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Reconstructing Christchurch:
A Seismic Shift in Building Structural Systems
February 13, 2019



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Course Description

Reconstructing Christchurch: A Seismic Shift in Building Structural Systems
February 13, 2019

After the 2010–2011 Canterbury earthquakes, much of the Christchurch Central Business District was demolished, and a new city has emerged in its place. From a structural engineering perspective, the new “heart” of Christchurch is quite different from the old one. Where reinforced concrete buildings dominated the urban landscape, with almost all multistory buildings relying on RC frames or walls to resist earthquake shaking, the emerging Christchurch has a variety of structural forms, an extensive amount of steel structures, and some structural systems introduced to make the new Christchurch buildings more seismically resilient. A study (by Michel Bruneau (University at Buffalo, Buffalo, NY, USA) and Greg MacRae (University of Canterbury, Christchurch, New Zealand) was conducted to (a) quantify the extent to which various types of structural system have been used in the new buildings constructed (for data collected up to March 2017), and (b) identify some of the drivers that have influenced decisions about the selection of structural material and specific structural systems used. This Webinar will review results from that study and provide valuable insights into some of the mechanisms that can dictate structural engineering decisions during the post-earthquake reconstruction of a modern city. The Christchurch experience may be unique today, but it could repeat itself in other similarly developed cities worldwide after future devastating earthquakes.



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Learning Objectives

- Identify the types of earthquake damage found in buildings of the Christchurch Central Business District (CBD).
- Describe the reconstruction and repair strategies adopted by the design and construction community of Christchurch.
- List the structural building systems that have been chosen for recently-constructed new buildings of Christchurch CBD.
- Explain how the priorities of the various decision-makers (i.e., developer, architect, engineer) have shifted as a result of the earthquakes in Christchurch.



Reconstructing Christchurch: A Seismic Shift in Building Structural Systems



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Reconstructing Christchurch: A Seismic Shift in Building Structural Systems

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Department of Civil and Natural Resources Engineering
University of Canterbury



<https://www.aisc.org/technical-resources/seismic>
<http://resources.quakecentre.co.nz/reconstructing-christchurch/>



Why this study?

- Rebuilding of Christchurch
 - Steel construction seemed to dominate (as anyone could see strolling through downtown)
 - Is it true? Why?
- The Christchurch experience is likely to repeat itself in other similarly developed urban centers worldwide after future devastating earthquakes
- As such, the Christchurch rebuilding experience provides a unique insight into some of the mechanisms that can dictate structural engineering decisions during the post-earthquake reconstruction of a modern city



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Introduction

- Overview of pre-2011 Construction Practice in Christchurch
- Overview of 2011 Christchurch Earthquake(s)
 - General
 - Performance of RC and Steel Buildings
- Repair Issues and Role of Insurance in Recovery
- Reconstruction of Christchurch
 - Quantitative Findings
 - Qualitative Findings – who decides structural system?
- Conclusions



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Where is New Zealand?



Figure from: <https://www.towinsome.com/is-the-world-upside-down/>



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Where is Christchurch in New Zealand?

- Population of New Zealand
 - 4.8 million
- Population of South Island
 - 1.04 million



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Where is Christchurch in New Zealand?

- Population of New Zealand
 - 4.8 million
- Population of South Island
 - 1.04 million
- Population of Christchurch
 - 376,300 in 2010
 - 355,100 in 2012
 - 375,000 in 2016
 - 388,400 in 2018

From <https://www.ccc.govt.nz/culture-and-community/christchurch/statistics-and-facts/facts-stats-and-figures/population-and-demographics/population/current-pop/#PopulationChange>

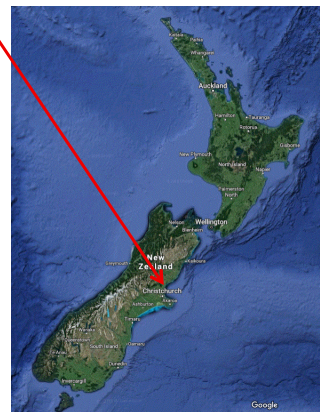


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Reinforced Concrete in Christchurch

- RC construction dominated Christchurch before EQ
- Plenty of cement, water, and aggregate readily available (from the river gravels) in NZ (e.g. Waimakariri near Christchurch)
- RC construction, incl. structural walls, since the 1930s
- RC MRF with masonry infill common until about 1970
- Non-ductile RC MRF used until about 1980
- Ductile RC MRF: started in 1970s; prevalent after 1980s
- Multistory tilt panel buildings in 1980s
- Influences of Park, Paulay, Priestley at University of Canterbury helped “cement” concrete as the major construction material in Christchurch



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Cost of Steel

- Mid-2008, steel peaked at record high of \$1265^{US} per metric ton
- Quickly decreased by mid-2009 and fluctuated since
 - Record low: 10% of peak price (\$90^{US} per metric ton)
- Low price of steel makes it more attractive as a building material

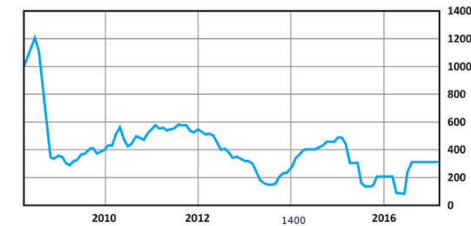


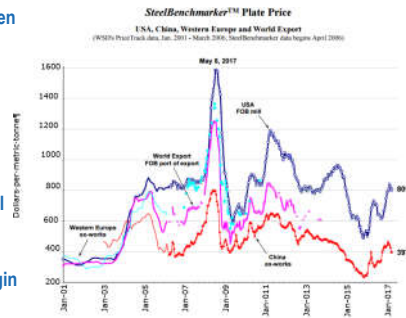
Figure 2-1: Steel price chart in US dollars per metric ton (Trading Economics, 2017a)



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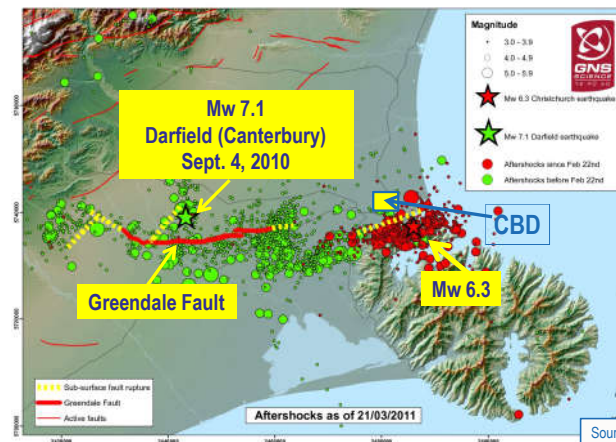
Cost of Steel

- Significant difference in price between US and Chinese steel
- Production 1990-2017 in China increased 14-fold (to 77,000+ tons)
- Accusations of steel dumping
- Issues with quality of steel imported from parts of Asia
 - Some only allow steel from local or pre-approved overseas mills
 - Others rely on extensive testing or their own staff at point of origin
- Parts of steel structures often fabricated in Asia before shipping to New Zealand for final site assembly
- Last 2 multistory buildings in Christchurch before EQ were steel



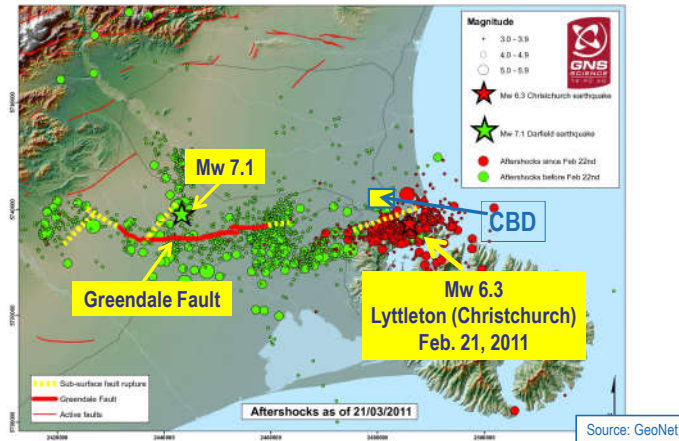
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Mw 7.1, Darfield (Canterbury), Sept. 4, 2010



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Mw 6.3, Lyttleton (Christchurch), 21 Feb. 2011



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Reconnaissance Reports

- Comprehensive
 - New Zealand Society of Earthquake Engineering [NZSEE]. (2011). 2011 Christchurch earthquake special issue. Bulletin of the New Zealand Society for Earthquake Engineering, 44(4), 181-430.
 - New Zealand Society of Earthquake Engineering [NZSEE]. (2016). 2016 Kaikoura Earthquake special issue. Bulletin of the New Zealand Society for Earthquake Engineering, 50 (2).
- Performance of Steel Structures
 - Clifton, C., Bruneau, M., MacRae, G., Leon, R., Fussell, A., (2011). "Steel Structures Damage from the Christchurch Earthquake of February 22, 2011, NZST," Bulletin of the New Zealand Society for Earthquake Engineering, Vol.44, No.4, pp.297-318.
 - Bruneau, M., Anagnostopoulou, M., MacRae, G., Clifton, C., Fussell, A., (2010). "Preliminary Report on Steel Building Damage from the Darfield (New Zealand) Earthquake of September 4, 2010", New Zealand Society for Earthquake Engineering Bulletin, Vol.43, No.4, pp.351-359.

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Mw 7.1 event

- 4:36 a.m. local time
- 1 fatality (heart attack)
- 2 serious injuries
- initial cost estimate:
 - \$4.5-7.5 billion



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Mw 7.1 event

- 4:36 a.m. local time
- 1 fatality (-4)
- 2 serious injuries
- initial cost estimate:
 - \$4.5-7.5 billion

Mw 6.3 event

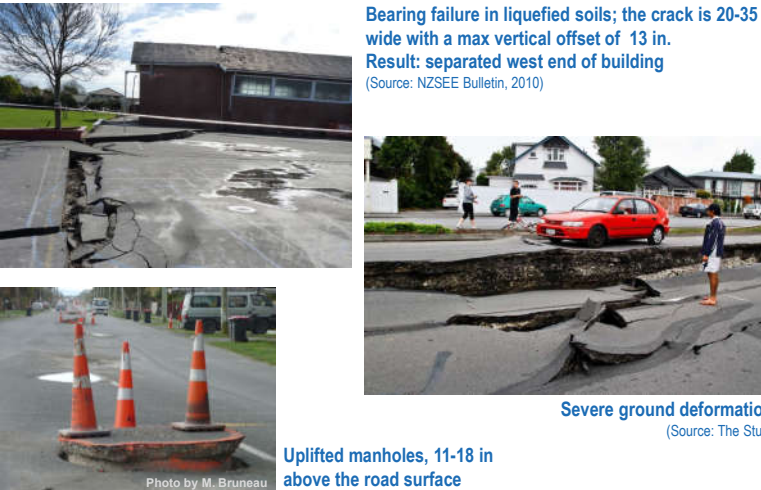
- 12:51 p.m. local time
- 185 fatalities
- 164 serious injuries
- Initial cost estimate:
 - \$7.5-12 billion



- For both earthquakes:
 - Faults not previously identified
 - 9000+ aftershocks
 - Extensive damage due to Liquefaction




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Bearing failure in liquefied soils; the crack is 20-35 in wide with a max vertical offset of 13 in.
Result: separated west end of building
(Source: NZSEE Bulletin, 2010)

Uplifted manholes, 11-18 in above the road surface
Photo by M. Bruneau

Severe ground deformation
(Source: The Stuff)



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Silty-sand and water covering streets indicate extensive liquefaction
(Source: NZSEE Clearinghouse, 2011)



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Lateral spreading in residential areas due to liquefied soils



Result: separated end of building
(Source: NZSEE Bulletin, 2010)

Result: extensive tilt and separation of foundation
(Source: NZSEE Bulletin, 2010)



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Avonside Drive Pedestrian Bridge

Deck and bearings

- Bearing connection at abutment had shear type failure in longitudinal direction indicating large longitudinal compressive force in bridge structure
- Large longitudinal force in bridge structure lead to global lateral torsional buckling of entire bridge deck



Photo by F. Sarti

Photo by F. Sarti

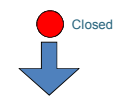


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Avonside Drive Pedestrian Bridge



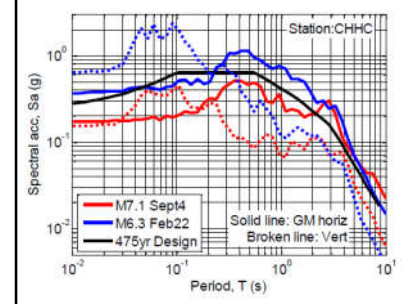
Photo by M. Bruneau



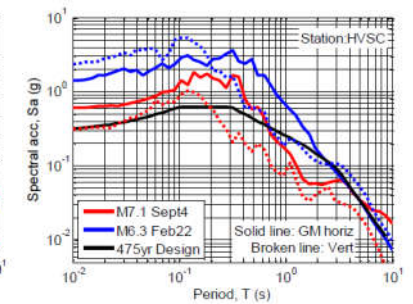
Nonetheless used at 7:30am by a drunk going back home who didn't think much of it (next bridge being 2000' away).



