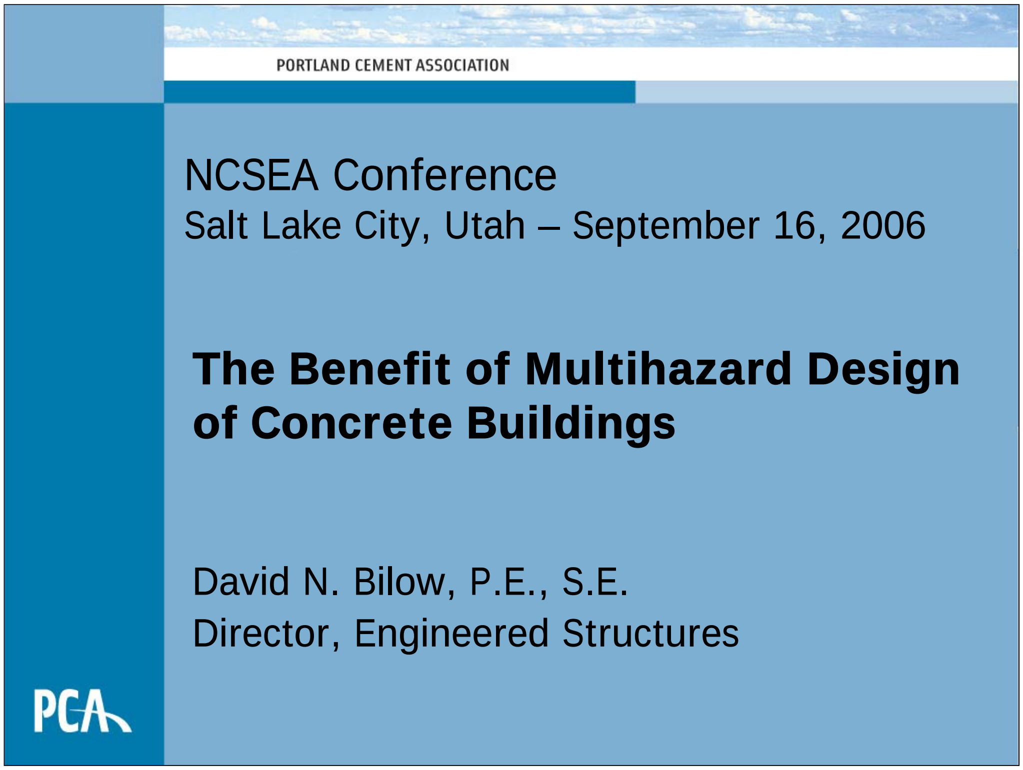

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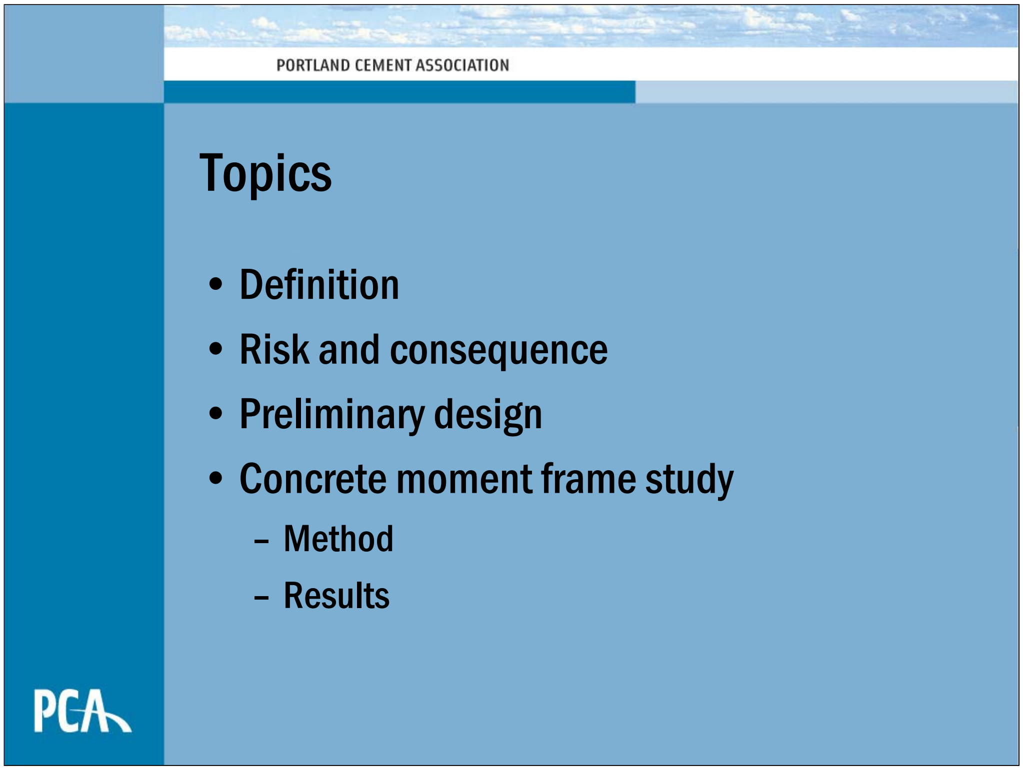
NCSEA Conference
Salt Lake City, Utah – September 16, 2006

The Benefit of Multihazard Design of Concrete Buildings

David N. Bilow, P.E., S.E.
Director, Engineered Structures

PCA

The Federal Emergency Management Agency (FEMA) has used the phrase multihazard design in several of their publications and this presentation explains how multihazard design applies to concrete buildings.



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Topics

- Definition
- Risk and consequence
- Preliminary design
- Concrete moment frame study
  - Method
  - Results

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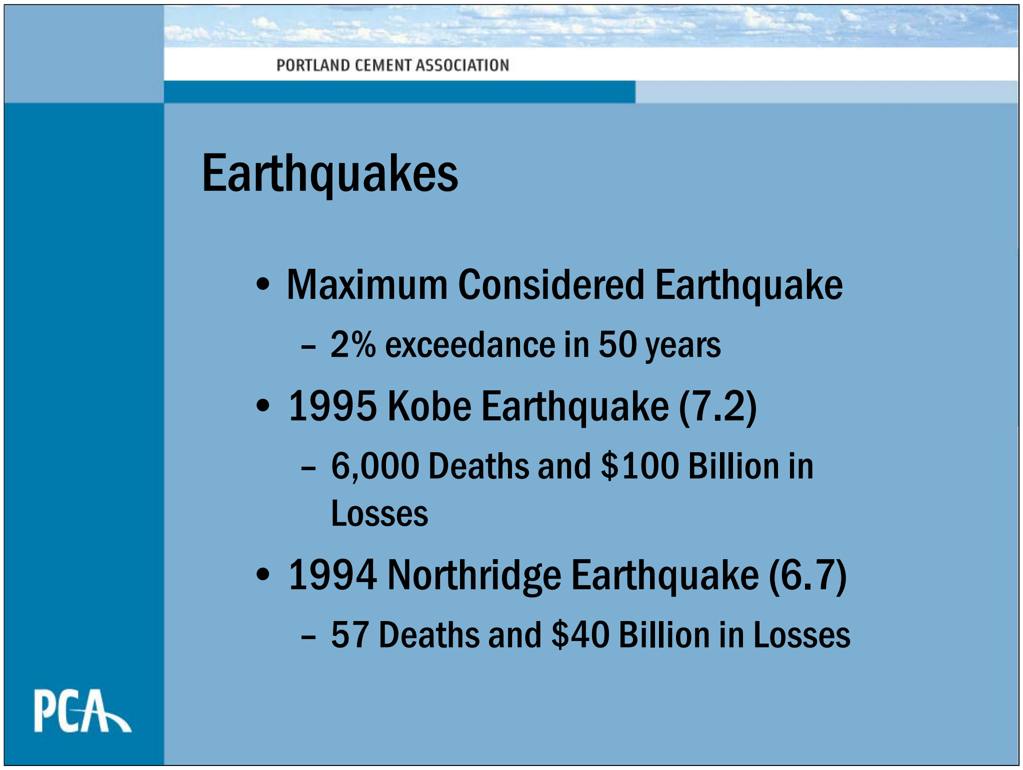
Multihazard Design

- Earthquake, flood, wind, fire, & blast
- Integrated approach
- Design for one hazard helps for other hazards
- Reduce construction cost

PCA

Hazards to be discussed in this presentation include earthquake, flood, wind, fire, & blast. The idea of multihazard design is to address these hazards in an integrated approach because the design for one hazard may be beneficial for buildings to resist other hazards. The ultimate goal is to provide a safe building at minimum construction costs.



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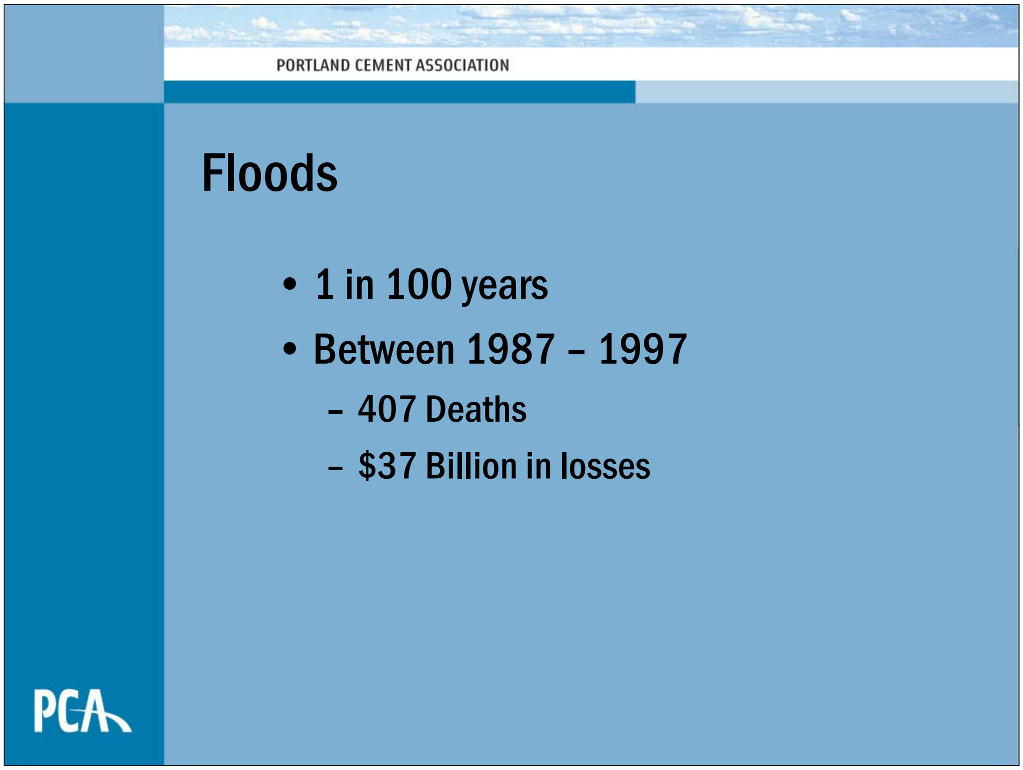
Earthquakes

- Maximum Considered Earthquake
  - 2% exceedance in 50 years
- 1995 Kobe Earthquake (7.2)
  - 6,000 Deaths and $100 Billion in Losses
- 1994 Northridge Earthquake (6.7)
  - 57 Deaths and $40 Billion in Losses

PCA

Comparing the risks and consequences of hazards is enlightening. Current codes require that earthquakes with a 2% probability of exceedance in 50 years be used for the design of buildings which is equal to a 1 in 2,500 year event.. Codes now require earthquake design in many areas not previously designed for earthquakes. Examples of the death and monetary loss consequences of earthquakes include the 1995 Kobe earthquake and the 1994 Northridge earthquake shown on the slide.

References are as follows: ASCE 7-05 pg 207 probabilistic MCE and FEMA Report #424 Jan 2004 pg 3-7.



