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Guide to Seismic Design & Detailing of Reinforced Concrete Buildings in Australia

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And a special thanks to:

- **Professor John Wilson**, Swinburne University for his review & foreword

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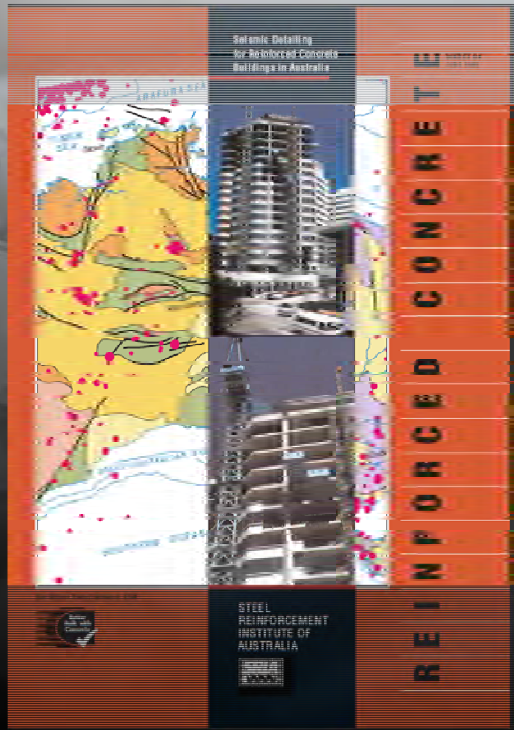
Current Earthquake Detailing Guide

- Original SRIA Seismic ‘Detailing‘ Guide was published in 1995

- Followed the second Australian Earthquake Standard AS 1170.4-1993 *Minimum design loads on structures, Earthquake loads*



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Australian Standards and Technology Development

- Since the 1995 publication there has been:
  - Two versions of AS 3600 Concrete Structures
  - A new earthquake standard AS 1170.4-2007
- Significant advances in analysis software for building structures and elements

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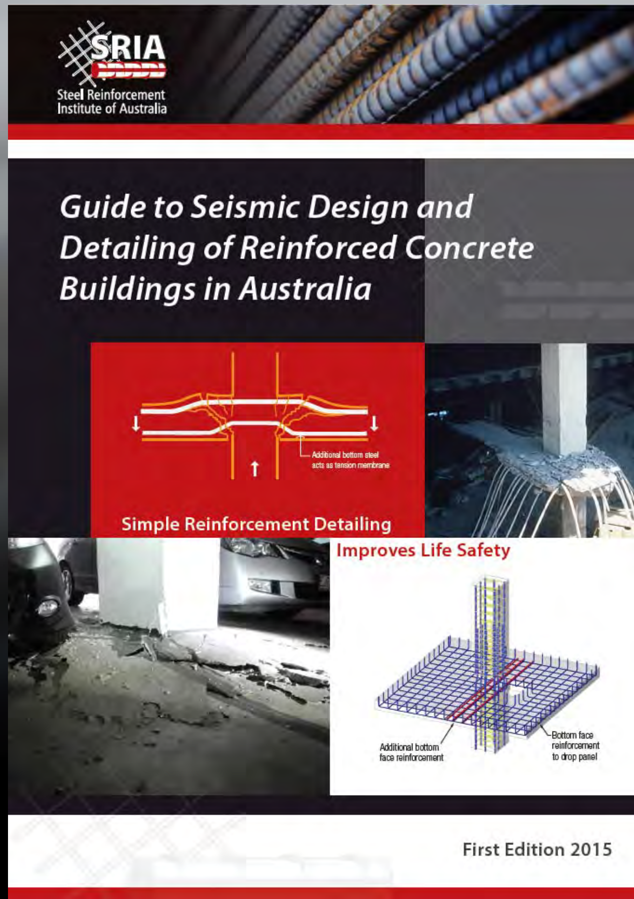
Aim of the new SRIA Guide to Seismic Design & Detailing

- The new Guide will assist graduate to senior level Engineers with the primary aspects of practical seismic design & detailing
- There are excellent overseas texts on design for seismic actions
- There is no dedicated Guide in Australia setting out the seismic ‘design & detailing’ of concrete buildings to Australian Standards
- The art of detailing is to provide reinforcement in the right places required by the design and to meet the expected demands.



Extract: Foreword by Professor John Wilson, Swinburne University

Important items for Engineers to consider in seismic design:

- Importance of systems thinking and practical detailing
- Imperative that designers ensure viable load paths exist
- History has shown that earthquakes exploit the weakest link in structures

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Australian Seismic Design Practice

- Australian Standards provide minimum rules to meet Australia's moderate seismicity, low risk but high consequence
- Most commercial buildings are cast insitu reinforced concrete designed & detailed to AS 3600, reflecting this risk and deeming the structure to have adequate ductility as a life safety measure
- For lower values of **structural ductility factor (μ)**, detailing is only required to the main body of AS 3600. Typically Ductility Class L or N reinforcement is adopted
- For higher values of μ, detailing is in accordance with AS 3600 Appendix C, with Ductility Class N as a flexural reinforcement requirement
- For levels beyond AS 3600 'complete design & detailing' is required to NZS 1170.5 & NZS 3101 using Ductility Class E steels available from NZ mills

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RC Structures & Earthquakes

- The earthquakes in:
  - Canterbury NZ, 2010 & 2011
  - Kobe Japan 1995
  - Northridge LA, 1994

  were significant and large earthquakes
- Studies of building performance during these events have highlighted the strengths and weaknesses of reinforced concrete in terms of both material, design & detailing

The Kobe earthquake
(Photograph courtesy John Woodside)

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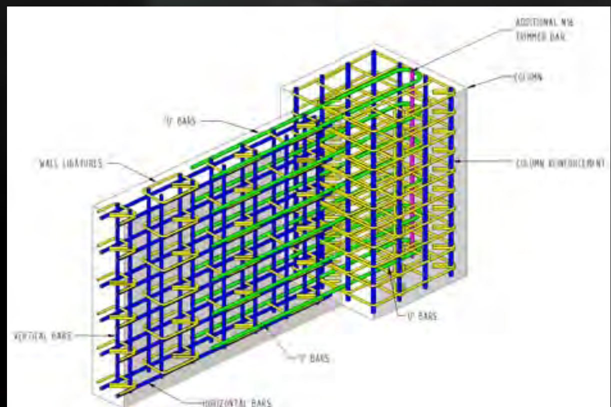
Attributes of RC Performance

- Detailing provides excellent ductility in flexure
- Detailing fitments for confinement provides good ductility under axial compression
- Result is a monolithic structure, with load path redundancy & good system continuity
- Fitment detailing to structural shear walls provides high lateral strength and stiffness while retaining significant ductility



Northridge LA, 1994

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Risk Mitigation and Low Damage Building Design

- Traditional worldwide focus for earthquake design is life safety with minimising building damage a secondary issue
- A proper compliant design therefore allows people to exit the building but can result in significant damage requiring either repair or demolition in extreme earthquakes

The Newcastle Worker Club
Subsequently demolished & rebuilt.
(Photo Courtesy Newcastle Library)