ARS vs. NZS1170 475-year



Station: CHHC
Christchurch CBD



Station: HVSC
Lyttleton near-source region

Source: B. Bradley

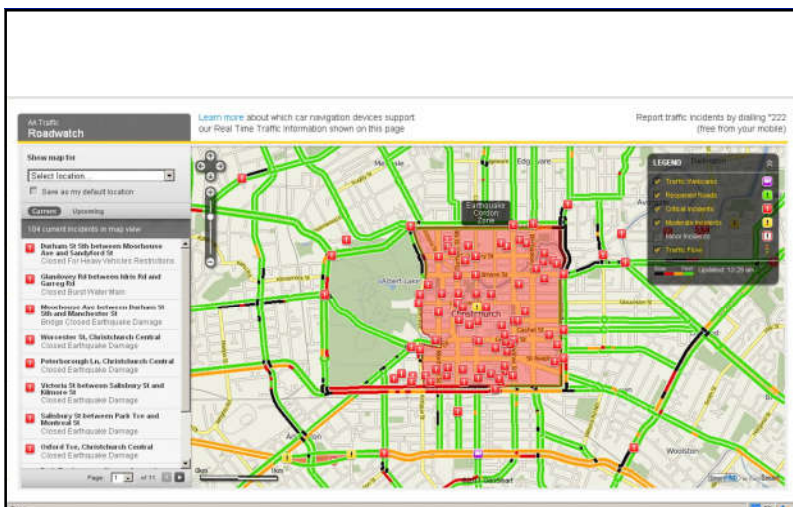
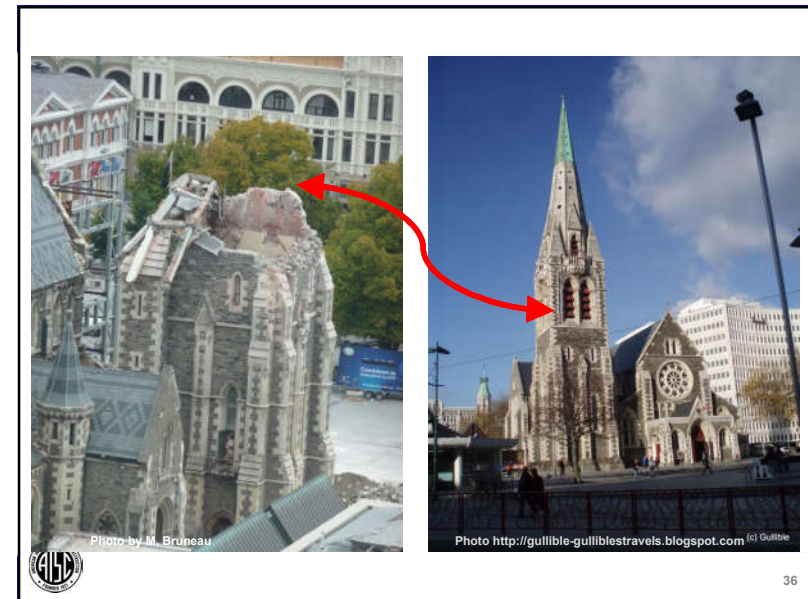
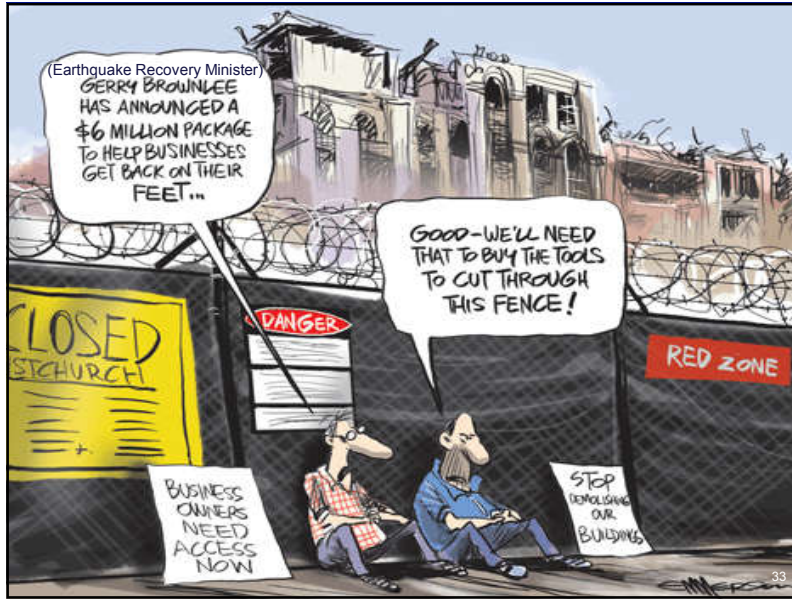
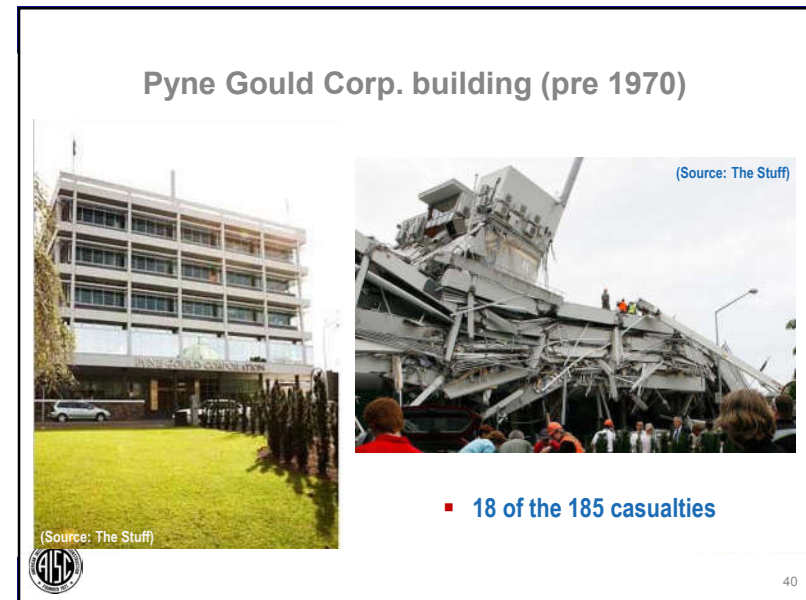
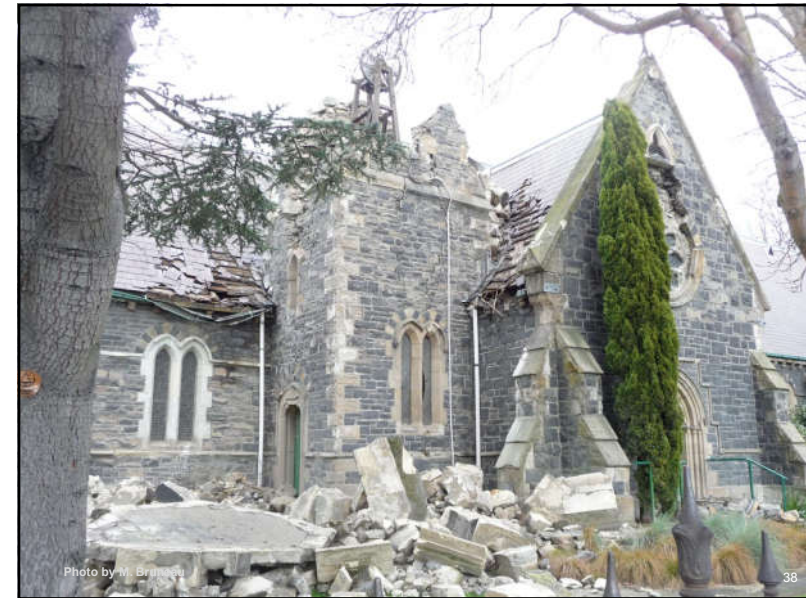


Photo by M. Bruneau







CTV Building

- 115 of the 185 casualties

Photo: Google

Photo: The Stuff



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Photo by M. Bruneau

- Both flights of stairs collapsed:
 - One side of stairwell up to Level 13
 - The other up to Level 15

<http://www.mbie.govt.nz/publications-research/research/building-and-construction/quake-forsyth-barr-stairs-report.pdf>



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Grand Chancellor Hotel (late 1980s)

(Source: The Stuff)




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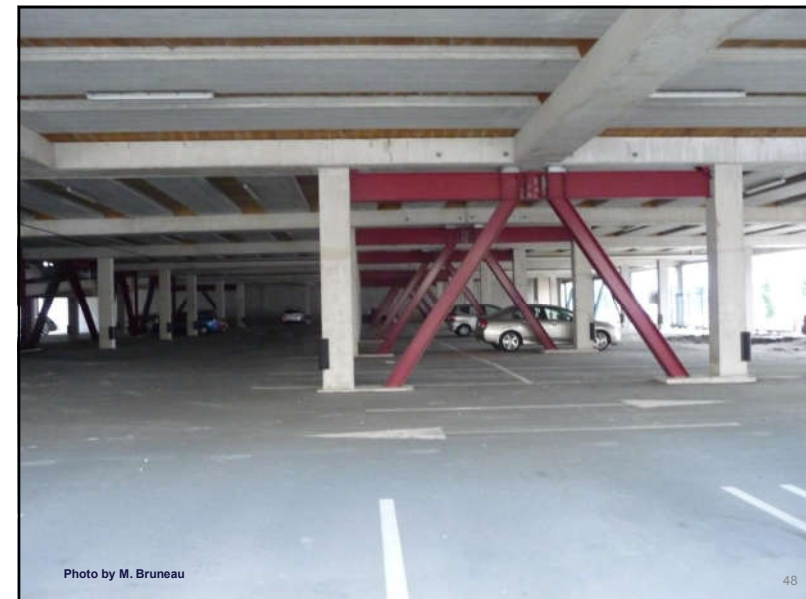
Steel Buildings

- Low number of steel structures in Christchurch area due to:
 - Cheap concrete aggregates in riverbeds
 - Labor disputes in 1970s crippled steel industry until 1990s
- Most steel buildings in Christchurch are recent vintage
- Table 1: Multi-storey steel buildings in CBD and suburbs

No of Storeys	Seismic-Resisting System	Floor System	Year Completed
22	EBFs and MRFs	Composite Deck and Steel Beams	2010
12	EBFs and MRFs	Composite Deck and Steel Beams	2009
7	Shear Walls and CBFs	Composite Deck and Steel Beams	1985
3	MRFs	Composite Deck and Steel Beams	2010
5	EBFs	Composite Deck and Steel Beams	2008
3+	^{Note 1} EBFs	Precast columns and hollowcore units with topping	2003
5	EBFs	Precast columns and hollowcore units with topping	2010



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Photo by M. Bruneau

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Photo by M. Bruneau

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(Gardiner, S., Clifton, G.C., MacRae, G.A., (2013) "Performance, damage assessment and repair of a multistorey eccentrically braced framed building following the Christchurch earthquake series". Steel Innovations Conference 2013, Christchurch, New Zealand.)

APPROX. 1600

400 @ 4

19MM Ø X125MM NELSON STUDS OVER ACTIVE LINK STIFFENERS AND @ 300MM C/C. NO STUDS DIRECTLY ABOVE LINK ZONE OR INTERIOR STIFFENERS

COMFLOR 80 DECK

200UC60

FRPW FLANGE (TYP)

