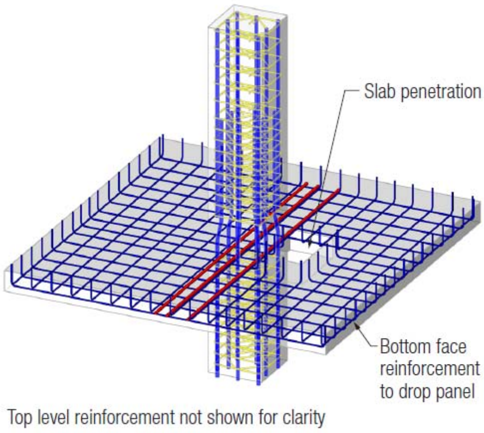


Figure 5 3D view of reinforcement at column-slab intersection showing structural integrity reinforcement in red (*detail courtesy of Wallbridge & Gilbert*)

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

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 is an example of punching shear failure where no structural integrity reinforcement was 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* [4], which is also 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 that were included as 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 [5] to clarify the requirements for structural integrity reinforcement for slabs.

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*).

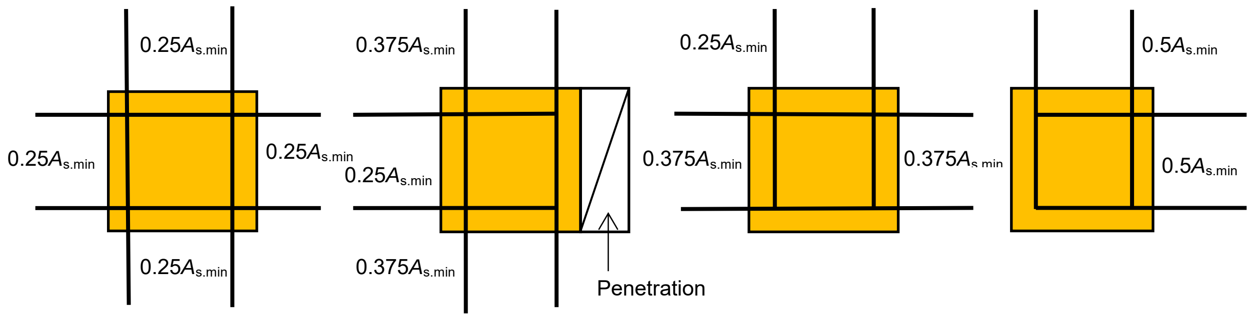
The area of reinforcement required is covered in Clause 9.2.2 of AS 3600 (2018). Paragraph 1 states that: “The summation of the area of bottom reinforcement connecting the slab, drop panel, or slab band to the column or column capital on all faces of the periphery of a column or column capital shall be not less than,

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

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

The area of reinforcement required by Equation 9.2.2 should be distributed evenly on all faces of the column **Figure 9**. Note that it 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 or AS 3600, or are provided as separate bars, extending a distance of $2L_{\mathrm{sy.tb}}$ past the face of the column or column capital. They should have hooked or cogged ends at discontinuous edges, including penetrations.



(a) Interior column (b) Penetration or edge column (c) Corner column

Figure 9 Example of the arrangement of reinforcement – total area all sides = $A_{\mathrm{s.min}}$

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 (refer example in **Figure 10**), but slab bands are not considered as beams in terms of structural integrity reinforcement and the nominal reinforcement that may be provided cannot be taken as satisfying 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, for which separate structural integrity reinforcement requirements apply.