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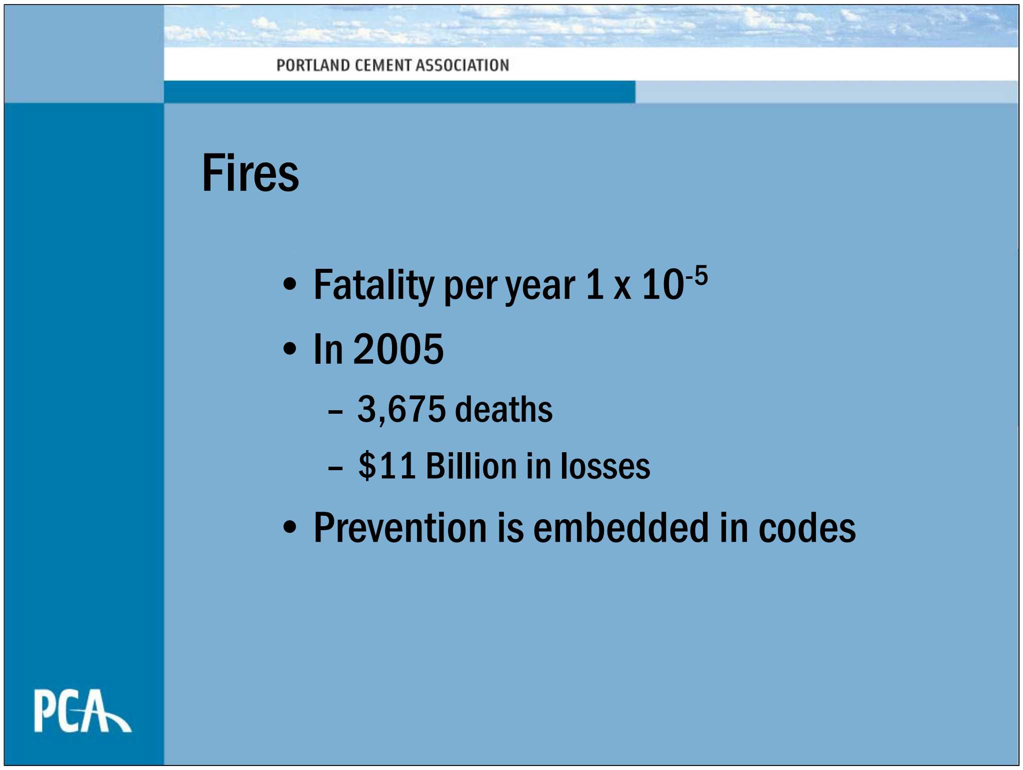
Floods

- 1 in 100 years
- Between 1987 – 1997
  - 407 Deaths
  - $37 Billion in losses

Codes require buildings to be designed for 1 in 100 year floods. In the 10 years from 1987 to 1997 there were 407 deaths and $37 billion in losses from floods.



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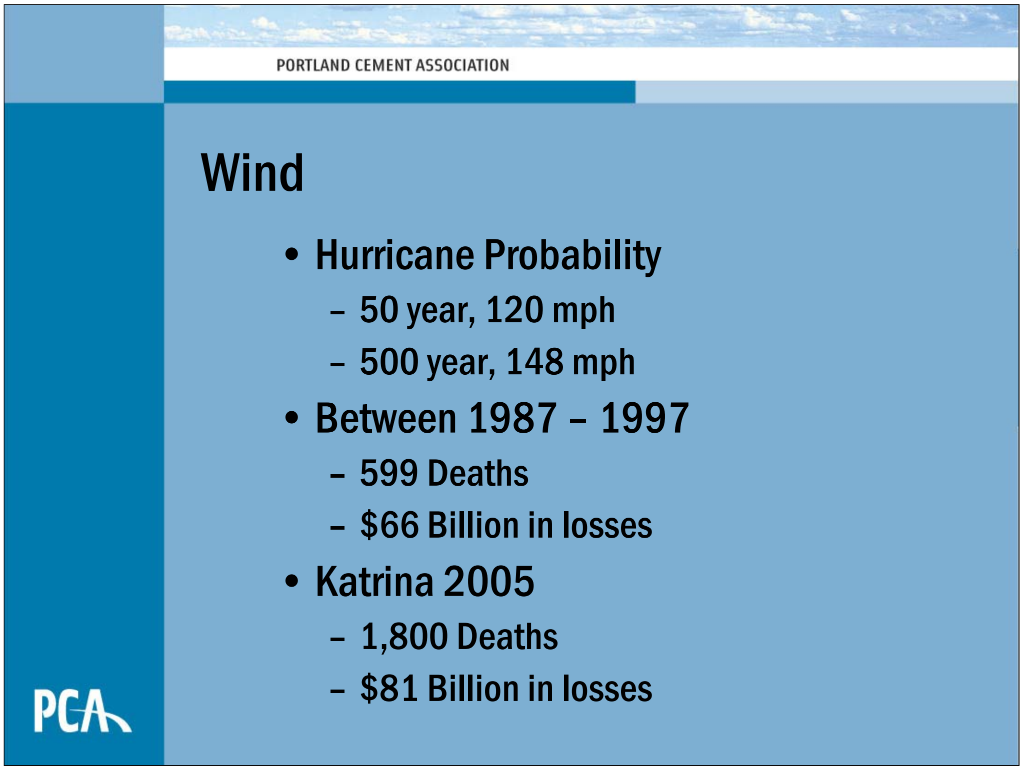
Fires

- Fatality per year 1 x 10^{-5}
- In 2005
  - 3,675 deaths
  - $11 Billion in losses
- Prevention is embedded in codes

It is estimated that there are 1 in 10,000 deaths per year from fires and $11 billion in losses in the U.S. during 2005. Design for fires is firmly embedded in building codes and material standards and is mostly prescriptive. However, in the future this may become more of a problem for structural engineers if performance design for fire is widely accepted.



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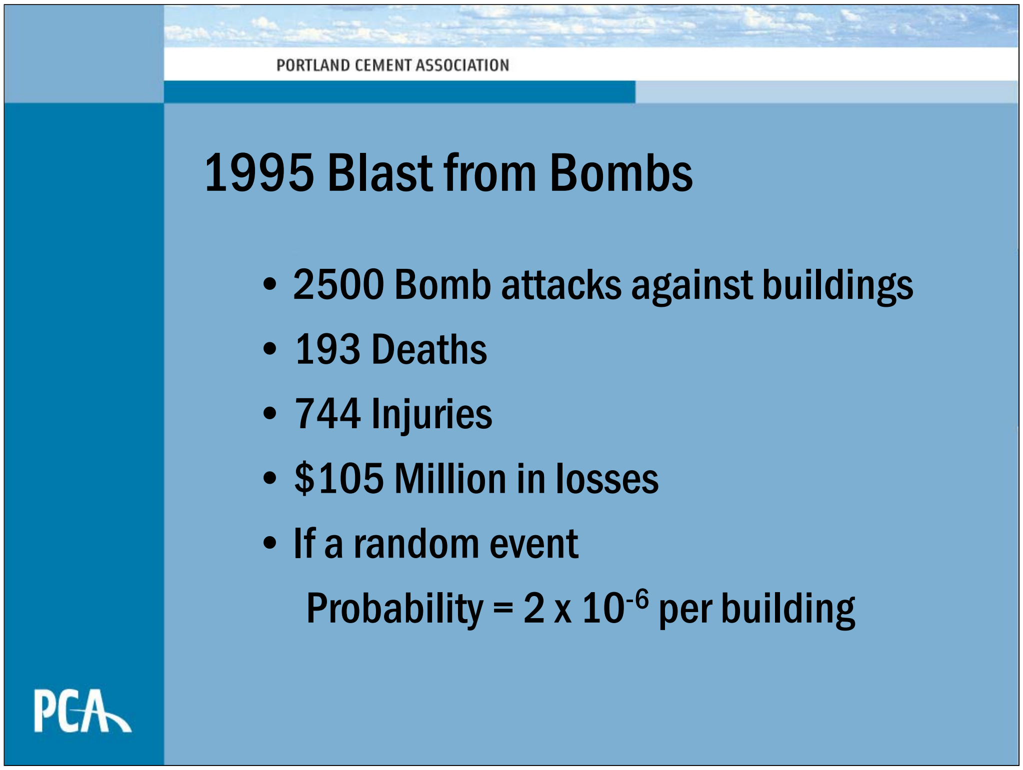
Wind

- Hurricane Probability
  - 50 year, 120 mph
  - 500 year, 148 mph
- Between 1987 – 1997
  - 599 Deaths
  - $66 Billion in losses
- Katrina 2005
  - 1,800 Deaths
  - $81 Billion in losses

PCA

The extreme winds of hurricanes are a media event. In a non-hurricane area along the Gulf of Mexico coast for example, 50 year winds of 120 mph are used for design while in a hurricane area, winds of 148 mph from a 500 year hurricane are now used for design. The number of deaths and losses are shown for a 10 year period and for Katrina. Reference is ASCE 7-05 pg 25 sec 6.5.4.2.



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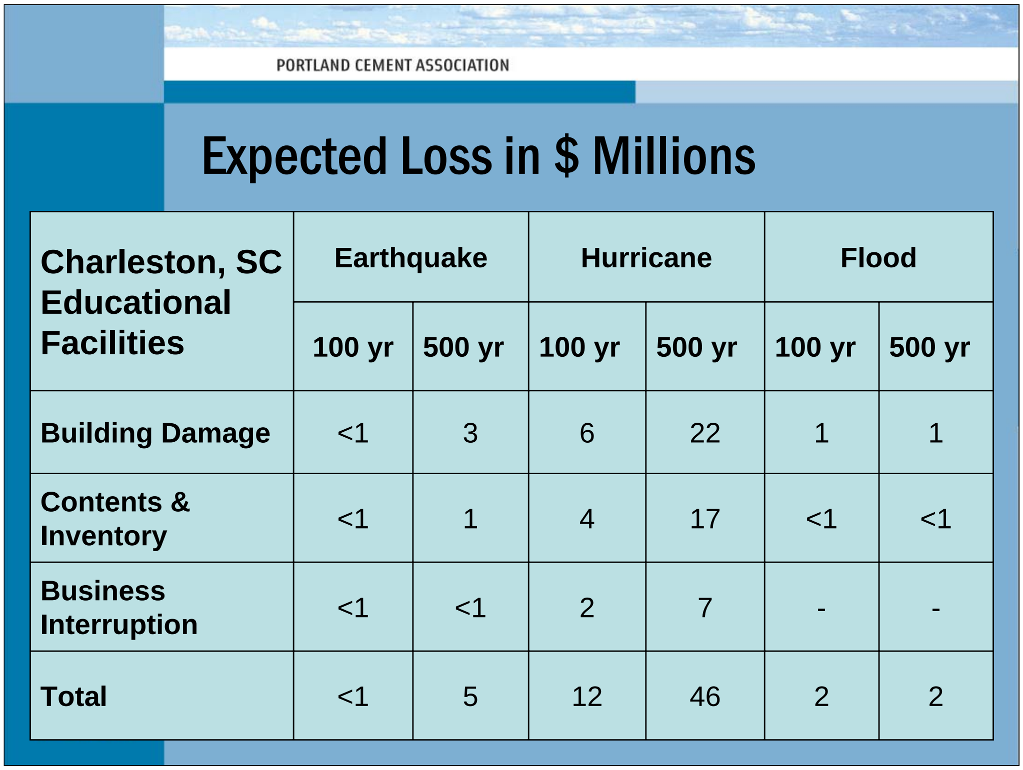
1995 Blast from Bombs

- 2500 Bomb attacks against buildings
- 193 Deaths
- 744 Injuries
- $105 Million in losses
- If a random event

  Probability = 2×10^{-6} per building

The final hazard is blast from bomb explosions. FBI data from 1995 indicate that there were 2,500 bomb attacks against buildings with 193 deaths and $105 million in losses. Professor Ellingwood of the Georgia Institute of Technology estimates that this is a probability of 2 X 10 -6 per building if it is considered a random event. However, the probability for particularly attractive targets such as tall symbolic buildings is probably much higher. The Murrah Building bombing occurred in 1995 which added to the deaths and injuries in that year.



