An example of finite element modelling of progressive collapse

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Outline of the presentation

- Requirements of progressive collapse analysis
- Recent studies on modeling progressive collapse
- Objectives of present study
- Description of selected building
- FE model development
- Numerical results
- Plan for verification & validation
- Final remarks

Requirements of progressive collapse analysis:

- loading configurations including abnormal loads
- measures of progressive collapse quantitatively defining the collapse phenomenon
- adequate analysis methods

General Services Administration (GSA) (2000)

US Department of Defense (DoD) (2002)

- loading configurations:

  $DL+\eta LL$ & Column Removal

- measures of progressive collapse:
  - structural bays directly associated with the instantaneously removed vertical member and located directly above the removed member,
  - 167 m^2 (1,800 ft^2) at the floor level directly above the instantaneously removed vertical member.

- adequate analysis methods:
  - flow-chart procedure,
  - linear or nonlinear,
  - static or dynamic (time history),
  - 2D or 3D

Recent studies on modeling progressive collapse :

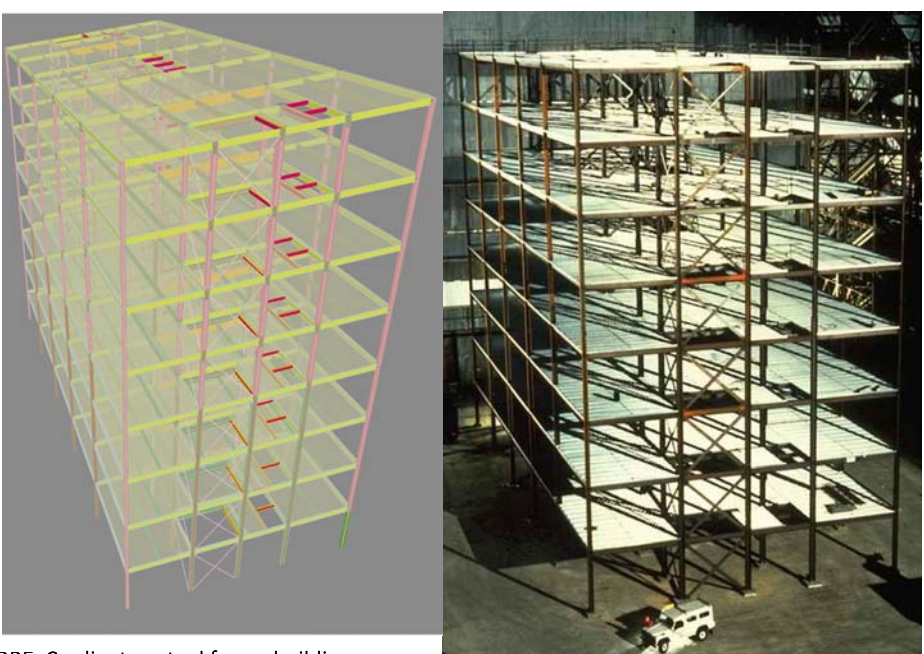
- need for global modeling – large scale structures, portions or entire buildings
- metal (steel) structures are more often considered
- threat independent approach - notional column removal
- multilevel strategy - subsystem or component level before global analysis
- commercial nonlinear FE programs are usually used
- beam element models and 2D subsystems dominate
- limitations of computational time and recourses excuse model simplifications

Objectives of present study:

- feasibility study through a case study - progressive collapse analysis for a selected multistory building
- identify modeling parameters affecting the final result
- propose verification and validation program for reducing outcome uncertainties