6 TYP

INTERMEDIATE STIFFENER ONE SIDE 6FWAR 6 TYP

200UC50 500

200UC60 500

CUT EXISTING BEAMS / BRACES AS SHOWN. INSTALL NEW FABRICATED LINK & FRPW IN PLACE

ALL STIFFENERS F=10MM

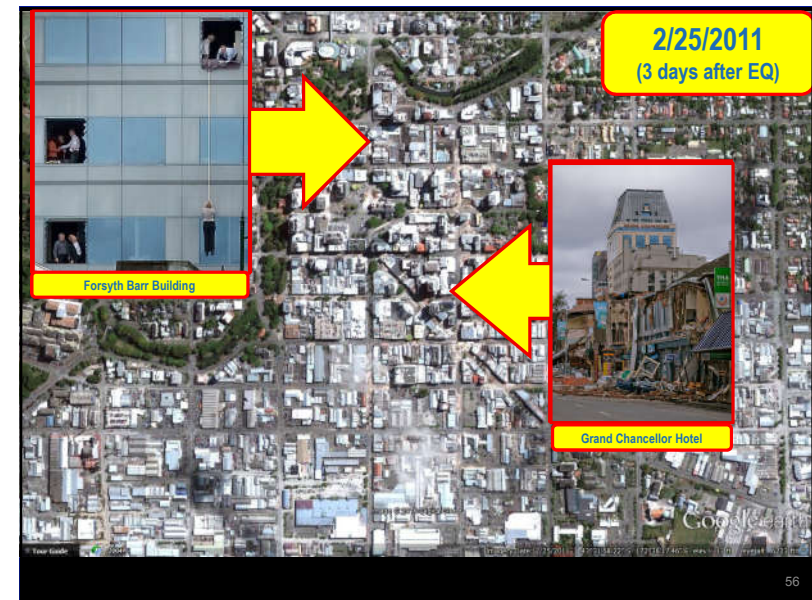
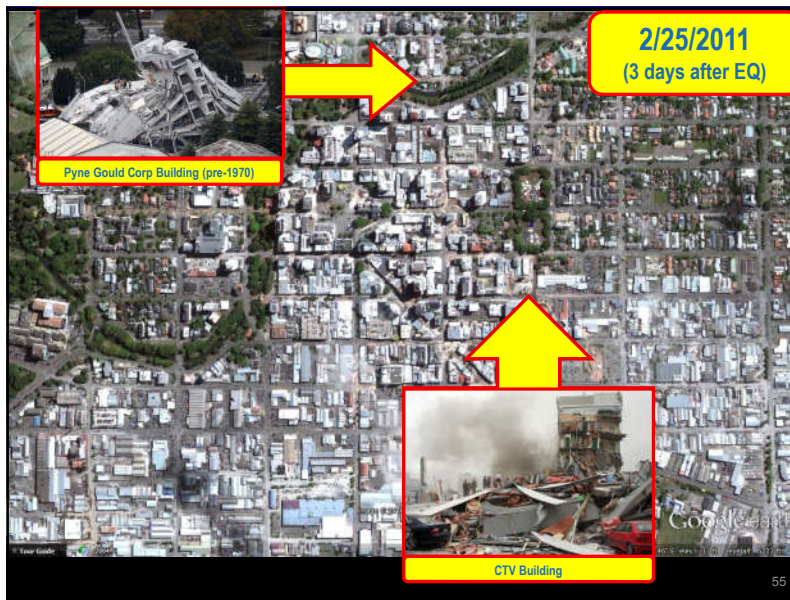
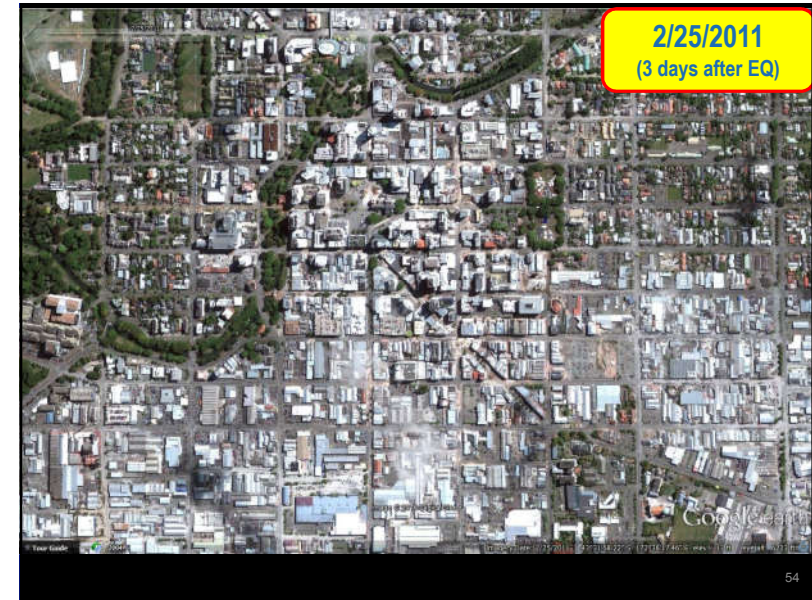
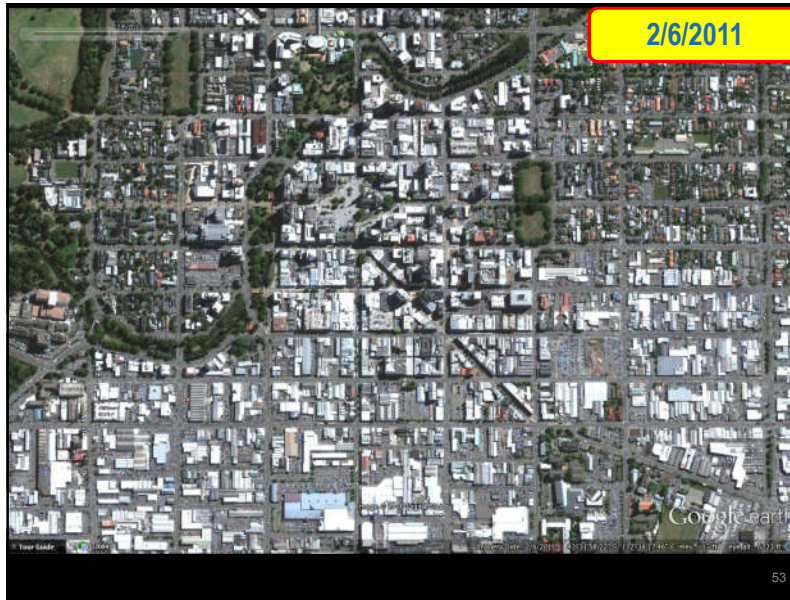
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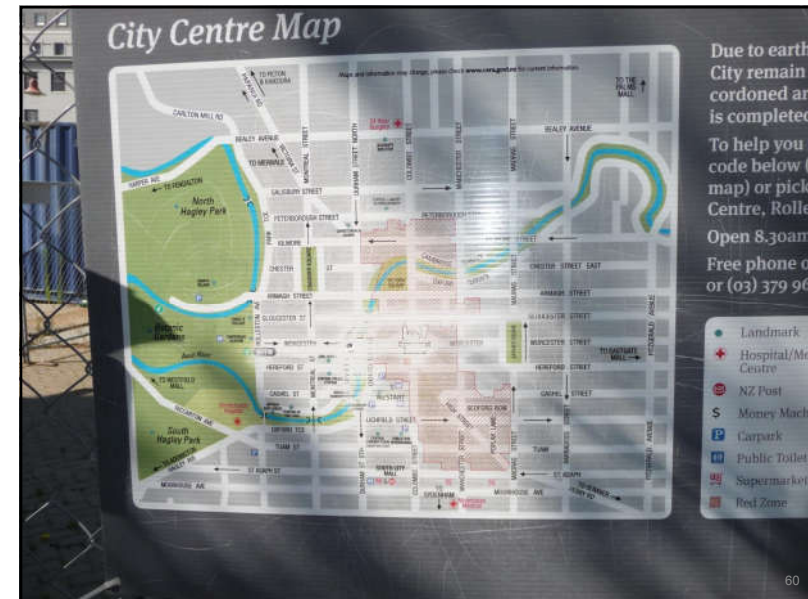
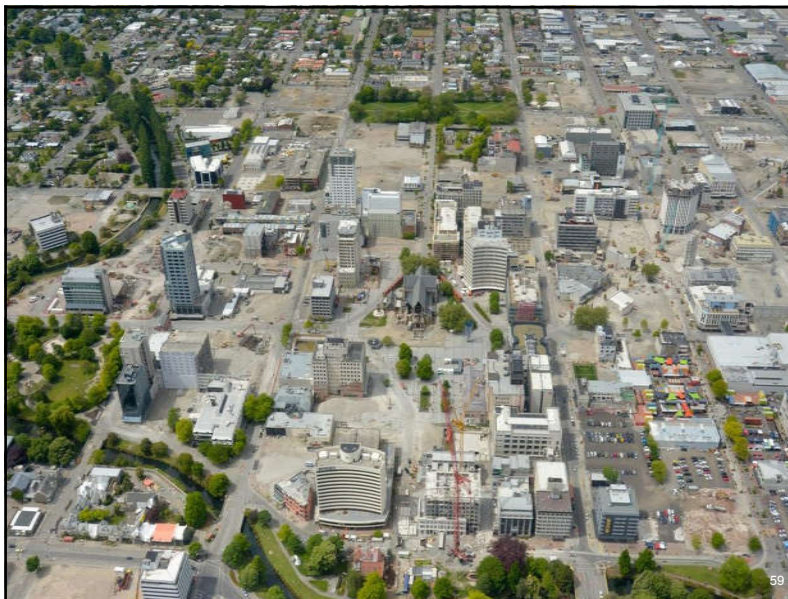
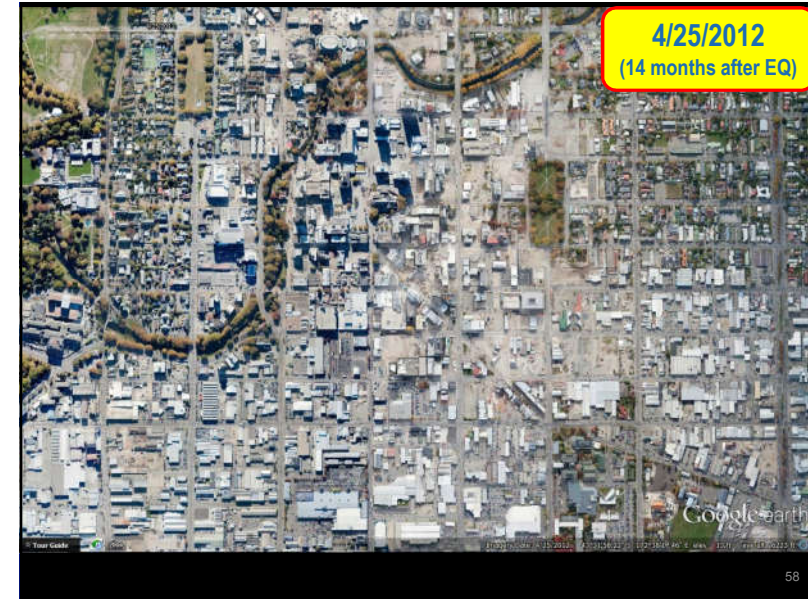
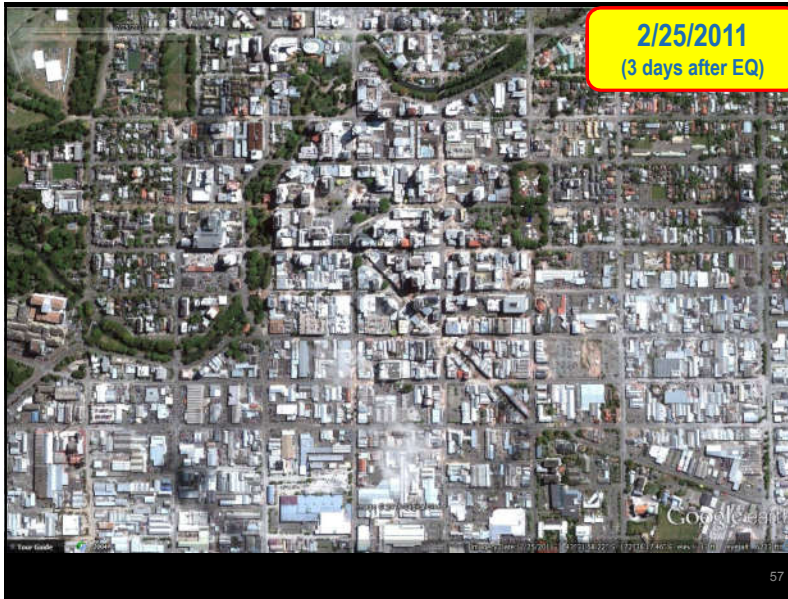
Photo by M. Bruneau



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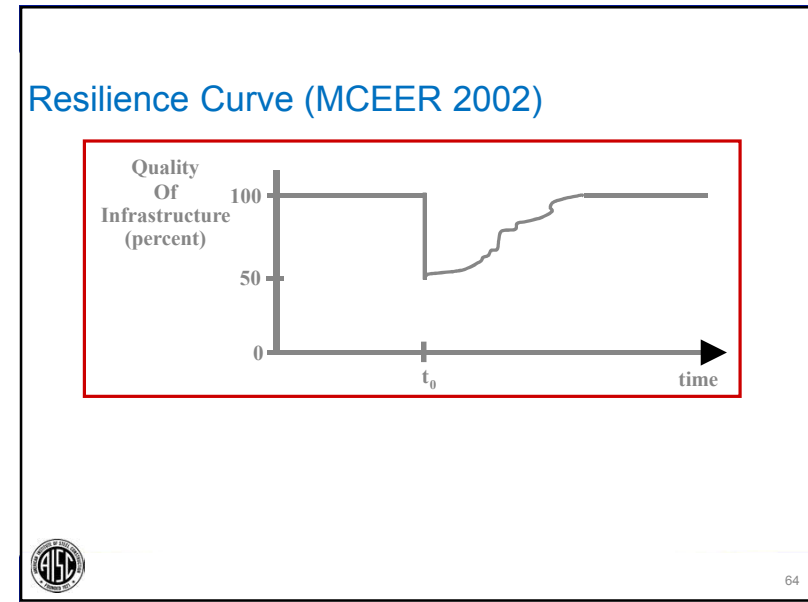
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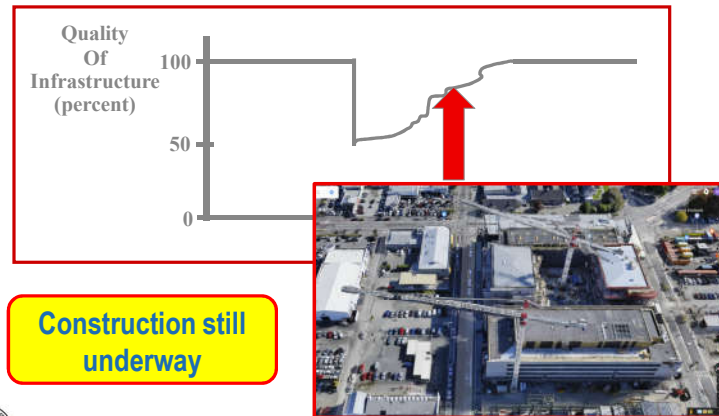
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Resilience Curve (MCEER 2002)



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EQ Insurance Coverage in NZ

- Approximately 80% of the losses in the Christchurch earthquake sequence were covered by insurance (Marquis et al., 2015)
 - Lending banks require that buildings be insured
 - NZ Earthquake Commission insurance program (covers first \$100,000 of residential claim) does not apply to commercial structures, but has insurers comfortable with earthquake insurance market, resulting in a number of distribution channels for relatively cheap insurance
 - Loss of rent and business interruption costs were add-ons included in many insurance policies
 - Generally: upper limit on insured losses



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Insurance Payment for EQ Losses

- Terms of insurance have generally been for “reinstatement” to an effective “as new” condition
- Interpretation: Assessing whether remaining low-cycle fatigue life (and/or ability to resist earthquakes) is likely to be similar (or not) to that required/provided by new structure
- Difference in answers = major differences in repair costs or lead to demolition and reconstruction
- In many cases, cash payments were taken, providing owners with flexibility to sell “as is”, repair, or replace
- Long negotiations for payments delayed demolition and reconstruction
- Lack of available insurance (for a while) delayed reconstruction
- Ongoing aftershock sequence compounded the problem (“why should we insure a building that is still burning?”)



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Impact of Insurance on Building Codes

-



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Impact of Insurance on Building Codes

- None



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Impact of Insurance on Building Codes

- **None - Translation:**
 - Per NZ Insurance Council: NZ insurance sector unable to encourage use of specific types of construction with seismic performance beyond code requirements, or of better design/construction of non-structural elements
 - e.g.: URM still being insured in Wellington
 - NZ is < 0.1% of global reinsurance market, and other international drivers control conditions in NZ
 - While insurance costs went up (~300%) initially after Canterbury events, lack of worldwide disasters over the past few years led to a surplus of reinsurance funds, and insurance cost decrease to pre-EQ levels



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Legislative Context

- Structures incorporating base isolation, buckling restrained braced frames, rocking walls, and other “low-damage” systems not covered by NZ design standards and are considered Alternative Solutions
- Alternative Solutions approach is quite flexible
 - Onus on engineers/peer reviewers to ensure system satisfactory.
- In NZ, a single peer reviewer is required
 - Outcome depends on his/her specialized knowledge and impartiality
 - Engineers reported challenges/delays when advocates of competing systems (e.g., lead-rubber bearing isolators and sliding-friction bearings) are at odds in their recommendations



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Design Requirements

- After EQ, NZ standards did not change to encourage more resilient construction, but
 - Christchurch seismic zone factor increased from 0.22 to 0.30
 - Serviceability level event increased from 25% to 33% of 500-year EQ for ordinary structures, but in late 2016 returned to 25% again
 - i.e., during 2012-16, design force considered for serviceability analyses increased by 80% (i.e., $0.30/0.22 \times 0.33/0.25 = 1.8$)

Annual Probability of Exceedance	Return Period Factor, R	Building Importance Levels			
		IL1 Low hazard structures	IL2 Normal buildings	IL3 Important buildings including schools	IL4 Critical post-disaster buildings
1/2500	1.8				ULS
1/1000	1.3			ULS	
1/500	1.0		ULS		SLS2
1/100	0.50	ULS			
1/25	0.25		SLS1	SLS1	SLS1



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Design Requirements

- For the 500-year EQ, spectra design values use ($R=1.0$)
- Spectra values multiplied by 1.8 for 2500-year EQ
- Lateral-force-reduction factor, $k\mu$, is the minimum of:
 - Value specified for a particular structural material
 - Ratio of ULS and SLS ($1/0.25 = 4$ for IL2 structure) (=3 from 2012-16)
- No MCE explicitly specified in NZ
- Rebuild: Some Engineers used 7500-year EQ used for some IL4 buildings

Annual Probability of Exceedance	Return Period Factor, R	Building Importance Levels			
		IL1	IL2	IL3	IL4
		Low hazard structures	Normal buildings	Important buildings including schools	Critical post-disaster buildings
1/2500	1.8				ULS
1/1000	1.3			ULS	
1/500	1.0		ULS		SLS2
1/100	0.50	ULS			
1/25	0.25		SLS1	SLS1	SLS1



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Methodology (in a few words)

- 4 steps:
 - A street survey (2013-2016);
 - A scoping exercise (2016);
 - Data collection (2017) – databases from SCNZ, CCC, + Engineers; and
 - Data analysis and writing of the report (2017)
- Scoping Study – Preliminary interviews clear message:
 - Gather data by visiting engineers in their own offices to talk through their experiences with individual buildings
- Data Collection Focus:
 - Buildings having 2+ stories in CBD and Addington
 - Engineering firms with greatest number of new buildings in Christchurch
- Full details on methodology in report itself
- Disclaimer: The authors are not social scientists and have not conducted a rigorous social science study; results should be interpreted accordingly



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Quantitative results

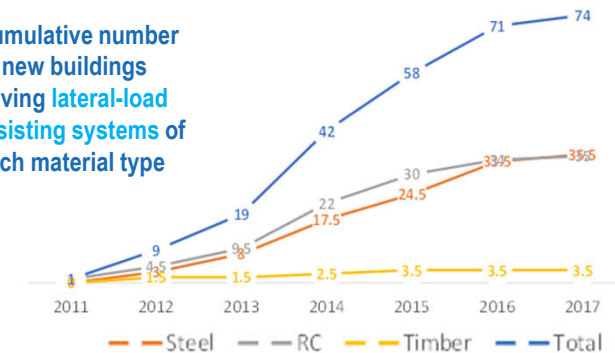
- Information presented as a function of year of consent (=year of building permit in a North American context)
 - Note: Results for 2017 are only for the first three months of the year (data collected up to March 2017).
- Data on 74 buildings, adding to 482,317 m² floor space.
- For buildings with different types of structural systems in orthogonal directions, each direction was counted as one half of a building when tallying the numbers.
 - One building had masonry walls in one direction (counted as 0.5 building), but this small number was lumped together with the concrete walls.