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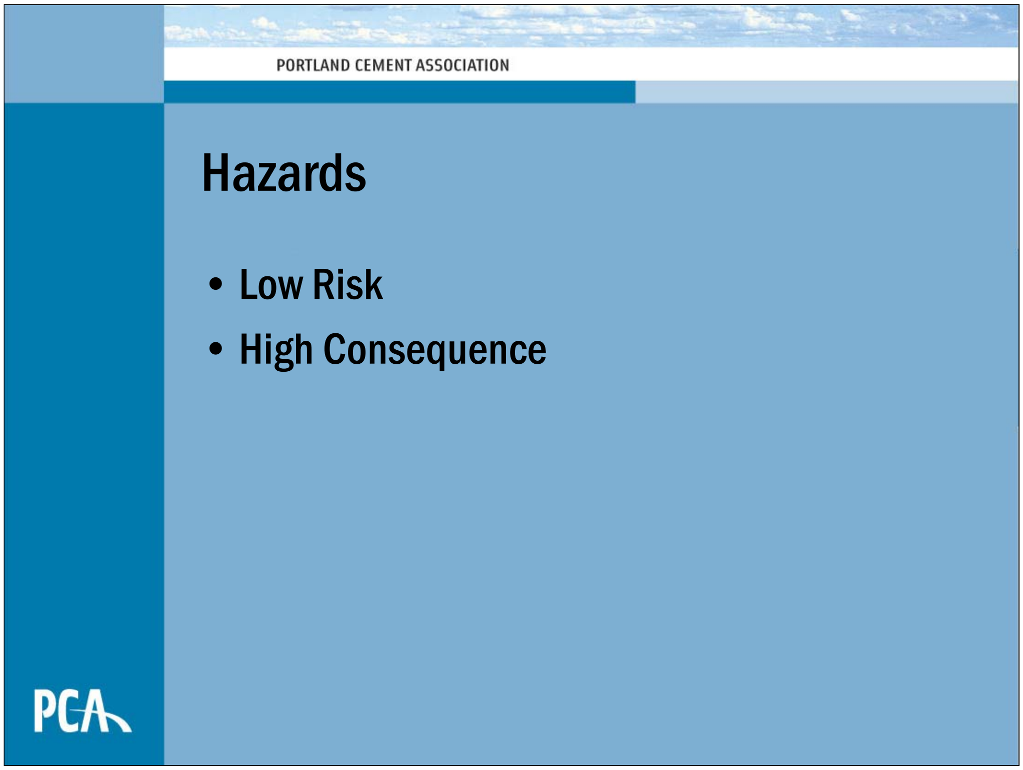
Expected Loss in $ Millions

Charleston, SC Educational Facilities	Earthquake		Hurricane		Flood	
	100 yr	500 yr	100 yr	500 yr	100 yr	500 yr
Building Damage	<1	3	6	22	1	1
Contents & Inventory	<1	1	4	17	<1	<1
Business Interruption	<1	<1	2	7	-	-
Total	<1	5	12	46	2	2

This table is based on FEMA Report 424 for educational facilities in one city, Charleston SC. The expected losses for the educational facilities from three hazards are shown in the table. The 500 year hurricane has a much greater consequence than other hazards. In Salt Lake City, earthquakes would likely have the greater consequence.



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Hazards

- Low Risk
- High Consequence

The point of the previous slides is that the risk (probability) of these extreme hazards is low but the consequences are very significant.

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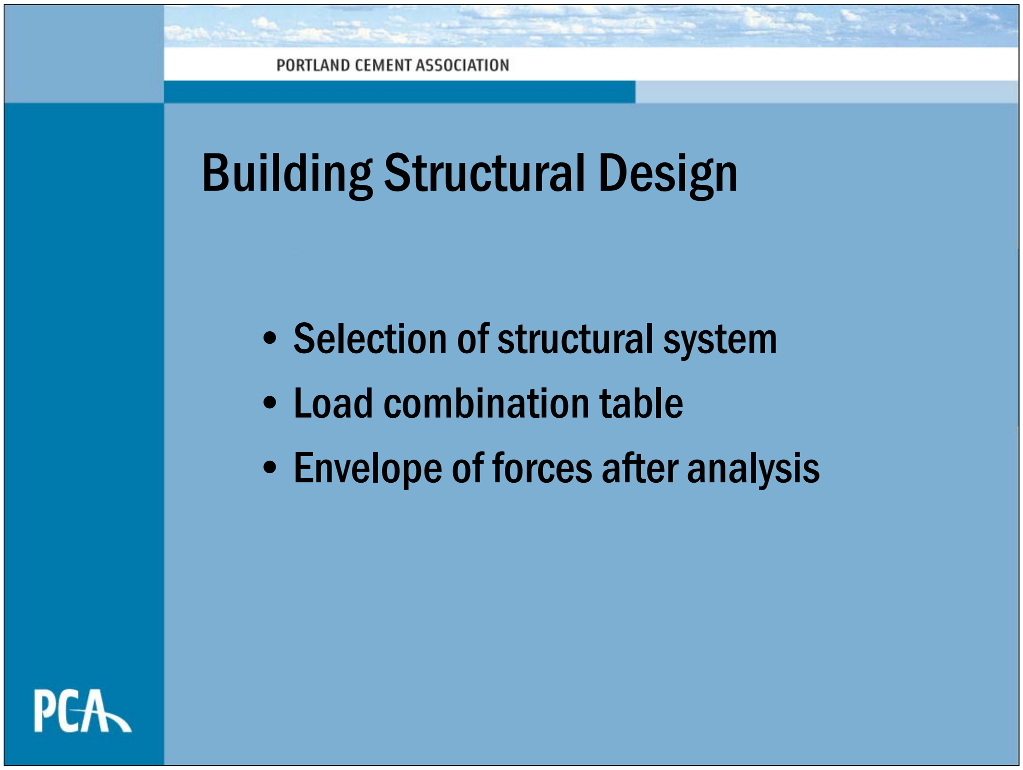
Why Design for Hazards?

- Code mandated
- Owner mandated
- Government mandated

PCA

The design for hazards is required by building codes, owner requirements, and government mandate. Can you think of other reasons to design for hazards?



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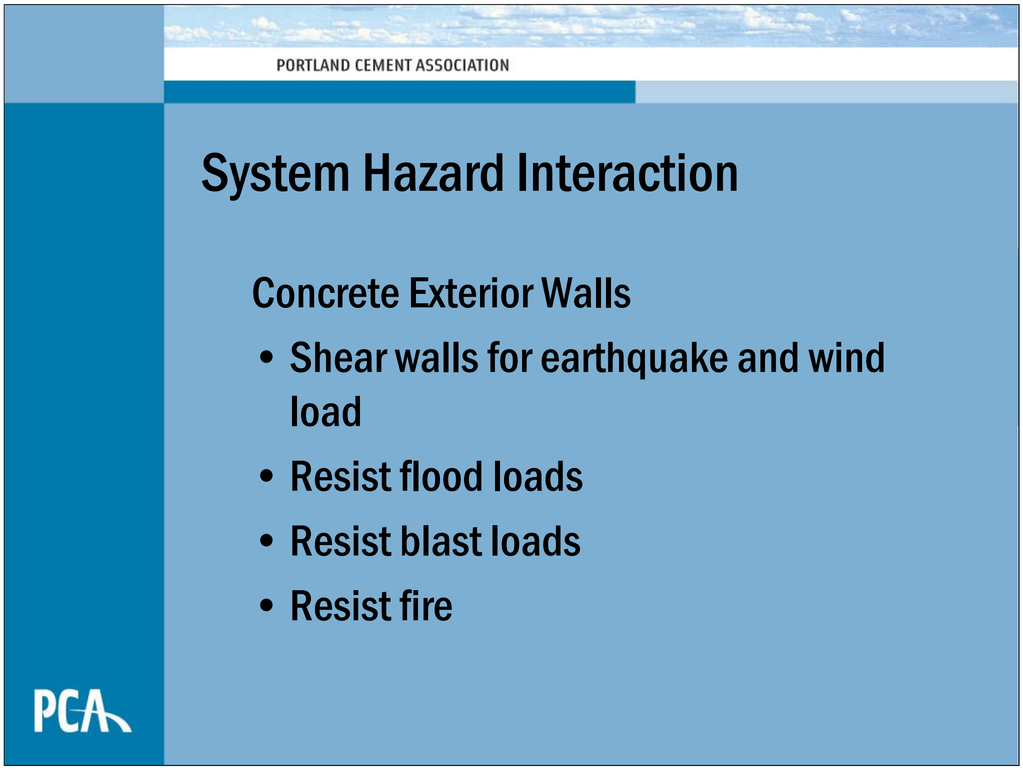
Building Structural Design

- Selection of structural system
- Load combination table
- Envelope of forces after analysis

PCA

The structural engineer must consider the mandated hazards when selecting the structural system and major structural components. Designing for several hazards is not new for structural engineers. During the design of nuclear facilities in the 1970s, extensive load combination matrices were used to ensure that all the hazards were covered and combined with correct live and dead load factors. Some of the combinations could be deleted by inspection. Following the structural analysis an envelope of maximum moments and forces was created.



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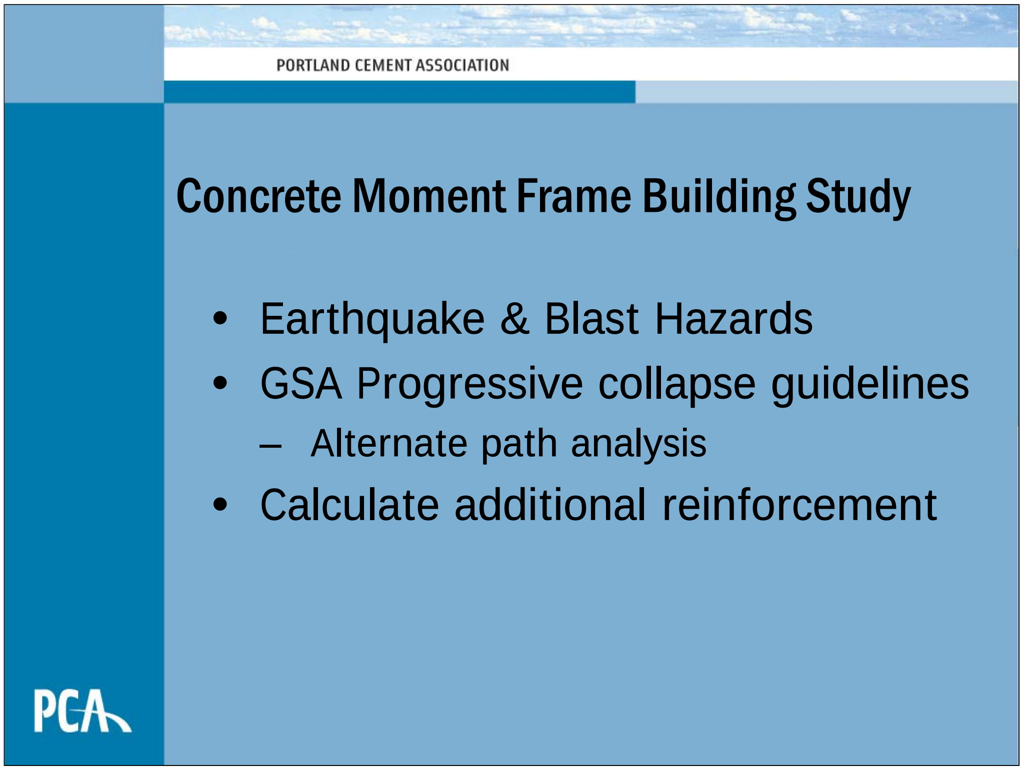
System Hazard Interaction

Concrete Exterior Walls

- Shear walls for earthquake and wind load
- Resist flood loads
- Resist blast loads
- Resist fire

A concrete wall is a simple example of a component which can be used to resist several different hazards. It can be a shear wall to resist wind and earthquake forces and at the same time resist blast loads and flood loads perpendicular to the plane of the wall. Of course the wall can also resist fires.