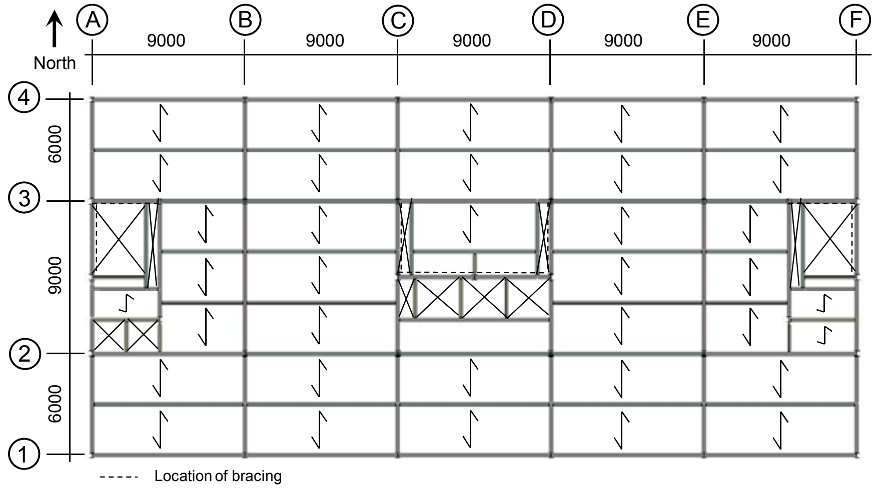
Selected building:

- existing 8-story (33 m) building
- built for fire tests
- located at the Cardington Large Building Test Facility in the UK
- well documented
- representative example of a modern multistory office building
- steel framed structure with composite - light concrete slab cast onto profiled steel decking and supported on a network of secondary and primary steel beams



BRE. Cardington steel frame building.

http://www.mace.manchester.ac.uk/project/research/structures/strucfire/DataBase/TestData/default1.htm



General floor layout of the Cardington steel frame building, [34], [42].

FE model development

General assumptions:

- detailed model (max. 1,823,696 elements)
- nonlinear dynamic simulations
- use of commercial program LS-DYNA with explicit time integration
- advantage of parallel processing on multiprocessor computers

FE model development

Challenges:

- column removal
- material models – concrete, damage and failure, element erosion
- joints – local effects, mesh resolution, contact, bolts
- slabs – solid vs. shell elements, multilayered composite, reference surface

FE model development

Geometry, mass and stiffness distribution:

- only the steel framework and concrete slabs have been modeled
- walls built of hollow blocks in the stage 4 of the construction are neglected
- columns, spine members, ribs, trimmers - 3D shell element models
- composite concrete steel slabs - multilayer shell elements with user defined through thickness integration
- bracing - truss elements

FE model development

Vertical loading:

- The vertical loads recommended by General Services Administration GSA [8] for dynamic analysis

Load = DL + 0.25LL

DL=3.65 kN/m^2 LL=3.5 kN/m^2 0.25LL=0.88 kN/m^2

- Constant gravity loading applied to the steel frame

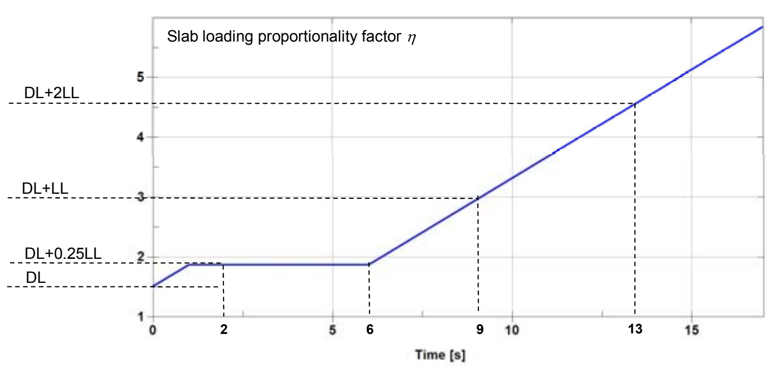
FE model development

Vertical loading:

- Scaled gravity loading, time dependent, applied to the slabs

DL → η=1.51

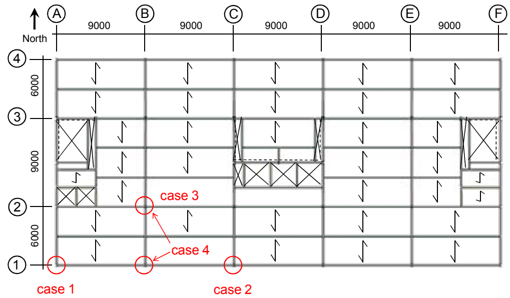
0.25LL → η=0.36



FE model development

Notional column removal :

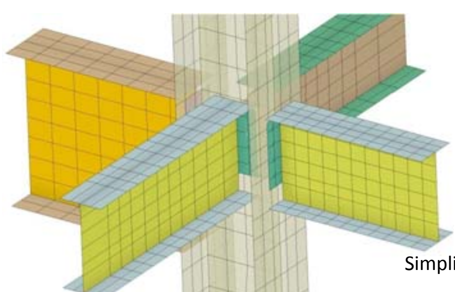
- Four cases considered:
    1. corner of the building
    2. middle of the long side
    3. one internal column
    4. two columns



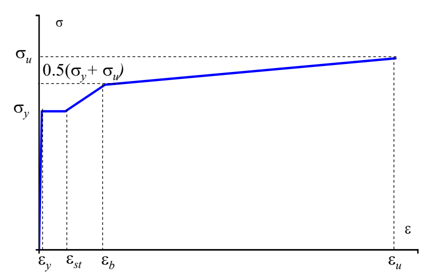
- *LOAD_REMOVE_PART - shock effects are prevented by gradually reducing the stresses prior to deletion

FE model development

Joints:



Automatic single surface self contact - most of the parts

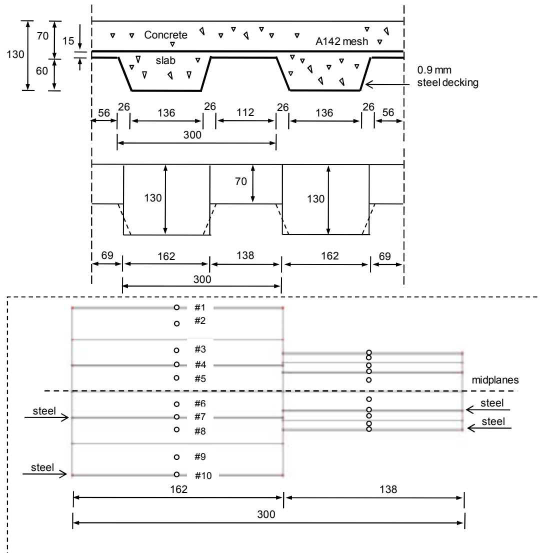


Simplified stress-strain curve proposed by Galambos (2000).

Property	Ratios	Magnitudes [46]	Magnitudes applied in the FE model	
		ASTM A36 [46]	S275	S355
Yield stress	σ_y [MPa]	331	303	469
Yield to ultimate stress ratio	σ_y/σ_u	0.71	0.65	0.73
Yield strain	$\varepsilon_y=\sigma_y/E$	0.00158	0.00144	0.00189
End of yield	$\varepsilon_{st}/\varepsilon_y$	10	6 [47]	6 [47]
Hardening strain	$\varepsilon_b/\varepsilon_y$	25	28 (ε_b=4% [47])	17 (ε_b=4% [47])
Strain hardening modulus	E_{SH} [MPa]	16819 (Figure 2)	2700 [47]	2700 [47]
Failure (total) strain	$\varepsilon_u/\varepsilon_y$	136	126	82

FE model development

Composite concrete-steel slabs:



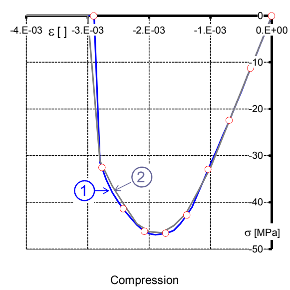
FE model development

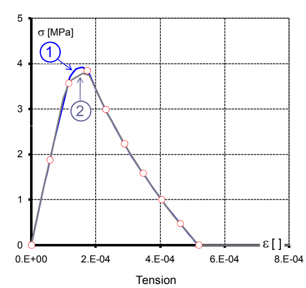
Material models for concrete

1 - model type 72, so called Karagozian & Case (K&C) Concrete Model [15] (solid elements only - automatic input data generation

2 - model type 124 MAT_PLASTICITY_COMPRESSION_TENSION (shell elements)

*MAT_ADD_EROSION - combination of diffrent failure/erosion criterion



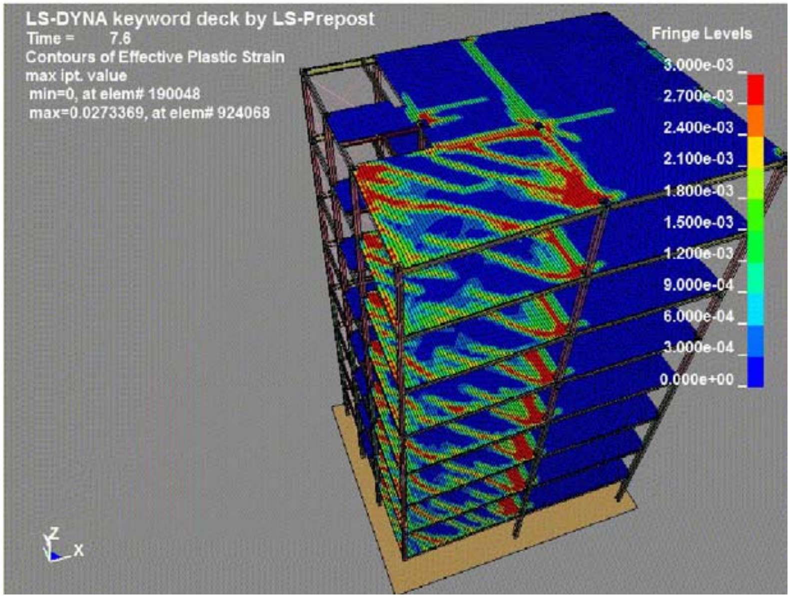


Property	Symbols Units	Magnitudes applied in the FE model concrete
Density	ρ t/m^3	2.00 [42]
Modulus of elasticity	E [GPa]	32.5 [42]
Poisson ratio	ν	0.2 [42]
Compressive strength (yield stress)	f'_c (σ_y) [MPa]	47 [52]
Tensile strength (yield stress)	f_t (σ_y) [MPa]	3.92*
Maximum (failure) plastic strain in tension and compression	$\varepsilon_t = \varepsilon_c$	0.003