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Number of Buildings (Steel / RC / Timber)

- Cumulative number of new buildings having lateral-load resisting systems of each material type



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Gravity System in RC Buildings

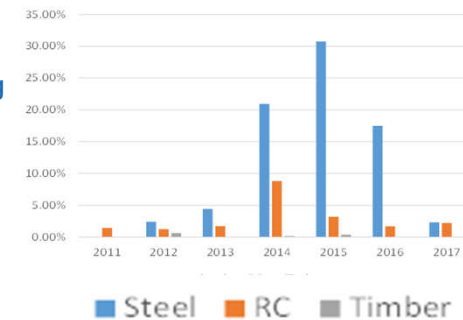
- Gravity-resisting frame systems (i.e., steel beams+columns) used in:
 - Approximately $\frac{3}{4}$ of buildings having lateral-force-resisting system consisting of RC walls (still counted as a RC building in presented quantitative results)
- For this reason, the number of buildings containing structural steel is significantly greater than that indicated by the quantitative results presented here



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Floor Area of New Buildings (m²)

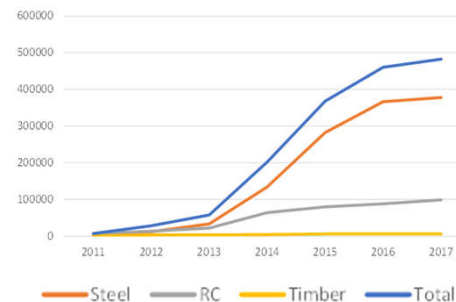
- Floor area of new buildings having lateral-load resisting systems of each material type:
Yearly Percentages
- 2015-16: 10:1 Ratio



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Floor Area of New Buildings (m²)

- Floor area of new buildings having lateral-load resisting systems of each material type:
Cumulative numbers
- Steel: 78.4%,
- RC: 20.4%,
- Timber: 1.2%



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Type of Structural System

- BRB= Buckling Restrained Braces (11 total),
- CBF=Centrically Braced Frames (3 total),
- EBF=Eccentrically Braced Frames (2 total),
- EBR=Eccentrically Braced Frames with replaceable links (4 total),
- MRF=Steel Moment Resisting Frames (9.5 total);
- MFF=Steel Moment Resisting Frames with friction connections (1 total),
- MRD= Steel Moment Resisting Frames with Reduced Beam Sections (4.5 total),
- RCW=Reinforced Concrete Walls (32.5 total),
- RCF=Reinforced Concrete Moment Resisting Frames (0.5 total),
- RFS=Rocking Frame Steel (1.5 total);
- RFC=Rocking Frame Concrete Precast Walls (0.5 total),
- LVL= Laminated Veneer Lumber (2.5 total),
- B=Base Isolation (11 total),
- D=Dampers (2 total),
- H=Hybrid (7 total).



From <http://themontebellohillsblog.blogspot.com>



80

Type of Structural System

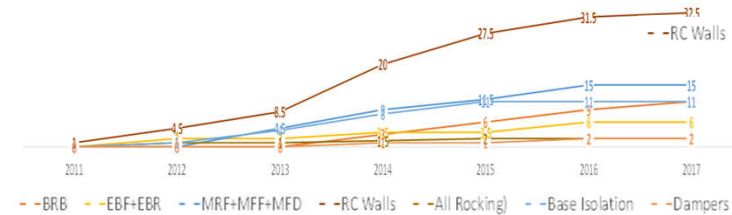
- Data obtained on same 74 buildings, but, for clarity:
 - Not considered:
 - A building with masonry walls in one direction (0.5 masonry building)
 - A building with braced plywood walls (1.0 building)
 - New $\Sigma = 72.5$ buildings
- Some systems counted twice:
 - For example: A system on top of base isolators is counted twice (once as the structural system type, and once as a base isolated structure)
 - Same for buildings with dampers and hybrid buildings.
- Total of 92.5 buildings = 72.5 systems + 11 base isolated buildings + 2 dampers + 7 hybrids



81

Type of Structural System

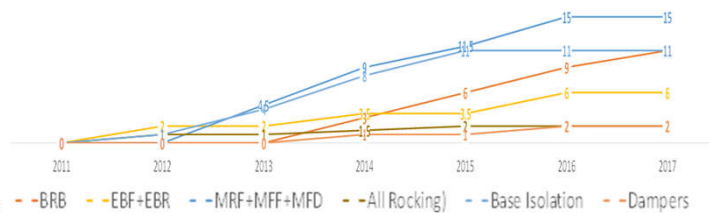
- RC walls = largest number because this category (contrary to others) is not broken down into sub-categories
- Data shows only a few moment frame with friction connections, rocking systems, LVL systems, CBFs, and dampers



82

Type of Structural System

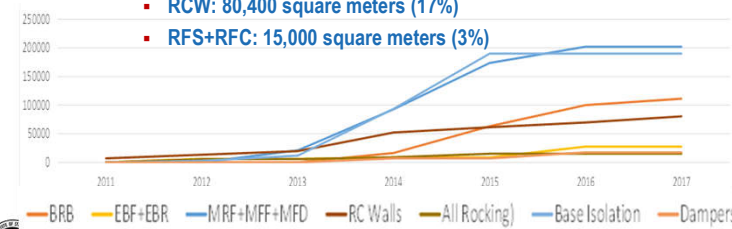
- Focusing on steel structures:
 - Rapid implementation of base isolation and rocking systems in the early years after the earthquake, with fewer numbers in the past few years
 - Base isolated buildings were first consented in 2012, rapidly growing and plateauing at a total of 11 by 2015 (i.e., 15% of the 74 buildings)
 - Results also show that BRBs were first consented in 2014, and have since grown in numbers at a steady pace, reaching a total of 11 by 2017



83

Type of Structural System

- Results show that the following lateral load resistance systems have been used for buildings totaling the following floor areas:
 - BRB: 111,000 square meters (23%)
 - CBF: 38,500 square meters (8%)
 - EBF+EBR: 27,500 square meters (6%)
 - MRF+MFF+MDF: 202,000 square meters (43%)
 - RCW: 80,400 square meters (17%)
 - RFS+RFC: 15,000 square meters (3%)

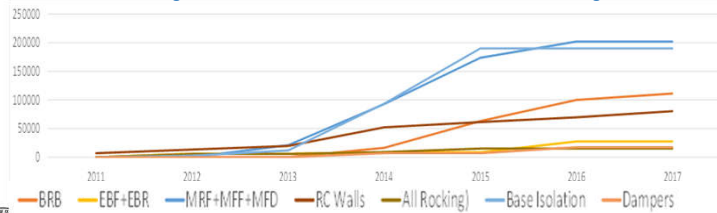


84



Type of Structural System

- The 11 base isolated buildings (15% of number of buildings) alone provide 190,000 m² = 40% of total floor area of buildings considered
- The base isolated buildings have generally been large buildings
 - The two largest base isolated buildings alone, built specifically for public sector tenants = 102,000 m² (21% of the total floor area)
 - The three largest = 129,000 m² (27% of the total floor area)
- Strong correlation between m² of base isolated buildings and steel MRFs



85

Type of Structural System (Non Base isolated buildings)

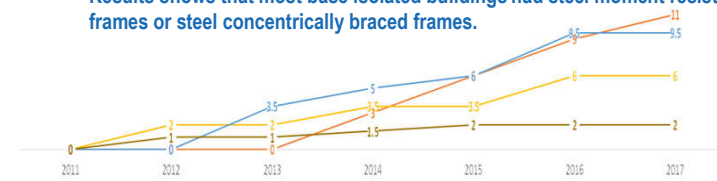
- Worthwhile to consider (for steel structures – no change for RC), because:
 - More base isolation in years following earthquake, so data on non-isolated buildings could be indicative of future trends
 - Firms comfortable designing systems outside of standards (such as base isolation) might be over-represented in interviews
 - For its own sake, interesting to identify which systems more dominantly used when buildings not base isolated



86

Type of Structural System (Non Base isolated buildings)

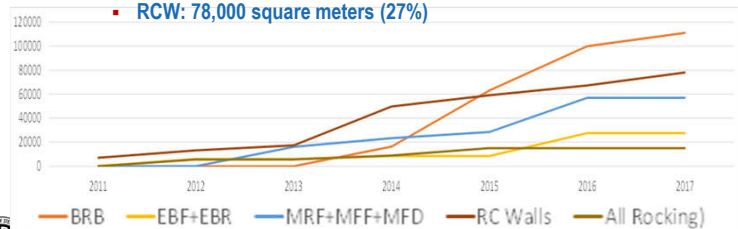
- For all steel frame systems, most commonly used are:
 - BRBs (11 buildings)
 - MRFs (9.5 buildings)
 - EBF (6 buildings)
 - RC Wall buildings number remain the same (31.5 buildings – not shown)
- Results shows that most base isolated buildings had steel moment resisting frames or steel concentrically braced frames.



87

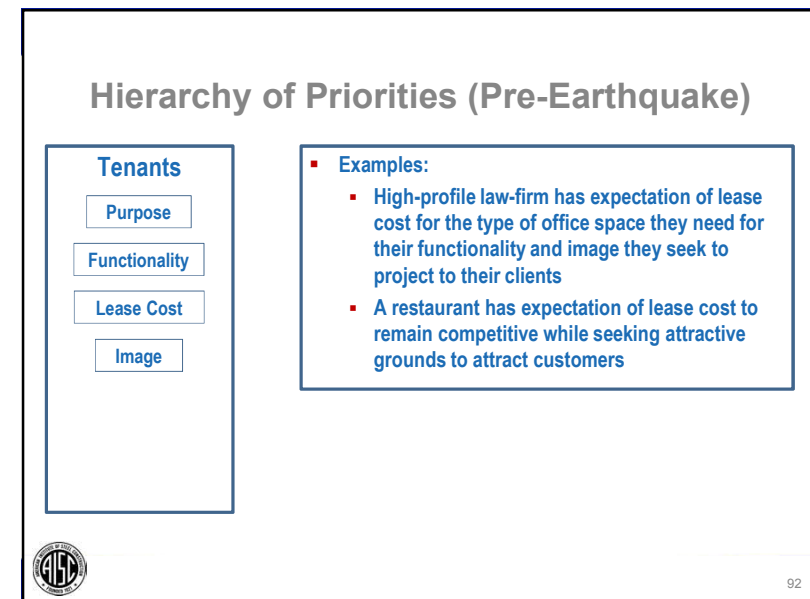
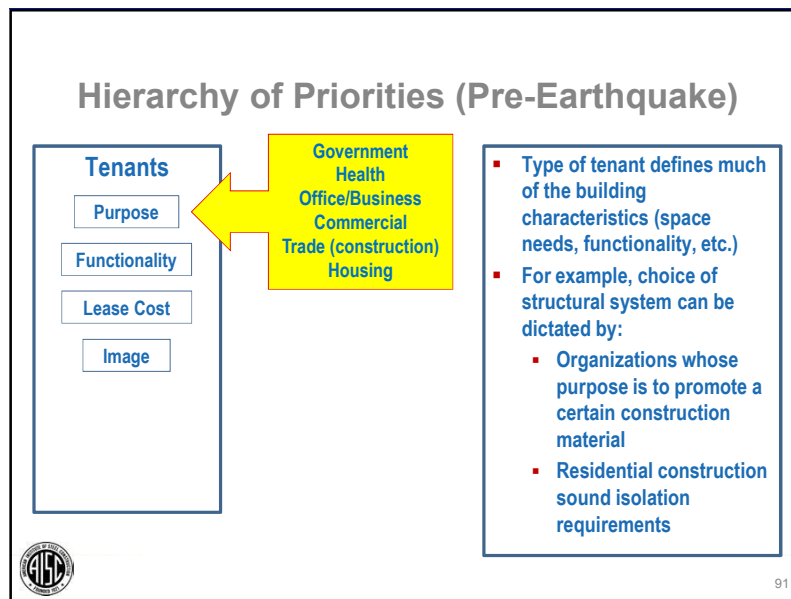
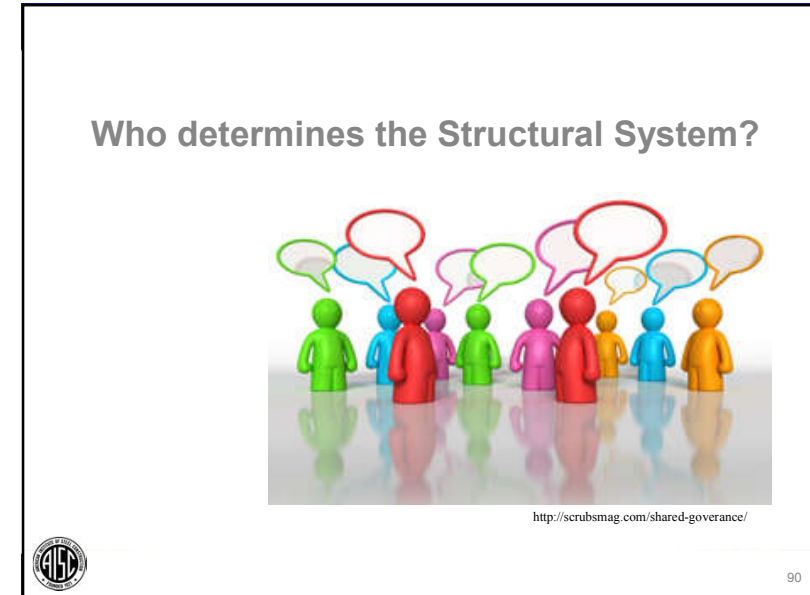
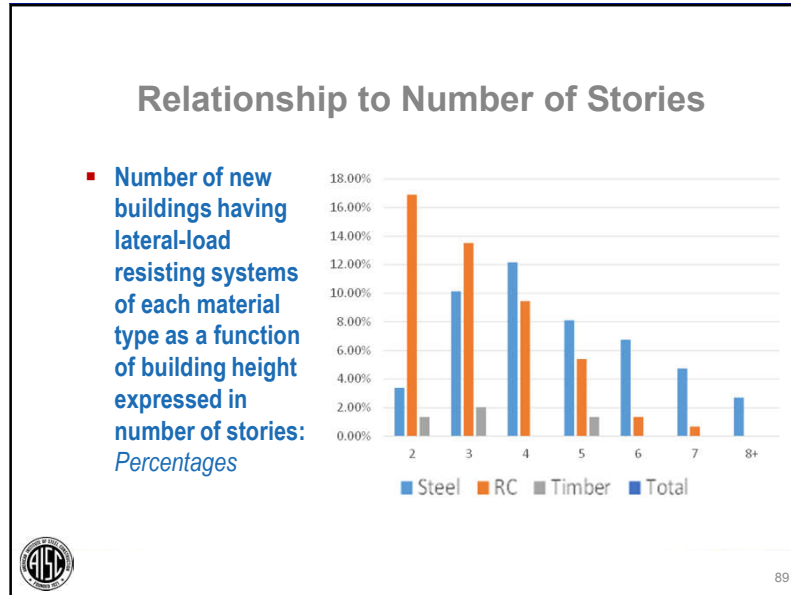
Type of Structural System (Non Base isolated buildings)

