ROLE OF ENGINEERS IN SEISMIC DESIGN AND DETAILING OF REINFORCED CONCRETE BUILDINGS IN AUSTRALIA

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ABSTRACT: *Australia is not immune to earthquakes as demonstrated by the 1989 Newcastle event which is now all but a distant memory for many of the populace. An event of this magnitude or greater could in fact impact any of Australia's major capital cities. Design for earthquake is a mandatory design case under the National Construction Code. Australian engineers have little seismic knowledge due a lack of experience and tertiary training. Wind load is often larger so engineers typically stop and design only for the wind condition. As a result there are potentially unsafe building designs being produced that do not have the necessary redundancy to resist high intensity cyclic earthquake loadings. Many engineers still work through the minimum standard requirements where they should be required by Standards to consider at least the level of simple seismic detailing to improve robustness. Design and the detailing are fundamental to the necessary elastic-plastic performance to absorb seismic energy. Appropriate detailing is required to ensure that the structure will respond under the seismic loading as assumed in design. Engineers have a role to communicate seismic risk to the community and reduce seismic risk for the community.*

KEYWORDS: Reinforcement, seismic, design, detailing, concrete, redundancy, robustness, life safety.

1 INTRODUCTION

In Australia there is a generation of engineers, contractors and clients who are not convinced that damaging earthquakes occur in Australia, despite the long history of earthquakes in Australia and the 1989 Newcastle Earthquake [1,2]. It may be perception or a simple lack of experiencing an earthquake event. With the pressures of modern design and construction, this does not allow adequate time to think about the issues that are required by the Building Code of Australia (BCA)[8].

The fundamental principle of concrete design for the successful performance of a concrete structure under seismic actions is that <u>design and detailing of reinforcement are inseparable</u>. Engineers have the role of selecting appropriate detailing which is crucial to ensure that the structure will respond under seismic loading in the manner for which it has been designed. This is also a delicate balance between life safety and the client's cash flow. Time and time again, earthquakes have shown that correct detailing of reinforced concrete structures can significantly improve the capacity of the building to resist seismic actions, even for a poorly designed structure or a structure subject to a much larger event.

The Steel Reinforcement Institute of Australia (SRIA) has spent the past 2 years researching and redeveloping the former 1995 brochure on seismic design. The new *Guide to Seismic Design and Detailing of Reinforced Concrete Buildings in Australia* has now developed into a publication and now covers design. SRIA is shaking up the understanding of seismic design and detailing in Australia with an overarching goal of trying to improve the robustness of the built form.

Key outcomes from this Guide to deliver this overarching goal are:

- for designers to better appreciate that the risk from seismic hazard in Australia is 'real' and that it must be properly considered during design
- for designers to clearly understand the key philosophical differences between designing for wind and earthquake and the design consequences that follow for design
- to highlight common mistakes that designers are currently making (often unknowingly) in their seismic designs
- to suggest a few simple cost effective design and detailing improvements that will improve robustness

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- to promote/provide reliable reference material, including the new Guide, and relevant conference papers for further reflection and study

Fortunately significant earthquakes in Australia are rare and probably will not occur during the average lifetime of a building. The top 4 worst Australian onshore earthquakes in modern times ranked by cost, magnitude and damage, according to an Australian Geographic July 2012 article are:

- Newcastle NSW, 28 Dec 1989, M5.6
- Beachport SA, 10 May 1897, M6.5
- Meckering WA, 14 Oct 1968, M6.9
- Ellalong NSW, 6 Aug 1994, M5.4

Both Newcastle and Meckering struck on public holidays greatly reducing the death toll while Meckering hit in the daytime further reducing expected fatalities. In this respect Australia has been fortunate in the past. However, the reality is earthquakes are a regular occurrence and while the return periods can be long and they often occur in isolated areas it is only a matter of time until we experience one in a major capital city. On average Australia <u>will</u> experience:

- 1 shallow earthquake of magnitude 6 or more every 10 years (equivalent to the 2011 Christchurch earthquake)
- 1 shallow earthquake of magnitude 5 or more every 2 years (equivalent to Newcastle)

A major earthquake will generate the most severe structural demand ever experienced by a building. Given the rare and extreme nature of earthquakes, for economic reasons, designers are largely concerned about preserving life and preventing structural collapse. For most concrete structures, this will require the structural system to resist the imposed deformation in-elastically over a number of load cycles.

