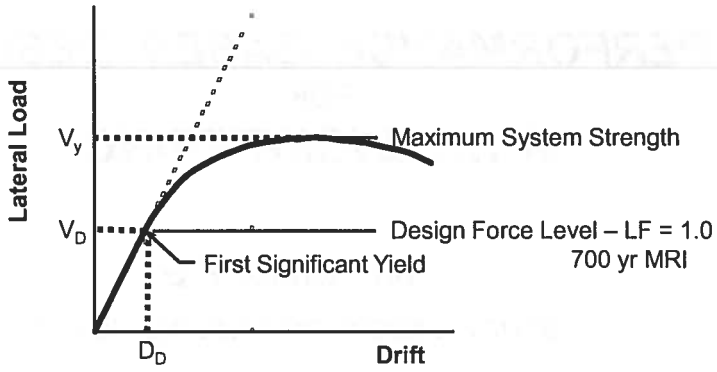
PERFORMANCE BASED DESIGN
FOR
WIND ENGINEERING

Larry Griffis, P.E.
Walter P Moore and Associates, Inc.

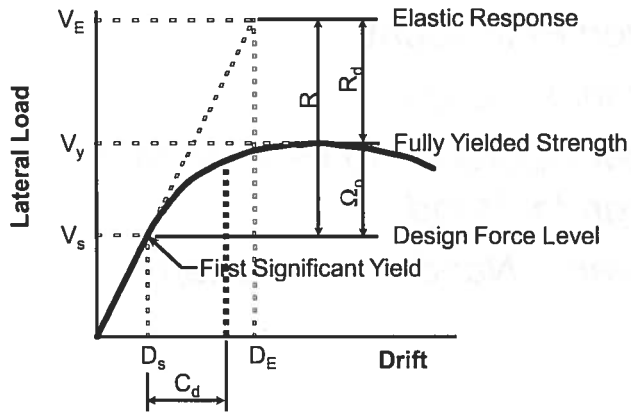
Presentation Outline

- *Design Philosophy*
- *Current Practice*
- *A New Approach to Performance Based Design for Wind*
- *Research Needs – Next Steps*

Designing for Wind
An Elastic Approach



Wind vs Seismic Design



A Wise Man's Observation
Dr. Kishor Mehta

"There is no record of failure under wind load for a properly designed (ASCE -7) and constructed building"

Wind Engineering Design

Can we push the limits of a purely elastic performance?

Wind Engineering Design Current Approach

A Form of Performance Based Design

Current Approach Designing for Wind

Limit States (Performance Levels):

- *Strength: MRI = 700, 1700 Years (Code)*
- *Interstory Drift: MRI = 10,50,100 Years (Engr. Judgment)*
- *Perception to Motion: MRI = 1,10 Years (Engr. Judgment)*

Design Wind Loads

Static Equivalent Wind Loads:

- *Building Code (normal buildings)*
- *Wind Tunnel – (tall buildings and slender structures)*

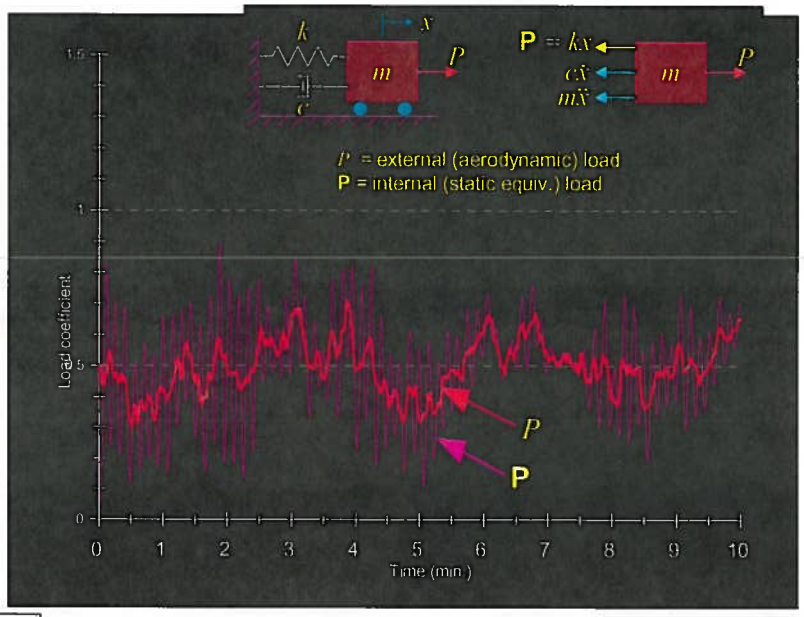
Static Elastic Analysis Design Procedure