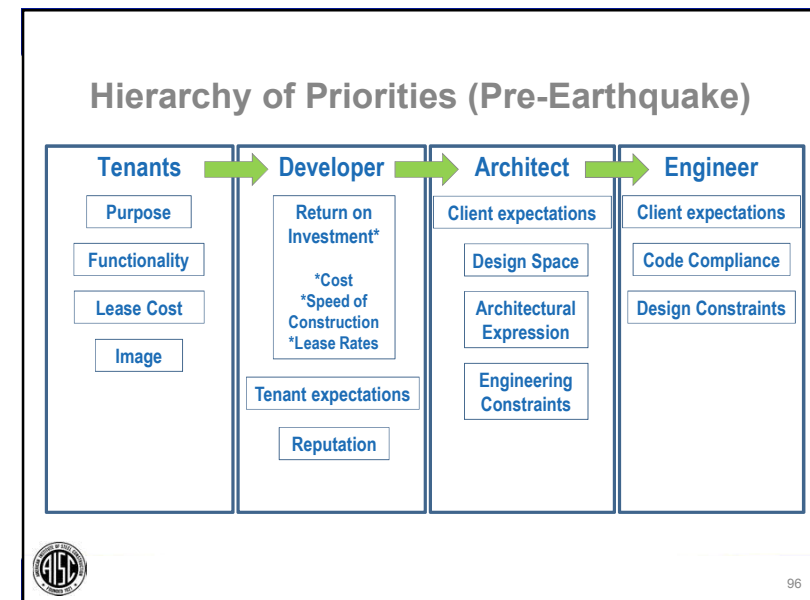
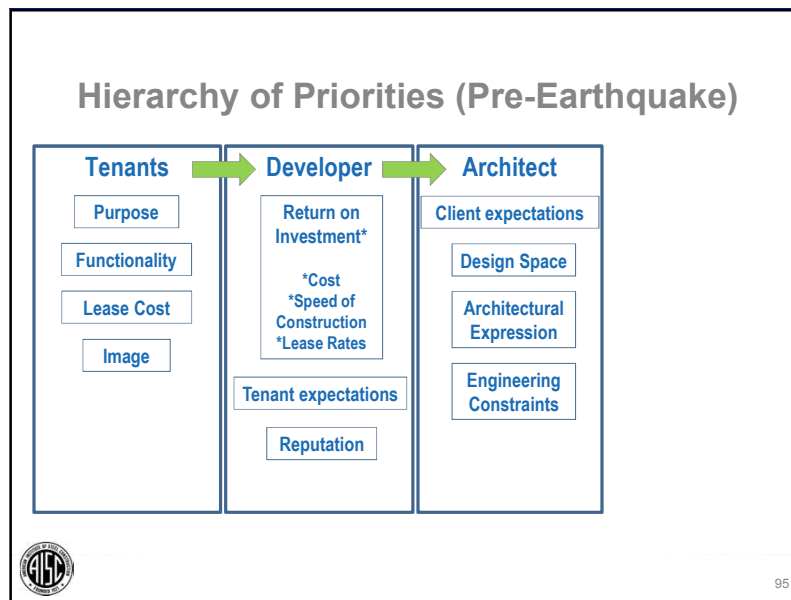
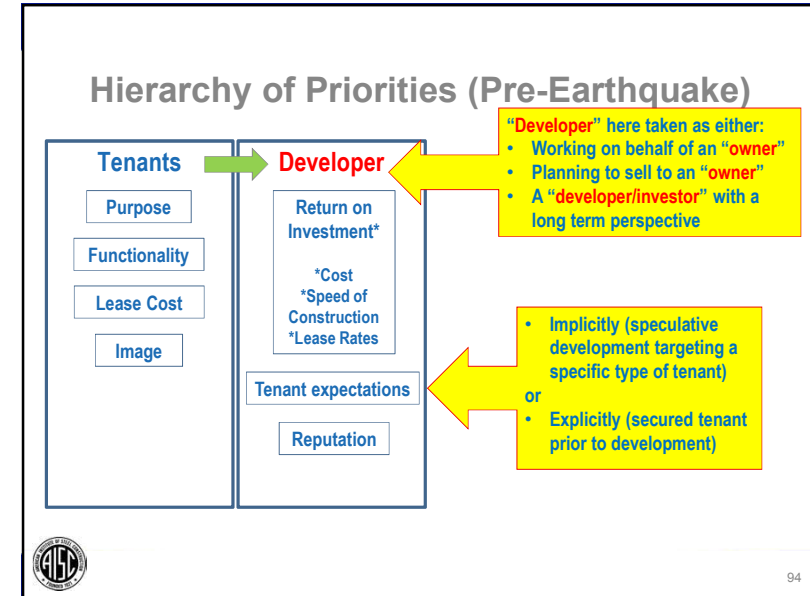
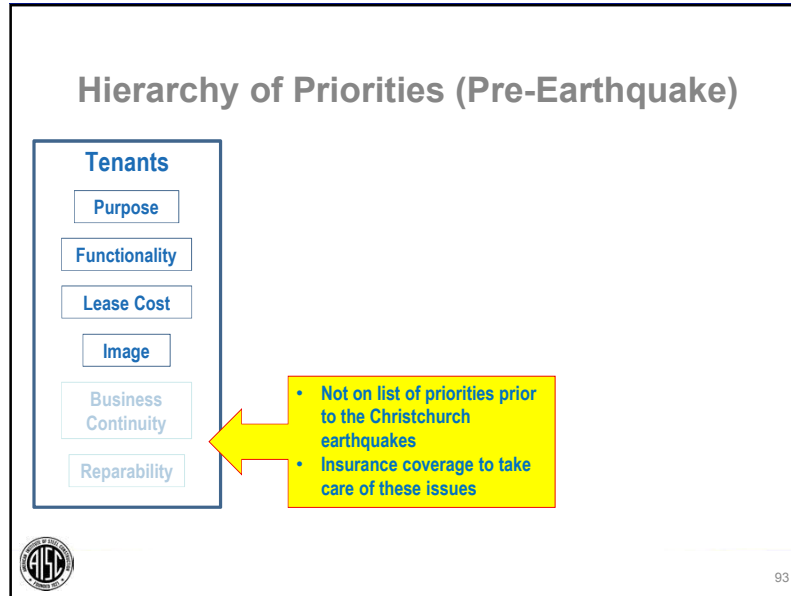
- Total non-base-isolated reconstruction floor area is:
 - BRB: 111,000 square meters (38%)
 - CBF: 0 square meters (0%)
 - EBF+EBR: 27,500 square meters (9.5%)
 - MRF+MFF+MDF: 57,000 square meters (20%)
 - RCW: 78,000 square meters (27%)

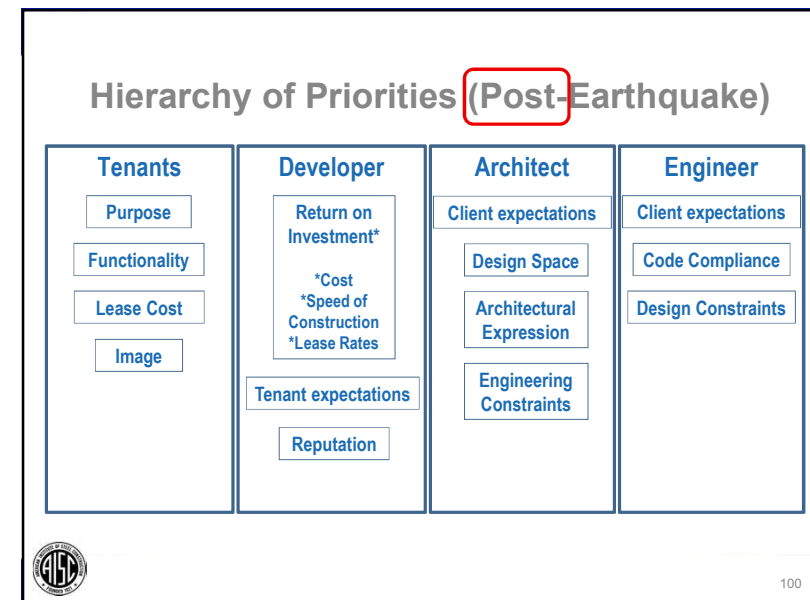
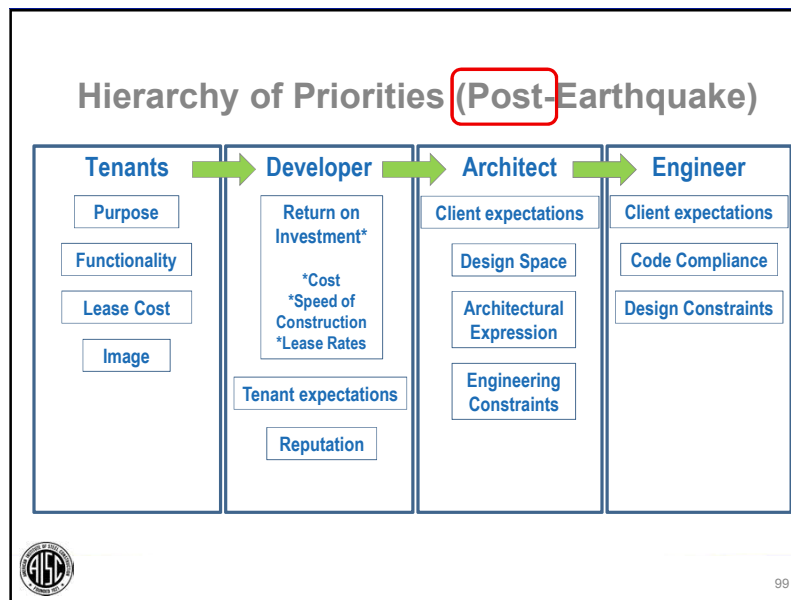
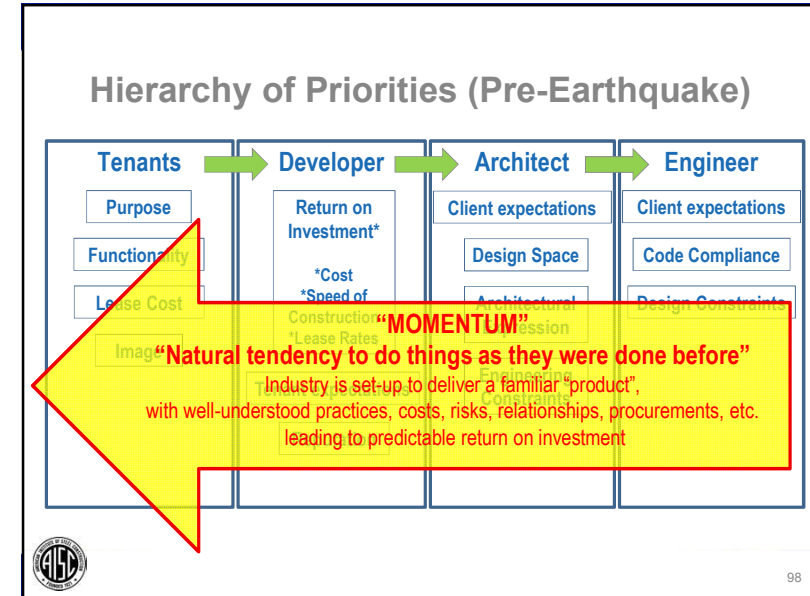
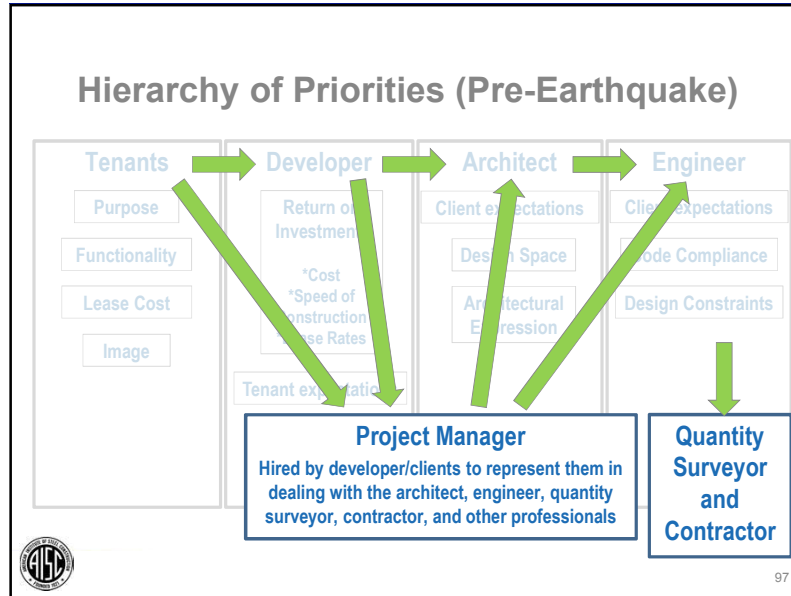