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AS 1170.4

Figure 3.2(G) of AS 1170.4

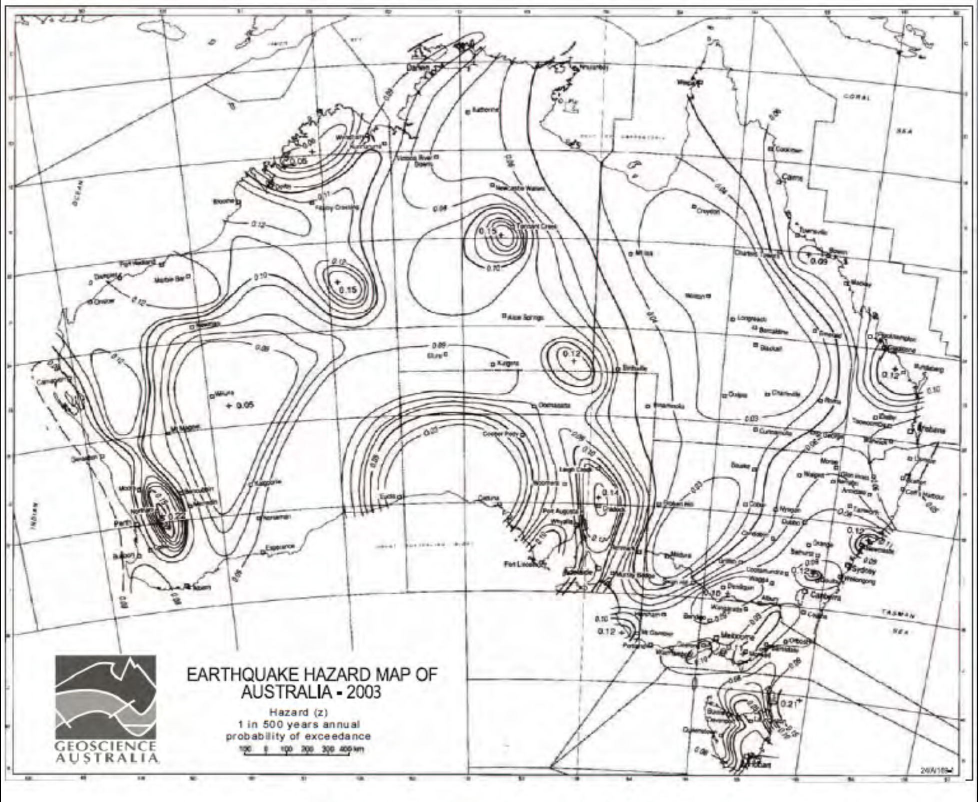
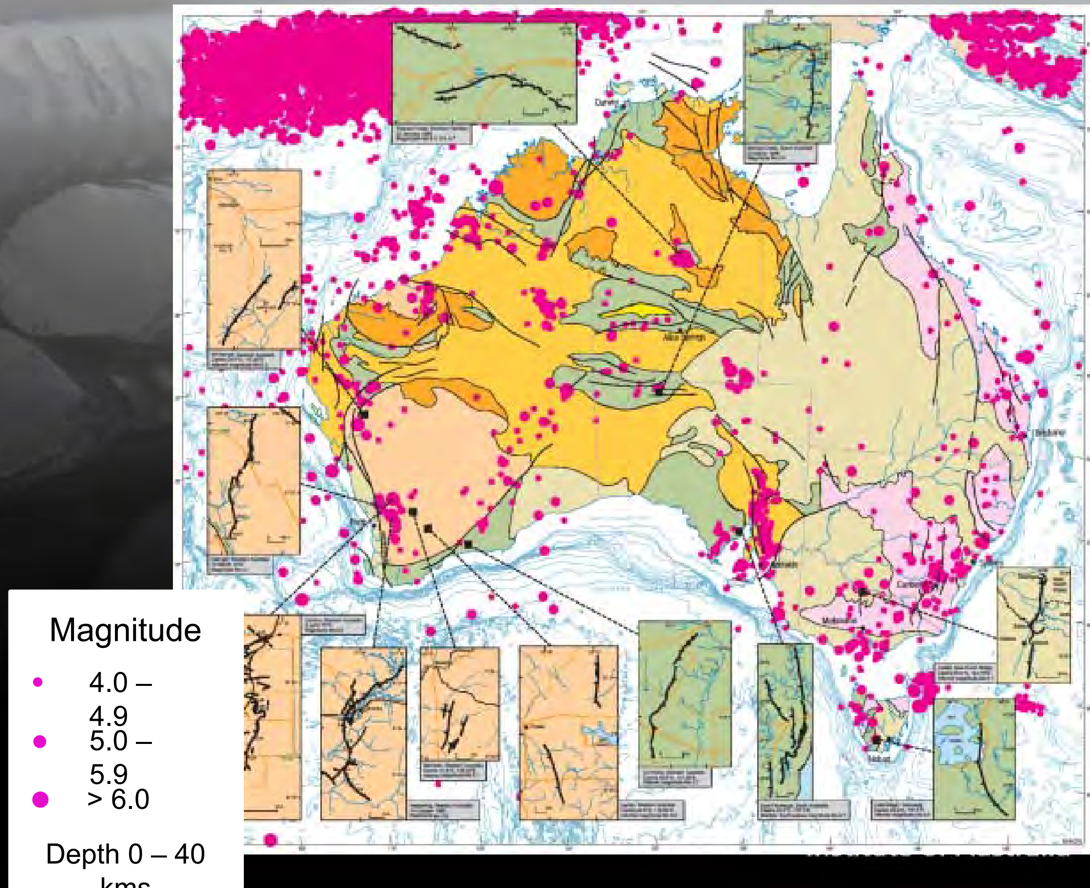


FIGURE 3.2(G) HAZARD FACTOR (Z)

Earthquake epicentres in Australia 1841-2000 and recent fault scarps

(Image courtesy Geoscience Australia)



AS 1170.4

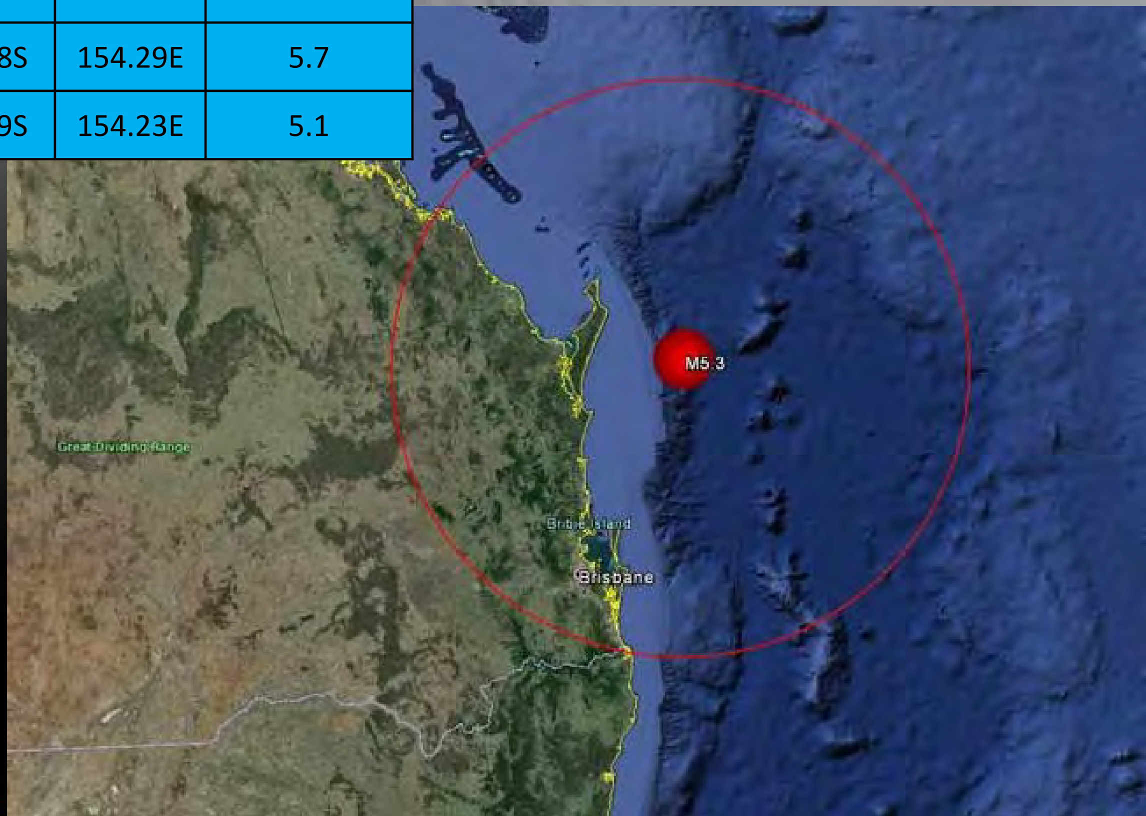
Recent Earthquakes – Fraser Coast (Geosciences Australia)

Date	Time	Depth (kms)	Lat.	Long.	Magnitude
30/7/2015	9.41	53	25.54S	154.00E	5.3
1/8/2015	13.38	10	25.38S	154.29E	5.7
1/8/2015	14.46	0	25.39S	154.23E	5.1

- Largest earthquake in region since 1918
- Felt in Brisbane and Gold Coast

Christchurch earthquake
22 February 2011
Magnitude M6.3

(Image courtesy Geoscience Australia)



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Designing for Earthquakes compared to Wind

From Peter McBean – Wallbridge & Gilbert

- Many designers don't understand the **fundamental differences between designing for wind and earthquakes actions**.
- Designers often undertake a quick earthquake base shear check, compare it to the wind design actions, find that wind "governs", and stop.
- This practice **ignores the detailing requirements** necessary to achieve structural behaviour consistent with the earthquake design base shear.
- BCA requires designers to consider both wind & earthquake as separate design events.

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Designing for Earthquakes compared to Wind

From Peter McBean – Wallbridge & Gilbert

- For wind, members are proportioned to be stronger than the maximum anticipated demand.

- For earthquake design, we intentionally proportion members to be significantly weaker than would be required to survive the design earthquake elastically and rely on achieving ductile behaviour to accommodate the earthquake demand.

