Advances in Progressive Collapse Analysis of RC Frame Buildings

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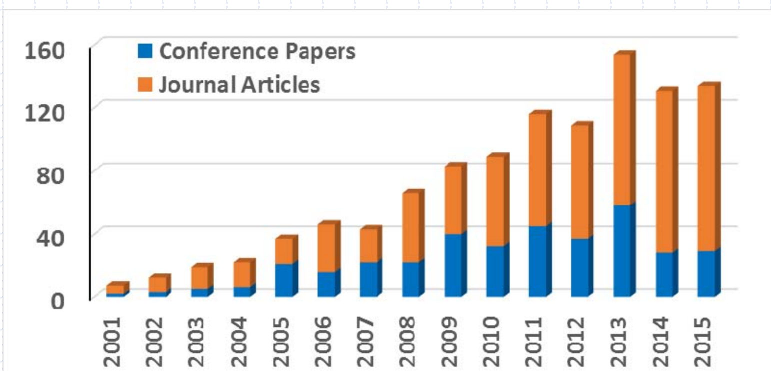
Increase in published papers on Progressive Collapse



Keywords: Structure + progressive collapse / disproportionate collapse

Background and Objectives

- Develop and calibrate **simplified** models to simulate structural behavior under large displacements during progressive collapse
- Validate models using high fidelity analyses as well as available experimental data at component/connection and system level
- Develop measures of "robustness" to assess progressive collapse resistance

Background

- Progressive collapse
  - *A situation where local failure of a primary structural component leads to the collapse of adjoining members which, in turn, leads to additional collapse. (GSA 2003b)*

Ronan Point building after May 16, 1968 collapse

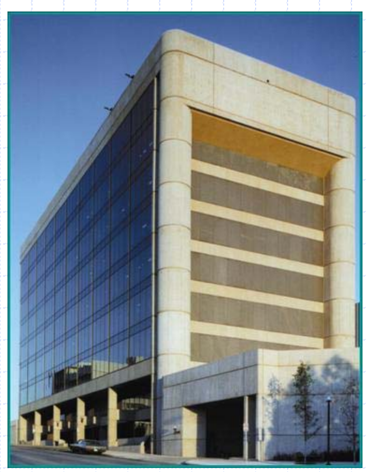
Recent Interest in US on Progressive Collapse

Structural Robustness:
Ability of a structural system to accommodate local damage and arrest the progression of failures

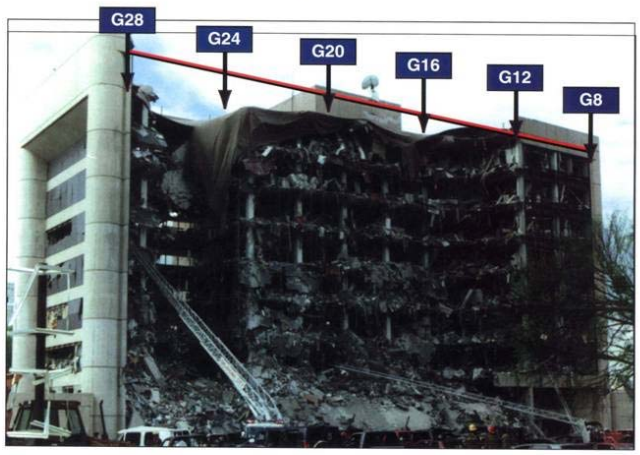
Example: Murrah Building, Oklahoma, USA

Building constructed 1974-1976

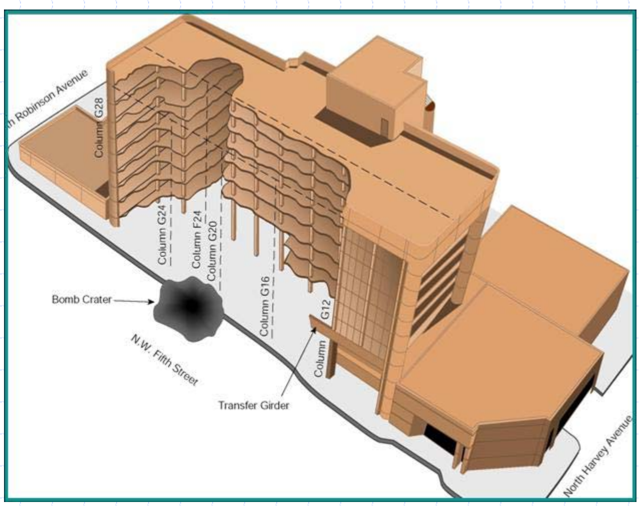
Office building:
9-story R/C frame +
shear wall structure

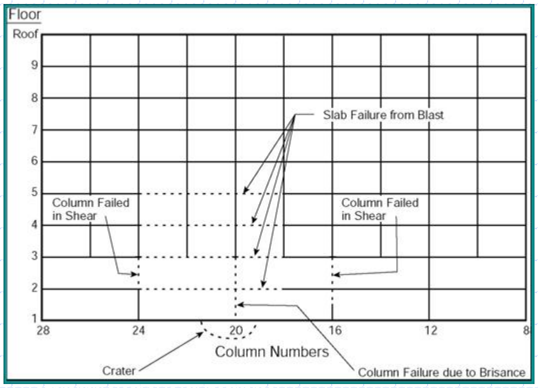


Murrah Federal Building (1995)

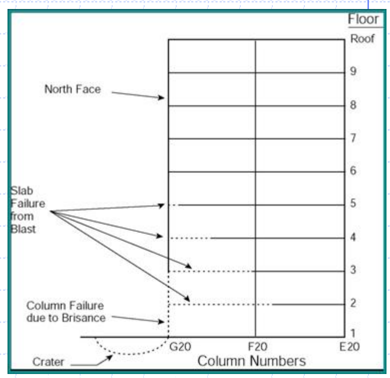


Blast and Progressive Collapse Damage to Original Building





Schematic Diagrams of Blast Damage in Original Building



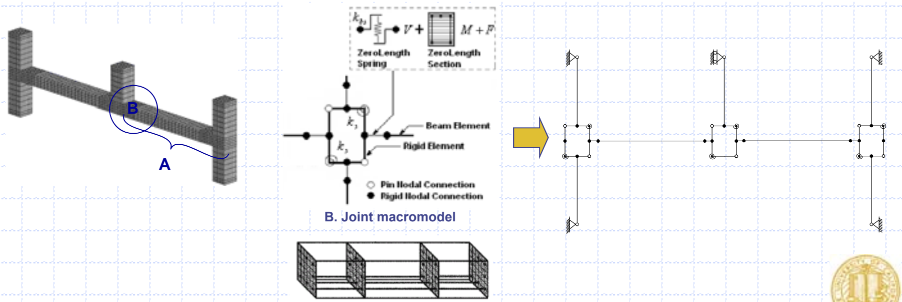
- **Total Building Floor Area: ~ 137,800 SF**
- **4% (~ 5,850 SF) destroyed by blast**
- **42% (~ 58,100 SF) destroyed by blast + progressive collapse (source: NIST)**