* generated using K&C material model type 72

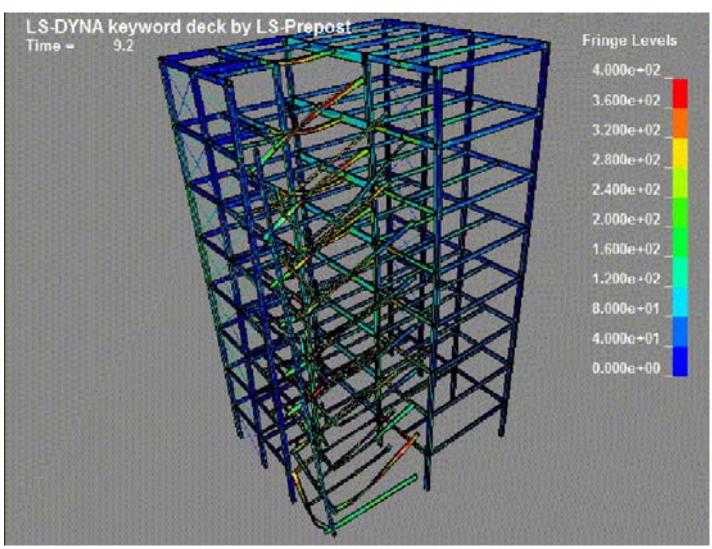
Numerical results

Case #1 Corner column removal

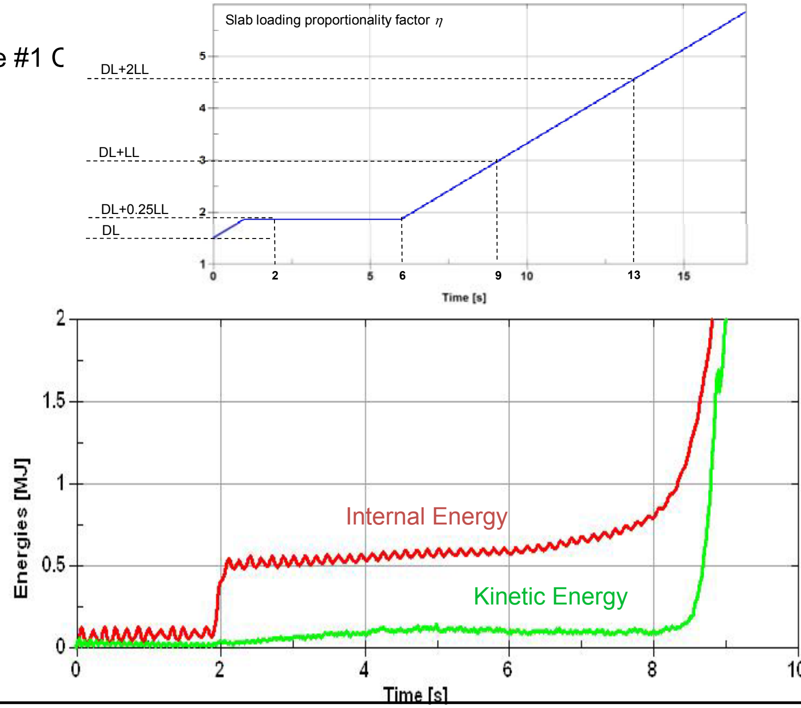


Numerical results

Case #1 Corner column removal

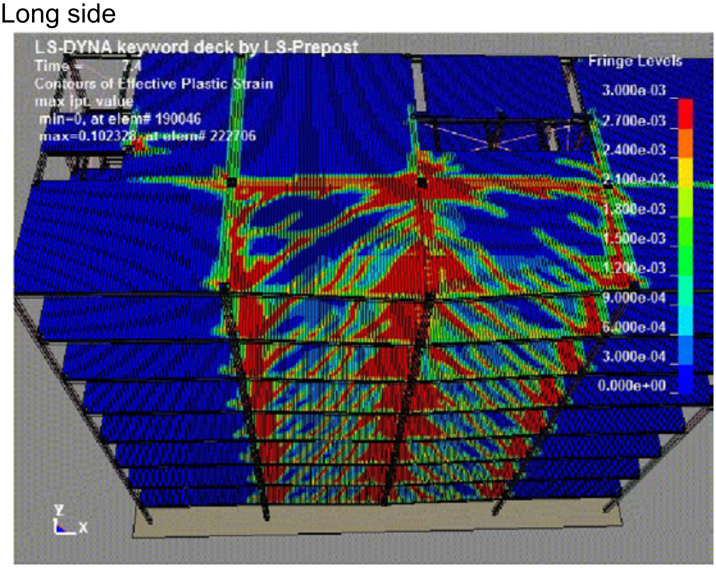


Case #1 C



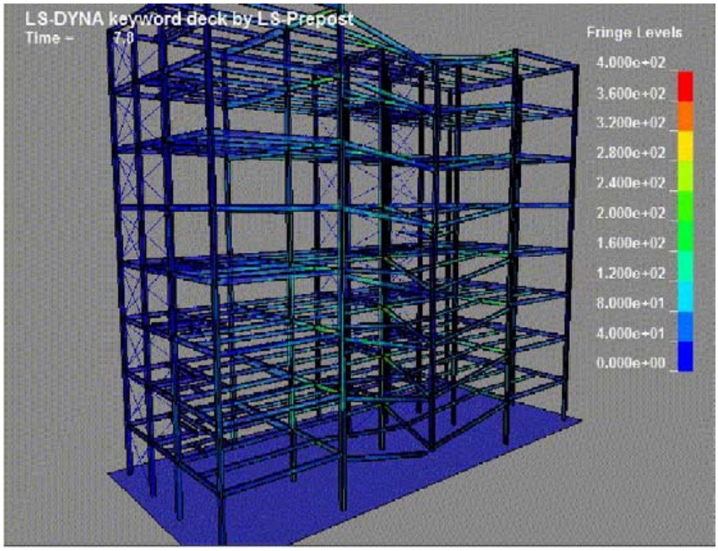
Numerical results