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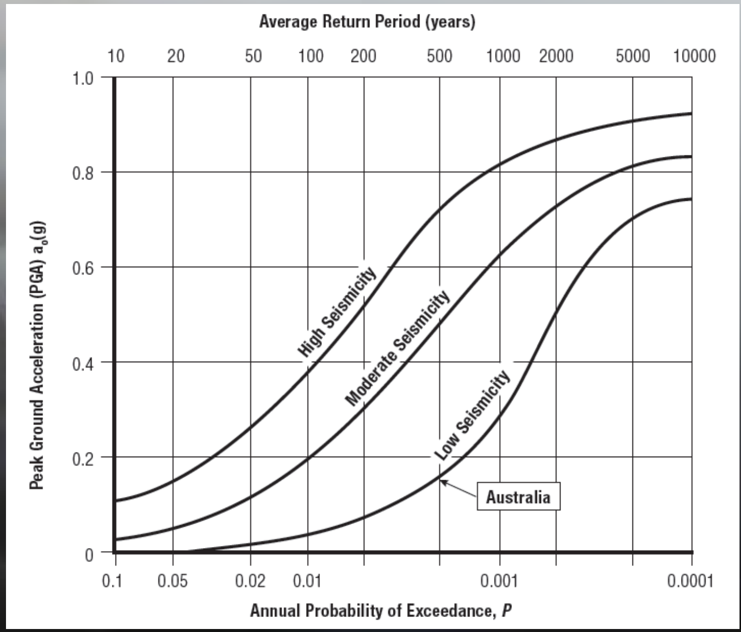
The Importance of Ductility Demand

Return Period - Potential issue

- Should a major earthquake occur which exceeds the average return period commonly 1/500 years (e.g. Australia with low seismicity) , the increase in peak ground acceleration and increase in the lateral forces can be significant for a rare event with a return period of 1/2500 years
- For structures designed in a high seismicity area, the increase in peak ground acceleration is not as significant
- Low seismicity is where system performance & seismic detailing are crucial factors



Graph from Paulay and Priestley

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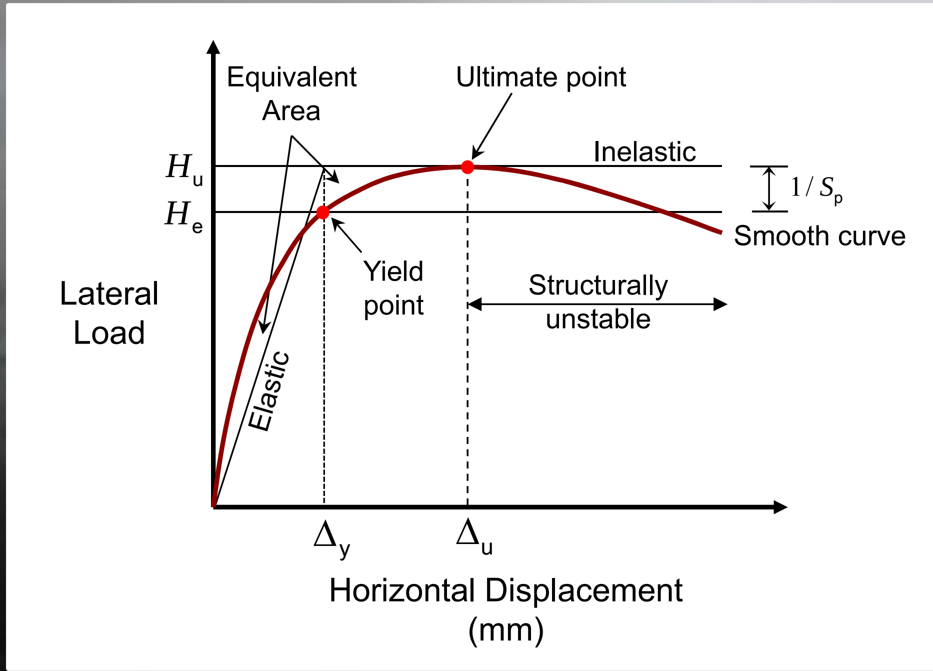
Ductility by Design & Detailing

- Only lateral seismic actions are considered
- Designing for inelastic response of structural systems the designer is able to use loads 30-60% lower than may be elastically required during a large earthquake
- The goal is improved load cycle resistance by increased ductility via design and detailing



$$\mu = \frac{\Delta_u}{\Delta_y}$$

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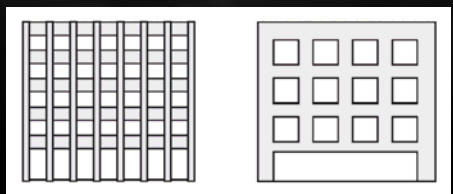
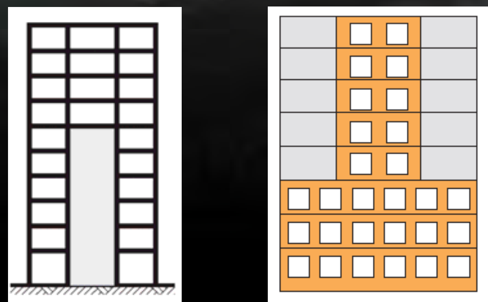
Regularity of Structures

Some of the issues include:

- Irregular buildings will always perform badly under seismic actions if not adequately designed and detailed
- AS 1170 .4 makes no distinction between regular and irregular buildings however the NZS 1170.5 has requirements
- Engineers need to pay careful attention to items such as: soft storeys, transfer beams and short columns



Soft first storey



Vertical irregularity

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Moment-resisting Frames

Ductility of Concrete Structures (part Table 6.5(A) of AS 1170.4)

Description	μ	S_p	S_p / μ	μ / S_p
Special moment-resisting frames (fully ductile)* ·	4	0.67	0.17	6
Intermediate moment-resisting frames (moderately ductile)	3	0.67	0.22	4.5
Ordinary moment-resisting frames	2	0.77	0.38	2.6
Ductile coupled walls (fully ductile)*	4	0.67	0.17	6
Ductile partially coupled walls*	4	0.67	0.17	6
Ductile shear walls	3	0.67	0.22	4.5
Limited ductile shear walls	2	0.77	0.38	2.6
Ordinary moment-resisting frames in combination with limited ductile shear walls	2	0.77	0.38	2.6
Other concrete structures not listed above	2	0.77	0.38	2.6

* The design of structures with $\mu > 3$ is outside the scope of the Australian Standard

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Moment-resisting Frames

Ordinary Moment-resisting Frames

- Need no specific detailing of the concrete for seismic resistance
- Detailing is set out in the main body of AS 3600
- Higher earthquake design forces

  Lower μ, higher S_p / μ value

- Provides only limited frame ductility
- Primarily as a result of the poor beam column joint performance

- Should provide sufficient robustness to cater for forces it may experience during an earthquake larger than the one assumed in design

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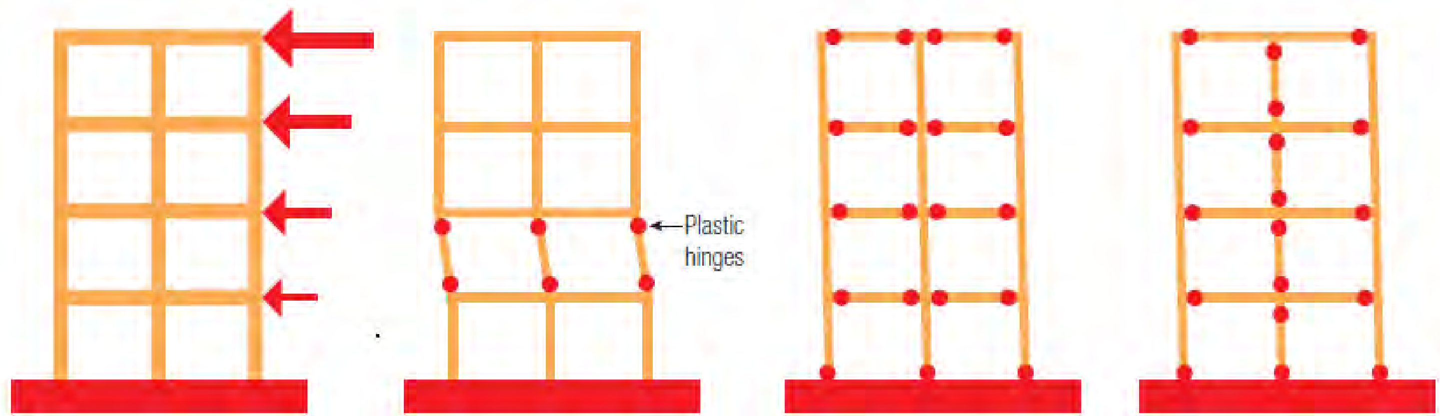
Moment-resisting Frames