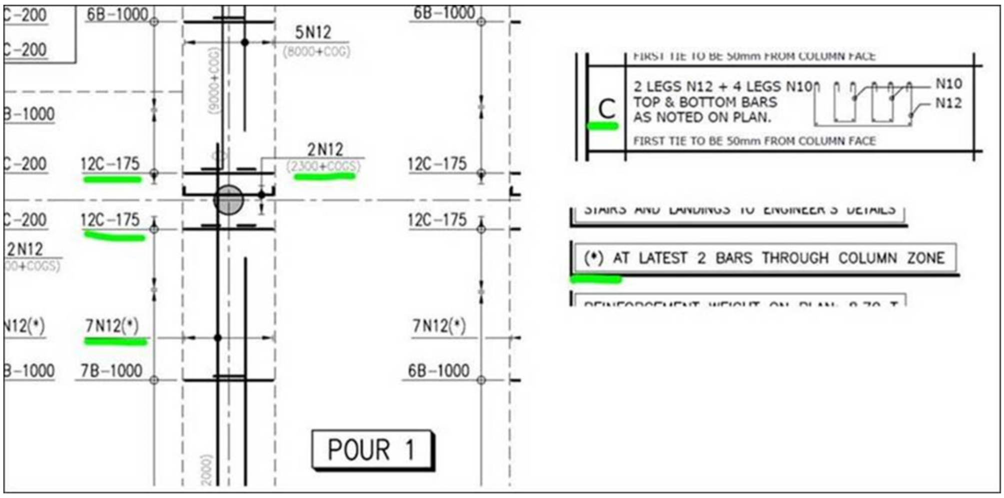


Figure 10 Example of nominal reinforcement to a slab band of a post-tensioned slab (*from SRIA Technical Enquiry*)

Note that in the example shown in **Figure 10**, 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 11**, 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 for punching shear as they will fracture. The collapse of the Christchurch post-tensioned carpark slabs shown in **Figure 12** demonstrates the importance of providing the required structural integrity bottom reinforcement.

Figure 11 Post-tensioned slab band (*from SRIA technical enquiry*)

Figure 12 Remains of post-tensioned carpark floor at Christchurch, New Zealand showing punching shear failure at columns (*photograph courtesy Peter McBean*)

Post-tensioned bonded tendons placed in the top can be used for general robustness calculations, where the designer is allowing for the removal of a column but not for punching shear structural integrity reinforcement which is to provide ductility in a punching shear failure.

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 and cannot punch. Slab bands should 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 the provisions in AS 3600. This is why the SRIA has released a new Technical Note 8 [5] which is available for download from the Resources tab on the SRIA website: sria.com.au.

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 [6] was published in March 2022, **Figure 13** 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 13** “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.”

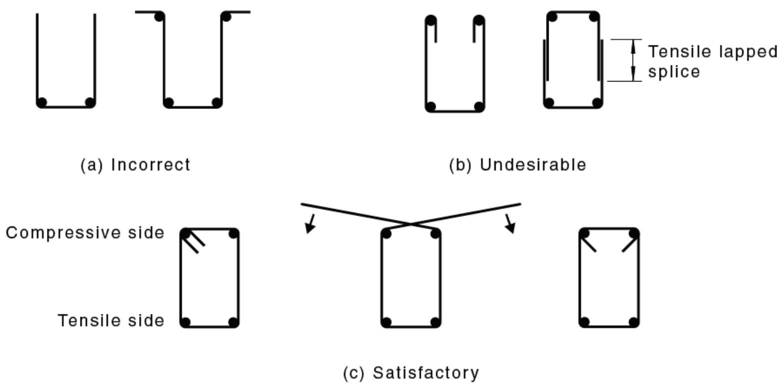


Figure 11 Anchorage of fitments in beams (Figure C8.3.2.4(B) of AS 3600 Commentary [6])

Another issue with open fitments such as shown in **Figure 14**, 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 [7], requires a closing tie at the top of the beam if open ties with hooks at the top are used **Figure 15**. Clause 9.7.7.1 of ACI 318M-19 [7] 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 13**).

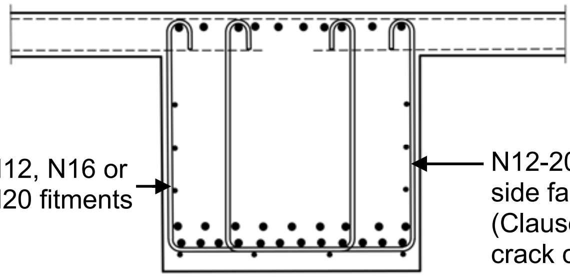


Figure 14 Example of open fitments to transfer beam

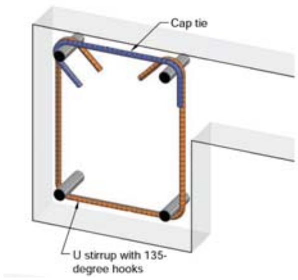


Figure 15 Cap tie (or closing fitment) for open fitments (Figure R9.7.7.1 from ACI 318M-19 [7])

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.