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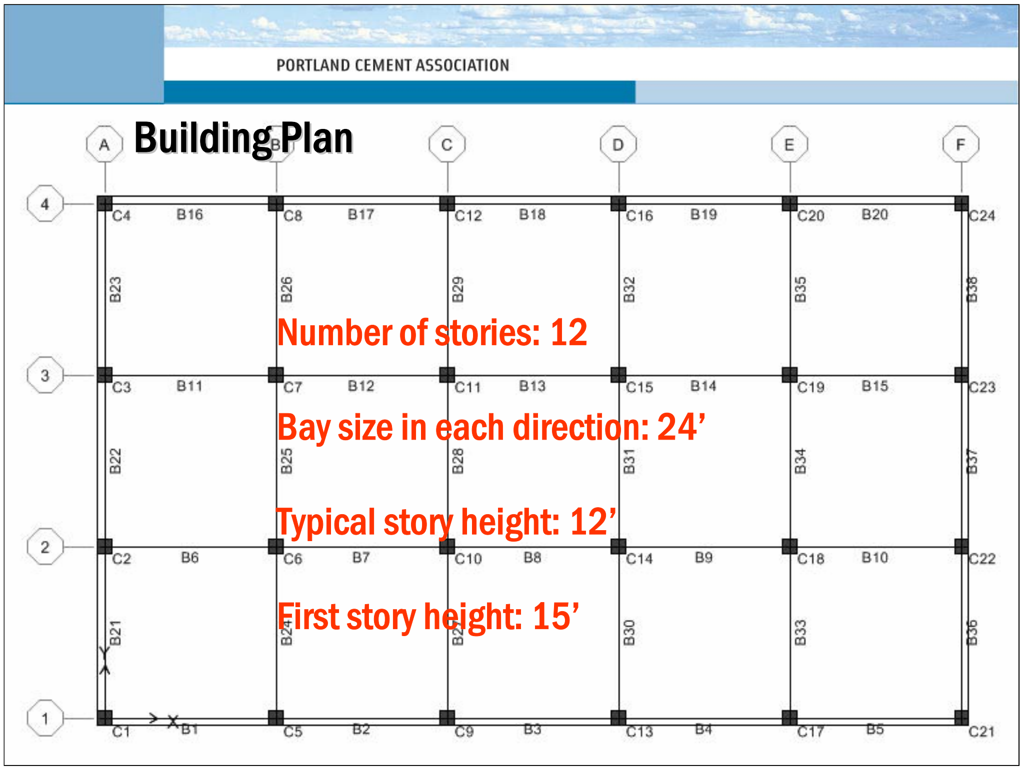
Concrete Moment Frame Building Study

- Earthquake & Blast Hazards
- GSA Progressive collapse guidelines
  - Alternate path analysis
- Calculate additional reinforcement

PCA conducted a study of the design of concrete moment frame buildings for two hazards, earthquake and blast. The goal was learn how to apply the GSA criteria and to determine the amount of additional reinforcement needed when the GSA progressive collapse guidelines are applied to concrete buildings designed for three different seismic zones.



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Building Plan

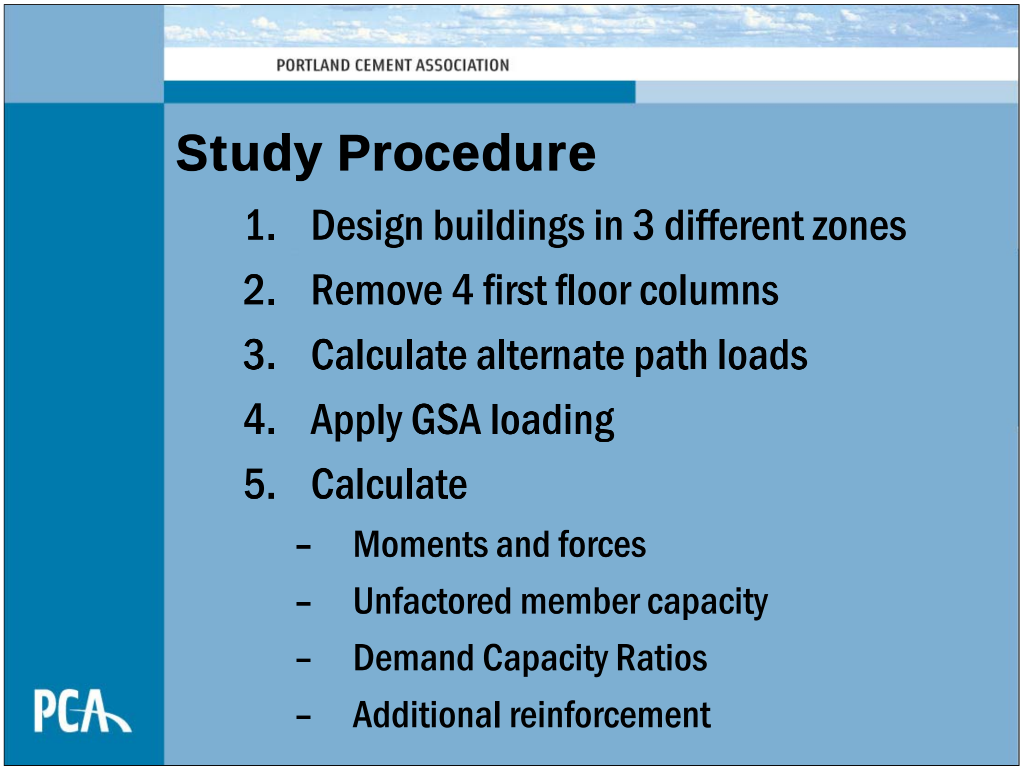
Number of stories: 12

Bay size in each direction: 24’

Typical story height: 12’

First story height: 15’

The plan of the 12 story building is shown in this slide. The prototype building has two way slabs, column line beams in two directions, columns on 24’ centers, and 12’ story heights above the 15’ high first floor. A similar example structure can be found in some of the PCA publications.



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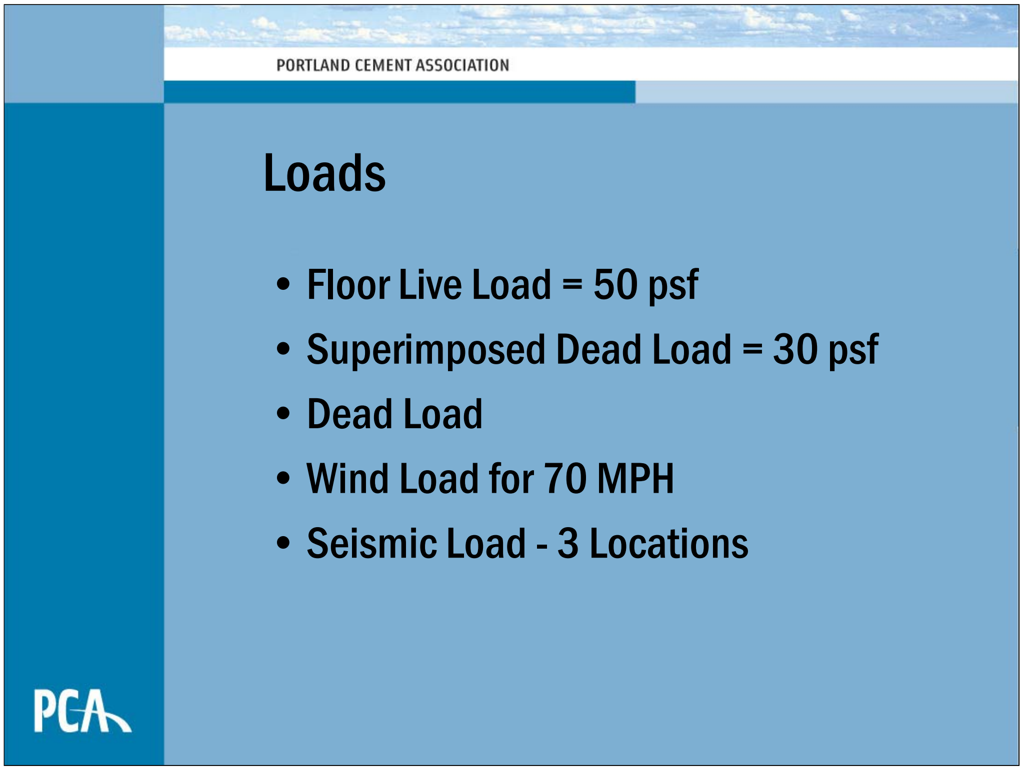
Study Procedure

1. Design buildings in 3 different zones
2. Remove 4 first floor columns
3. Calculate alternate path loads
4. Apply GSA loading
5. Calculate
    - Moments and forces
    - Unfactored member capacity
    - Demand Capacity Ratios
    - Additional reinforcement

PCA

Three building structures, one in each seismic zone, were modeled in ETABS, members sized and reinforcing determined for the appropriate load combinations. Then columns were removed per the GSA criteria, new load combinations applied, and the alternate path forces calculated in ETABS. After determining the demand capacity ratios, additional reinforcement required to resist the alternate path loads was calculated.



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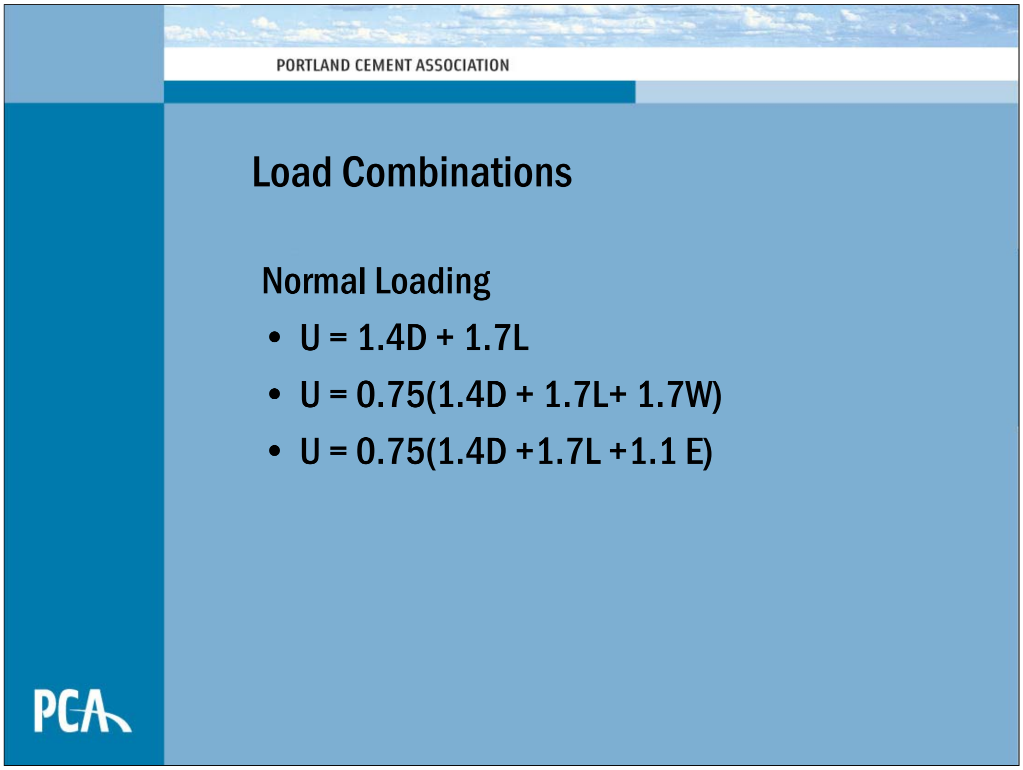
Loads

- Floor Live Load = 50 psf
- Superimposed Dead Load = 30 psf
- Dead Load
- Wind Load for 70 MPH
- Seismic Load - 3 Locations

Loads used in the design of the three buildings are shown on this slide.



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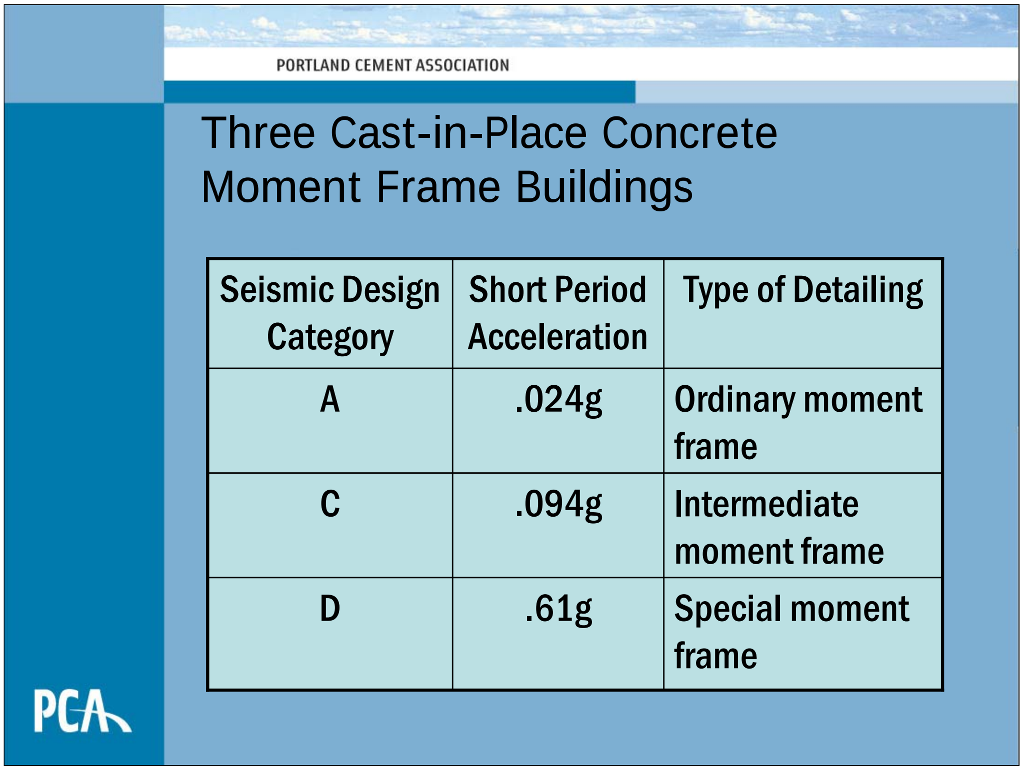
Load Combinations

Normal Loading

- U = 1.4D + 1.7L
- U = 0.75(1.4D + 1.7L+ 1.7W)
- U = 0.75(1.4D +1.7L +1.1 E)

Three load combinations were used in the structural design.