The Wind Pressure Equation

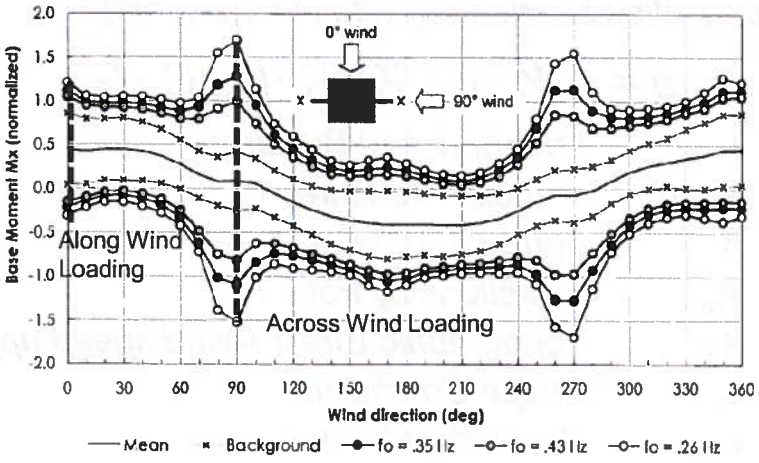
Along Wind Loads Only (static equivalent)

$$p = I \cdot \tfrac{1}{2} \rho V^2 \cdot K_d \cdot K_z \cdot K_{zt} \cdot C_p \cdot G_f$$

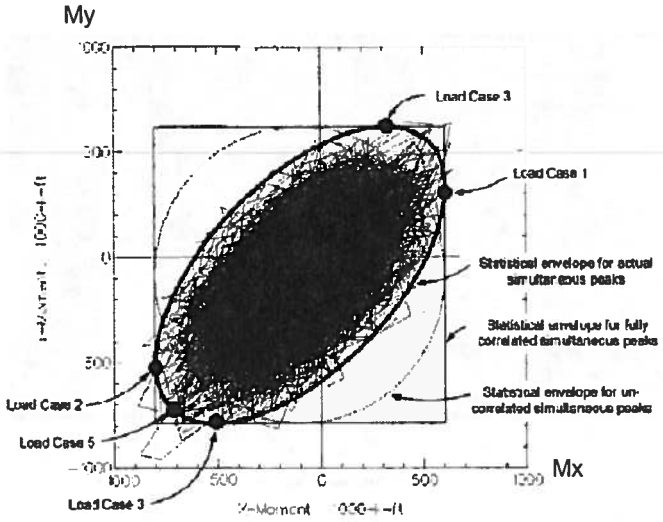
I	*Importance of Building*
$\frac{1}{2}\rho V^2$	*Velocity Pressure*
K_z	*Terrain Exposure*
K_d	*Directionality Factor*
K_{zt}	*Topographic Effect (Wind speed up)*
C_p	*Shape Coefficient*
G_f	*Gust Effect Factor*