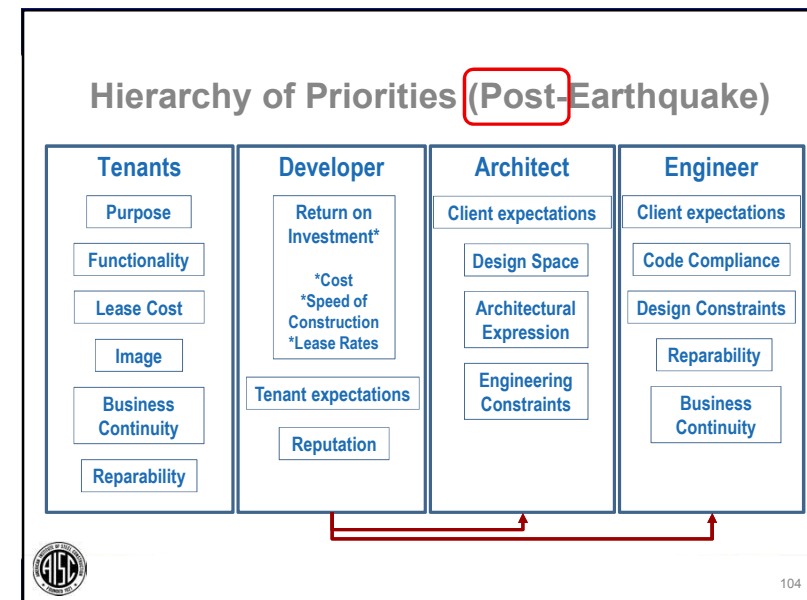
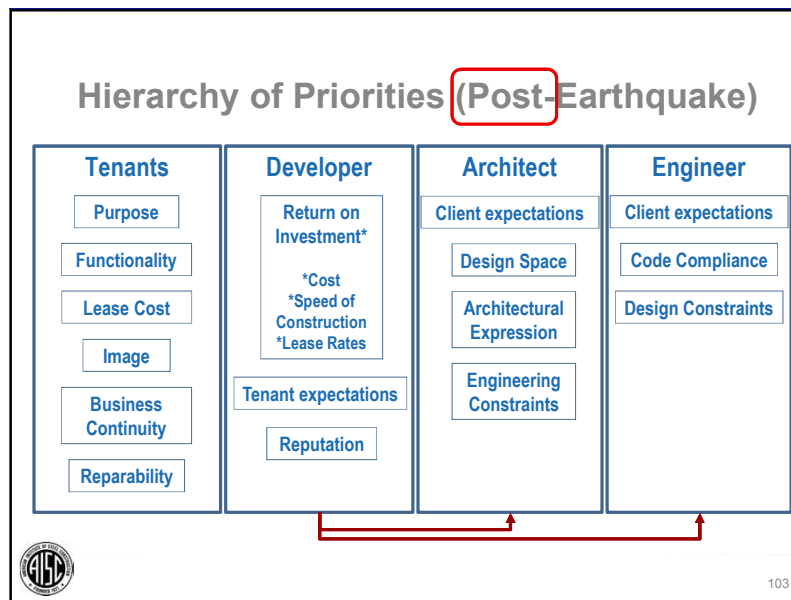
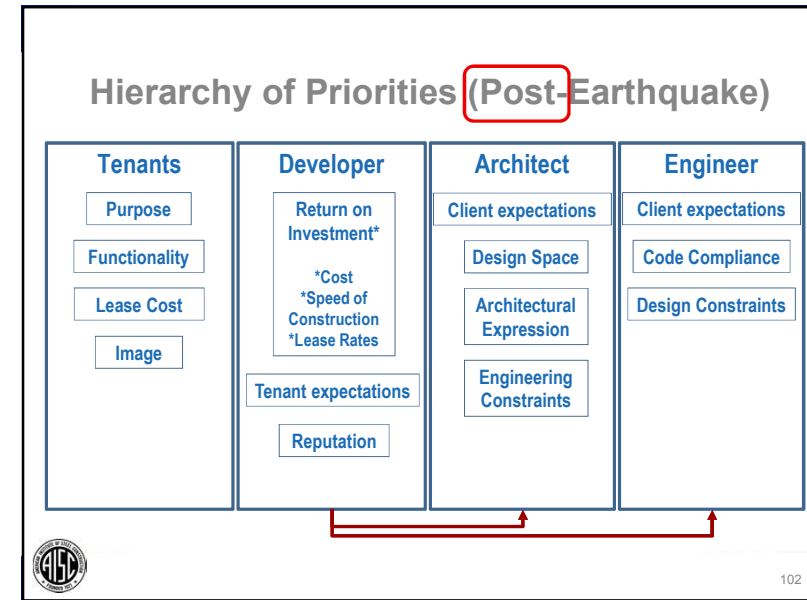
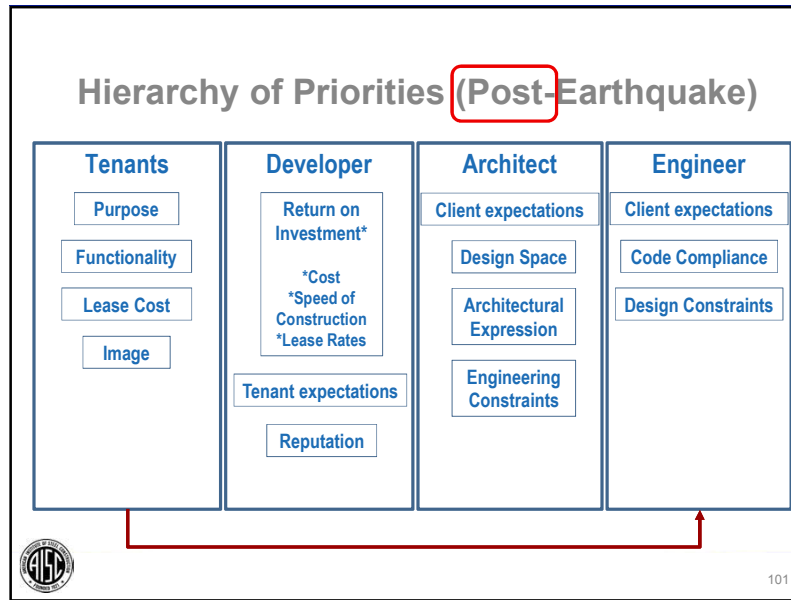
88

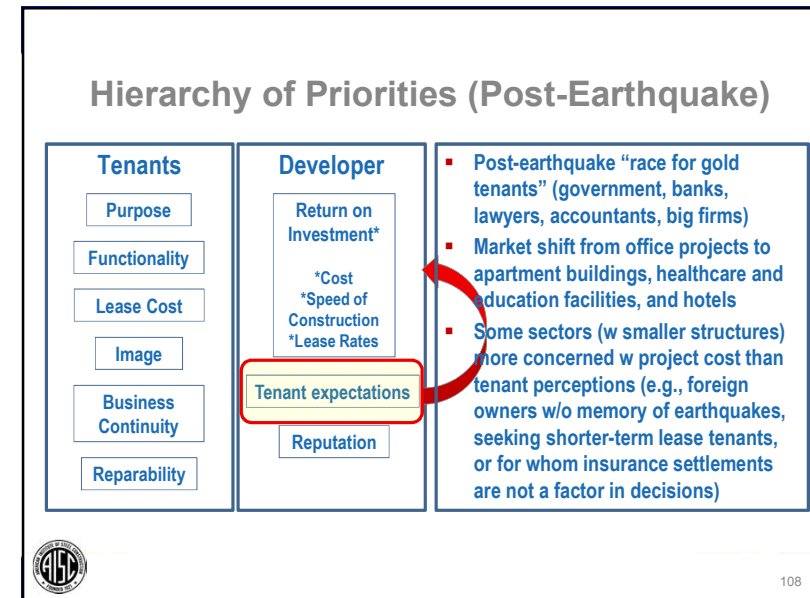
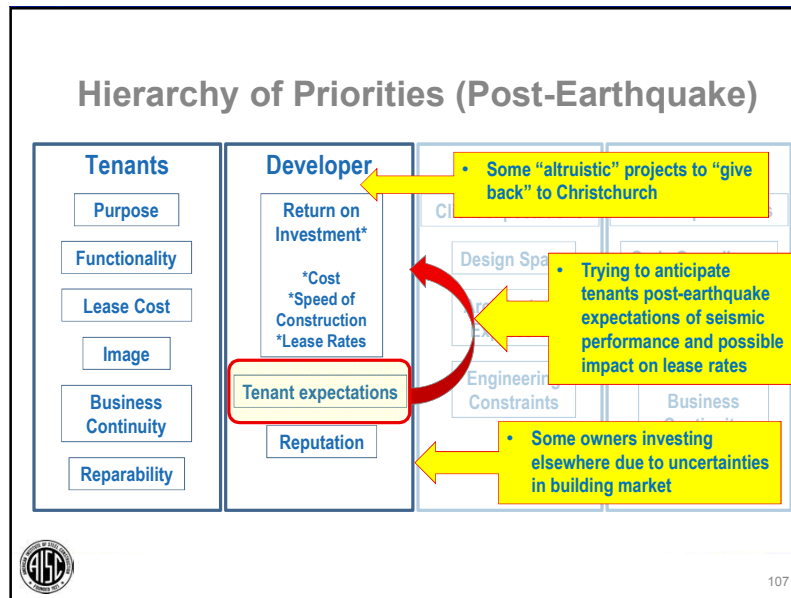
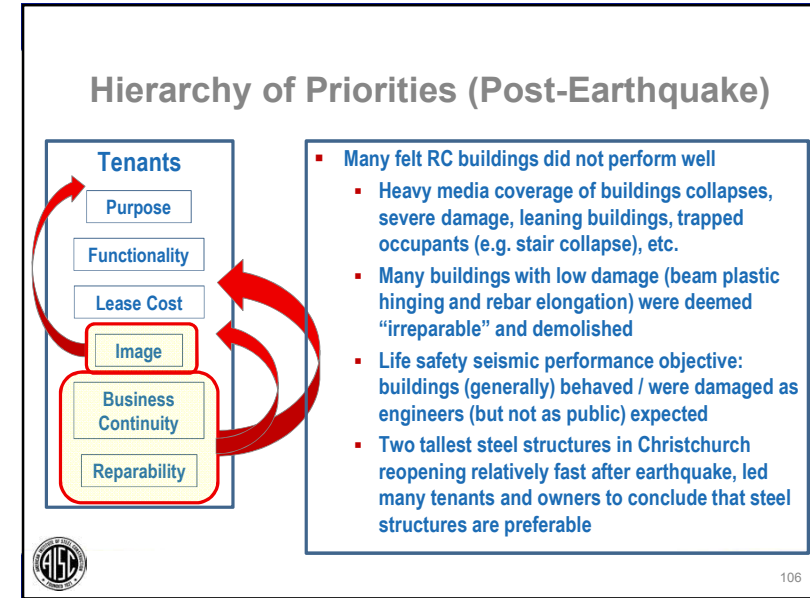
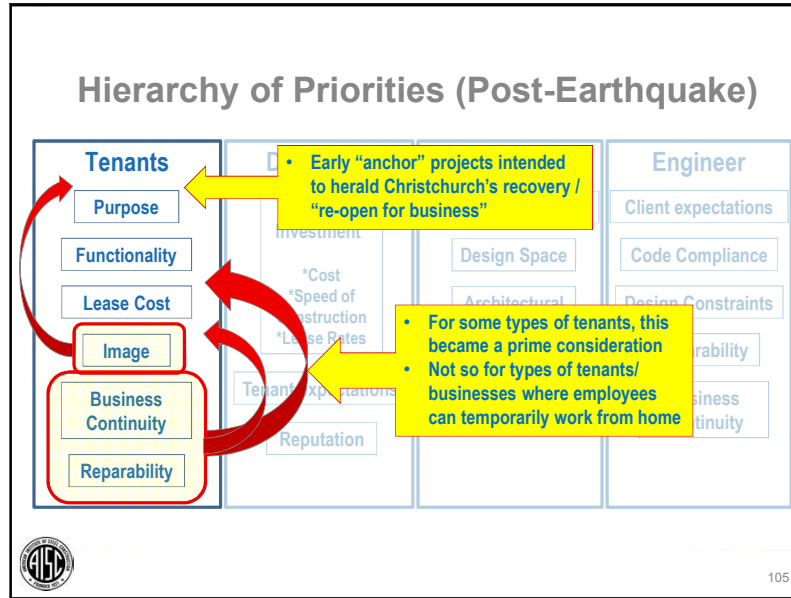