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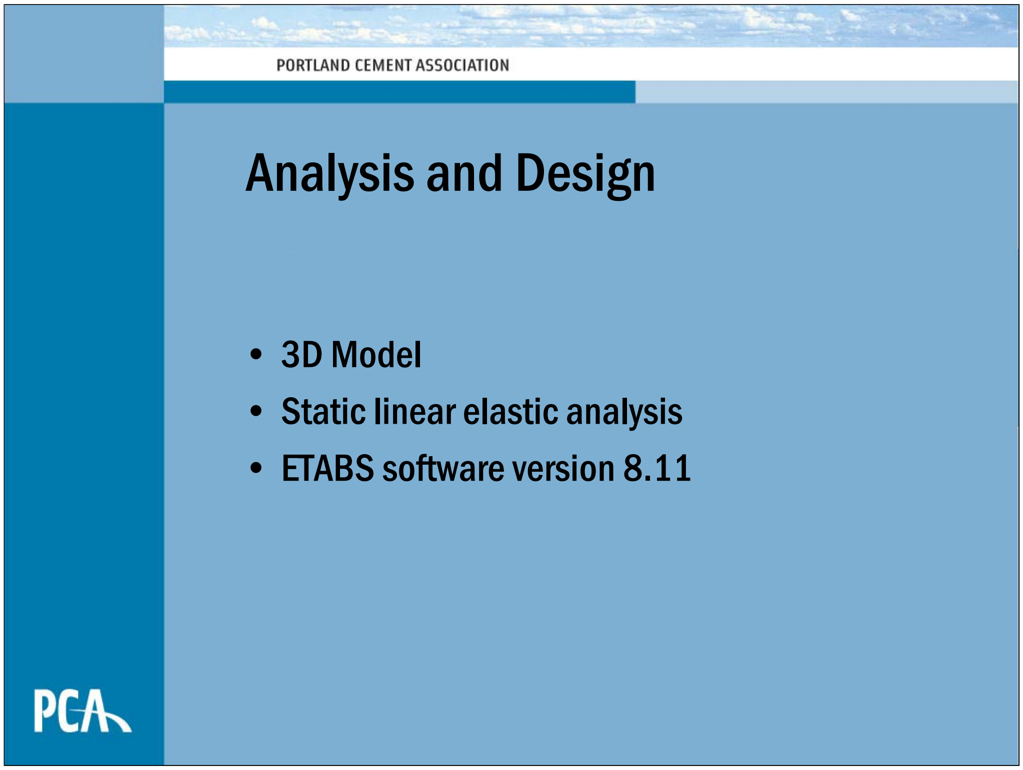
Three Cast-in-Place Concrete Moment Frame Buildings

Seismic Design Category	Short Period Acceleration	Type of Detailing
A	.024g	Ordinary moment frame
C	.094g	Intermediate moment frame
D	.61g	Special moment frame

Each of the three buildings was designed for one of the seismic design categories A,C, or D. The short period acceleration is shown along with the type of detailing that is required for each category per the ACI 318 standard.



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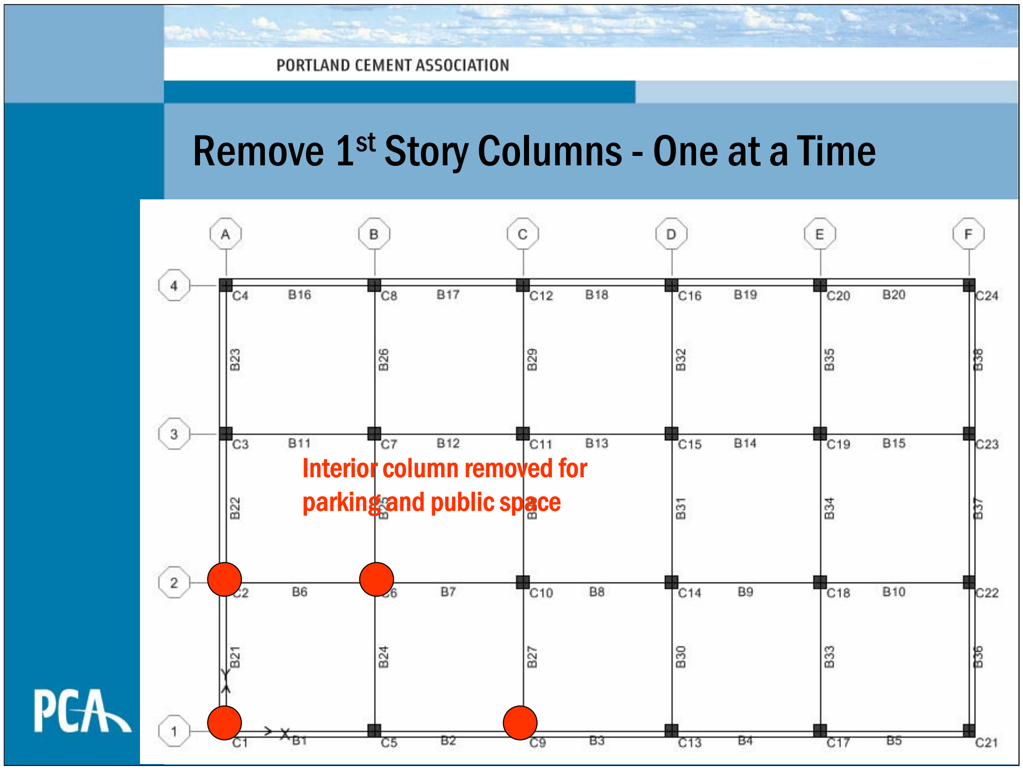
Analysis and Design

- 3D Model
- Static linear elastic analysis
- ETABS software version 8.11

A 3D model with linear elastic analysis in ETABS version 8.11 was used during the analysis and design of the three buildings.



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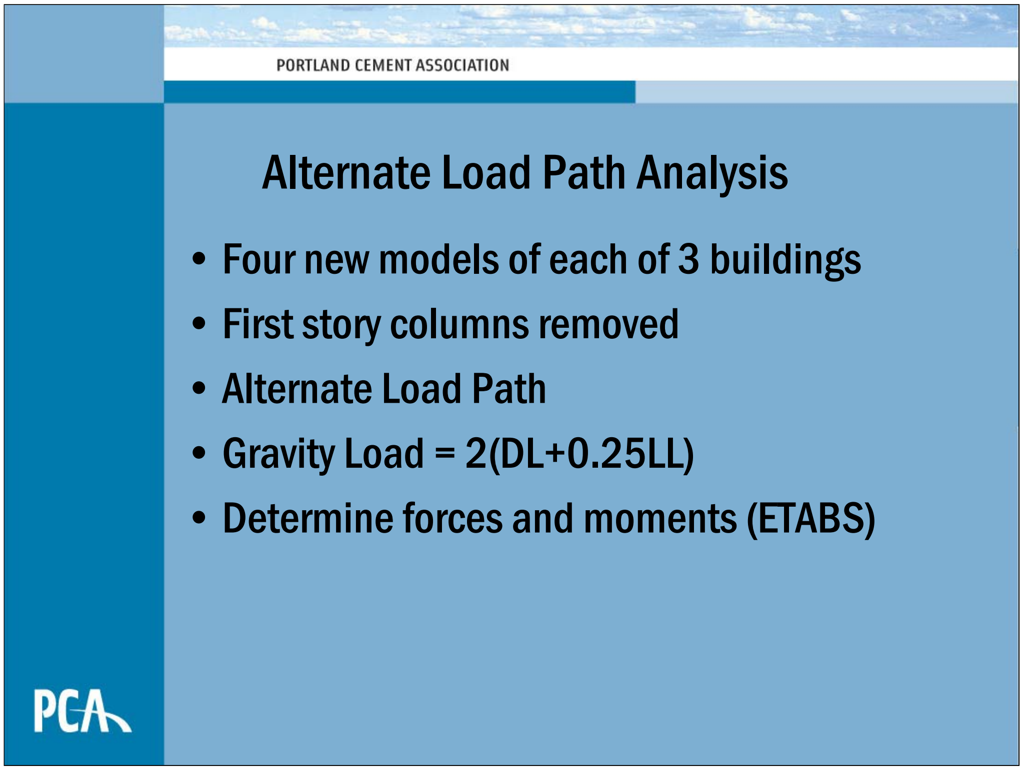
Remove 1st Story Columns - One at a Time

Interior column removed for parking and public space

The red dots on this plan indicate were the ground floor columns are removed: one column in the middle of the long side, one column in the middle of the short side, a corner column and an interior column. The GSA criteria only requires removal of one column at a time. After removal of one column, an analysis is performed for the entire building to determine the moments and forces in the remaining members.



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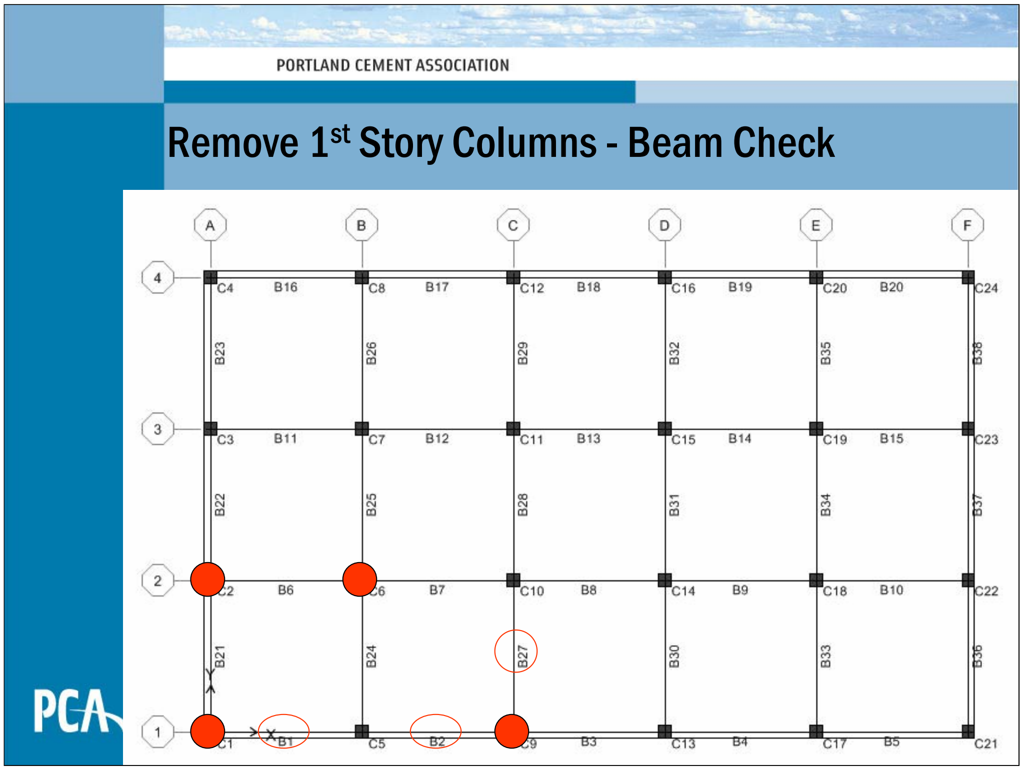
Alternate Load Path Analysis

- Four new models of each of 3 buildings
- First story columns removed
- Alternate Load Path
- Gravity Load = 2(DL+0.25LL)
- Determine forces and moments (ETABS)

PCA

This study required that four new models of each of the three buildings be analyzed. The new models take into account the alternate load path after a column is removed. The GSA criteria requires that the gravity load be taken as 2(DL+.25LL) to account for the dynamic nature of the load and the fact that only part of the live load will likely be on the floor during this extreme event. Forces and moments in the members of the 12 structures with removed columns were determined in ETABS.