Case #2 Long side



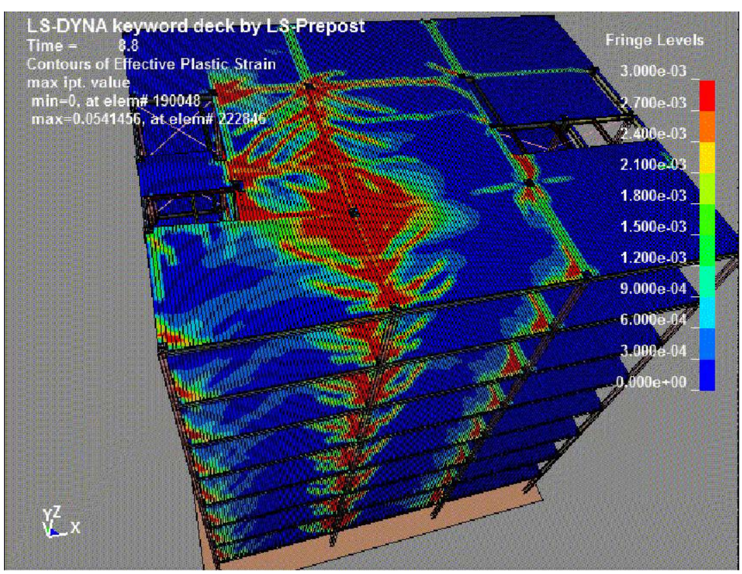
Numerical results

Case #2 Long side



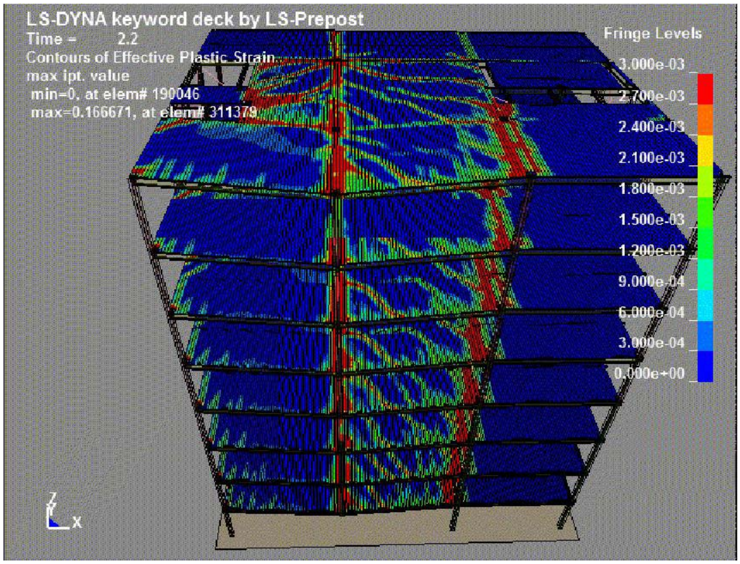
Numerical results

Case #3 One internal column



Numerical results

Case #3 Two columns



Verification & Validation

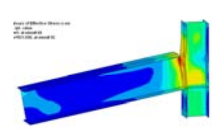
Hierarchical verification and validation