AS 3600 [4] and AS 1170.4 [5], provides Australian designers with the minimum design rules for earthquake design for buildings to meet the typically lower seismicity of Australia. Most commercial buildings in Australia are insitu reinforced concrete, designed and detailed in accordance with AS 3600. Complying with the Standard for regions of lower seismicity deems the structure to have adequate ductility <u>as a life safety measure</u>. However, this concept of life safety is often poorly understood or not properly articulated by designers.

For lower values of the ductility factor $\mu \leq 2$, detailing of the concrete is only required in accordance with the body of the Standard and for higher values of ductility factor μ, detailing is required in accordance with Appendix C of AS 3600. Levels of ductility $\mu > 3$ are outside the scope of the Standard, and design and detailing to NZS 1170.5 [6], and NZS 3101 is suggested.

The SRIA Guide is not a complete document covering all design situations or requirements, but an assortment of basic seismic principles, design advice, and fundamentals to assist and help designers of all experience levels. Over the past two decades there has been significant advances in analysis software and our understanding of earthquake design has improved through advances in research and combined with actual performance of buildings under seismic loads. The Guide focuses on key, functional and practical aspects of seismic design and detailing of reinforcement with references to specialist information, as technology and reduced design and construction times is shifting the focus away from the vital reinforcement detailing phase of the project.

2 RISK MITIGATION AND LOW DAMAGE DESIGN FOR BUILDINGS

As demonstrated in the recent Christchurch event, client and society expectations compared with the reality of seismic performance may not match the minimum requirements of the Standards for life safety. Questions should be asked at the early phases such as does a building in the event of an earthquake require protection of irreplaceable contents such as a museum or is there a need for the continuing use of the building such as a hospital after the event, or in the extreme condition that it contains dangerous materials such as a biological laboratory dealing with dangerous viruses? The new Seismic Guide has checklists to initiate these client/designer discussions so these issues establish the scope from the project outset.

The highest level of protection for a building available is base isolation which is common in high seismic areas such as Japan, but it has not been used in Australia due to our lower seismicity. The next level of protection is to minimise the damage by using a more robust and regular structure with a higher level of ductility. This basic parameter will protect the primary structure even in the most severe earthquake expected, with many alternative load paths and backup systems designed and detailed for greater forces than the minimum required by the Standard. The great advantage of this approach is that the structure should be operational and repairable; insurance may be less, and the mitigation of the risk of structural damage and business continuity is achieved but at an increased cost to the original construction of the reinforced concrete building. It is thought that the increased cost would be as little as 1% to 3% of the total construction cost of a concrete building over the lowest level of protection required by the Standard. This assumption is based on a structural cost being 25% of the total cost of the building, and the additional design and detailing would result in an increased structural cost in the order of 5-10% including professional fees.

The lowest level is to adopt the minium requirements of the Standard which are intended to provide life safety, but result in the probable demolition of the building after the event. This soltuion may also not be adeqaute for more than the current 1/500 year event.

3 ANALYSIS AND DESIGN

Design experience delivers well-conceived and quality design with adequate detailing including the earthquake design. This process of engineering analysis and design satisfies the clients brief by delivering a safe, serviceable, aesthetic, economical and sustainable structure. Designers should always strive for simplicity, clarity and excellence in their design and detailing and maintain a strong focus on the detailing of reinforcement for seismic loads, as part of the design process, not as an afterthought.