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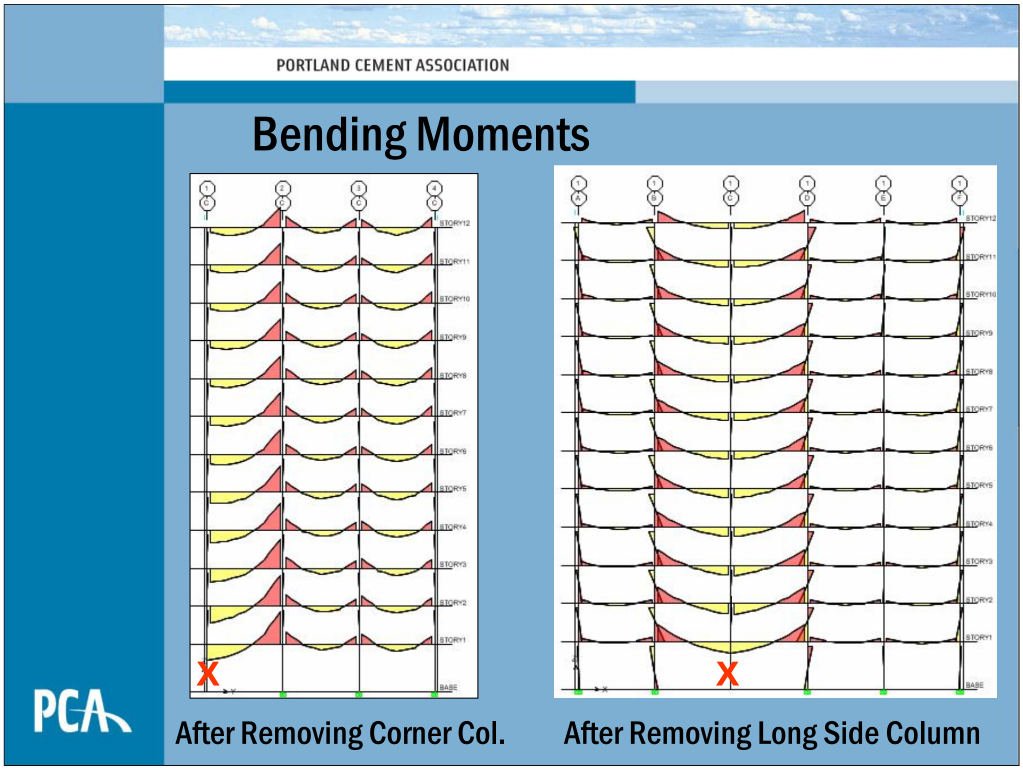
Remove 1st Story Columns - Beam Check

Since the building is symmetrical, only the moments and forces in selected members are shown here. As examples the beams B1, B2, and B3 are used to illustrate the alternate load path forces and moments.



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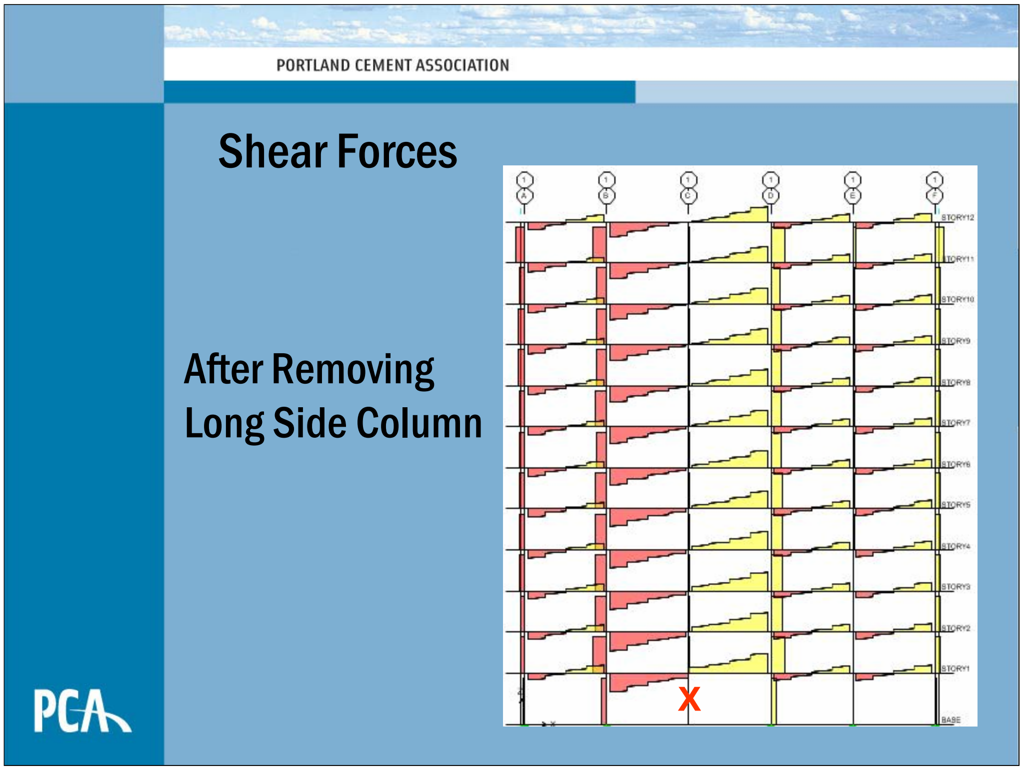
Bending Moments

After Removing Corner Col.

After Removing Long Side Column

Shown here are the moment diagrams on two sides after removing a corner column and after removal of a column on the long side of the structure. The beams span over the removed column. Also, note that the beam moment decreases with increasing distance above the removed column.



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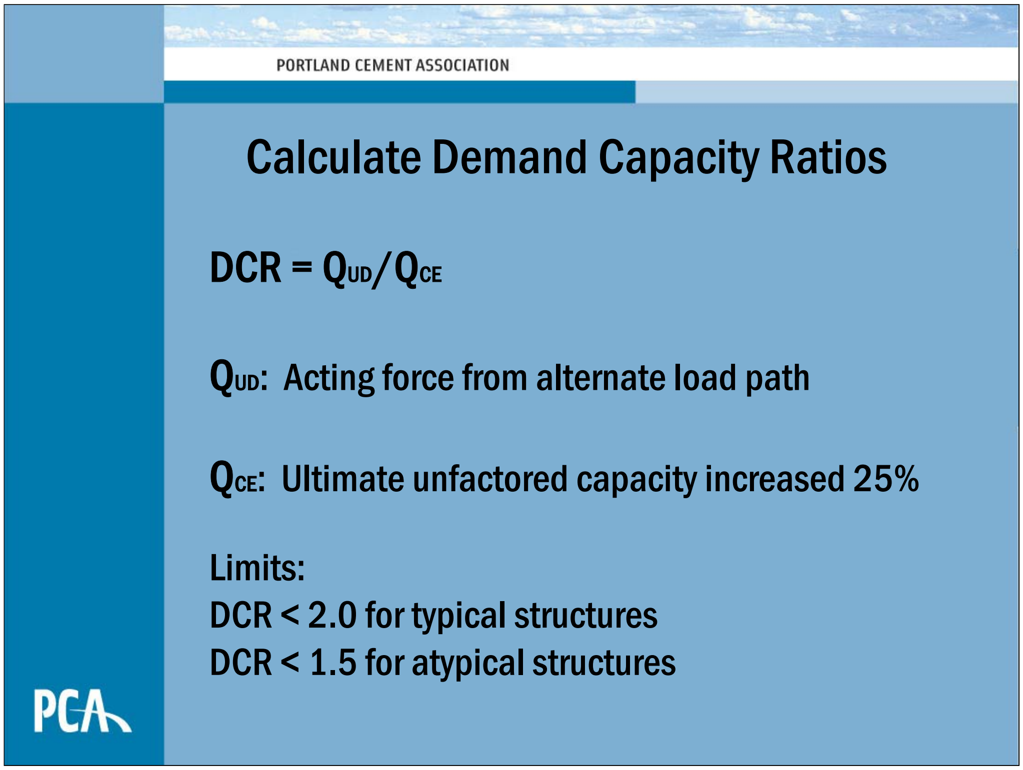
Shear Forces

After Removing Long Side Column

PCA

Shown in this slide is the shear diagram after removal of the long side column. Shear forces in the beams decrease with increasing distance above the removed columns.



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Calculate Demand Capacity Ratios

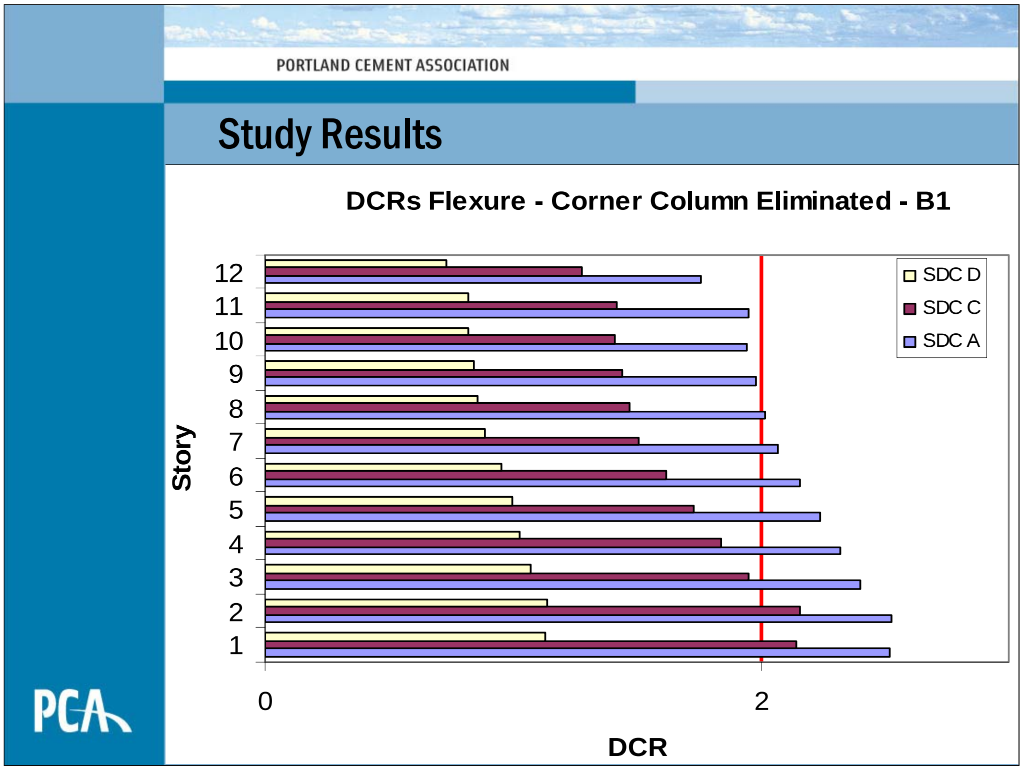
DCR = Q_{UD}/Q_{CE}

Q_{UD}: Acting force from alternate load path

Q_{CE}: Ultimate unfactored capacity increased 25%

Limits:
DCR < 2.0 for typical structures
DCR < 1.5 for atypical structures

To calculate the demand capacity ratio (see equation above) for each member per the GSA criteria, the ultimate capacity was recalculated based on strength reduction factors equal to one. The acting force and moment for each member for the removed column case was taken from the ETABS analysis. If the DCR for any member exceeds the limits shown above, the member must be strengthened.