Ordinary Moment-resisting Frames

- Avoid plastic hinges in columns – Strong column/weak beam approach
- No requirement to provide in body of AS 3600 (refer Appendix C for IMRF's)
- As a result, any of the 3 modes of failure can occur



Frame

a) Column sidesway mechanism
- soft storey (strong beam/weak column)
- non-preferred arrangement

b) Beam sidesway mechanism
- plastic hinges in beams only (weak beam/strong column)
- preferred arrangement

c) Mixed sidesway mechanism
- interior columns form plastic hinges
- acceptable with adequate design and detailing for ductility

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Moment-resisting Frames

Intermediate Moment-resisting Frames

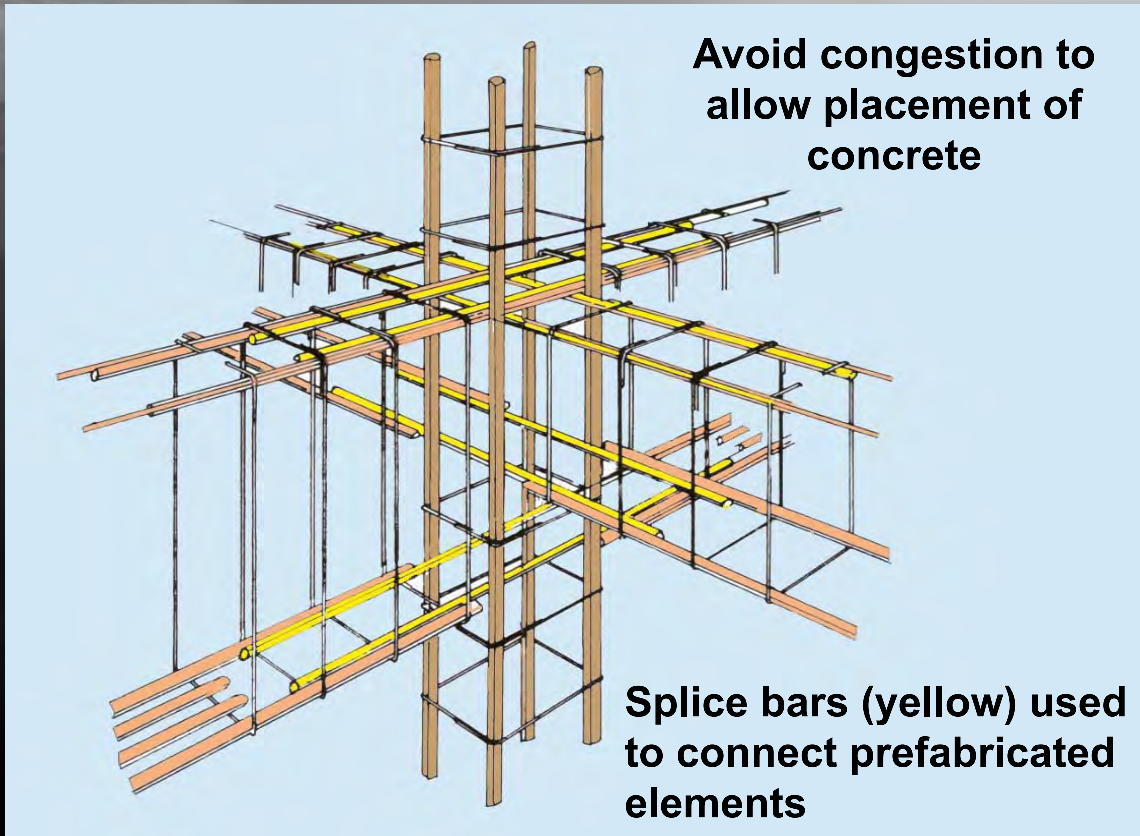
- Regarded as ductile if the additional detailing requirements of Clause C4 of AS 3600 are adopted
- Because of the detailing they are designed for lesser seismic loads than for an ordinary moment-resisting frame
- Consider and detail beam column joints to provide a strong column/weak beam configuration

Special Moment-resisting Frames

- Extra detailing over an intermediate moment-resisting frame
- Increased ductility allows for reduced seismic actions
- For design:
  - AS 3600 refers designers to NZS 1170.5
  - Could use ACI 318M-14

Detailing Beams - OMRF

Loose bar detailing

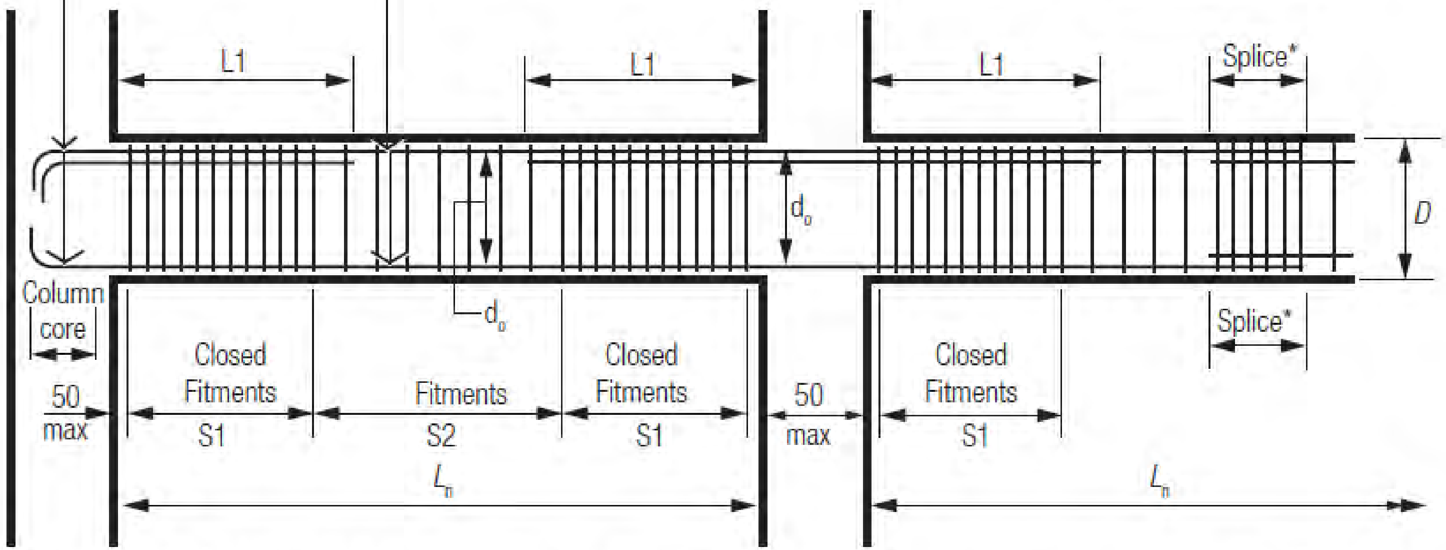


Detailing Beams - IMRF

Extend $L_{sy.t}$ straight or 0.5 $L_{sy.t}$ where cogged into core

Longitudinal reinforcement, top amd bottom +ve moment strength ≥ 33% -ve moment strengthat face of either column joint. Moment strength ≥ 20% maximum moment strength at face of either column joint. ≥ 33% total -ve moment tensile reinforcement required at support shall be extended D beyond the point of contraflexure, per Clause 8.1.10.3. Minimum of 2 bars, continuous top and bottom

*Lap splices to be confined by at least 2 closed fitments at each splice Note: position of splice to be determined by designer to avoid position of maximum moment



Terminate all required top and bottom bars at the far face of the column core, providing minimum distance $L_{sy.t}$ for tension per Section 13.1 of AS3600

Engineer must provide dimensions L1, S1,S2, fitment and closed fitment spacing, anchorage length, cut-off points of discontinuous bars and $L_{sy.t}$

Maximum fitment spacings

In length S1, spacing for closed fitments ≤ $0.25d_o$; $8d_b$;$24d_f$; or 300mm, whichever least.