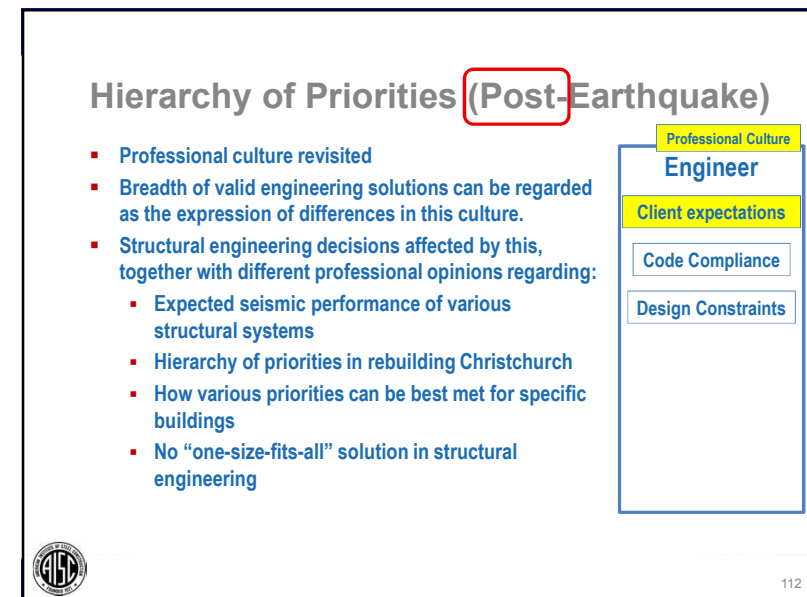
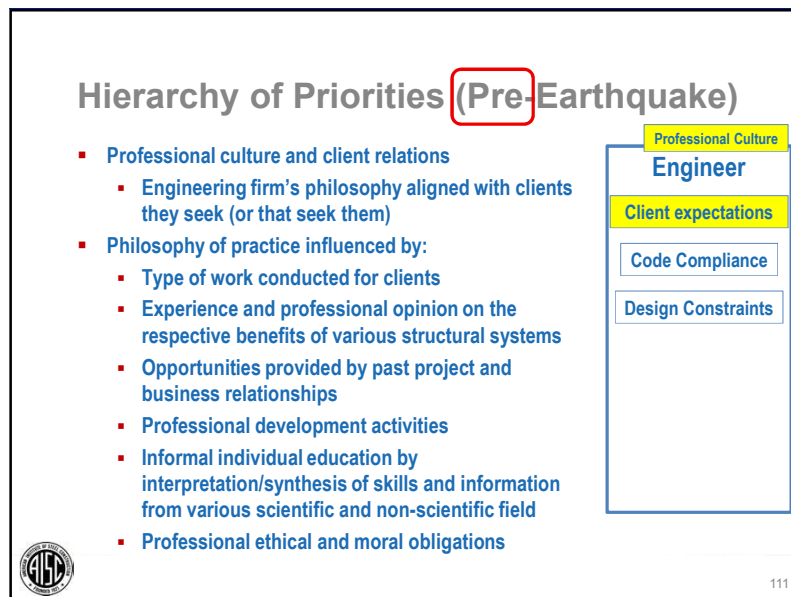
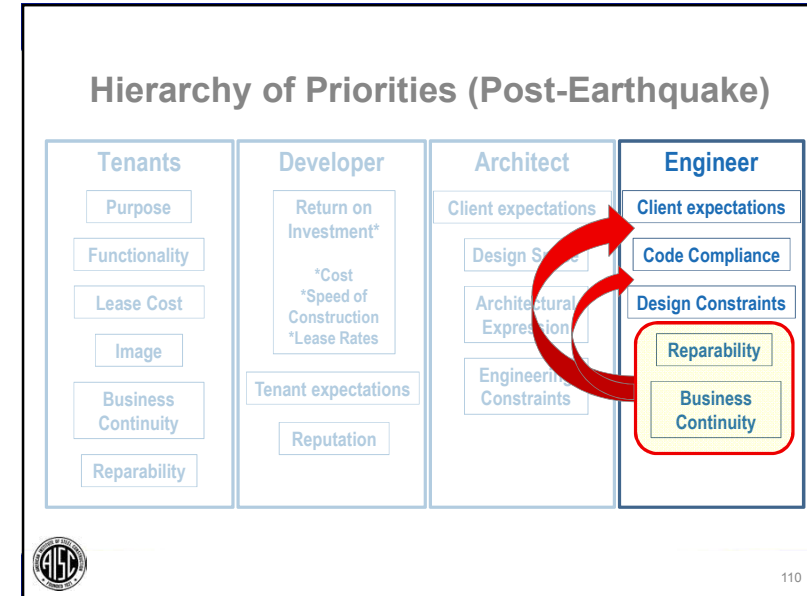
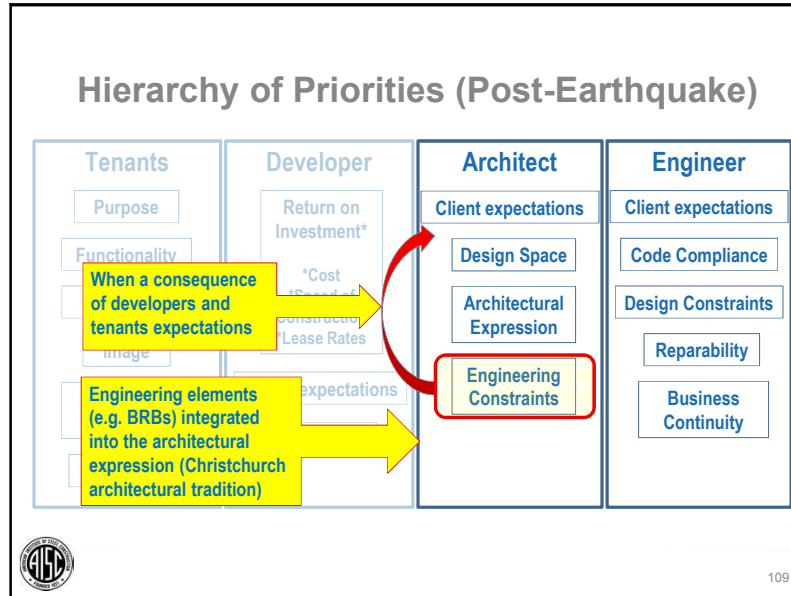






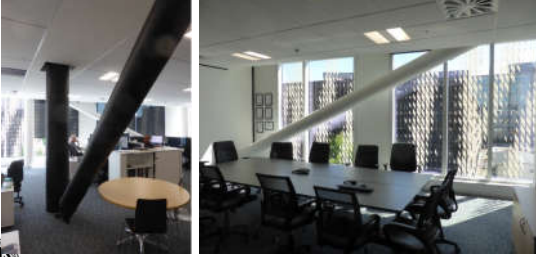






Hierarchy of Priorities (Post-Earthquake)

- Nearly all engineering firms interviewed designed the building containing their office, including:
 - 3 in base-isolated buildings
 - 2 in buildings having BRBs
 - 1 in a building with viscous dampers.



Professional Culture

Engineer

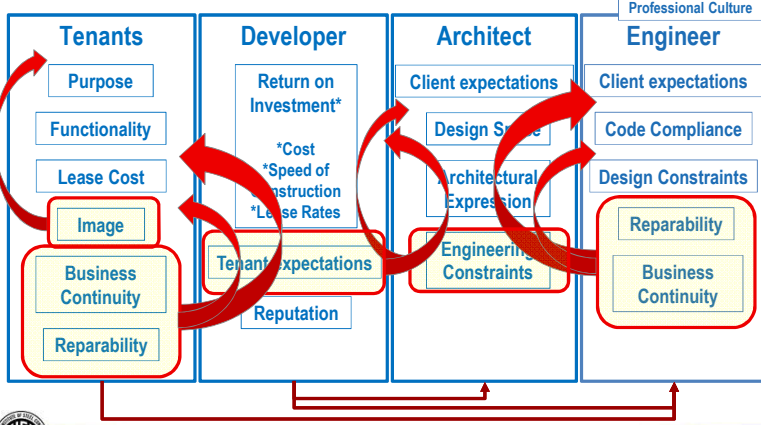
Client expectations

Code Compliance

Design Constraints

113

Hierarchy of Priorities (Post-Earthquake)



Professional Culture

Engineer

Client expectations

Code Compliance

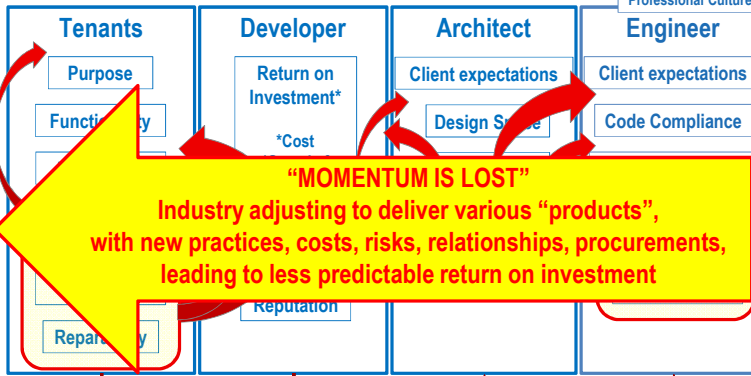
Design Constraints

Reparability

Business Continuity

114

Hierarchy of Priorities (Post-Earthquake)



Professional Culture

Engineer

Client expectations

Code Compliance

Design Constraints

Reparability

Business Continuity

115

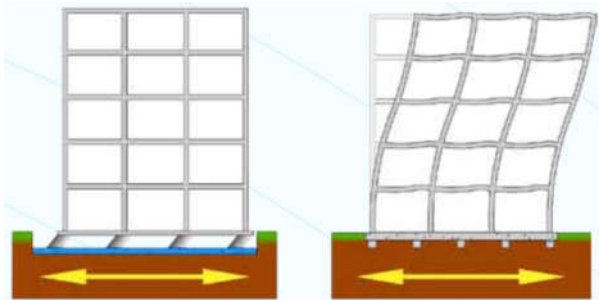
Qualitative Factors Affecting Momentum

- 50 pages of the report present opinions expressed by engineers, in their own words (or paraphrasing) on:
 - The various issues and types of structural systems used
 - Base Isolation, Low Damage, IL4, IL3, Reparability, Buckling Restrained Braces, Viscous Dampers, Eccentrically Braced Frames, Steel Structures (General Issues), Reinforced Concrete Walls, etc.
 - These are not necessarily the authors' opinions
- A select sample of these opinions are summarized next, for a subset of structural systems

116

Base Isolation

- Basic concept of base isolation



http://www.dis-inc.com/pdf_files/DIS%20Seismic%20Isolation%20for%20Buildings%20and%20Bridges.pdf



117

Base Isolation (Client Perception)

- New Zealand public is somewhat familiar with base isolation
 - NZ engineers have pioneered its development
 - Implemented in a number of buildings throughout NZ
 - News reports and showcasing isolators at Wellington's base-isolated Te Papa Museum and Beehive (Parliament)
- Whereas clients typically did not express any preference for specific structural systems when approaching engineers, base isolation is the exception to that rule (for some projects)
 - Some of these projects were developed as intended
 - Others were switched to different structural systems as part of the development and cost-assessment process



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Base Isolation (Client Perception)

- Some have promoted fact that their buildings are base isolated
 - E.g., Christchurch Justice and Emergency Services Precinct, a 42,200 m² public "anchor project" for 2000 employees, has webpage and Facebook page "showcasing" government's commitment to investing in Christchurch's reconstruction
- Some owners insisted on base-isolation, even if engineer believed it provided no benefits over other structural systems, to provide "peace of mind" to tenants
- Other owners specifically did not want base isolation, because advised by a professor that it was a bad idea in Christchurch
- Other client objection was that the resulting design reduced the leasable floor space within a fixed lot boundary



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Base Isolation (Engineers Perception)

- All understand principles and potential benefits of base isolation, but engineering firms are not unanimous on whether base isolation is an appropriate structural system for Christchurch
 - Some engineering firms have actively promoted it
 - Others have significant reservations for some designs
- Engineering firms expressed different preferences and relationships (i.e., "not all bearings are similar") – concerns including:
 - Reliability of performance of specific devices
 - Tuning to a particular earthquake level
 - Behavior of isolated structure under vertical ground accelerations
- Cost important consideration
 - One engineer underscored that the oft-cited 5-7% of total building cost premium is for large buildings (like a hospital) but is a much higher percentage for an office building



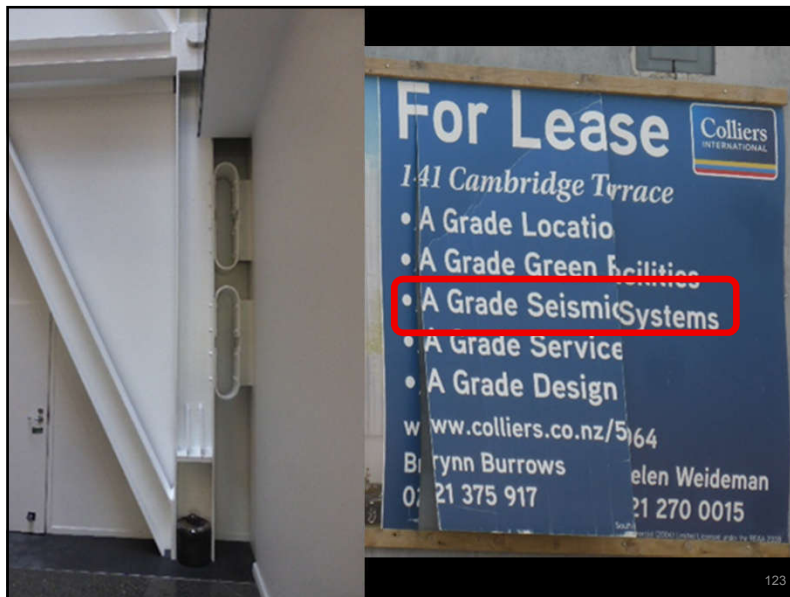
121

Low damage, IL4, IL3, Reparability

- Some clients, without asking for specific structural system, requested:
 - An IL3 or IL4 building design
 - Low-damage
 - Reparable structural system
- Request done either as part of:
 - Casual discussions
 - Project's specification brief
- Various motivations:
 - As asset to attract tenants and for future resale value
 - Protection against future code changes



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123

Low damage, IL4, IL3, Reparability

- Owners typically asking for IL3 structure generally plan to own their property for a long time, but do not necessarily wish for an IL4 building
- Others are owners who originally considered base isolation but backed away when cost estimates exceeded their desired price point
 - Particularly true for smaller buildings where cost-impact of base isolation makes the solution more uneconomical
- Interesting example where opposite occurred:
 - Client was contractor not intending to use any innovative systems to keep costs down: A design with CBFs was therefore completed
 - When some tenants came with a 10-year lease prospect and asked for an IL3 building, the braces were substituted with BRBs: with a special layout of the BRBs across bays and stories, column sizes remained reasonable and system ductility increased

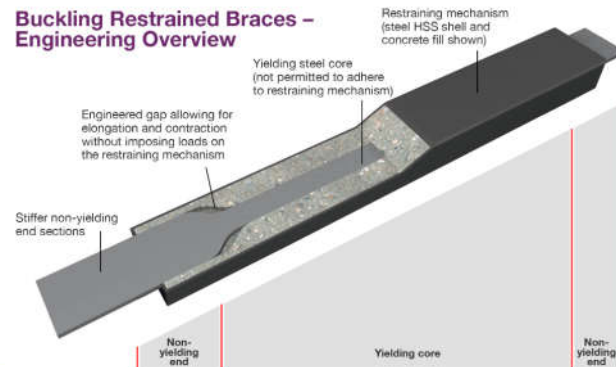


124

Buckling Restrained Brace

- Basic concept of Buckling Restrained Brace (BRB)

Buckling Restrained Braces – Engineering Overview



https://www.aisc.org/globalassets/modern-steel/archives/2011/04/2011v04_getting_the_most.pdf

125

Buckling Restrained Braces

- Timely promotion by BRB manufacturers following EQ
- Engineers were looking for alternative “low-damage” designs (i.e., limiting drifts) that would allow rapid return to service (i.e., rapid to repair), while being lower cost than base isolation
- Some firms stated easier to replace BRB than EBF
 - + “A lot of moment frame action and maybe more energy dissipation capacity still exists” when BRB is removed, whereas moment frame action is completely lost when replacing the yielded link of an EBF



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Buckling Restrained Braces

- Engineers stated that, although BRBs more expensive than regular braces, their fabrication is quick and they are considered to be a **well-tested and robust system** – with **caution** against “blindly accepting test results” from others
 - Some BRBs in one project were manufactured incorrectly and experienced problems when tested (problems have apparently been ironed out since)
- A number of engineers have highlighted that BRB frames can be “**tuned**” to demands, eliminating unnecessary overstrength
- Some engineers aware of **on-going research questions** about limited testing of BRBs in 3D