Evaluation Methodologies

- Direct analysis
  - Imposed loading is modeled explicitly (earthquake, shock wave etc.)
  - Iterative process involves element removal algorithms and criteria for element removal
- Indirect analysis or threat independent method
  - "Post-event", evaluation on the effects of the damage resulting from loading event
  - Alternate Path Method (APM) by General Services Administration (GSA 2003)
    - Pre-assumed scenarios: removal of critical elements in structure (typically a lower floor column or wall)
    - Structural analysis for a prescribed set of load combinations
    - Evaluation for the potential of progressive collapse

Modeling Approaches

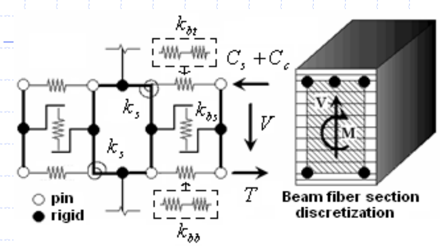
- Microscopic modeling: continuum-based, detailed model
  - Good for analyzing local behavior
  - Intensive computational effort
- Macroscopic modeling: component-based, simplified model
  - Not suitable for analyzing detailed effects but ideal for analyzing complete structural system
  - Computational efficiency



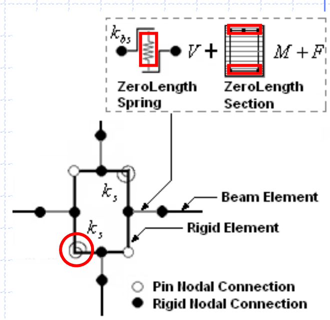
B. Joint macromodel

A. Fiber beam element

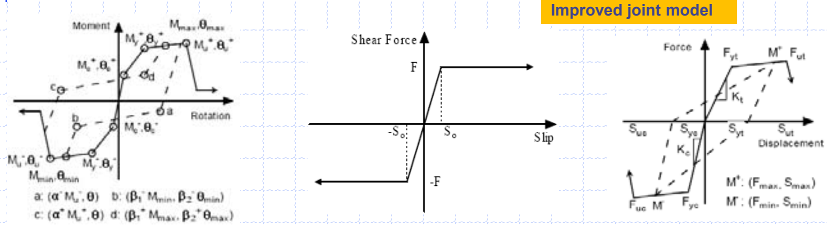
Joint Model



Spring-assembly joint model



Improved joint model



k_s Panel Shear Spring Property

Reference: Vecchio & Collins (1986)

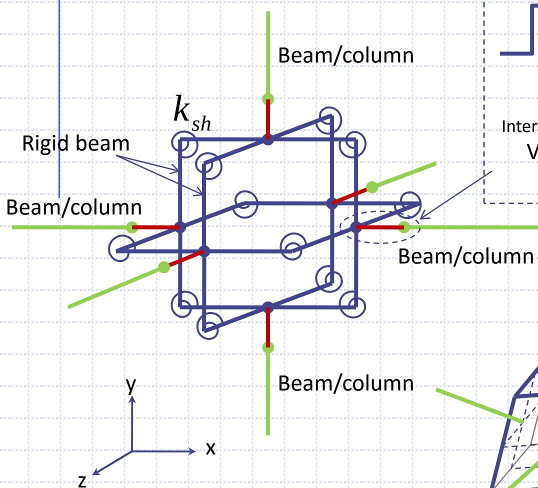
k_{bs} Interface Shear Spring Property

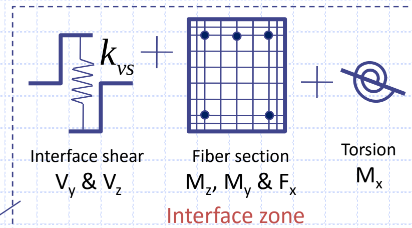
Reference: Walraven (1981)

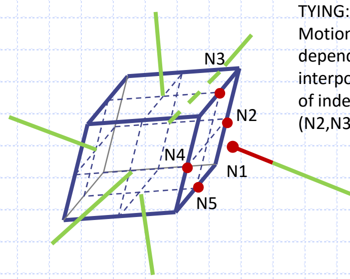
Bond-Slip Property

Reference: Lowes & Altoontash (2003)

Beam-Column Joint Model (3D)



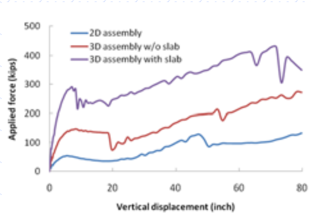


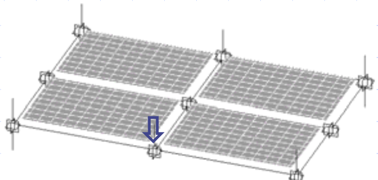


TYING:
Motion of single dependent node (N1) is interpolated from a set of independent nodes (N2,N3,N4,N5)

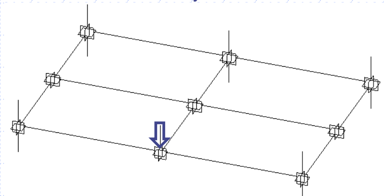
Modeling Approaches

- Other considerations
  - Implicit vs. Explicit
    - ✓ Computational cost
    - ✓ Convergence
  - Planar vs. 3D modeling
    - ✓ Beam-slab composite action
    - ✓ Slab membrane action