In length S2, spacing of fitments ≤$0.5D$ or 300mm, whichever least

L_n = clear span and ≥ $4D$ (Clause 12.1.1)

L1= distance required by design for moment plus anchorage length(= $L_{sy.t} + D$)

d_b = diameter of smallest longitudinal bar enclosed by fitment

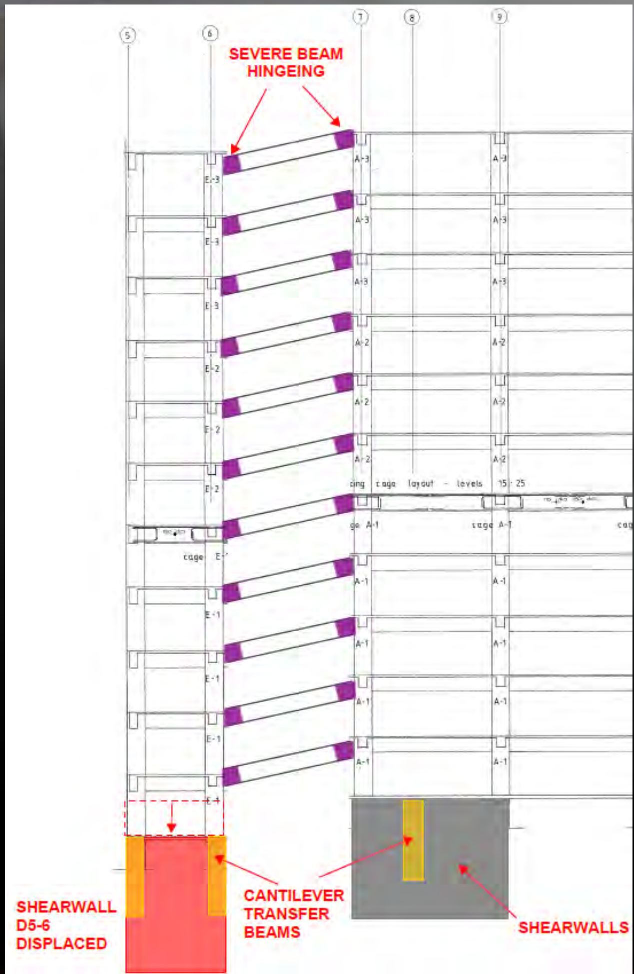
d_f = diameter of bar forming fitment

d_o = design depth for -M and +M

S1 ≥ $2D$

Example: Plastic hinges in beams

Hotel Grand Chancellor, Christcurch, NZ



(Images courtesy Dunning Thornton Consultants Ltd)

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Example: Detailing Beams

Failure of a beam column joint at Copthorne Hotel, Christchurch 2011

Bottom bars not adequately anchored in the confined region of the column

(Photograph courtesy Peter McBean)

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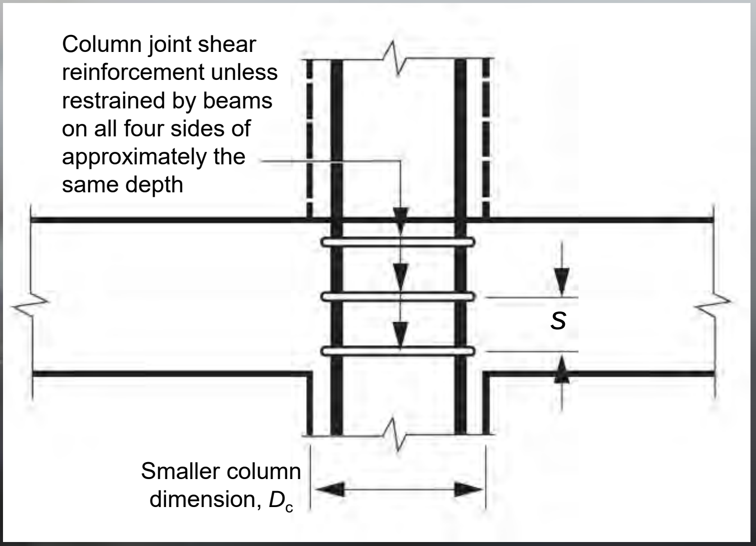
Column joint reinforcement

Ordinary moment-resisting frame (OMRF)

- If not restrained on 4 sides……
- Area of closed fitments Cl 10.7.4.5

$$A_{sv} \geq \frac{0.35\, bs}{f_{sy.f}}$$

for $f'_c \leq 50$ MPa



- Spacing of closed fitments, *s* (Cl 10 7.4.3)

  Single column bars - D_c or $15d_b$

  Bundled bars - $0.5D_c$ or $7.5d_b$

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Column joint reinforcement

Intermediate moment-resisting frame (IMRF)

- Area: $A_{sv} \geq \dfrac{0.35\,bs}{f_{sy.f}}$ for $f_c' \leq 50$ MPa

  For $f_c' > 50$ MPa refer Clause 10.7.3 of AS 3600

  ACI 318 Cl 15.4.2 $A_{sv} \geq 0.062\sqrt{f_c'}\dfrac{bs}{f_{sy.f}}$

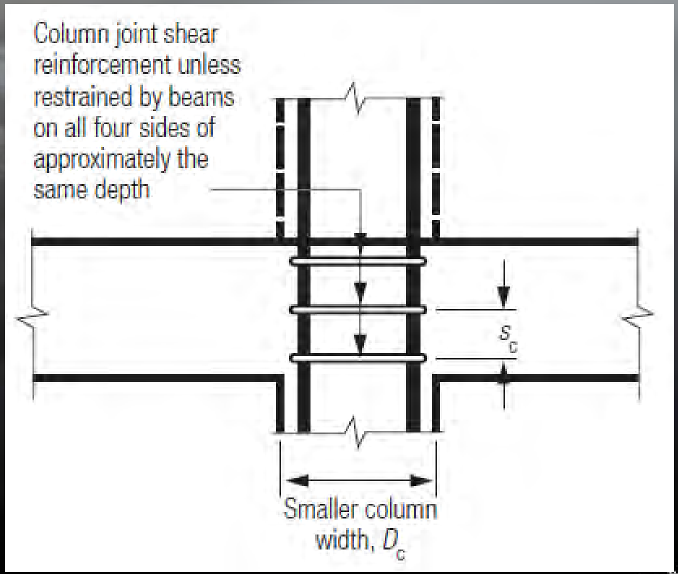
- Spacing of closed fitments, s_c

  $0.25d_o$, $8d_b$, $24d_f$, or 300 mm

- Closed fitments may be spaced at $2s_c$ (or s_c with $0.5A_{sy}$) for the depth of the shallowest beam provided beams frame into the column from all four sides

- Maximum spacing of fitments - $10d_b$ or 200 mm

  Cl 15.4.4.4 NZS 3101.1 (2006)



Note: The above spacing requirements s_c from the 2001 version of AS 3600 have been lost in the 2009 revision of AS3600

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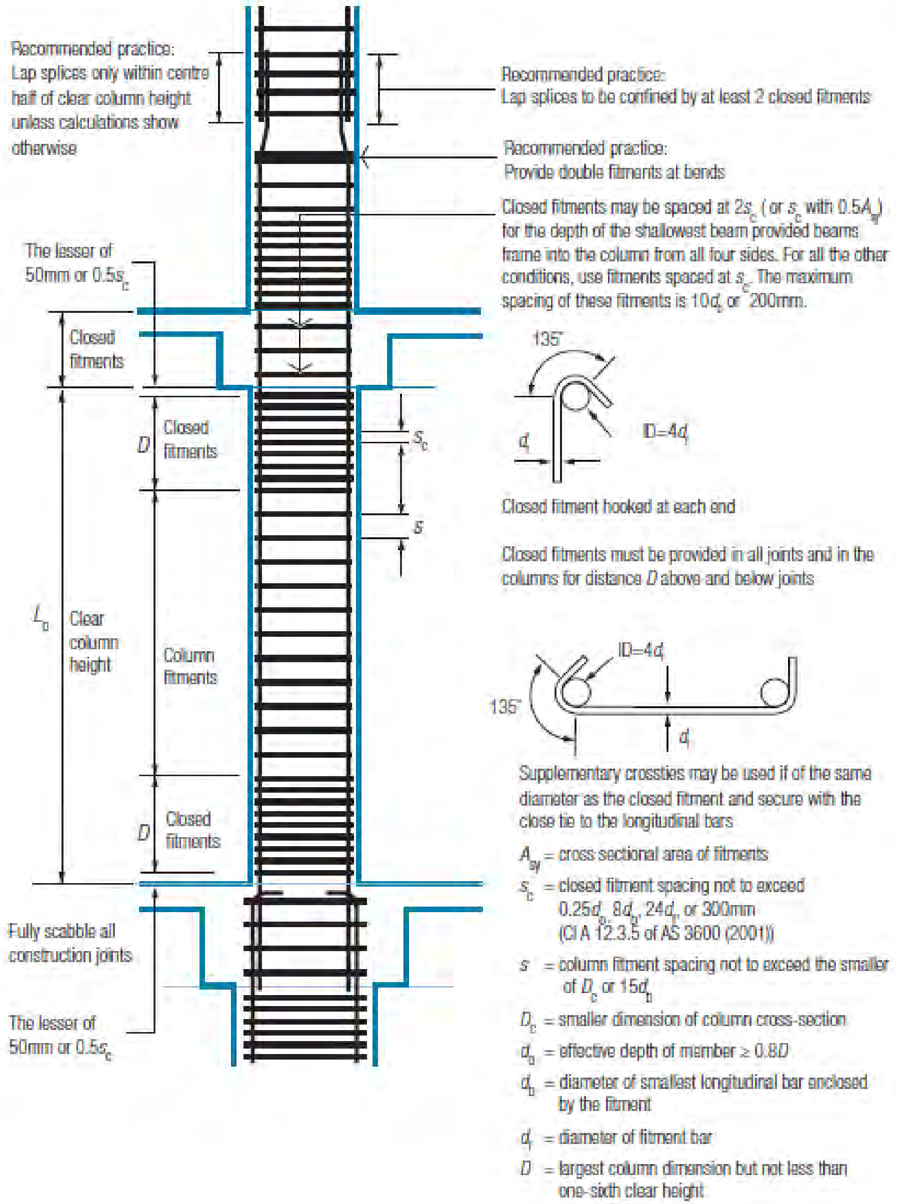
Detailing IMRF Column Confinement Reinforcement