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Buckling Restrained Braces

- Many engineers stated that **architects in CHCH** desire modern architecture and have **showcased** BRBs in many projects
- Architects prefer BRB frames to EBF because BRBs can be “snaked” along the building in different patterns, and connection gussets can be shaped different ways, thus giving more freedom to architectural expression
- One engineer went as far as saying, “BRB is the **vernacular of Christchurch**”



128

Low damage, IL4, IL3, Reparability

- Buckling Restrained Braced Frames for this purpose
- Strategies implemented to assess the extent of their yielding during future earthquakes:



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Viscous Dampers

- Used in only one building by 3/2017 (and one “in the pipeline”)
 - Client wanted low-cost building, but a bit above minimum
 - Engineering firm (as main tenant) was permitted by client to design structural system of their choice provided they met a specified budget comparable to that for a BRB system
- One engineer volunteered that:
 - While he preferred viscous dampers to braces, adding a \$30k viscous damper to a structure is a “hard-sell” when comparable brace is \$4k
 - Market in NZ might be more in retrofit of older RC MRFs



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Eccentrically Braced Frames

- Split opinions on EBFs with or without replaceable links
 - Some expressed strong preference for bolted replaceable links and decoupling of link and link-beam design
 - Others held that replacing links might not be performed as easily as foreseen
 - Many held that replacing the link in a conventional EBF is not necessarily more difficult: links can be cut and replaced by new segments welded-in-place (as done in a number of post-Christchurch repairs)
- Concerns voiced that some of the replaceable links in new buildings appear out of proportion with the rest of their frame



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Steel Structures (General Issues)

- Momentum has shifted:
 - To paraphrase one engineer: While the local industry was geared to do RC buildings out of habit and practice, the industry in Christchurch is now geared to do steel on a large scale
 - Earthquakes gave engineering community an opportunity to “brush up” and “get up-to-speed” on steel design
- Many engineers commented on specific new buildings that were designed with either all steel or part steel but “would have been all-concrete” design prior to the earthquake
- One engineer stated that, before the earthquakes, the industry had already started to move away from RC frames because they were too slow to build, and that it was “the right decision” because steel has the advantage that damage is more visible when it happens



132

Reinforced Concrete Moment Frames

- Mentioned multiple times as part of the interviews that prior to CHCH earthquakes, many buildings had RC *frame* structural systems, both for gravity and for lateral-load resistance
 - None of the engineers indicated a desire to design such systems in the future
 - An engineer cited the example of a building that had been designed as an RC MRF before the earthquakes, redesigned and built as a steel MRF after the earthquake (although with precast walls on both side walls)
- Steel gravity frames also replaced the RC beams and columns in the non-seismic frames of the building.



133

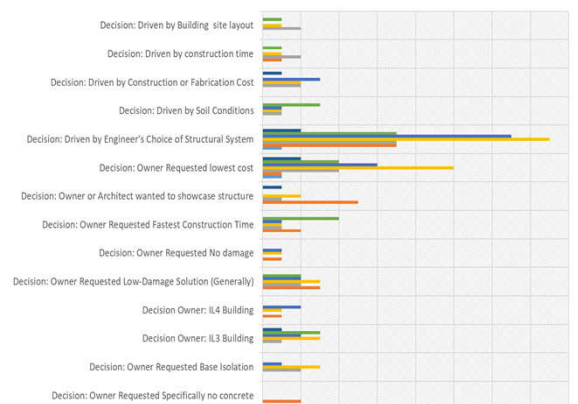
Drift Control and Design Ductility

- Drift limits in NZ Code have not changed after Christchurch earthquakes
- Many engineers indicated preference for systems that can provide lower drifts under the design earthquake level, to limit non-structural damage
- While not a general rule or standard practice, nearly all firms interviewed indicated a tendency to steer their new designs far from the 2.5% drift limit
 - Drift demands of 1% to 1.5% were often cited as a desirable outcome (i.e., “in-house design guidance targets”)
 - More difficult to obtain with MRF, rather than braced or wall, structures
- Low drift limits seen in performance specifications for some projects
- Likewise, many firms expressed preference for lower values of design ductility demand
 - Some firms indicated always using effective design ductilities of 3 or less (as a consequence of SLS considerations governing design)



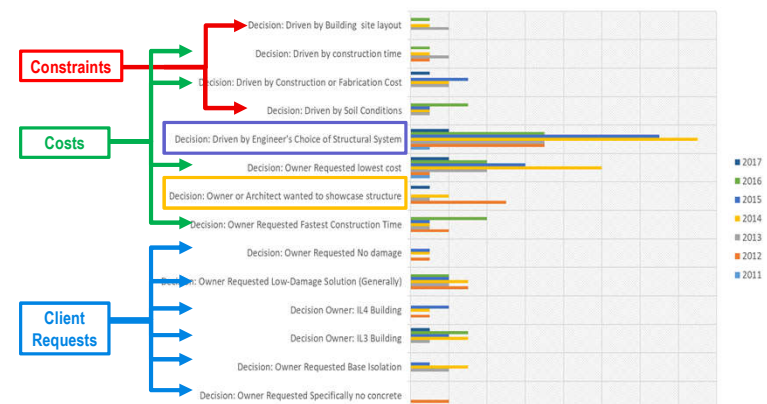
134

Factors driving decision of structural system



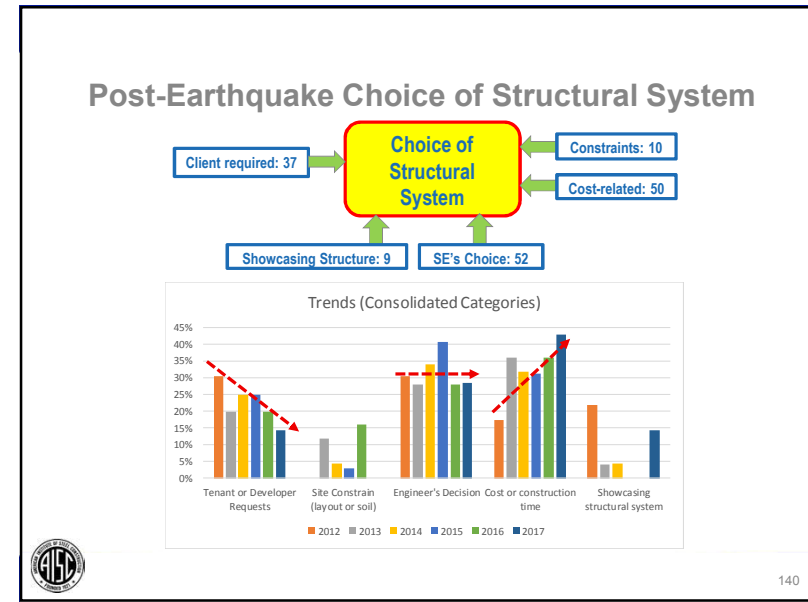
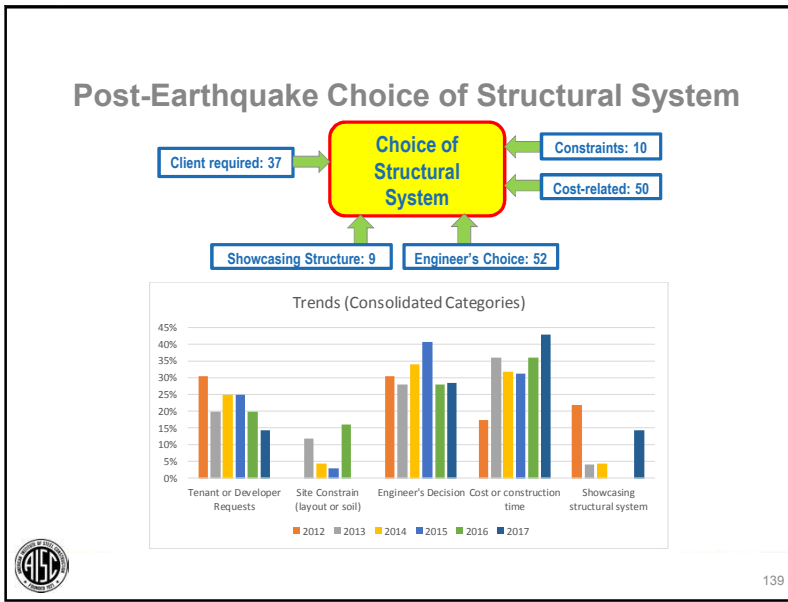
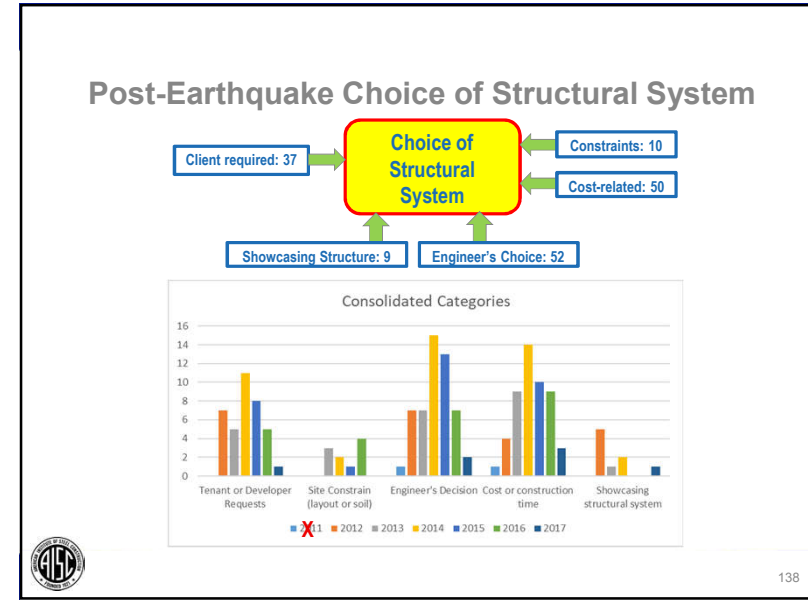
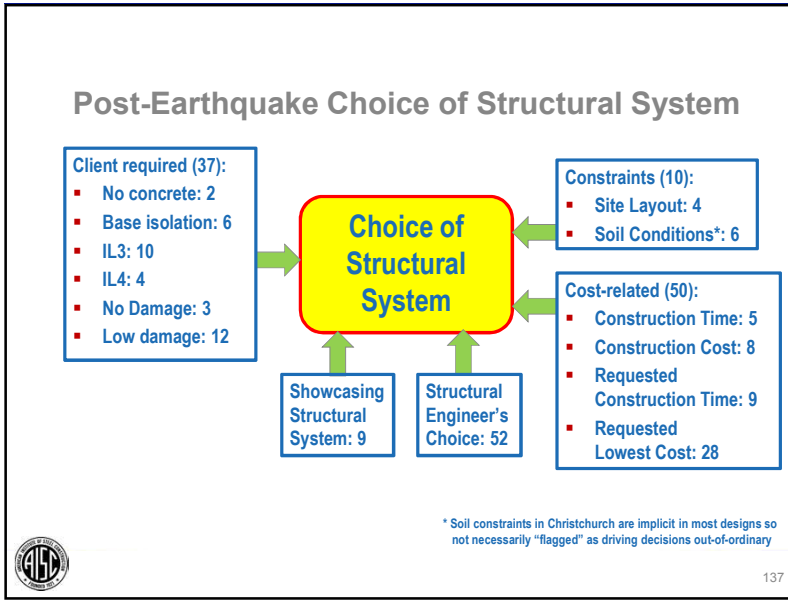
135

Factors driving decision of structural system



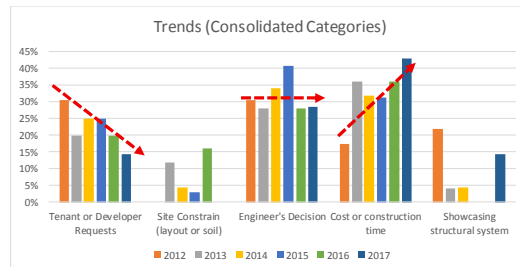
136





Post-Earthquake Choice of Structural System

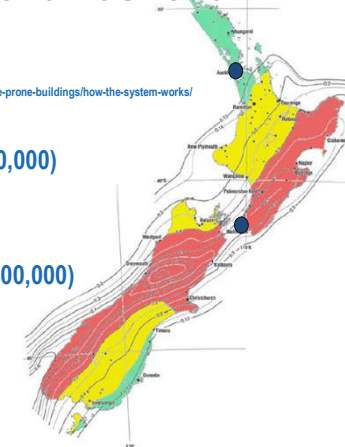
- An engineer stated: “clients have had a natural tendency to forget the earthquake and return to the code minimum solution. However, continued aftershocks and other recent New Zealand earthquakes have countered this natural tendency for now by sustaining awareness of the possible need for greater than minimum seismic performance.”



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Impact on Wellington and Auckland

- Revised Seismic Zones Map → <https://www.building.govt.nz/managing-buildings/managing-earthquake-prone-buildings/how-the-system-works/>
- Auckland:
 - Largest city in NZ (pop.: 1,500,000)
 - Low seismic zone
- Wellington:
 - 2nd Largest city in NZ (pop.: 400,000)
 - National Capital
 - Largest seismic zone



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Conclusions and Key Points

- There are:
 - “Conclusions”: From the quantitative information
 - “Key points” drawn on the basis of above findings and discussions with those interviewed
 - “Conclusions” would be a summary of presented findings, so, in closing, focusing here instead on 6 “key points” arising from this study



From <http://www.midlamminiatures.co.uk>



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6 Key Points:

- It is becoming a more widely held belief that preventing loss of life as a seismic performance objective is simply not sufficient for a good modern structure
- Structural engineers' opinions impact the adoption of low-damage systems
- Tenant expectations strongly impact choice of structural systems
- Additional increase in seismic performance, if desired for all buildings, would need to come from government regulation
- Context affects final decision outcome
- Reconstruction experience has paralleled increase in stakeholder knowledge



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AISC | Questions?



Smarter.
Stronger.
Steel.

CEU / PDH Certificates


- You will receive an email on how to report attendance from: registration@aisc.org.
- Be on the lookout: Check your spam filter! Check your junk folder!
- Completely fill out online form. Don't forget to check the boxes next to each attendee's name!



Smarter.
Stronger.
Steel.

CEU / PDH Certificates

- Reporting site (URL will be provided in the forthcoming email).
- Username: Same as AISC website username.
- Password: Same as AISC website password.



Smarter.
Stronger.
Steel.



AISC | Thank you.



Smarter.
Stronger.
Steel.