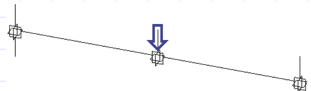




3D assembly w/ slab



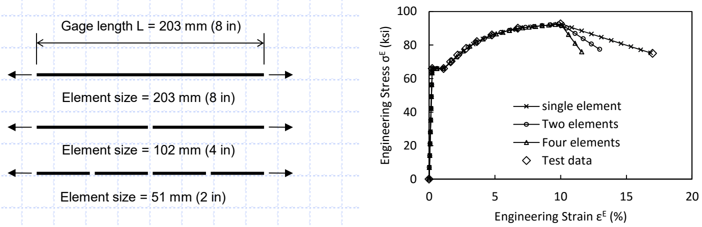
3D assembly w/o slab



2D assembly

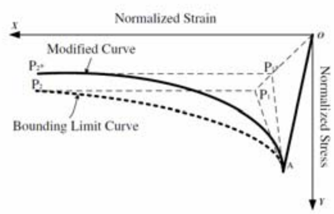
Material Modeling

- Softening behavior and mesh sensitivity



Bao, Lew, Kunnath, *J. Struct. Eng.* 140(1), 2014

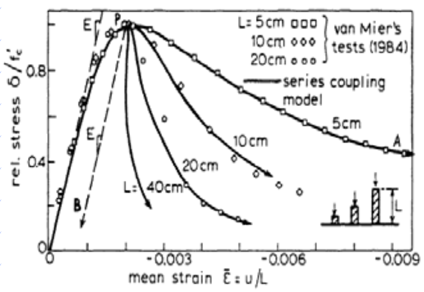
- Reinforcing steel
  - ✓ Buckling effects

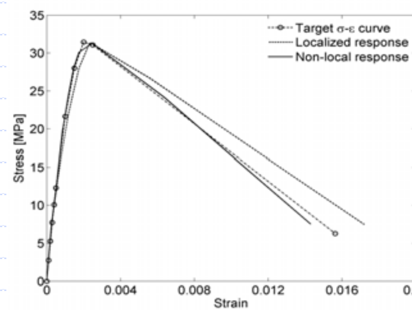


Zong, Kunnath, Monti., *J. Struct. Eng.* 140(1), 2014

Material Modeling

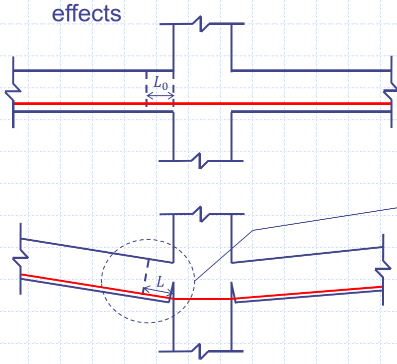
- Post-peak behavior of concrete in compression
  - ✓ Avoiding localization



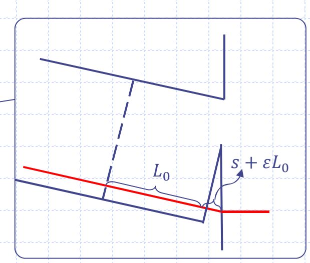


Material Modeling

- Bond effects
  - ✓ Premature bar fracture due to fully-bonded assumption
  - ✓ Anchorage failure modes
  - ✓ Modified strain-stress relation of reinforcing bar to considering bond effects

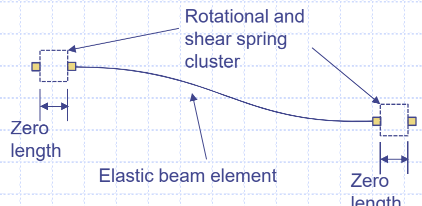


$$\varepsilon' = \frac{L-L_o}{L_o} = \frac{s(\sigma)+\varepsilon L_o}{L_o} = \frac{s(\sigma)}{L_o} + f(\sigma) = f'(\sigma, L_o)$$

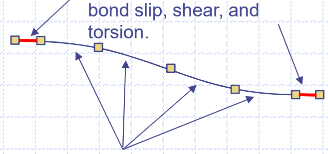


Structural Member Models

- Detailed finite element models or discrete element models
  - ✓ Reinforcing bars are directly modeled and bond effects are considered through interface elements or contact.
  - ✓ Reinforcing bars are indirectly modeled (springs, steel layers, or homogenized reinforced concrete materials) and bond effects are included implicitly or often ignored.
- Macroscopic (or reduced) models
  - ✓ Lumped plasticity models
  - ✓ Distributed plasticity models

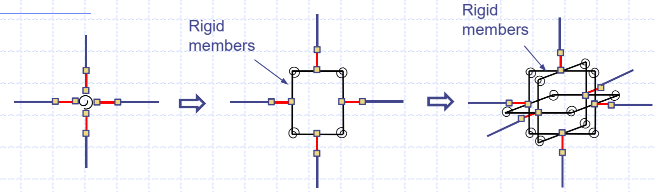


Lumped plasticity

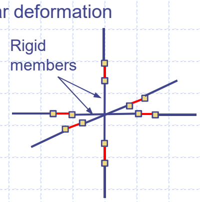


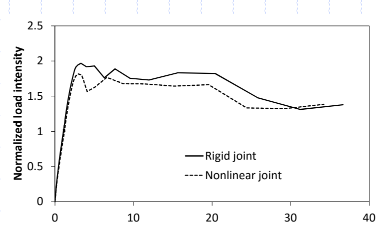
Distributed plasticity

Beam-Column Connection Models

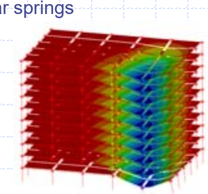


Experimental observation: no significant joint panel shear deformation

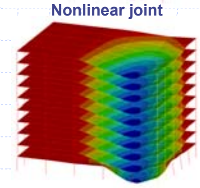




Push-down analyses of the NIST 10-story building SDC-C with different types of joint model