Traditionally earthquake design has been based on a quasi-static forces approach where hypothetical static loads are applied to simulate the dynamic forces of an earthquake. This may in fact bear no resemblance to the forces in an actual earthquake event, as earthquakes do not know about Standards, methods of design or indeed the building being designed. For this reason, the earthquake actions will almost certainly not be those specified by the Standards and demonstrates why detailing of reinforcement delivers the actual building performance.

There are a number of fundamental problems with the force-based method of analysis. These include choosing the right model, the selection of appropriate member stiffnesses and determining the static forces that are appropriate for the design being considered. Member stiffnesses cannot be resolved until the design is complete, and yet they will change during a seismic event. In addition, the static design lateral forces applied to the structure may not bear any relationship to the actual dynamic forces applied under earthquake cyclic action. For example Australian Standards currently have no allowance for vertical accelerations. The distribution of local forces is based on elastic estimates of stiffness. This tends to concentrate the resistance to applied forces in elements having the greatest potential of brittle failure, such as walls.

There have been large advances in the past 20 years in our understanding of how concrete performs under seismic loads, in the technology and design of concrete, changes to reinforcement and enormous advances in computers and software and analysis tools. The computing power and software now available to designers has led to far more elaborate and sophisticated analysis and design of buildings and indeed more refined design.

This technology can lull the designer into a false sense of security, believing they fully understand how the structure will act under the dynamic loads of an earthquake, when the actual effects of an earthquake may be far different from the computer model. This is because the structure is sized on non-seismic load considerations; member stiffnesses will change during the earthquake and other factors such as local failures will affect the model. This may result in the model and sophisticated analysis being entirely inappropriate in a major earthquake event.

Analysis is only part of the design process. Good designers know there is far more to design than just analysis and designers must understand the behaviour of each member and how they are expected to resist all of the applied actions and why these members need to be detailed for the seismic actions. This is a process of systems thinking combined with practical detailing and it is imperative that designers ensure viable load paths exist.

History has shown that in real structures, earthquakes exploit the weakest link. The behaviour under load of individual elements can be complex depending on the materials used and many other factors, which will change under earthquake actions. Idealised computer models of the frame or structure are used for the analysis of a structure to simulate how the real structure may behave, but we must not lose sight of the fact they can be very crude when assessing the structure under seismic loads.

4 REINFORCEMENT AND CONCRETE

For a structural ductility factor $\mu \leq 2$, AS 3600 Appendix C, allows the structure to be designed and detailed in accordance with the main body of the Standard and both Ductility Class L and N reinforcement may be adopted as flexural reinforcement (Ductility Class L only in the form of mesh) and both classes as fitments. Although, not covered by AS 3600, any chord members, collector reinforcement or drag bars used in diaphragm action should be Class N reinforcement, because of the anchorage requirements and ductility demands for this reinforcement.

For a structural ductility factor, $2 < \mu \leq 3$, structures have to be designed and detailed in accordance with the main body of AS 3600 and Appendix C, with Ductility Class N used for flexural reinforcement. Ductility Class L steel is permitted to be used for fitments and non-flexural reinforcement eg shrinkage and tempertaure.

For IL4 buildings and $\mu > 3$, Ductility Class L reinforcement is not recommended in structural elements except where used as fitments for beams and columns, shrinkage/temperature reinforcement, for reinforcement to steel metal decking or non-structural elements, because of the increased ductility demands.

The quality of procured reinforcement steels must be verified to support the earthquake design assusmptions and deliver the required building performance. This is achieved by simply obtaining 3rd party material certifications.

While structures will have concrete strengths typically in the range of 25 to 40 MPa, high strength concrete up to 100 MPa is allowed under AS 3600. High strength concrete is principally used in columns and walls where the size of such elements needs to be minimised. Designers should be careful using high strength concrete in columns and walls for buildings designed for a structural ductility factor $\mu > 2$ or with a post disaster function, as high strength concrete is a brittle material requiring additional detailing of the reinforcement to prevent brittle failure.