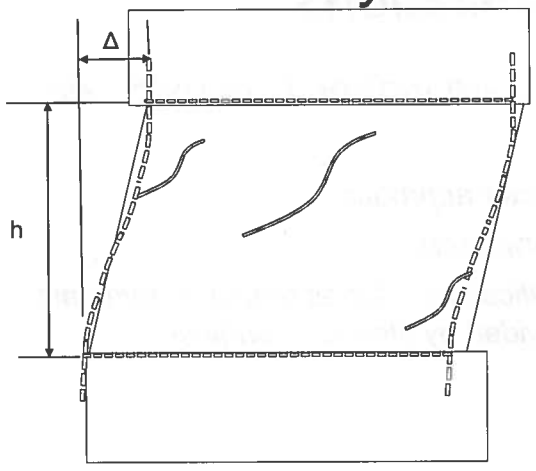
Dynamic Nature of Wind Loads



Wind Load Cases



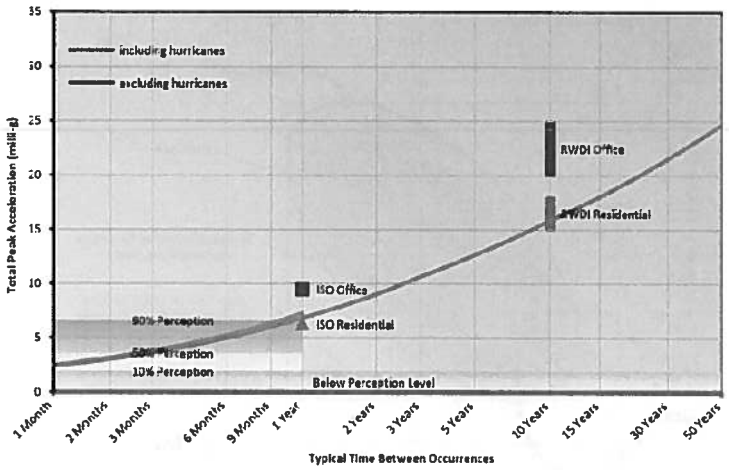
Interstory Drift Control



MRI = 10, 50, 100 Years

$\Delta / h \leq 0.0025$

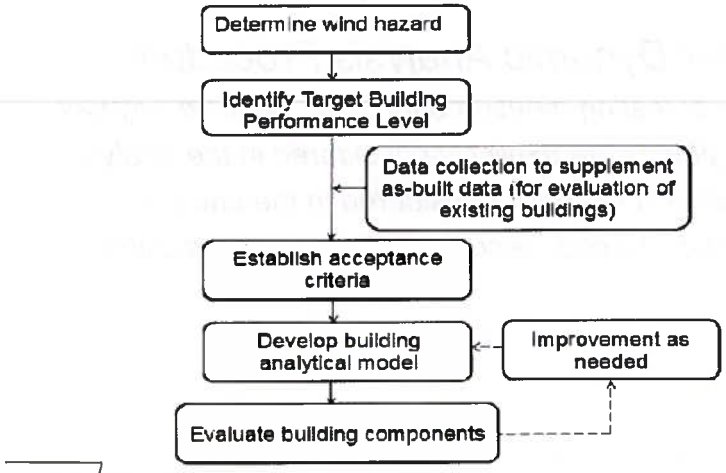
Perception to Motion



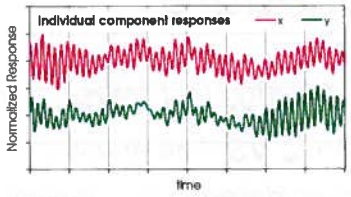
Current Practice Limitations

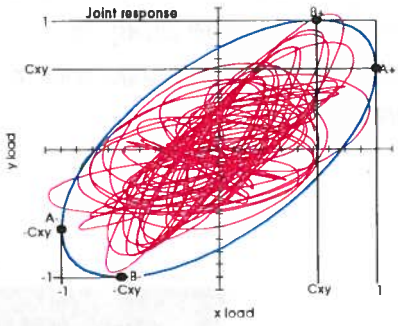
- *Dynamic effects are indirectly considered*
  - *Code Approach*
    - *Gust Effect Factor approach*
  - *Wind Tunnel Approach*
    - *Dynamic amplification of loads based on dynamic properties provided by structural engineer*