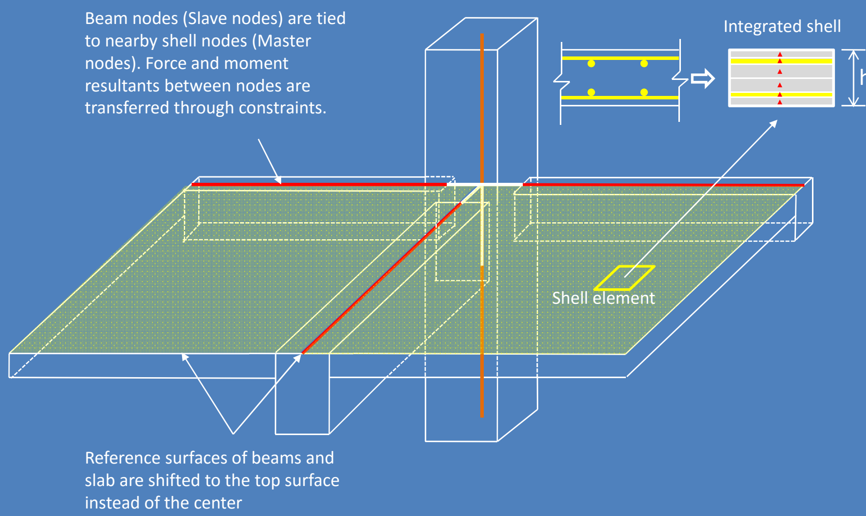


Nonlinear joint

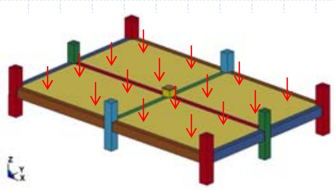


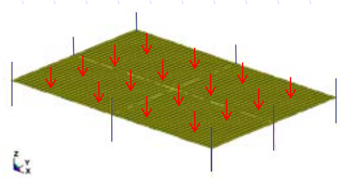
Rigid joint

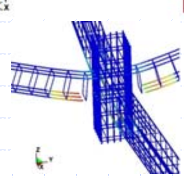
3D Floor System Modeling (LS-DYNA)

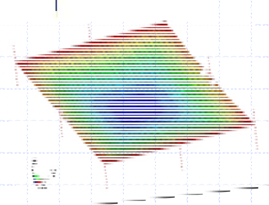


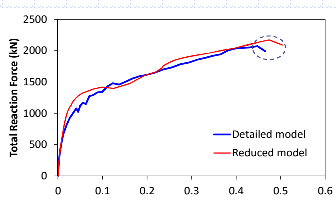
Validation of reduced order model









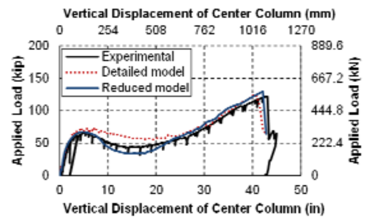


Detailed model
No. of Elements: about 220,000 (192,000 solid, 25000 beam)
Simulation Time: about 17 hours (8 processors, MPP solver)

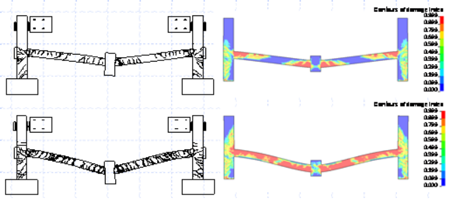
Reduced model
No. of Elements: about 2,000 (1,700 shell, 230 beam)
Simulation Time: about 34 mins (8 processors, MPP solver), 30 times faster than the detailed model

Validation of Computational Models

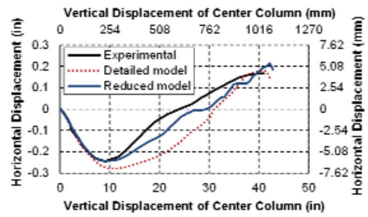
- Detailed and reduced models (**Bao et al.**, *J. Struct. Eng.*, 140, 2014) validated by two full-scale assembly test (**Lew et al.**, *ACI Struct. J.*, 111(4), 2014).



Applied load vs. center vertical

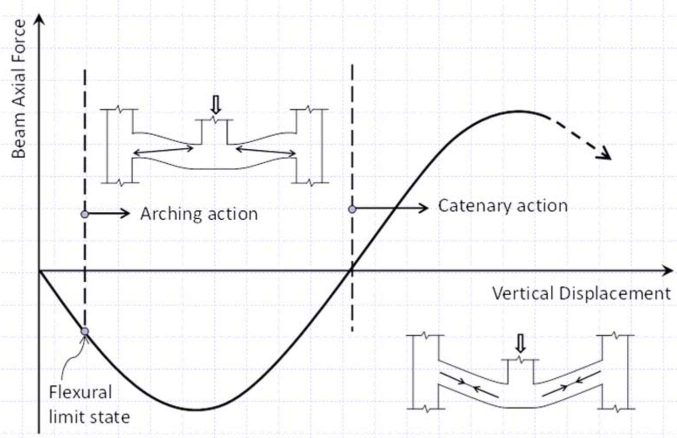


Crack patterns vs. damage contours

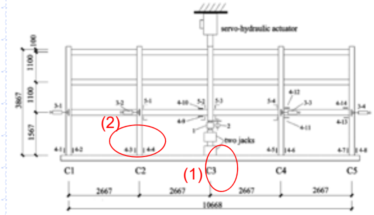


Horizontal displacement vs. center vertical displacement

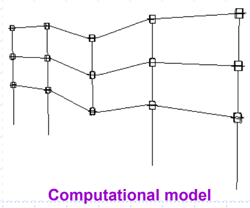
Axial force variation in beams with increasing vertical displacement



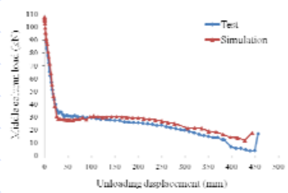
Validation of Computational Models



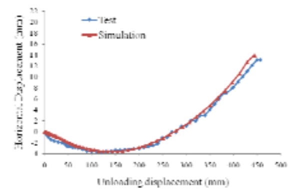
Experiment conducted at Hunan Univ. – Yi, He, Xiao, Kunnath, *ACI Struct. J.*, 2008



Computational model



(1) Column load vs. vertical disp.

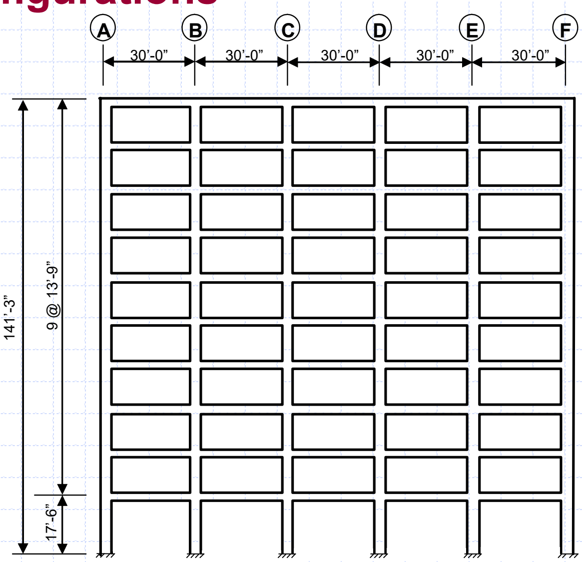


(2) Horizontal disp. vs. vertical disp.