5 ROBUSTNESS

Structural robustness is discussed briefly in the commentary to AS 1170.0 [7] but is not well defined. There are no specific requirements for design for structural integrity (the prevention of progressive collapse) or robustness in the BCA [8] or AS 3600. The AS 3600 Commentary [9] has some limited information on this requirement. Nevertheless, because of overseas experience and failures, designers must consider the robustness of reinforced concrete buildings including reinforcement detailing.

In simple terms a structure should be safe and the Eurocode provides the following definition of robustness *"the structure shall be designed and executed in such a way that it will not be damaged by events like fire, explosion, impact, or the consequences of human error, without being damaged to an extent disproportionate to the original cause."*

Progressive and disproportionate collapse must be avoided at all times. This means that the failure of one member should not set off a chain of events where the structure progressively collapses as occurred in the failure of the columns of the Newcastle Workers Club in 1989, Melcher and Woodside [10,11].

Robustness will require that all elements have a resistance to lateral loading, and if none are specified, then a notional percentage of the vertical load should be adopted. Redundancy is also an important issue as a failure of any load-bearing member must not lead to the collapse of the entire structure.

The building structural form will significantly affect its robustness and for this reason needs to be considered at the concept stage. An example of this might be a large transfer beam supporting a large part of the building, where failure of this element would be catastrophic and should be avoided if possible, or the design robust enough to provide a considerable reserve of strength. These critical elements can be designed elastically for the full earthquake load to ensure robustness.

Columns and walls should not be heavily loaded and designed so that the design values are below the balance point and be well detailed [12]. Compatibility of drift must also be considered.

Precast and tilt-up structures are more susceptible to the effect of abnormal actions than some traditional forms of construction because of the presence of joints between the structural elements. However, experience has shown that it is possible to manage these issues by effectively tying together the various elements of the structure and providing correct detailing. [13, 14]

Buildings should have sufficient robustness to survive without collapse if subjected to ground motion in excess of that specified by Australian Standards. Well-proportioned and well detailed insitu reinforced concrete structures are inherently robust if detailed to ensure that plastic hinges do not form in undesirable locations. A weak beam strong column system is most preferable. This is where systems thinking is essential to ensure the structure is tied together; can resist some notional lateral load, and the failure of a particular element will not lead to progressive collapse. There are several overseas documents on structural robustness and progressive collapse [15, 16].

Reinforcement detailing for robustness also needs to address some basic requirements as follows:

- Minimum reinforcement should be provided in both faces of horizontal members such as beams and floor slabs

even if the design does not require it or detailing is not required in the Standard.
- Detailing in accordance with Appendix C of AS 3600 will be required to minimise damage, for buildings with a post-disaster function and for buildings where the ductility $\mu > 2$.
- Critical members should be reviewed for their role in the structure, detailed as required, and alternative load paths considered.
- Eliminate punching shear failures at columns at flat slabs and similar by providing additional bottom face reinforcement as shown in Figure 1.

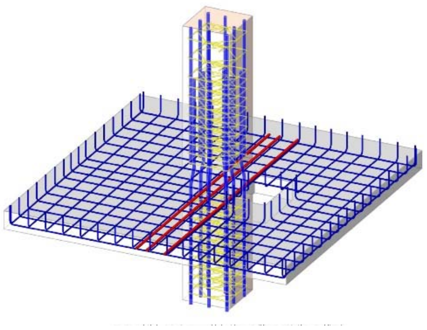

***Figure 1:** Drop panel bottom layer reinforcement 3D view. Note: Top layer reinforcement not shown for clarity. (Photograph courtesy Peter McBean, Wallbridge and Gilbert)*

6 ACCEPTABLE DRIFT LIMITS

AS 1170 .4 sets out the maximum drift requirements for buildings. However, the maximum inter-story drift due to reduced stiffnesses must not exceed 1.5% of the storey height at each level at the ultimate limit state. These lateral displacements can be large (in the order of 30 to 50 mm). Many structures may not be able to accommodate such drifts without premature failure of structural elements. Also, calculations associated with drift are often poorly understood as stiffness assumptions have varying degrees of accuracy.