Therefore, when $V^* \leq \phi(V_{uc} + P_v)$ and $T^* \leq 0.25\phi T_{cr}$ 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 16**.

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 [8] dealing with the requirements for fitments.

Clause 9.6.3.1 of ACI 318M-19 [7] also states: "For repeated loading of beams, the possibility of inclined cracks forming at stresses appreciably smaller than under static loading should be taken into account in design. In these instances, use of at least the minimum shear reinforcement expressed by

9.6.3.4 is recommended even though tests or calculations based on static loads show that shear reinforcement is not required." In these situations, providing at least the minimum shear reinforcement would thus be adviseable.

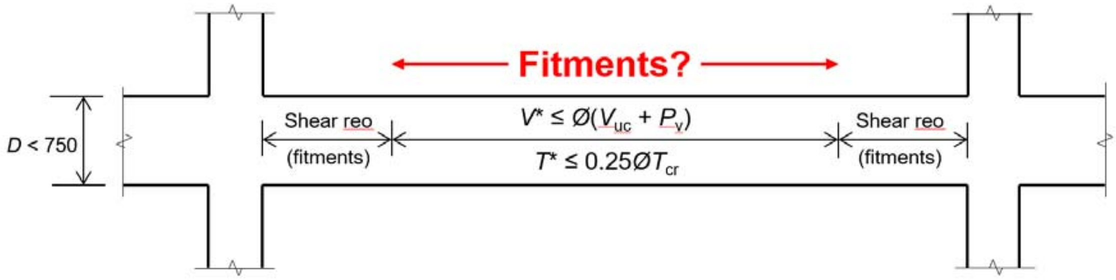


Figure 16 Length where no requirement exists for spacing of fitments

CONCLUSIONS

This paper has highlighted the need to consider the revised reinforcement detailing provisions incorporated into the 2018 revision of AS 3600 to address the issue of resilience against earthquake loading, and in particular those relating to structural integrity reinforcement and fitments. 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 to provide the important life safety in seismic events and minimise disruption to the community and associated social costs.

REFERENCES

1. Australian Business Roundtable for Disaster Resilience & Safer Communities, Deloitte Access Economics, *Special report: Update to the economic costs of natural disasters in Australia* (2021).
2. Commonwealth of Australia, *Royal Commission into National Natural Disaster Arrangements Report* (2020).
3. Standards Australia, AS 3600 *Concrete structures*, 2018.
4. SRIA, *Guide to Seismic Design and Detailing of Reinforced Concrete Buildings in Australia*, 2016.
5. SRIA, Technical Note 8 *Structural Integrity Reinforcement*, 2022.
6. Standards Australia, AS 3600:2018 Sup 1:2022 Concrete structures – Commentary (Supplement 1 to AS 3600:2018.
7. American Concrete Institute, *Building Code Requirements for Structural Concrete* (ACI 318M-19) and *Commentary on Building Code Requirements for Structural Concrete* (ACI 318R-19), 2019.
8. SRIA, Technical Note 9 *Requirements for Fitments*, 2022.

BIOGRAPHIES

Scott Munter - Scott Munter is a structural engineer and Executive Director/CEO for the Steel Reinforcement Institute of Australia. Previously Scott worked for BlueScope Steel (3 years), Australian Steel Institute (7 years) and has a 15 year Structural Consulting Engineering track record across commercial, industrial and residential. As a Fellow of Engineers Australia he holds Chartered Professional Engineer & NER (Structural) status. He is a member of many Standards Australia committees relating to the design and specification of reinforced concrete.

Eric Lume - Eric is a Civil and Structural Engineer with a wealth of industry experience, including 14 years in consulting, 15 years with Cement Concrete and Aggregates Australia (CCAA), 5 years as senior lecturer at the University of Wollongong, a year with a Consulting Engineering firm in Christchurch, NZ assisting with the rebuild of earthquake damaged structures, and the last seven and a half years with the SRIA.