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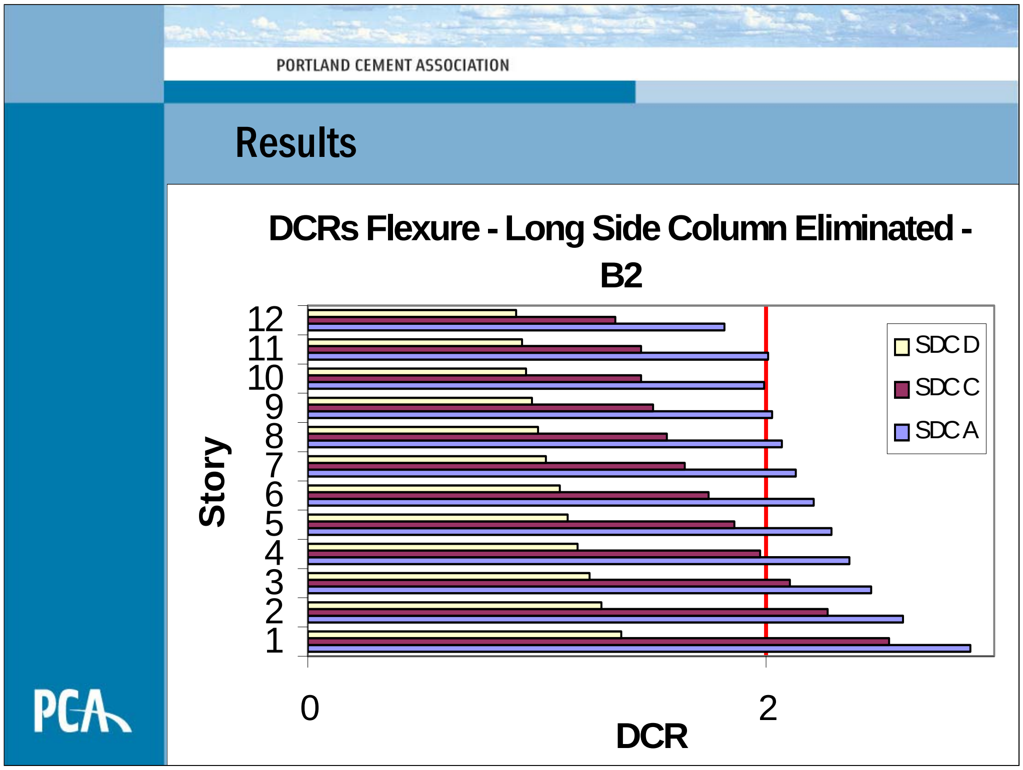
Study Results

For each beam the demand capacity ratio was calculated for the top and bottom reinforcement in addition to the demand capacity ratio for the shear. For each beam the maximum DCR was determined. This graph shows the DCRs for flexure in beam B1 for each of the three seismically designed buildings. The beam B1 (and symmetrical beams) in the levels 1 through 8 of the SDC A building exceed the allowed DCR value and require additional flexural reinforcement. Similarly for the SDC C building's first two levels. Beam B1 DCR values for SDC D building are all less than 2 and require no additional reinforcement.



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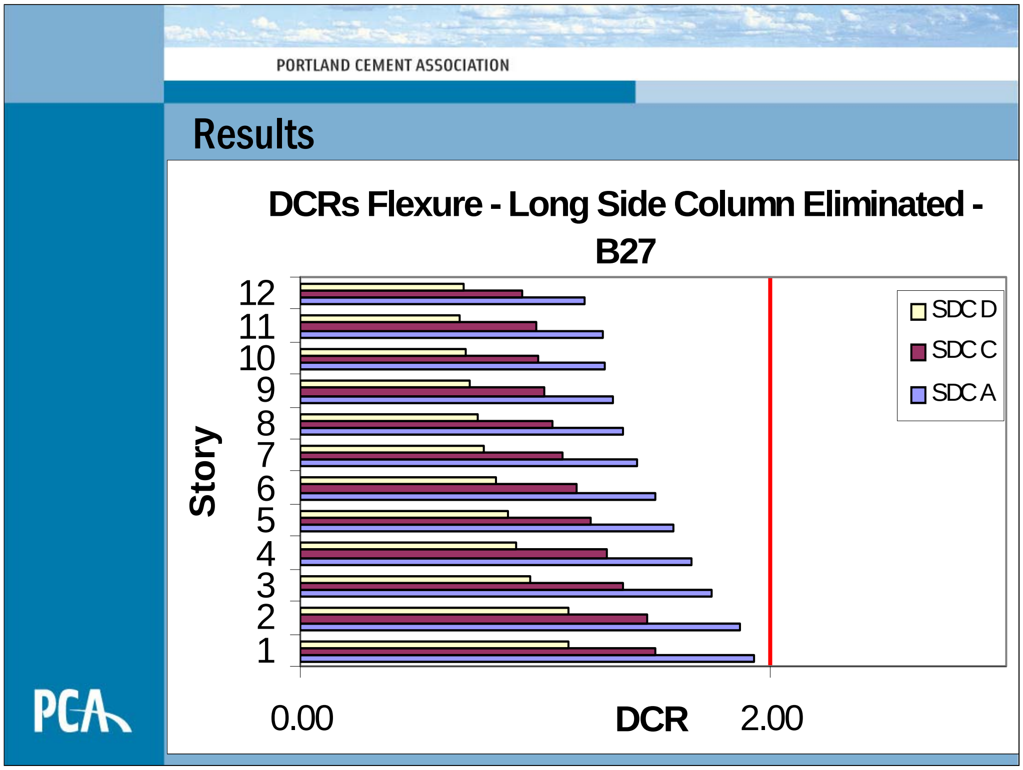
Results

DCRs Flexure - Long Side Column Eliminated - B2

This graph shows the DCRs for flexure in beam B2 for each of the three seismically designed buildings. The beam B2 (and symmetrical beams) in the levels 1 through 9 of the SDC A building exceed the allowed DCR value of 2 and require additional flexural reinforcement. Similarly for the SDC C building's lower three levels. Beam B2 DCRs for the SDC D building are all less than 2 and require no additional reinforcement.



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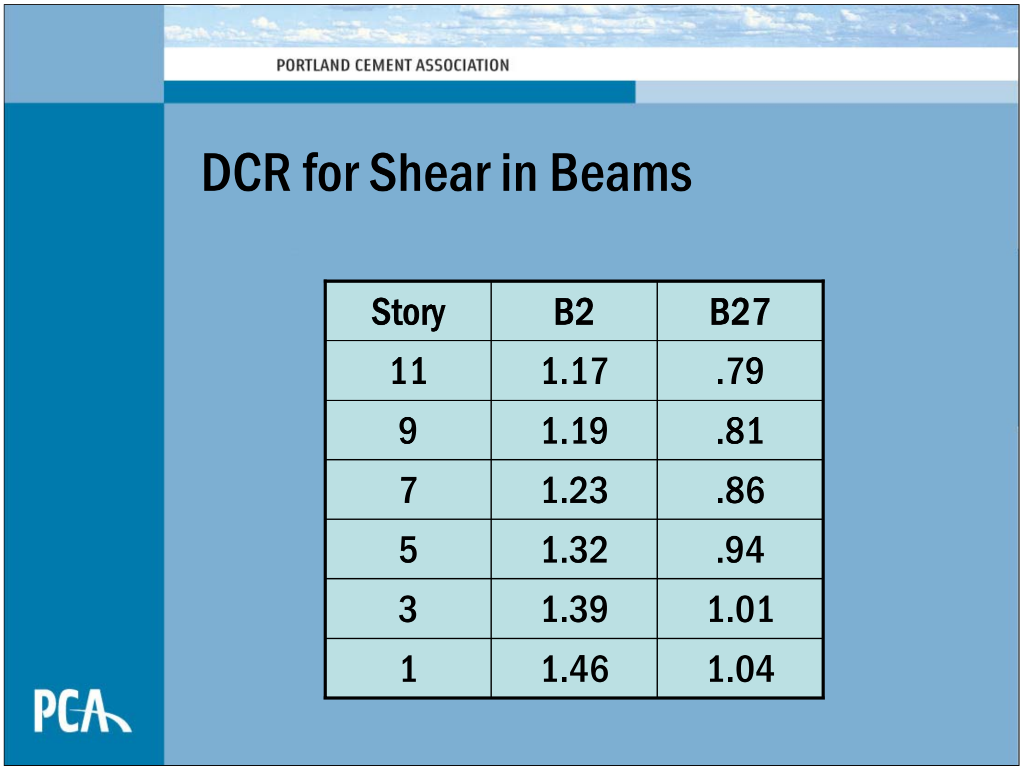
Results

DCRs Flexure - Long Side Column Eliminated - B27

This graph shows the DCRs for flexure in beam B27 for each of the three seismically designed buildings. The beam B27 (and symmetrical beams) in all levels of the SDC A, C and D buildings are within the allowed DCR value of 2 and therefore, additional flexural reinforcement is not required to resist progressive collapse.



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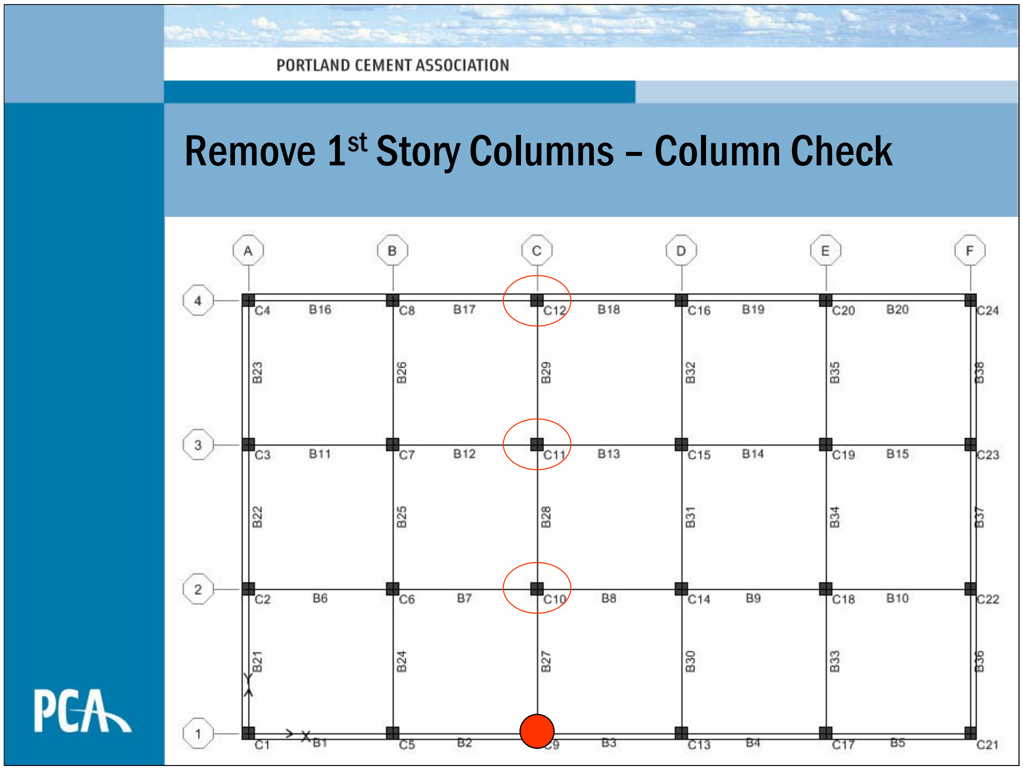
DCR for Shear in Beams

Story	B2	B27
11	1.17	.79
9	1.19	.81
7	1.23	.86
5	1.32	.94
3	1.39	1.01
1	1.46	1.04

This table shows the maximum DCRs for shear in beams B2 and B27 for the seismically designed buildings. The beams B2 and B27 (and symmetrical beams) in all levels of the SDC A, C and D buildings are within the allowed DCR value of 2 and therefore, additional shear reinforcement is not required to resist progressive collapse.