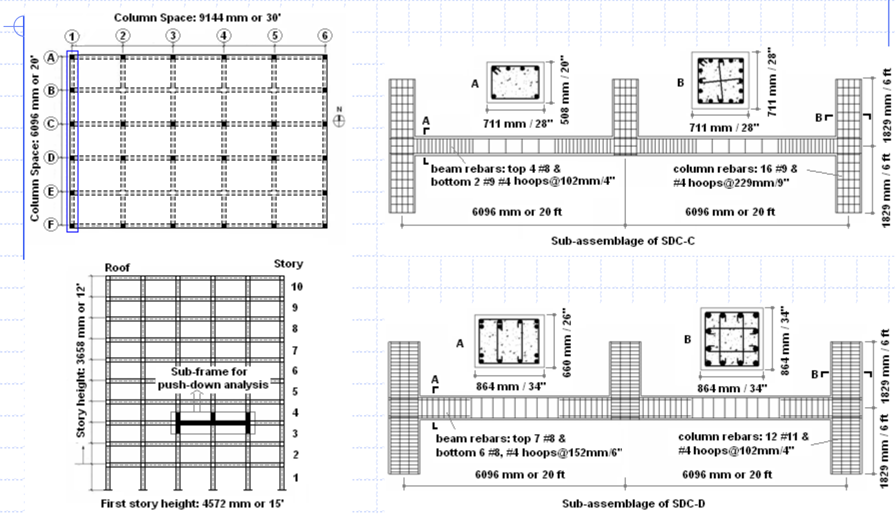
Building Configurations

Design of buildings for Seismic Design Categories:

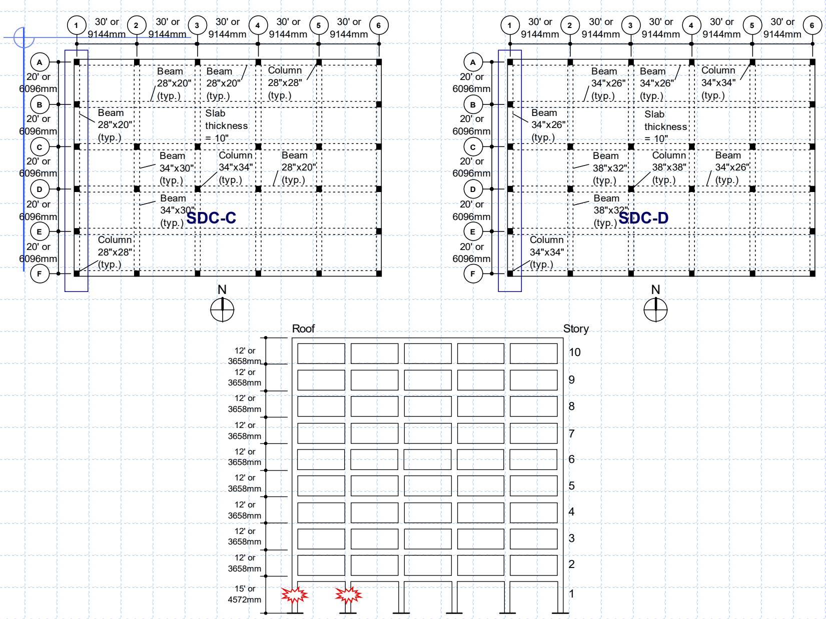
SDC C - Atlanta
SDC D - Seattle



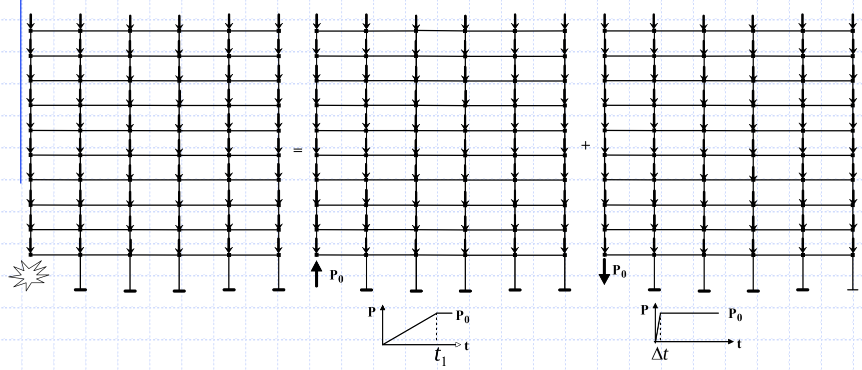
Validation: Example One



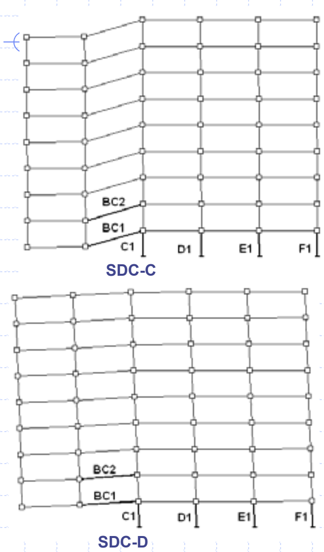
Numerical Simulations: Frame System

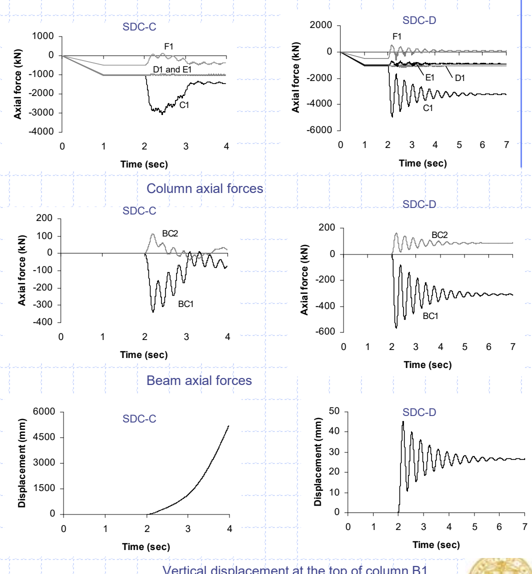


Simulating Column Removal



Comparison: SDC-C vs. SDC-D

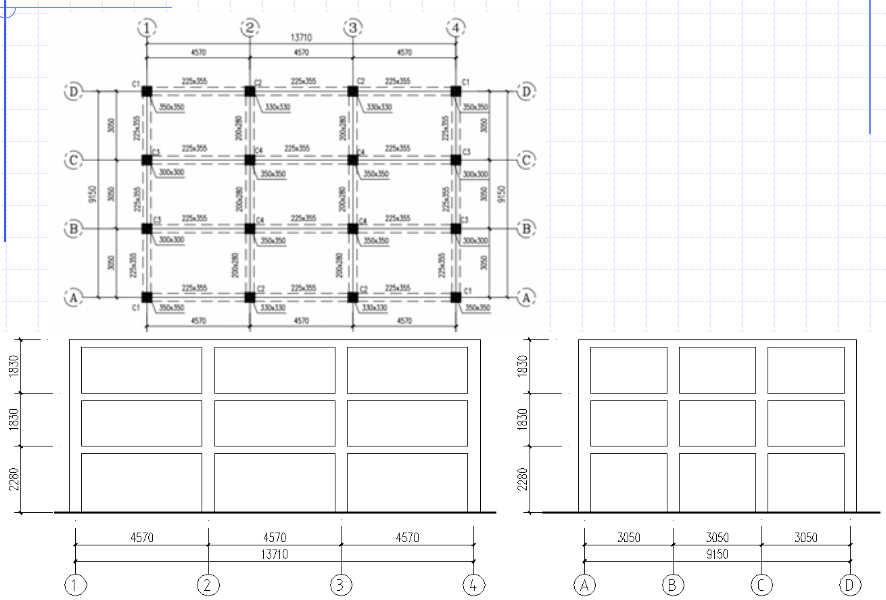




COLLAPSE TESTING

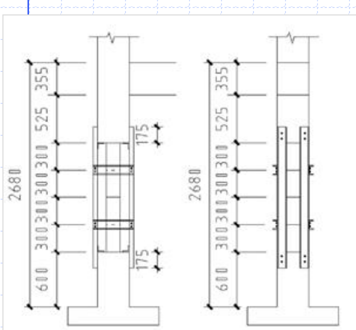
IN COLLABORATI0N WITH
HUNAN UNIVERSITY, CHINA