A Framework for Wind PBD



Conservatism: Dynamic Response to Static Equivalent Wind Loads





- *Code as well as the current wind tunnel procedure provides equivalent static loads*
- *Wind loads are not static!*
- *Code loads as well as wind tunnel loads may be representing peak load for a very short duration over a long design wind load event*

Possible Improvements Design Procedure

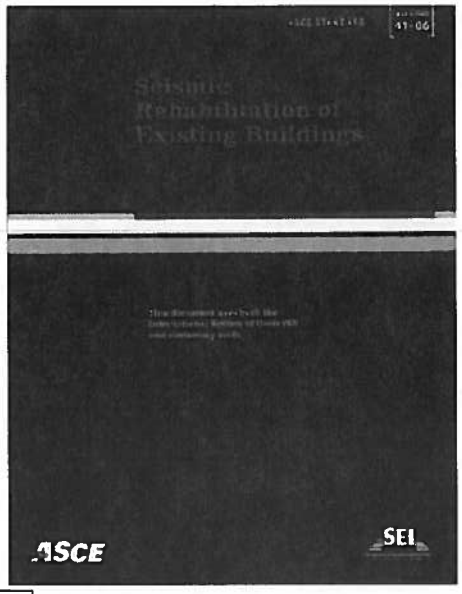
Use Linear Dynamic Analysis Procedure

- *Wind tunnel testing measures force versus time anyway*
- *Dynamic effects are explicitly considered in the analysis*
- *Directionality is explicitly considered in the analysis*
- *Rely on ACI 318 code recommendations for cracking effects*

Possible Improvements Design Procedure

Use Non-linear Dynamic Analysis Procedure

- *Wind tunnel testing measures force VS time anyway*
- *Dynamic effects are explicitly considered in the analysis*
- *Directionality is explicitly considered in the analysis*
- *Cracking effects explicitly considered in analysis based on load level and material properties*

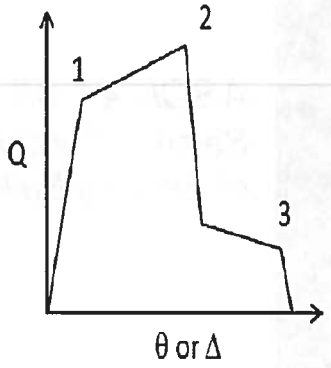


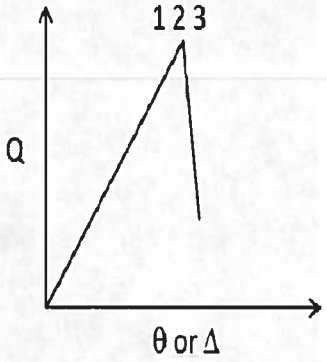
ASCE 41-06
Seismic Rehabilitation of Existing Buildings

Analysis Method

- *ASCE 41-06 frame work used*
- *Detailed procedure for shear wall modeling followed*
- *Fiber model used for walls representing concrete and reinforcing*
- *Displacement controlled behavior for flexure in wall and link beams*
- *Force controlled behavior for shear in wall and link beams*

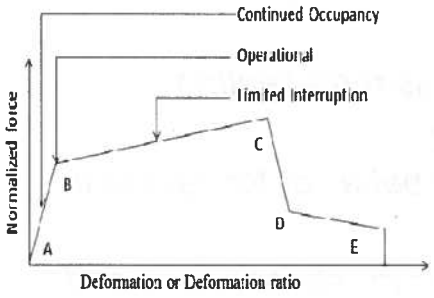
Component Force vs Deformation Curves



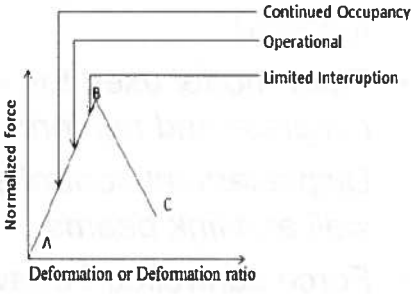


(a)Deformation Controlled Behavior (b) Force Controlled Behavior

Component or Element Deformation Acceptance Criteria



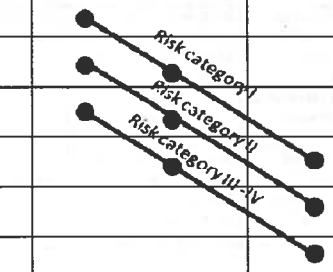
Deformation Controlled



Force Controlled

Performance Objective Matrix

Wind Hazard (MRI)	Performance Objectives		
	Motion comfort	Continued Occupancy / Operational	Limited Interruption
1 year	●		
10 years	●		
50 years			
100 years			
300 years			
700 years			
1700 years			



