Progressive Collapse Analysis: Reinforced Concrete Assemblies

White Paper

Progressive Collapse Analysis: Reinforced Concrete Assemblies

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Executive Summary:

The main purpose of this report is to demonstrate the capabilities of ASI's Extreme Loading® for Structures (ELS) software to accurately capture the non-linear behavior of reinforced concrete structures during progressive collapse.

The example chosen is of a National Institute of Standards and Technology (NIST) experiment published as NIST Technical Note 1720: An Experimental and Computational Study of Reinforced Concrete Assemblies under a Column Removal Scenario. The Technical Note focused on two experiments:

1. Intermediate Moment Frame (IMF) designed for Seismic Design Category C.
2. Special Moment Frame (SMF) designed for Seismic Design Category D.

This white paper studies the capability of modeling one of these experiments in ELS. In addition, it shows how the ELS can accurately capture the non-linear behavior of reinforced concrete beams under such loading cases. Moreover, it shows and compares the results of different methods of modeling reinforcement bars within ELS.

Keywords: Buildings; computational model; computer simulation; Extreme Loading for Structures; ELS; design standards; disproportionate collapse; progressive collapse; finite element analysis; FEM; applied element analysis; AEM; reinforced concrete structures; structural robustness; testing.

1. Experimental Data:

1.1. Geometry and Reinforcement Details:

Figure (1) shows concrete dimensions and reinforcement details of a beam and column joint connection typical to an intermediate moment frame (IMF) tested by NIST [Ref. 1].

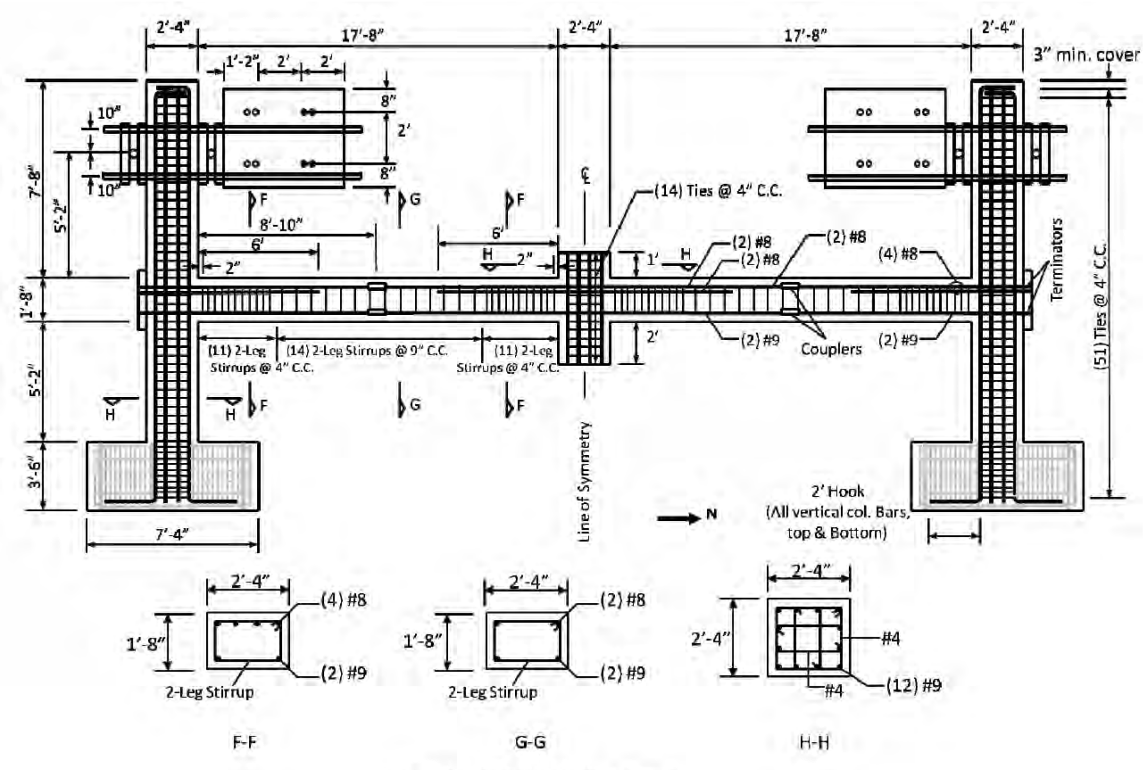

Fig. 1: Typical Intermediate Moment Frame (IMF) Connection [Ref. 1]

1.2. Loading Setup:

Figure (2) shows the loading setup of the IMF connection. The load was applied under displacement control. The top of the two end columns were restrained from horizontal movement by a two-roller fixture. The out of plane movement was restrained by four steel channels fixed to the reaction wall.

Fig. 2: Loading Setup [Ref. 1]

2. Analysis Model for Progressive Collapse:

Two models where created to validate the progressive collapse analysis capabilities inside ELS. The first model (Case 1) is modeling of the connection with three dimensional applied elements representing the steel bars and a bond interface material is used to model the interface between concrete and reinforcement. The second model (Case 2) is modeling the same connection where the concrete is modeled using 3D solid elements while the reinforcement is modeled using one dimensional shear and normal springs and assuming full bond between the reinforcement and the concrete.