Half-scale, 3-story model

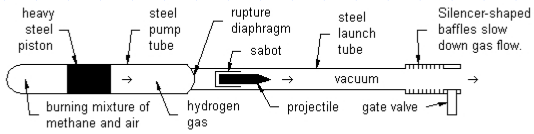


Construction

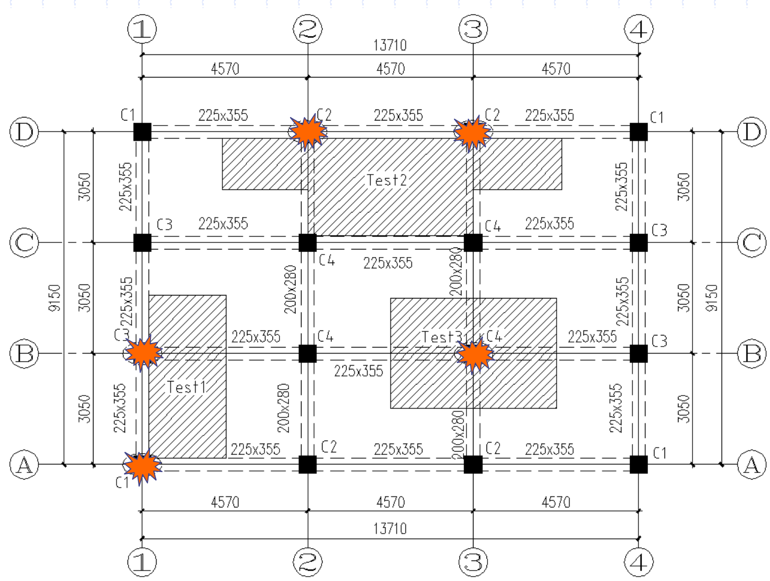
Design of columns to be removed



Gas Gun Trial Test

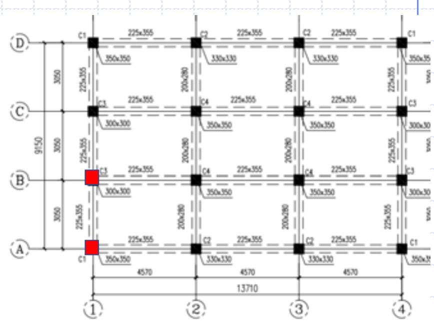


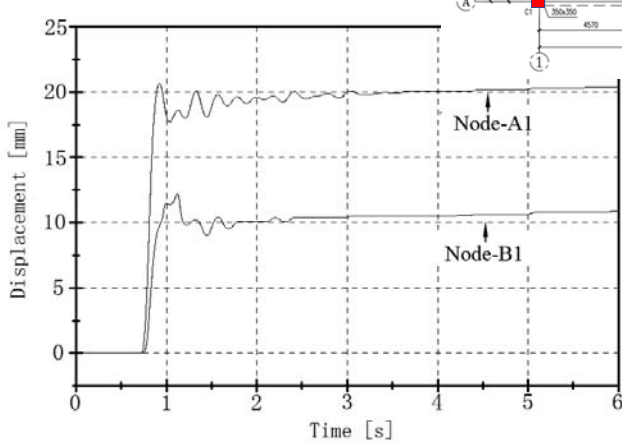
Proposed test protocol



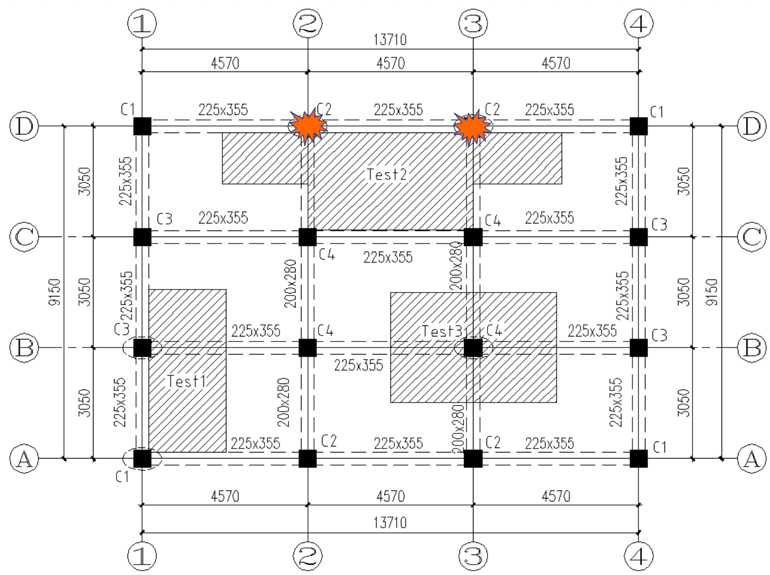
View of
Column removal

Vertical displacement responses

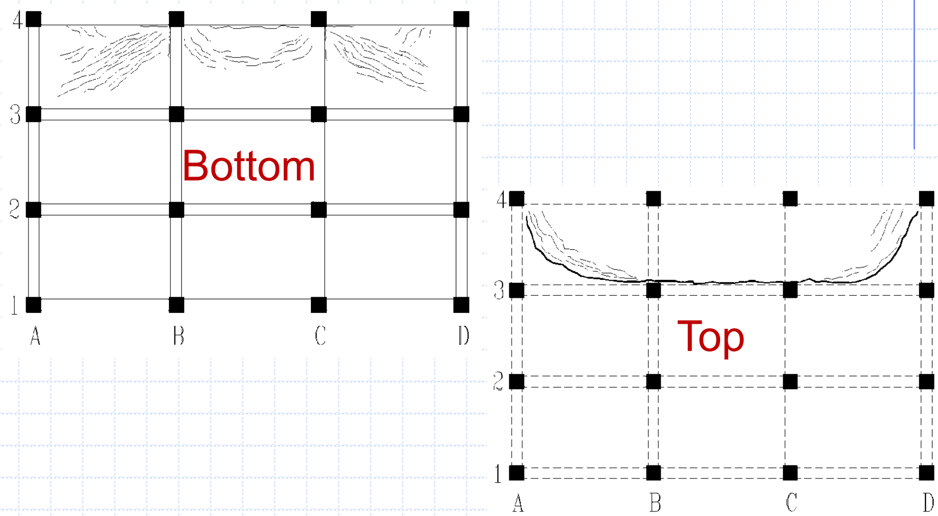




Proposed test protocol

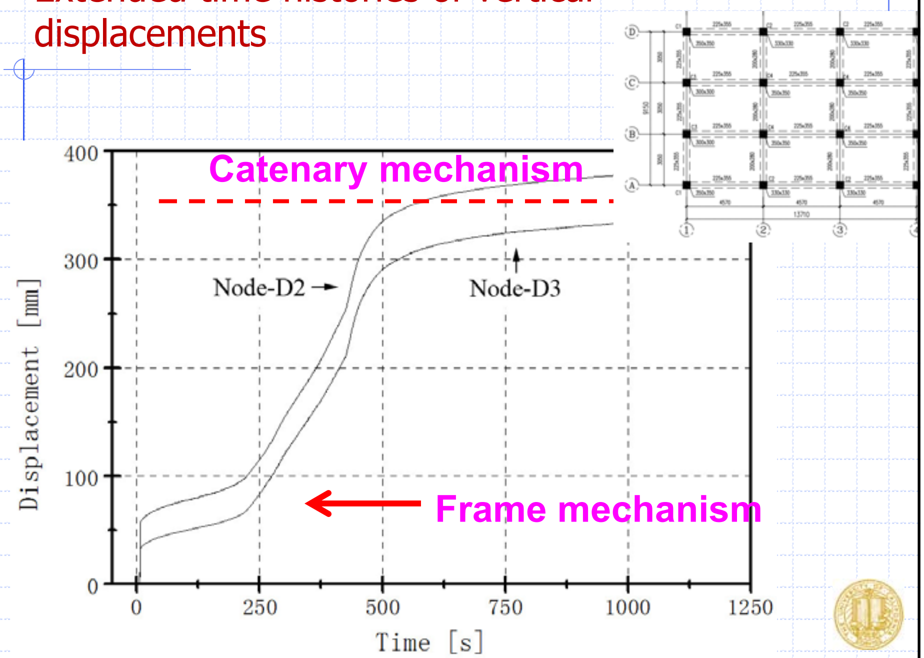


Observed cracking in slab



Observed damage

Extended time histories of vertical displacements



Robustness assessment

Deterministic Approaches:

Remove columns one-by-one and conduct push-down analysis to determine reserve strength

Remove columns one-by-one and assess ability of structure to resist design gravity loads

QUESTION: Order of column removal?

Remove column carrying largest fraction of applied gravity loads

(Fascetti, Kunnath, Nistico, *Eng. Struct*. 2015)

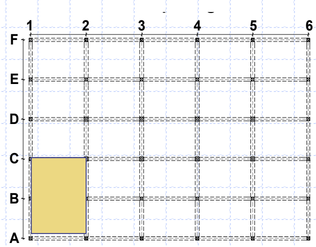
Proposed Energy-Based Approach

- Sequential loss of columns is characterized by a significant variation of internal energy
- Kinetic energy rises quickly when a column is removed and then drops to zero when the structure reaches a steady state.
- Strain energy also increases when a column is removed, because of the expected increase of deformations, and stabilizes around a value that includes both elastic and inelastic deformations.

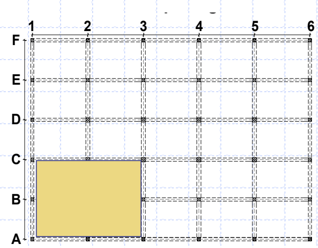
$$D_i = \alpha_\Delta \frac{KE_{local}}{KE_{global}}$$

α_Δ is the maximum deformation at any node in the "local area" normalized with respect to the story height

Local Area & Identifying next critical column



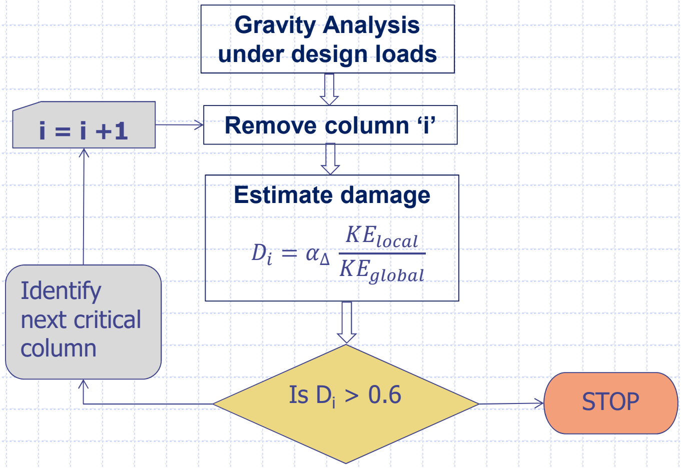
After removal of column B1



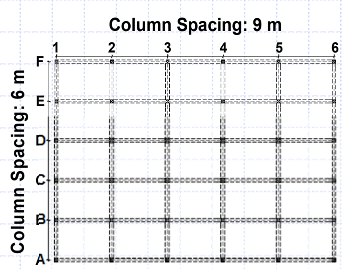
After removal of column B1 & B2

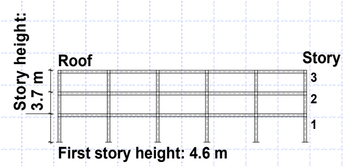
Strain energy density of the "affected zone" provides the best indicator of the next critical column. The "affected zone" of a column refers to the horizontal elements – beams and slabs – that directly connect to it.