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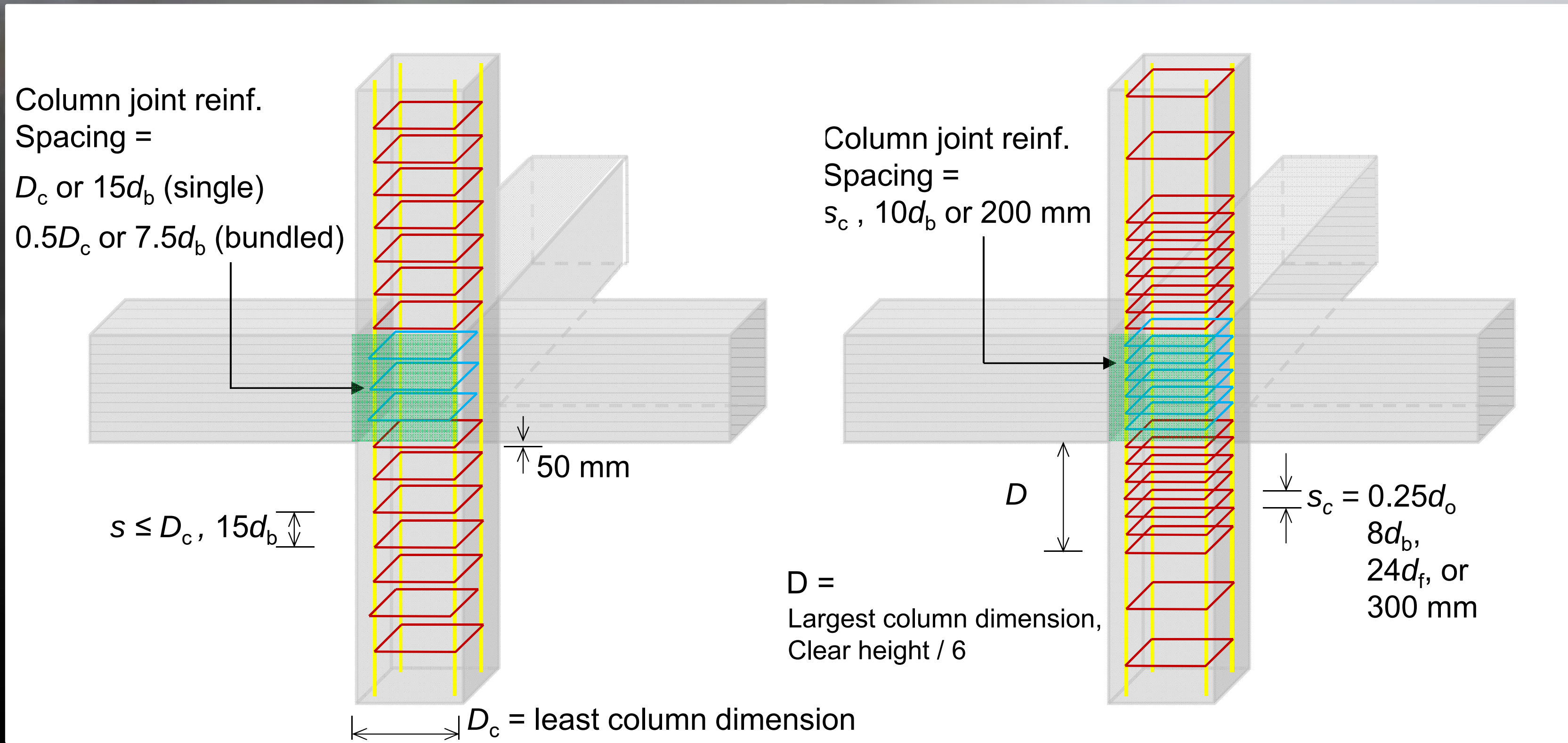
Column joint reinforcement

Beams not on 4 sides of OMRF **Beams not on 4 sides of IMRF**



Example: Column failure due to poor confinement

Insufficient lateral restraint of column reinforcement

Hotel Grand Chancellor, Christchurch, NZ
(Photograph courtesy Peter McBean)

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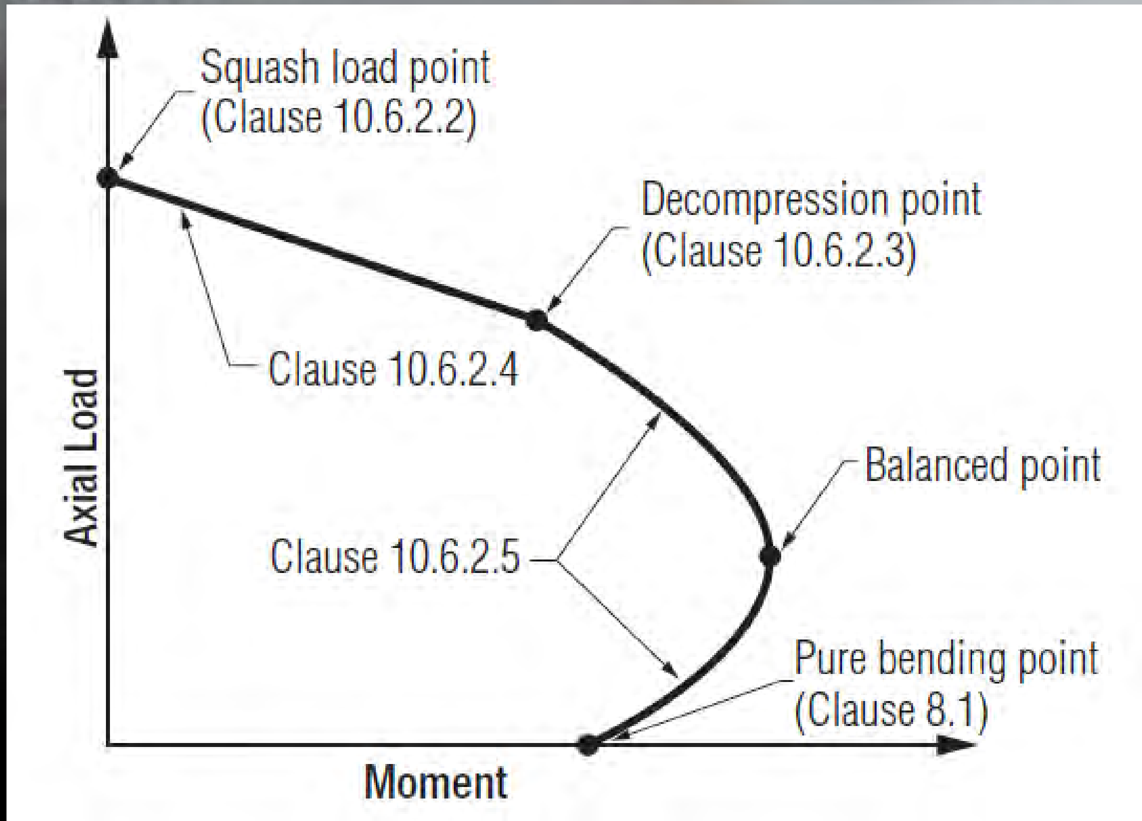
Column design

Design up to balance point to provide reserve capacity for earthquake cyclic lateral loading