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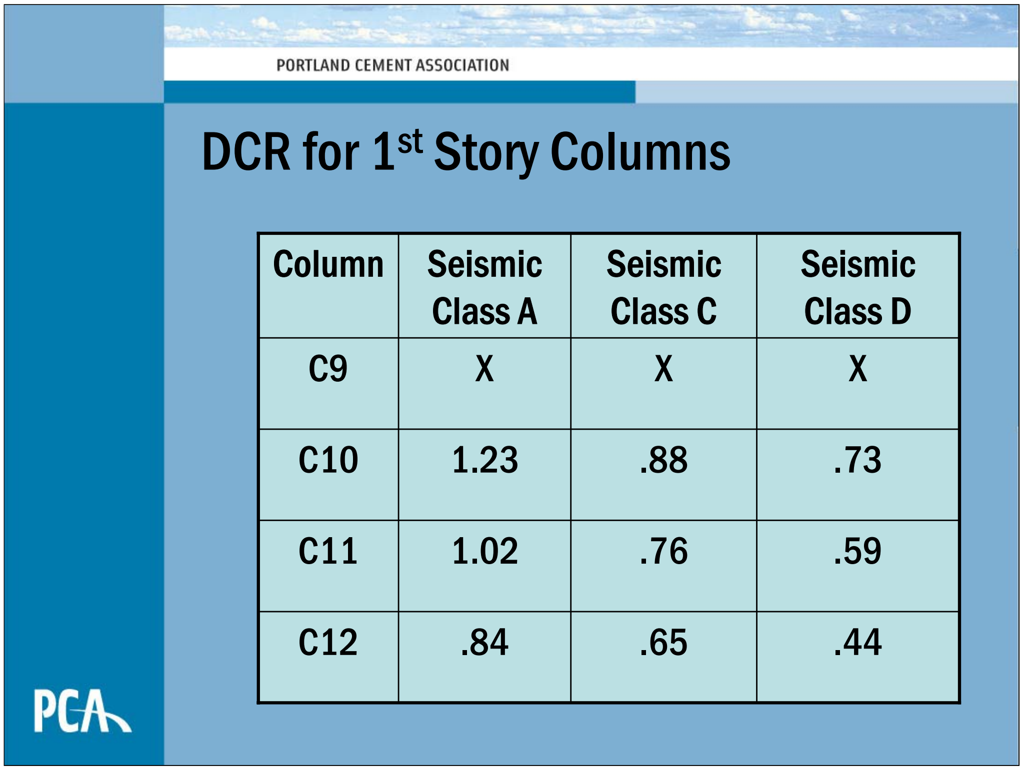
Remove 1st Story Columns – Column Check

Next we will look at DCRs for the three columns C10, C11, and C12 when the column on the long side, C9, is removed.



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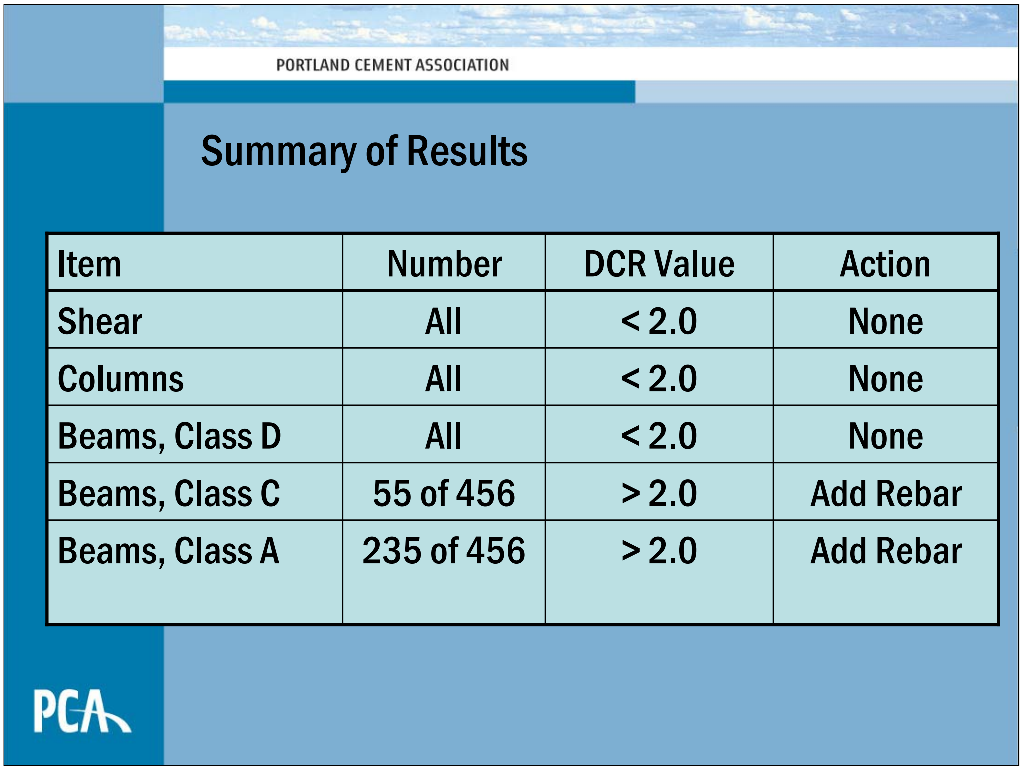
DCR for 1st Story Columns

Column	Seismic Class A	Seismic Class C	Seismic Class D
C9	X	X	X
C10	1.23	.88	.73
C11	1.02	.76	.59
C12	.84	.65	.44

This table shows the DCRs in columns C10, C11 and C12 for the three buildings when ground floor column C9 is removed. The columns (and symmetrical columns) in all levels of the SDC A, C and D buildings are within the allowed DCR value of 2 and therefore, additional reinforcement is not required.



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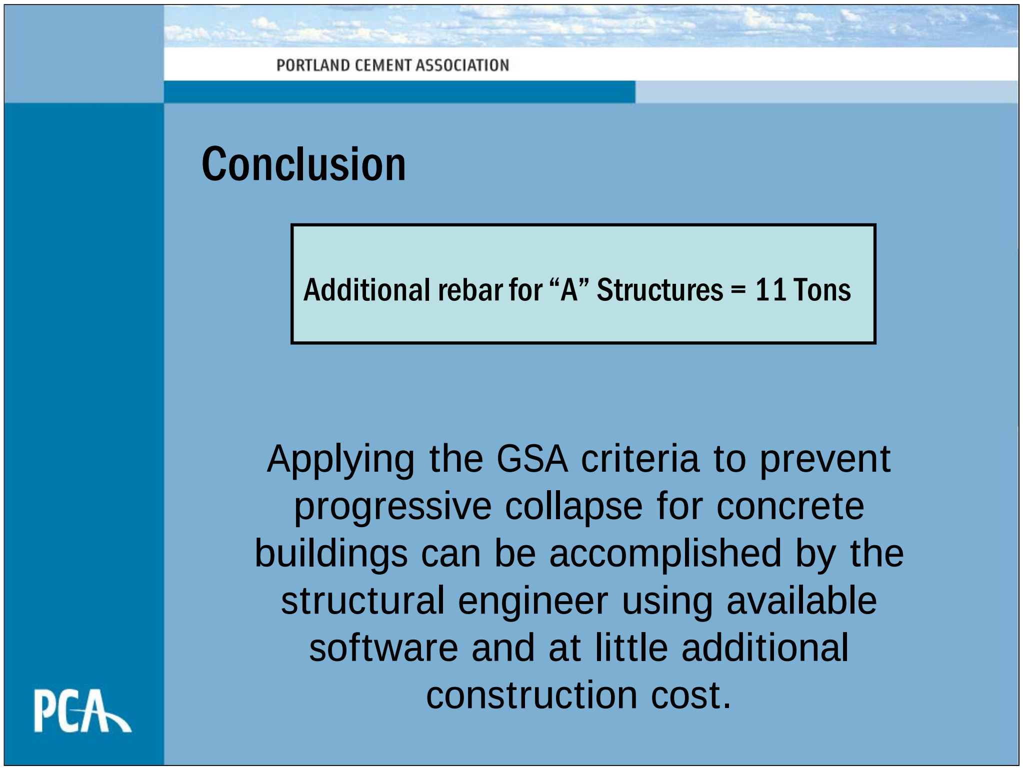
Summary of Results

Item	Number	DCR Value	Action
Shear	All	< 2.0	None
Columns	All	< 2.0	None
Beams, Class D	All	< 2.0	None
Beams, Class C	55 of 456	> 2.0	Add Rebar
Beams, Class A	235 of 456	> 2.0	Add Rebar

This table contains a summary of the complete DCR analysis of the four models of each of the three buildings, SDC A, SDC C, and SDC D. 55 beams out of a total of 456 beams in SDC C buildings and 235 beams out of a total of 456 beams in SDC A buildings exceed a DCR of 2 and therefore, need additional flexural reinforcement. Beam shear DCRs and column DCRs in all cases are less than 2 and therefore, additional reinforcement is not required to resist progressive collapse in the GSA alternate path analysis.



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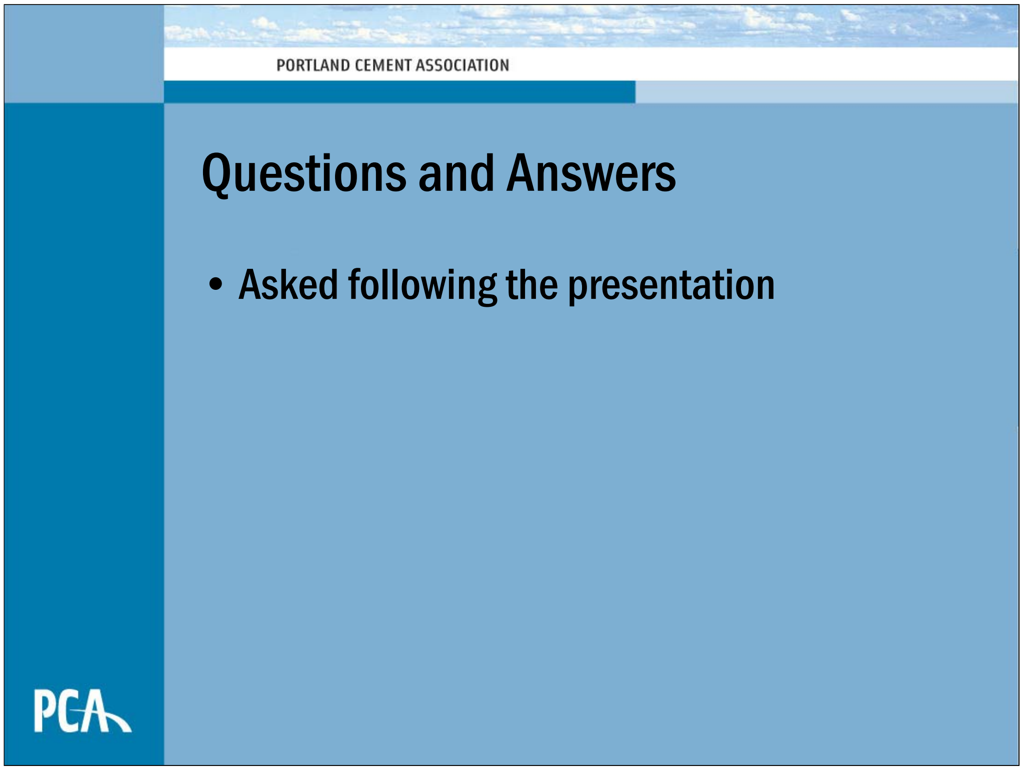
Conclusion

Additional rebar for "A" Structures = 11 Tons

Applying the GSA criteria to prevent progressive collapse for concrete buildings can be accomplished by the structural engineer using available software and at little additional construction cost.

The total reinforcement required for SDC A buildings to meet the GSA progressive collapse criteria is 11 tons which represents an increase in cost of only 1% of the total structural frame cost. In the study PCA found that applying the GSA criteria to prevent progressive collapse for concrete buildings can be accomplished by the structural engineer using available software and at little additional construction cost.



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Questions and Answers

- Asked following the presentation

PCA

1. Q. Is additional reinforcement required in the slabs?

   A. No additional reinforcement is required in the two way slabs since the beams and columns comprise the alternate path for the removed column for carrying loads down to the foundation.

2. Q. Does your estimate of the additional reinforcement include consideration of additional laps and embedment length?

   A. In the SDC A building, the estimate includes appropriate laps for the additional reinforcement.

3. Q. Are longer laps required in columns above the missing column since these columns are now in tension?

   A. After the ground floor column is removed, the load in the columns above the missing column is a very small compressive load so the lap splices will be adequate.

4. Q. Would you expect the same result for smaller buildings?

   A. The amount of additional reinforcement may increase since there is less redundancy in a smaller structure compared with the example structure.

5. Q. Would it be more economical to use moment frames on alternate rows instead of every row?

   A. Typically, cast-in-place concrete buildings are designed to use every row as a rigid frame since the beam-column frames are all continuous in any case.

6. Q. Would the result be different for flat slab or flat plate construction?

   A. Yes, the result will be different for flat slab or flat plate construction since shear in the floor slab may control in the progressive collapse case and would likely require shear reinforcement in the slab.