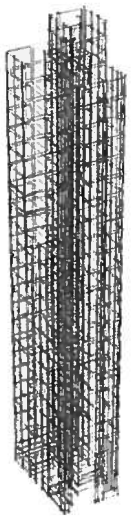
	Performance Level		
	Limited Interruption	Operational	Continued Occupancy
Overall Damage	Light	Very light	None
General	No permanent interstory drift. Structure substantially retains original strength with some reduction in stiffness in concrete structure. Some damage or cracking of façade, partitions and ceiling and non-structural elements.	No permanent interstory drift. Structure substantially retains original strength and stiffness. Minor damage or cracking of façade, partitions, ceiling and non-structural elements.	No permanent interstory drift. Structure substantially retains original strength and stiffness. No damage or cracking of façade, partitions, ceiling and non-structural elements.
Concrete structures	Minor spalling in a few columns and beams. Some flexural cracking in beams and columns and shear cracking in joints and link beams. Minor hairline cracking in structural walls. Coupling beams experience cracking < 1/8" (3 mm) width. Minor spalling	Minor hairline cracking. Limited yielding possible at a few locations. No crushing of concrete (strains < 0.003) Minor hairline cracking in structural walls. Coupling beams experience cracking < 1/16" (1.5 mm) width.	No observable damage to facades, partitions, ceilings or other non-structural elements.

Performance Levels

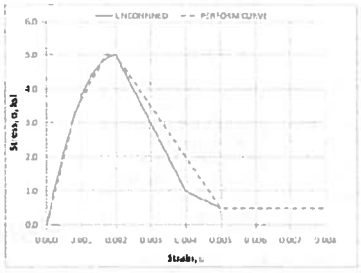
	Performance Level		
	Limited Interruption	**Operational**	**Continued Occupancy**
		repaired or replaced	
Drift damage index*	Curtain walls: H/140 Unreinforced Concrete Masonry: H/250	Curtain walls: H/120 Unreinforced Concrete Masonry: H/400	Curtain walls: H/400 Unreinforced Concrete Masonry: H/667
Steel structures	Minor local yielding at a few places. No fracture. Minor buckling or observable permanent distortion of some members.	Inception of local yielding and inception of buckling of some members.	No yielding or buckling of members
Cladding	Connections yield; minor cracks (<1/16" or 1.5 mm width) or bending in cladding.	Some cracked panes, none broken. Joints between cladding panels may fail and may need to be	No observable damage