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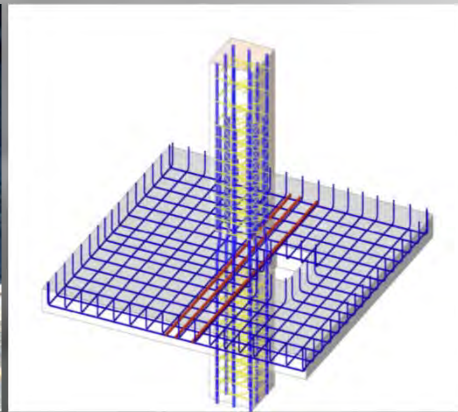
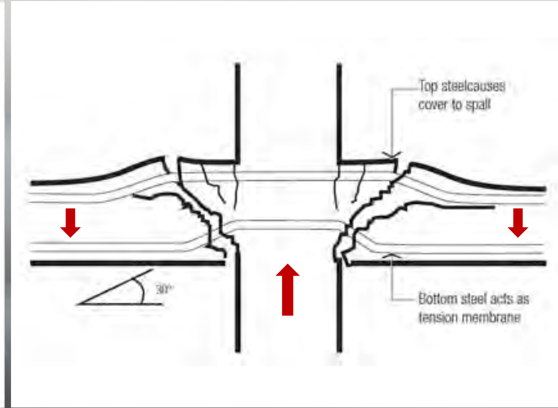
Slab column joint

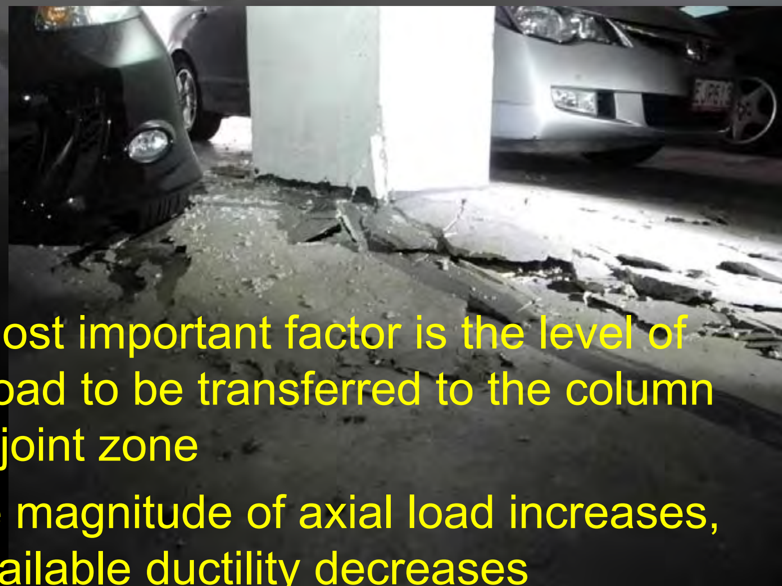
Tensile membrane steel at column-slab intersection





Remains of car park floor – Old Newcastle Workers Club NSW - Brittle failure & progressive collapse
(Photo courtesy Cultural Collections, The University of Newcastle, Australia)

(Photo Courtesy Newcastle Library)



- The most important factor is the level of axial load to be transferred to the column at the joint zone
- As the magnitude of axial load increases, the available ductility decreases

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Slab column joint

Area tensile membrane reinforcement (Structural Integrity Reinforcement)

ACI 352.1R-11 Guide for Design of Slab-Column Connections in Monolithic Concrete Structures

For internal connections

$$A_{sm} = \frac{0.5 w_u l_1 l_2}{\phi f_{sy}}$$

where :

$l_1 =$ Length of span in direction that moments are being determined

Measured centre - to - centre of supports (mm)

$l_2 =$ Length of span in direction perpendicular to l_1

Measured centre - to - centre of supports (mm)

$w_u =$ Factored uniformly distributed load

Not less than two times the slab dead load,

To be considered for resistance to progressive collapse (N/mm^2)

$\phi = 0.9$

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Diaphragms

Some of the issues include:

- Diaphragms are a critical element in the design of any building for seismic actions as they tie the structure together
- AS 1170 .4 makes brief reference to diaphragms in Clause 5.2.5, and AS 3600 in Clause 6.9.4 states, that *insitu concrete floor slabs can be assumed to act as horizontal diaphragms*
- Unfortunately, there is no guidance in either Standard on the design of these diaphragms or the transfer of actions from diaphragms into the vertical elements.
- **Engineers must consider the transfer of these primary loads through the structure and how to approach design**

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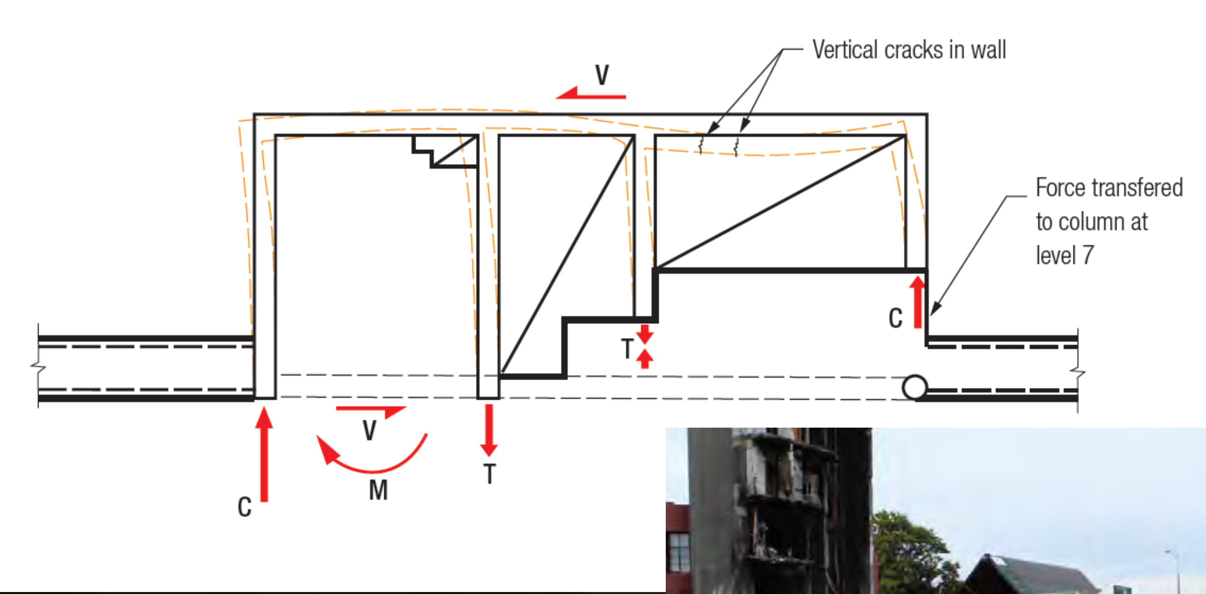
Diaphragms – ACI 318M-14

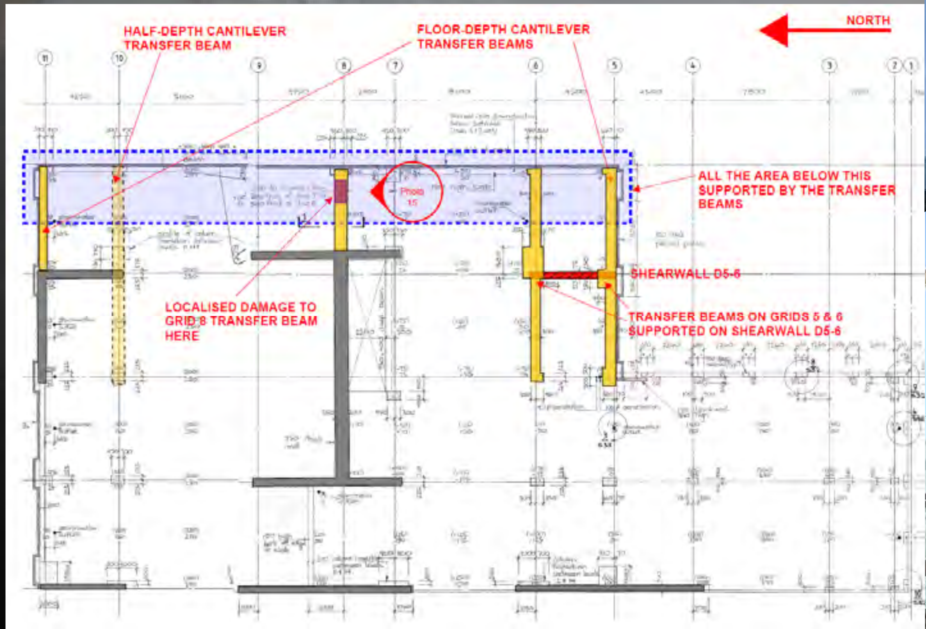
Failure of shear wall/diaphragm connection



From CTV Building,
Christchurch NZ
Royal Commission Report

Walls

Heavily loaded walls exhibit lower ductility



Failure of shear wall D5-6
Hotel Grand Chancellor, Christchurch, NZ
(courtesy Dunning Thornton Consultants Ltd)