Even if a part of a structure is not designed specifically to withstand seismic forces, it must be designed for the full drift (deflection) of the whole structure calculated in accordance with Clause 5.4.2, Clause 5.5.4 or Clause 6.7.1 of AS 1770.4. Moment frame systems are much more flexible than shear wall systems and need careful review for drift especially with associated shear walls.

7 DUCTILITY DEMANDS

One of the issues when designing structures in an area of low seismicity such as Australia is that when a major earthquake occurs which exceeds the design return period (annual probability of exceedance of 1/500 or 1/1000 years), then the increase in peak ground acceleration over the design event can be significant and therefore the increase in the lateral forces can be large. For a rare event with say a return period of 1/2500 years, this can be of an order of 3 or more. This increase is shown in Figure 2 Paulay and Priestley [17]. For structures however designed in areas of high seismicity, the increase in peak ground acceleration is not as significant, perhaps 30%.

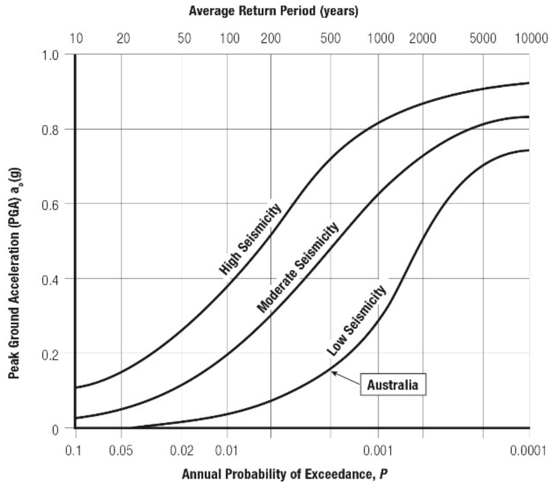

***Figure 2:** Increase in peak ground acceleration (From Paulay & Priestley, 1992)*

8 STRUCTURAL SYSTEMS

Structural systems should be as simple as possible with readily understood gravity and lateral stability load paths. Some structural systems are more satisfactory than others in resisting earthquake-induced forces. One of the early tasks of the structural designer is to select a structural system that results in the best system for seismic performance of the building within the constraints dictated by the client, architect, the site and other conditions. Wherever practicable, alternative structural configurations should be considered at the concept stage to ensure that an undesirable geometry or structural form is not adopted before the detailed design of the building begins. In particular, structural irregularities both vertically and horizontally must be considered early in the design phase, and sound structural engineering principles applied to avoid or mitigate these effects.

AS 1170.4 specifies that all parts of a structure shall be interconnected, in both the horizontal and vertical directions. Connections between structural elements are typically the weakest chain in the link and should be detailed to fail in a ductile manner to avoid rapid degradation of strength under earthquake actions as shown in Figure 3.

Figure 3: *Failure of Beam/Column connection. Copthorne Hotel, Christchurch (Photograph courtesy Peter McBean, Wallbridge and Gilbert)*

The connections must be capable of transmitting the calculated horizontal and vertical earthquake force in order to provide load paths from all parts of the structure, and the earthquake forces carried to the footings and foundation. In turn, the foundations must be robust enough to accommodate the overload due to large events without catastrophic loss of strength.

In Australia, stair and lift cores are typically constructed with concrete walls because of the fire rating and construction techniques, which have developed over many years. As a result, most buildings in Australia will be either a concrete shear wall system or a combination of concrete shear walls and moment frames or moment frame only. The designer has to choose whether the shear walls are ductile or limited ductile elements. Once the structural system is chosen, the structural ductility factor μ and structural performance factor S_p can be determined in accordance with Table 6.5 (A) of AS 1170.4 or Table C3 of AS 3600. Ductile shear walls are often chosen where earthquake forces are higher than wind as the seismic reduction factor will lead to smaller members particularly foundations, and the detailing is not too onerous. The decision as to which design route to take is left to the designer.