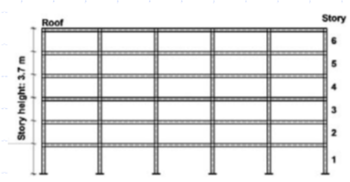
Procedure



Case study

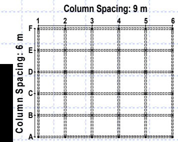




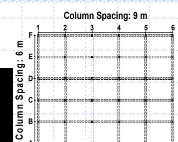


Beam Design			
Dimensions b x h [mm]		450 x 350	
		mid-span	support
Longitudinal reinforcement		3#4 top	4#7 top
		4#4 bot.	3#7 bot.
Shear reinforcement		#3@150mm	#3@120mm
Column Design			
Dimensions b x h [mm]		450x450	
Longitudinal reinforcement		16#7	
Shear reinforcement		#3@130mm	

Case 1: Sequence C3-C4-C5-C6



Case 2: Sequence A1-B1-A2

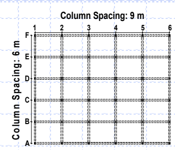


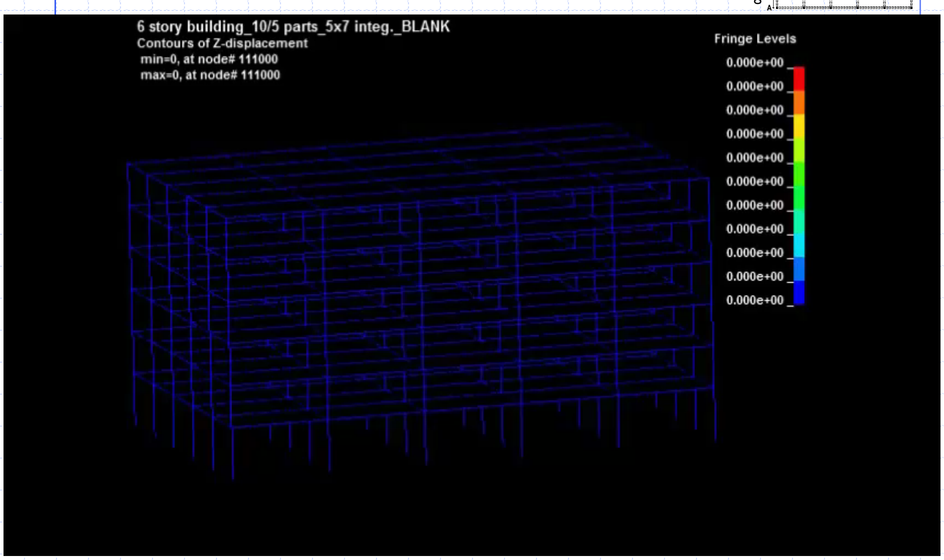
Displacement Ratio* & (Damage Index) after each column removal

	Case 1: C3-C4-C5-C6	Case 2: A1-B1-A2
1st column removal	1.58% **(0.01)**	2.47% **(0.04)**
2nd column removal	3.03% **(0.03)**	32.28% **(0.32)**
3rd column removal	4.39% **(0.05)**	➤ **100%** **(0.66)**
4th column removal	6.12% **(0.11)**	

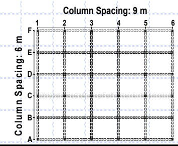
* Ratio of peak displacement to story height

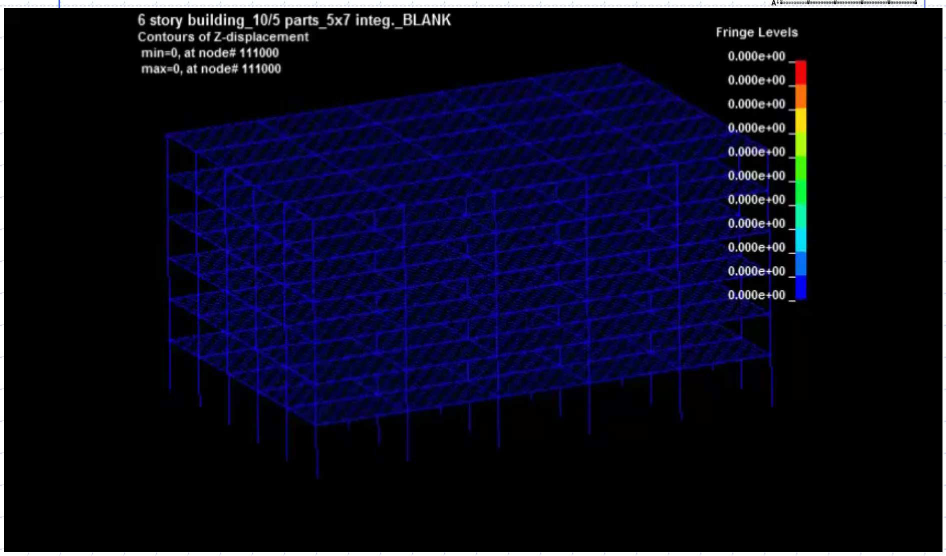
SEQUENCE: C3-B3-A3-D3





SEQUENCE: A1-B1-A2





Conclusions

- Validated material and component models are essential to accurately characterize the large deformation response during progressive collapse.
- Load transfer within critical beams is a three-phase process: arch action, plastic hinging and catenary response
- 3D and slab effects need to be incorporated
- Alternative Path Method (APM) is effective in assessing vulnerability of structures to loss of critical load-bearing members. It does not, however, provide information about the reserve capacity of a system
- Proposed Energy-Based Index is an adequate approach to assess proximity to collapse