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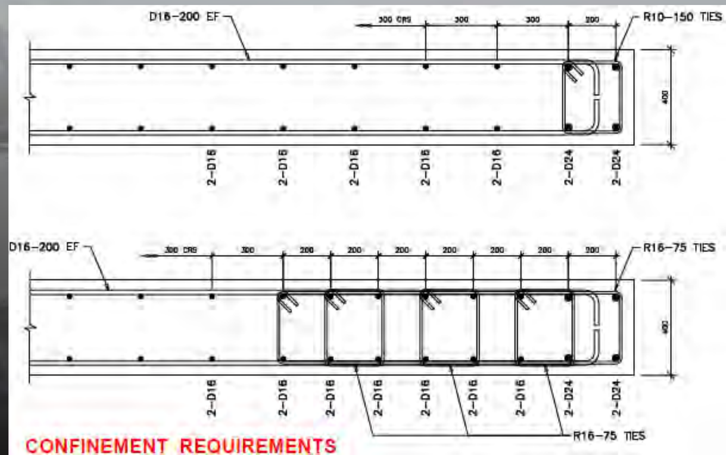
Walls

Ensure boundary elements are adequately detailed if compr. stress > $0.15 f_c'$

Aim is to provide ductile flexural yielding at base of wall to avoid shear failure



Existing confinement reinforcing (top)

Fully confined for maximum calculated load (bott)
NZS 3101:1982 and 2006

Hotel Grand Chancellor, Christchurch, NZ

(courtesy Dunning Thornton Consultants Ltd)

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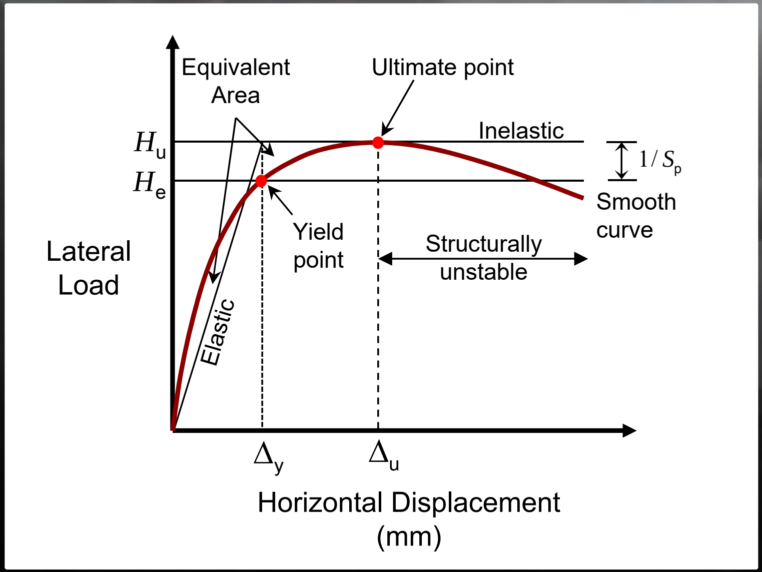
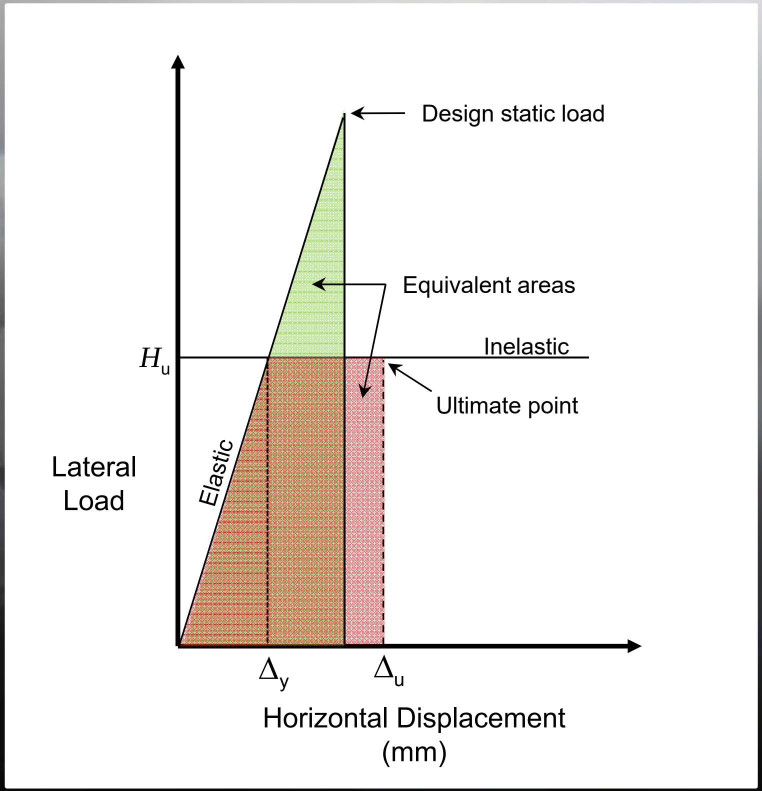
Transfer Structures

Design Elastically





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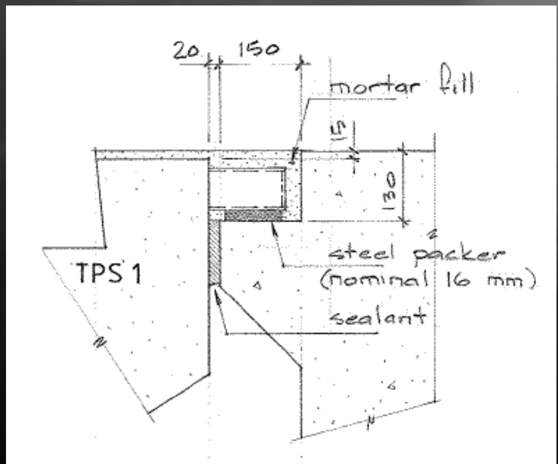
Stairs

Consider inter-storey drift of the structure

AS 1170.4 requires detailing to allow for 1.5 times the calculated inter-storey drift



Hotel Grand Chancellor, Christchurch, NZ

(courtesy Dunning Thornton Consultants Ltd)

Non-Structural Elements

- Non-structural elements such as building services, partition walls, cladding, or ceilings are also briefly covered in the new Guide
- Failure of these elements can lead to people being unable to safely exit the building

Figure 6.4.3.3-4 Flexible pipe connections at building separation (Photo courtesy of Mason Industries).

- Articulation of services crossing seismic joints

Figure 6.4.3.1-6 All-directional cable bracing of suspended piping (Photo courtesy of ISAT).

Restraint of services

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High-strength Concrete

Some of the issues include:

- A basic incompatibility of high strength concrete and required ductility under extreme seismic event
- There is limited experience of high strength concrete in overload situation
- Consider using maximum strength of 50MPa in IL4 buildings as good seismic practice

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Alternative Methods and Technologies now available to Reduce Risk of Damage

1. **Base isolation** (Highest level of protection)
   - Provides full operation post event
   - Increased construction cost estimated 8-10%
2. **Minimisation of damage** (Next level protection)
   - More robust, regular structure with higher ductility & alternative load paths
   - Lower risk of structural damage
   - Structure remains operational, repairable, lower insurance claims
   - Increase RC construction cost estimated 1-2%
3. **Compliance with BCA** (Minimum level)
   - Provides life safety allowing people to exit
   - Does little to prevent damage
   - Demolition likely following an extreme event

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Client/Building Owner's Expectations

Christchurch CBD: more than 800 buildings demolished

Designers must discuss the needs of 'life safety' or 'low damage' strategy at the early planning stage

- Typically building owners have different views on what seismic design entails
- They may mistakenly assume their building will survive a major earthquake without damage
- While probability of earthquake is low the damage can be extensive requiring demolition

Poorly confined column Kobe, Japan 1995

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Responsibility of Earthquake Design

It is vital that one Principal Designer owns the structural requirements:

- Ensures building integrity & continuity of overall structural systems
- Designs should be independently peer-reviewed by experienced colleagues

Where the Principal Designer subcontracts detailed design of project elements (e.g. precast or post tensioned systems)

- They should ensure the work is fully specified & controlled via detailed performance requirements
- They must retain complete responsibility for their design and subcontracts

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Conclusions

The new Guide to Seismic Design & Detailing of RC Buildings in Australia will:

- Provide valuable information including checklists to owners, designers & contractors
- Assist in the seismic design & detailing of resilient concrete structures
- Assist in establishing a consistent approach to high quality rational detailing by compiling a set of simple seismic design principles
- Attempt to compensate for our inability to accurately predict either the magnitude of earthquake actions or structural response
- Provide a significant increase in earthquake resistance for a relatively small additional design & construction cost
- Improvement in the drift performance of buildings through better conceptual design and detailing and through limiting the axial stress levels on the gravity carrying elements

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Thank you