Performance Levels

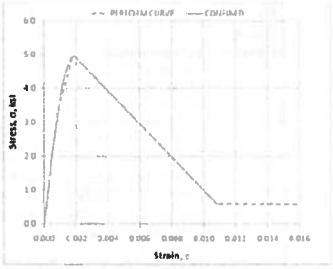
State-of-the-art Approach



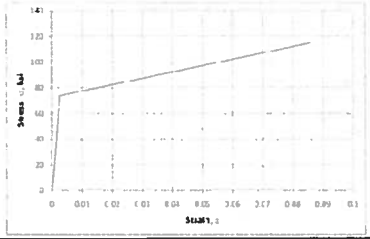
PERFORM-3D Model



Unconfined concrete model



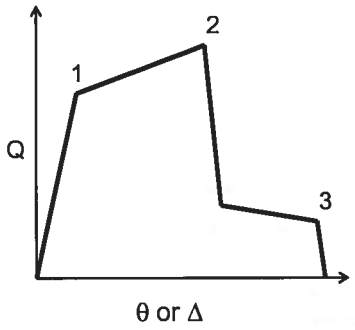
Confined concrete model



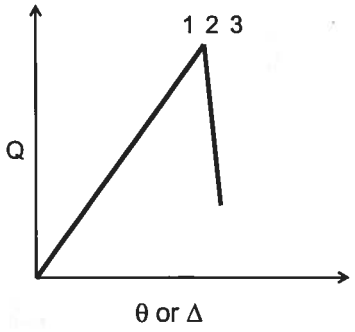
Steel reinforcement model

Material Non-linearity Modeled

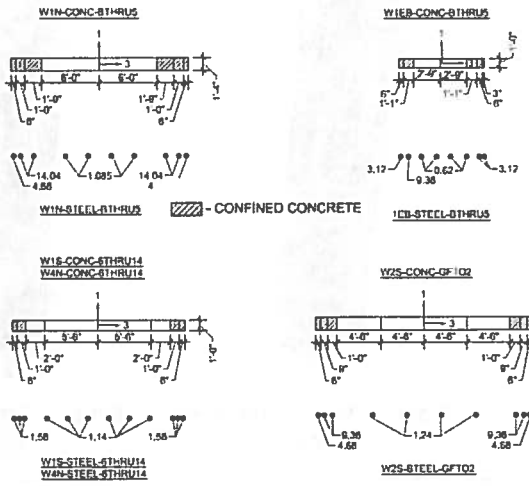
Deformation controlled behavior



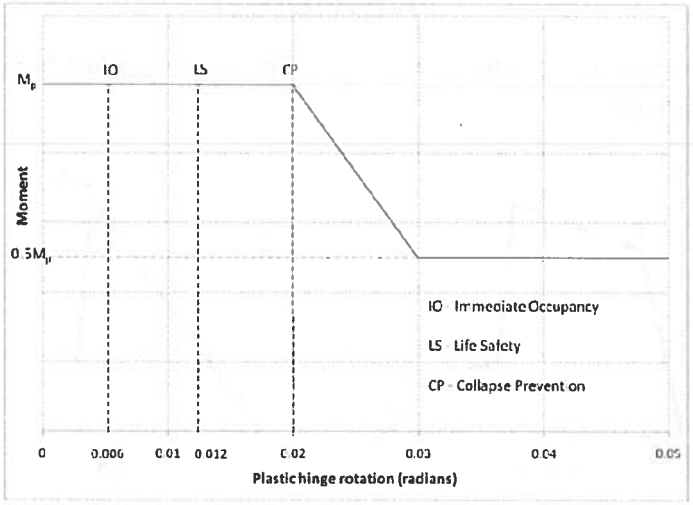
Force controlled behavior



PERFORM-3D Fiber Sections Walls



IO and LS Limits



Mode Shapes

Mode 1: Torsion
(4.63 s)

Mode 2: Translation (x-dir)
(3.77 s)

Mode 3: Translation (y-dir)
(2.63 s)

Case History

- *20 story concrete core shear wall building*
- *Failed to meet current building code in core shear wall*

Structural Problems

- *Moment and shear capacities of link beams were found to be deficient by as much as 50%*
- *In a few localized areas the required strength was more than four times the provided capacity*
- *Compression capacity of shear walls as calculated using ACI 318-08, Equation 14-1 was exceeded in many locations*

PBD Approach
Non-Linear Dynamic Analysis

- Non-linear analysis is required to redistribute the forces away from overstressed areas
- Evaluate Capacity/Demand Ratios