Because of the ratio of Structural Ductility Factor, μ, to the Structural Performance Factor S_p, the earthquake design actions will be increased by about 73% if the designer chooses an Ordinary Moment Resisting Frames (OMRF) over an Intermediate Moment Resisting Frame (IMRF). OMRF's are deemed to require no further detailing consideration from the detailing required in the body of AS 3600.

One problem with Moment Resisting Frames (MRF) is their lack of lateral stiffness and the large displacements (or drift) under earthquake actions, often together with incompatibility of the rest of the structure in resisting such drifts. This can result in significant damage to adjoining structural elements and non-structural parts and components. In addition, the importance of any plastic hinges forming in the beams and not the columns in an extreme event. Band beams usually are significantly stiffer than the columns, making the concept of strong columns and weak beams difficult to achieve.

Also where excess strength is provided above that theoretically required by the design through rationalising the design, less ductility is required for the element e.g. due to the provision of additional reinforcement for tying, or extra thickness or depth of section for fire requirements or deflections. Therefore, less detailing for seismic resistance may help buildability.

9 RESPONSIBILITY FOR THE DESIGN

It is recommended in the Guide that if a number of designers are working on the design and detailing of a concrete structure for seismic actions, the overall responsibility for the structural aspects of the project should be taken by one structural engineer called the Principal Designer.

The Principal Designer and the design team should preferably carry out all the structural design of the building. Where part of the design is assigned or subcontracted to others, the Principal Designer needs to understand and fully coordinate those designs and take overall responsibility for them. Examples of design by others are the design of precast concrete elements and post-tensioned floors.

The failure of the CTV building in Christchurch where 115 people lost their lives in this extreme event is attributed to the designer of the building, who was not experienced in earthquake design and did not fully understand what was required, and the senior engineer who did not supervise the inexperienced designer [18].

10 DETAILING AND DRAFTING OF CONCRETE ELEMENTS

Conceptualisation, structural analysis and design are the first part of the overall design process of a structure and detailing and drafting the second part. Detailing and drafting consists of satisfactory plans, elevations, sections and details and an understanding of how each part of the structure will perform under seismic loads.

Detailing of the reinforcement is a vital part of the seismic design process for reinforced concrete. There must be sufficient fitments to prevent shear or crushing failures, anchorage of reinforcement into areas of confined concrete and buckling of compression steel, once the cover to the concrete has been lost due to cyclic movements as shown in Figure 4. The main steel bars must not lose their anchorage into the surrounding concrete during the repeated reversing loading cycles in a major earthquake. Anchorage lengths must be sufficient to allow formation of plastic hinges where required.

Figure 4: *Failure of column at the Hotel Grand Chancellor, Christchurch due to poor confinement, (Photograph courtesy Peter McBean)*

Once designed correctly, the art of reinforcement detailing is to provide the reinforcement in the right places required by the design and to meet the expected earthquake demands. If the reinforcement is correctly placed and fixed in position and the concrete correctly placed around the reinforcement then the structure will comply with the intent of the design and should perform satisfactorily during its design life including seismic actions.

Detailing involves practical and detailed considerations on how and where the reinforcement should be placed. Experienced designers who understand the overall design and the seismic requirements of the building should be responsible for the clear detailing and specification of the reinforcement requirements on the drawings. Detailing must not be carried out by graduate, inexperienced engineers or drafters without senior supervision.

With the correctly detailed structural drawings, the reinforcement processer is able to process the reinforcement using the reinforcement schedules produced by the scheduler from the structural drawings, prefabricate any components and deliver it to the site. This will allow the steel fixers to fix the reinforcement arrangements correctly and the builder/contractor to place the concrete around the reinforcement.