Testing verification & validation

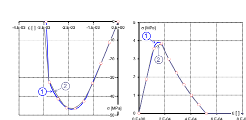
→ Entire structure (vibration tests)

→ Subsystem tests (composite floor)

→ Component tests (slab strip, joints)



→ Material characterization, single element tests



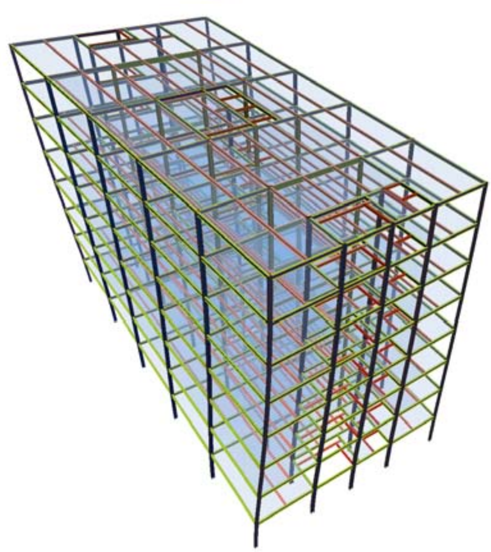
Verification & Validation

Comparison of weights and natural frequencies

Construction stage	1. Steel frame		3. Frame plus composite floors	
	[40]	FE	[40]	FE
1st frequency mode	0.98* EW1	0.998 EW1	0.69 EW1	0.694 EW1
2nd frequency mode	1.22* NS1	1.263 EW2	0.83 NS1	1.271 NS1
3rd frequency mode	1.71* θ1	1.550 NS1	0.89 θ1	1.357 θ1
4th frequency mode	3.30* EW2	1.551 θ1	2.10 EW2	2.500 EW2
Weight [t]	325	384	2302	1824
Number of elements	NA	723,816	NA	1,823,696
EW East-West direction NS North-West direction		θ Rotation 2 second ordered mode		* experimentally tested framework with four lower steel decks

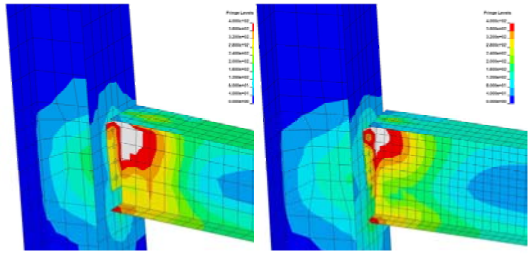
Verification & Validation

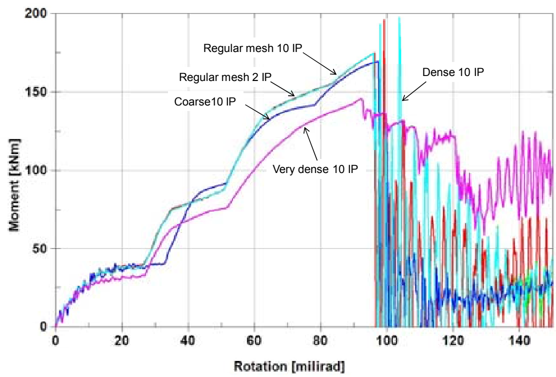
Comparison of weights and natural frequencies



Verification & Validation

Joints:





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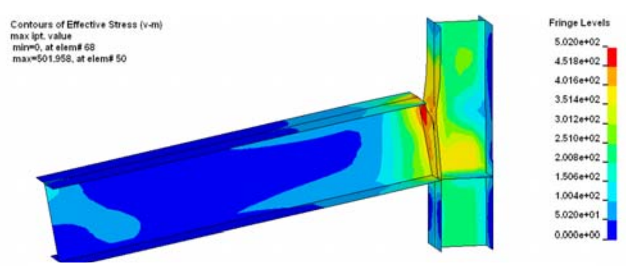
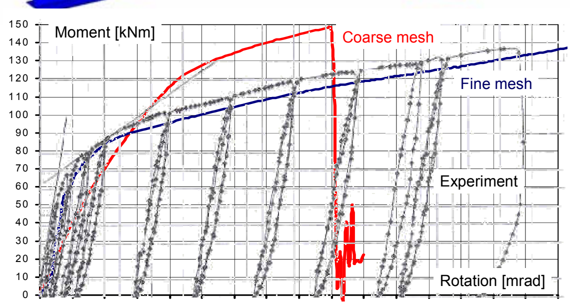
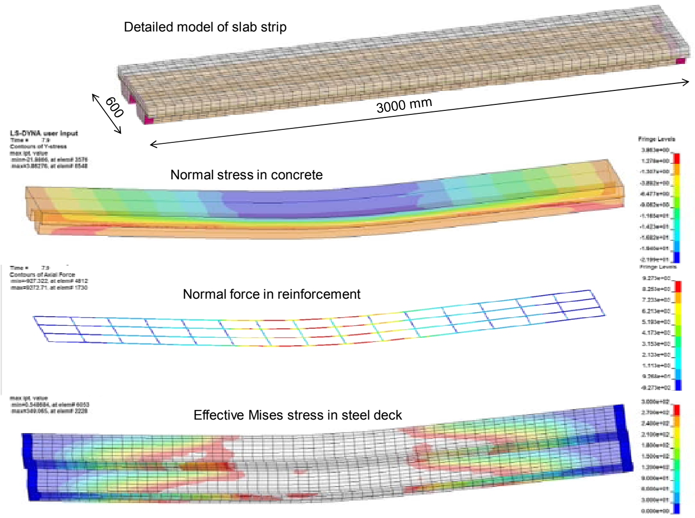




Comparison of experimental and numerical moment-rotation curves. Numerical results for coarse and fine meshes. Flush end-plate connection (Soderberg et al. 2005).

Verification & Validation

Composite concrete-steel slabs:



Verification & Validation

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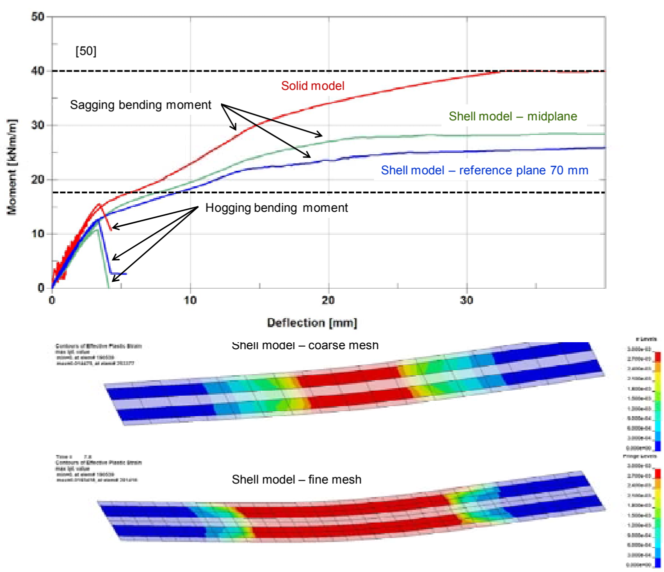

Final remarks

- Composite concrete-steel slabs – shell multilayer model, reference plane, catenary and arching action
- Need for designed validation tests especially on subsystem level
- Deterministic approach, bracket cases, resistance margins
- Beam vs. Shell element models (which one is complex?)
- Computational time, cost, limitations

  Faculty of Civil Engineering WUT – computational cluster

  Florida State University High-Performance Computing