Critical Wind Directions Determined

- Six directions for existing building configuration

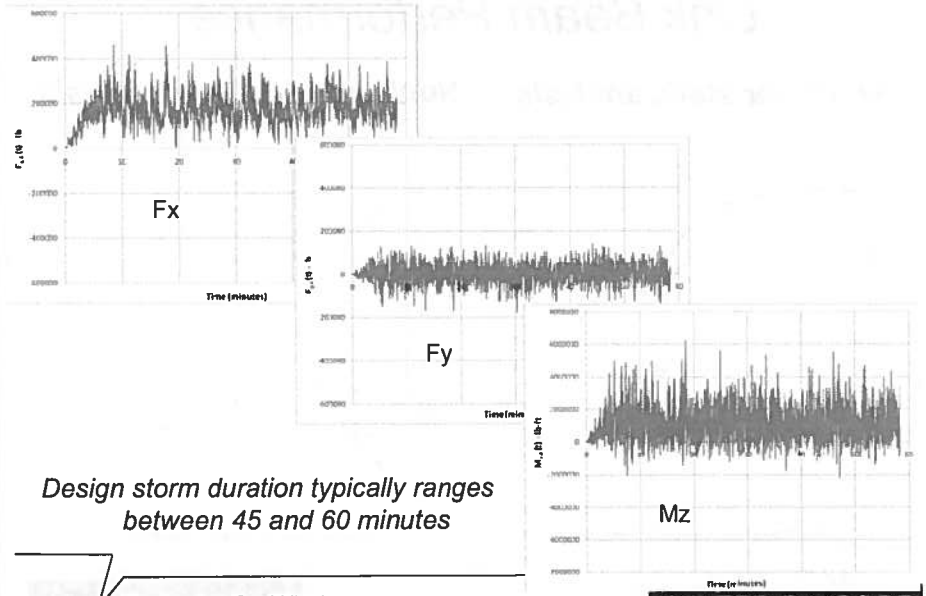
Case	Wind direction (degrees)	Design speed (mph, 3-sec)
1	320	123
2	350	131
3	360	133
4	180	126
5	120	117
6	230	122

NL Dynamic Analysis Procedure

- Seven sets of loads distributed along the height
- Each set has Fx, Fy and Mz
- (6 + 5) x 7 X 3 = Total 231 time histories

Step	Time (sec)	RampF	Fx7	Fx6	Fx5	Fx4	Fx3	Fx2	Fx1
1	0.203567116	0.000678557	56817.325	68418.709	115077.91	173331.44	231622.92	203682.21	74042.261
2	0.407134232	0.001357114	52724.6	67230.222	116380.91	175620.73	239705.67	204473.22	80880.394
3	0.610701347	0.002035571	49515.55	65112.568	118906.76	180064.79	242511.29	223571.45	82136.555
4	0.814268463	0.002714228	51120.124	71130.48	122071.1	190188.22	259701.59	259335.9	79535.427
5	1.017835579	0.003392785	55526.832	71117.924	125191.5	198654.22	258204.04	248055.05	80494.857
6	1.221402695	0.004071342	58358.882	70145.161	126415.48	194343.26	237415.37	244312.38	86490.331
7	1.424969811	0.004749899	60747.995	71147.514	124873.63	185541.59	236706.98	246516.95	90140.736
8	1.628536927	0.005428456	65610.784	74712.465	123041.49	180527.51	236039.59	245571.59	87227.243
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
18425	3750.927676	1	21950.303	26155.624	57205.737	82935.442	79584.457	66911.504	21407.655
18427	3751.131243	1	20955.101	25505.332	58509.06	81352.806	79453.062	71791.519	22429.056
18428	3751.334811	1	18613.564	25470.952	58927.103	81211.045	80180.781	76282.33	23081.491
18429	3751.538378	1	17762.37	26644.577	61070.085	81207.623	81277.03	77695.688	24778.748
18430	3751.741945	1	19573.501	31278.075	63866.606	80821.94	81041.923	78796.016	27664.276
18431	3751.945512	1	22050.872	35794.054	64837.526	83160.381	82329.75	81707.664	31828.93
18432	3752.149079	1	23430.314	35382.808	62308.001	85756.594	83507.319	83650.593	33555.074