The detailing of reinforcement often occurs in the later phase of the documentation process, after the design is substantially completed, and the final drafting of the structure has commenced. Where possible, the structural design, including the drafting and detailing of the reinforcement should be completed prior to construction commencing.

In the design and detailing process enough time must be left for suitable checking and coordination. Checking should occur prior to issue of the drawings for construction and manufacture of reinforcement.

The detailing requirements of AS 3600 generally follow those of ACI 318 [19] with one notable exception for confinement reinforcement. Appendix C of the current AS 3600 for an IMRF refers designers to the Clauses 10.7.3 and 10.7.4 in the body of the Standard for confinement and restraint of longitudinal reinforcement to avoid failures shown in Figure 4. In the 2001 version of AS 3600, the closed ties that extended over the distance D or $L_o/6$ where required to be spaced at maximum centres, s_c of $0.25d_o$, $8d_b$, $24d_f$ or 300mm with the first tie located a maximum of 50mm from the support face, or $0.5s_c$. This requirement appears to have been lost in the current 2009 edition of AS 3600 and requires amendment. The Guide reflects the former confinement provisions and is supported by other standards such as ACI 318-14[19]. This error will be addressed in the upcoming AS 3600 revision.

With the trend to prefabrication of reinforcement off-site, attention needs to be given by designers as to how the components can be prefabricated and joined by drop in splice bars, known as loose bar detailing [20]. The positioning of the splice outside plastic hinge locations is critical for IMRF's designed to AS 3600 Appendix C.

11 DIAPHRAGMS

Diaphragms in seismic design are the concrete floor and roof slabs. They are a critical element in the design of any building for seismic actions, as they tie the structure together and must be considered early in the design.

AS 1170.4 makes passing reference to the deflection of diaphragms in Clause 5.2.5. AS 3600 in Clause 6.9.4, states that insitu concrete can be assumed to act as horizontal diaphragms. Unfortunately, there is no guidance in either Standard on the loads, the design of the diaphragm or the transfer of actions from diaphragms into the vertical elements.

Diaphragms have a number of roles in a building including carrying gravity loads and imposed vertical loads; to provide lateral support to vertical load bearing elements; to transfer the lateral earthquake actions applied at each floor level into the vertical elements. They also have a number of other functions such as redistribution of loads around openings, redistribution of forces due to torsion, and for resisting inclined or offset columns.

One method for the design of diaphragms has been to consider them as a horizontal deep beam where the flanges take the tension and compression as shown in Figure 5. Designers can also use a strut and tie approach. Diaphragms can also be rigid or elastic, regular or irregular, and have large penetrations, all of which can complicate their design.

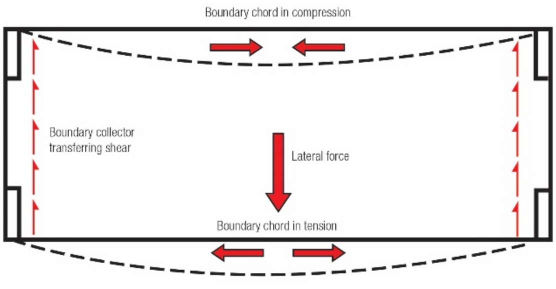

Figure 5: *Floor as diaphragm after ATC/SEAOC briefing paper*

Evaluating all the situations for the detailing of floor diaphragms requires experience and engineering judgement. For example, a building long and narrow in plan may be more flexible than thought, and the deformations may not be able to be accommodated by the walls at either end, resulting in separation of the walls from the diaphragm and potential failure below the design load.

Typically, edge beams form the edges of a diaphram. They need to be continuously reinforced with the longitudinal bars fully lapped for tension and compression, restrained for compression and adequately anchored to the concrete walls and columns.

Designers need to study how the forces from the diaphragm get into and out of the vertical elements, particularly shear walls. A good understanding of how these forces are transferred is necessary to ensure adequate detailing.

Volume changes due to creep, shrinkage, thermal and post-tensioning also need to be considered with diaphragms. Where floors are temporally uncoupled from shear walls such as cores and lift shafts to allow for initial shrinkage, axial shortening, and post-tensioning effects, then correct detailing is required to ensure they will act as diaphragms in the final condition and are properly connected to the vertical supporting elements.

Diaphragms will have a number of components depending on the design model adopted. Tension and compression members of the diaphragm are known as chords and collector elements collect the shear forces and transmit them into the columns and walls. The earthquake forces must be transferred into the vertical supporting element from the diaphragm, and these can be significant forces. The reinforcement used to transfer these forces is known as drag bars.

Failures of diaphragms in the recent high magnitude New Zealand Canterbury earthquakes were observed and a realisation that a more rigorous approach is required for the design of diaphragms and their connection to lateral restraining elements as shown in Figure 6. Designers need to consider these elements much more critically than they may have in the past [21, 22].

Figure 6: *The shear wall remains standing amongst the ruins of the CTV Building, Christchurch, New Zealand (Photograph courtesy Peter McBean)*

12 CONCLUSIONS

Australia is an area of low to moderate seismicity, of low probability but high consequence in comparison to areas such as Japan and New Zealand. This is reflected in the provisions for both the design and detailing of reinforced concrete structures in Australia in accordance with the BCA and referenced Standards.

The reality is that earthquakes are a regular occurance and it is only a matter of time before a major capital city is struck with a Newcastle magnitude or greater earthquake. To satisfy a minium sesimic level, building structures in Australia are required to at least be designed and detailed in accordance with the main body of AS 3600 using the specific clauses for detailing in each section of the Standard. The detailing requirements are not that onerous. Loose-bar detailing combined with efficient fabrication procedures and additional detailing considerations, to provide the levels of ductility and continuity of reinforcement, will allow the structure to meet the anticipated earthquake cyclic loading satisfactorily in a life safety event.

With some additional design and detailing to Appendix C of AS 3600, the building can meet higher levels of ductility, allowing it to resist greater earthquake loads inelastically. This could make a difference to the building surviving in a greater than expected earthquake event.

It is important to provide a minimum level of ductility in both beams and columns framing into a joint and to ensure adequate confinement of column reinforcement to established practice, regardless of the type of structural system employed.

With a limited additional quantity of appropriately detailed extra fitments and continuity reinforcement at negligible cost, plastic hinges can be induced to form at a given load. Yielding will be ductile (gradual), even if the design earthquake load is exceeded through formation of a hinge acting as a 'fuse' preventing transfer of the larger forces.

A fully elastic response by the structure is not intended and a non-elastic response is allowed by the BCA and referenced Standards. To prevent a catastrophic collapse and probable loss of life under a greater than design event, a ductile failure must still be ensured.

This minimum required level of ductility can be readily achieved by careful detailing and key design decisions such as reducing the axial stresses in the columns to ideally below the balance point. Close attention to walls and their axial stress levels plus boundary conditions is as critical as the primary columns.

Precast and tilt-up concrete construction requires additional care in detailing to ensure connection detailing is satisfactory and floors are adequately supported and will function as diaphragms in order to correctly transfer horizontal forces.

These simple performance improvements can be achieved using the Seismic Guide's effective design and detailing principles across these key areas of weakness observed in past events. Adopting these principles will improve collapse robustness, reduce damage and provide confinement for resistance under cyclic loading.

Real structure performance in earthquakes has demonstrated that this critical information will deliver improved seismic structural system response for regions of lower seismicity. To reduce risk, prevent future disasters, secure life and business continuity this publication has been made freely available on the SRIA website and is an essential resource for all building design professionals.

All Australian engineers should have a seismic design and detailing overarching goal of trying to improve the robustness of the built form to manage this real risk. To further assist the client/building owner, designers and the builder/contractor in this important process specific seismic design checklists have been developed to provide a series of key questions for conceptualising, designing and detailing reinforced concrete for structural performance under earthquake actions.

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