231 Time Histories



Design storm duration typically ranges between 45 and 60 minutes

Analysis Method

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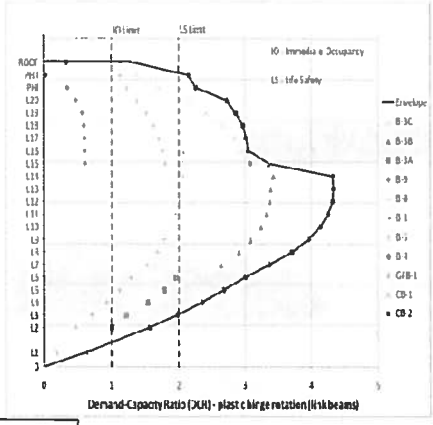
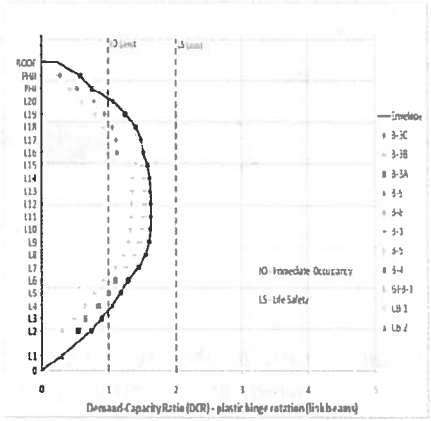
Link Beam Performance

Nonlinear static analysis



Nonlinear dynamic analysis



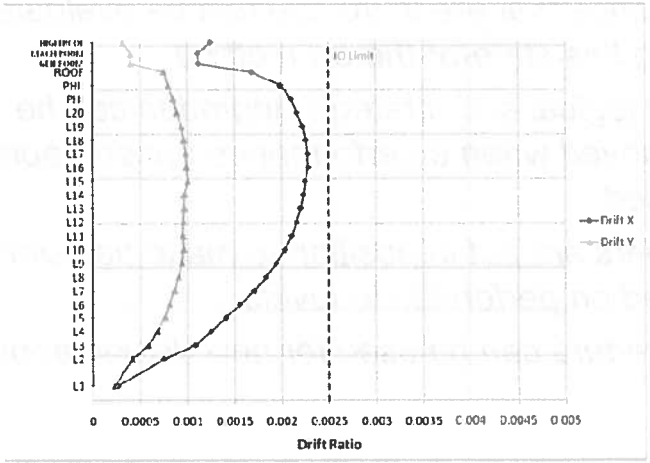
Summary - Link Beam Behavior

- *Dynamic analysis gave significantly favorable results*
- *The existing building beam performance did not violate LS limit*
- *Improvements will be needed to bring the performance to within LS limit for revised building*

Link beam upgrades at various locations will be tricky and will require additional analyses

Serviceability Performance

Nonlinear dynamic analysis under 25 year wind



Observations: PBD Dynamic Analysis

- *The peak responses in X and Y directions are not concurrent*
- *Peak load for a very short duration does not mean that overstress similar to that under the static load is guaranteed*
- *Inelastic response was much smaller in non-linear dynamic analysis than non-linear static analysis*

Observations

- *Buildings that are in trouble can be evaluated using this state-of-the-art method*
- *Very logical and strategic upgrades can be employed when a performance-based approach is used*
- *Owners are put in position to make decisions based on performance levels*
- *Procedure can be used for new design approach*

Conclusions

- *We were able to salvage a building that did not meet code*
- *We were able to understand building behavior when certain elements do not offer the required strength*
- *We were able to relate the inelastic behavior to damage level and ask owner to elect between a relaxed performance level and demolition of the building*
- *We are prepared to offer strengthening solutions that are targeted to improve building behavior*

Conclusions

- *PBD using non-linear dynamic analysis can be implemented with present software*
- *Provides a better understanding of building behavior under wind load*
- *Can result in a more rational and economical building design approach than current design approaches*

Continuing Research Needs

- *Investigate more structural systems/building heights*
- *Experiment with different structural system performance*
- *R Factors for Wind (R_{wind}) – starting point?*
- *More fragility curves for building components*
- *All-steel buildings: Can we design for strength and incorporate artificial damping for drift and perception control using PBD NL Dyn Analysis?*