2.1. ELS Models:

2.1.1. Case (1) Reinforcement Bars Modeled as Elements:

Figure (3) shows the ELS model for the structure where the structure is modeled using solid 3D elements. All the reinforcement details have been taken into consideration. In this model, the reinforcement in the girder was modeled as element while the reinforcement in the columns was modeled as springs. Figure (4) shows the reinforcement details in the ELS. The number of elements used in the model was 15100 elements.

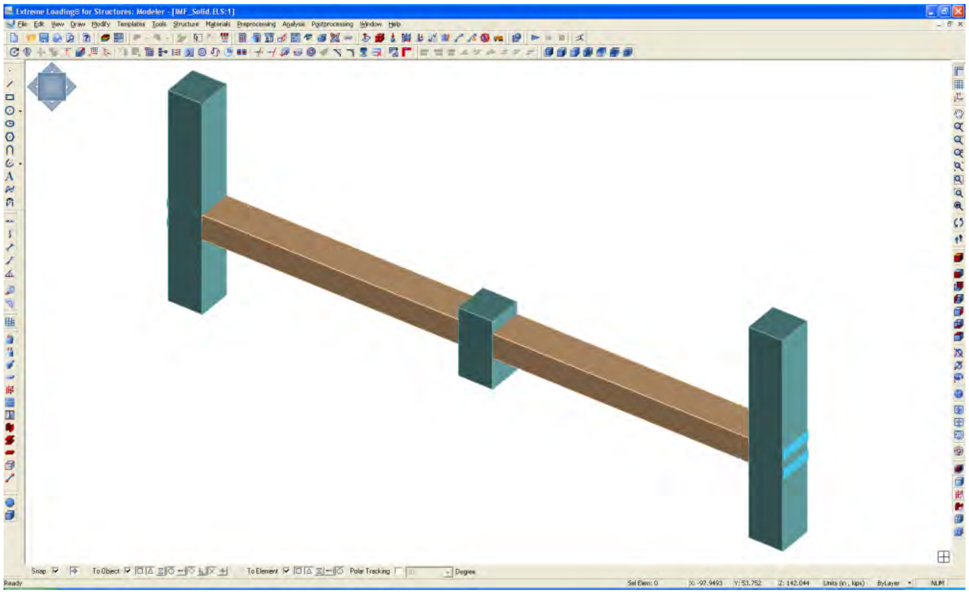

Fig. 3: ELS Model (Case 1)

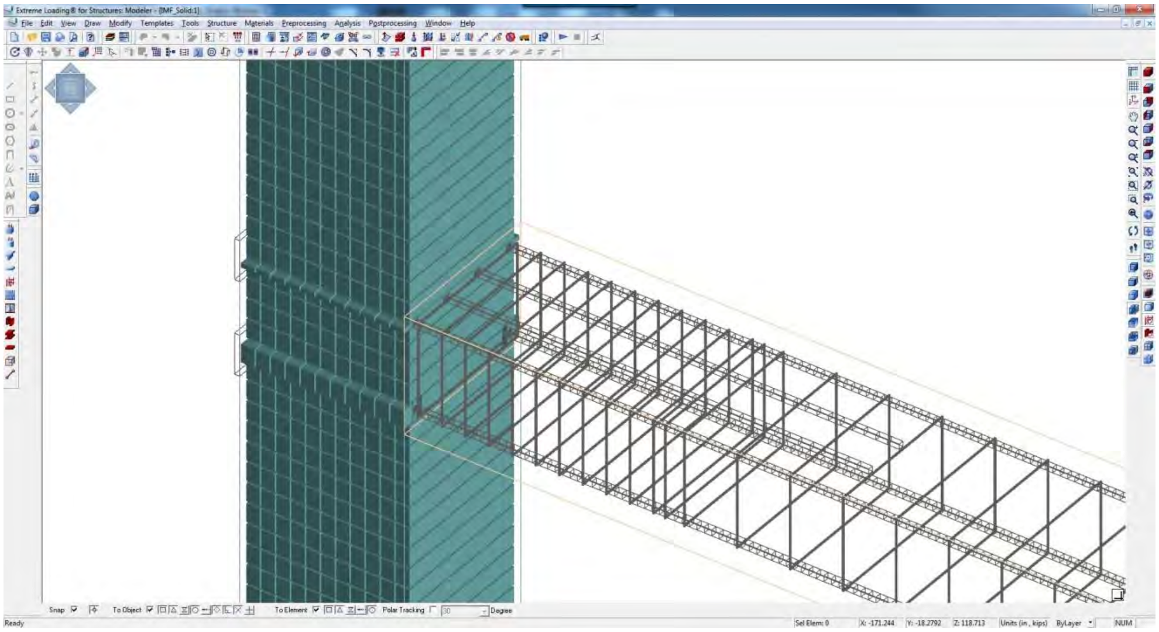

Fig. 4: ELS Model Reinforcement Details (Case 1)

2.1.2. Case (2) Reinforcement Bars Modeled as Springs:

Figure (5) shows the ELS model for the structure where the structure is modeled using solid 3D elements. All the reinforcement details have been taken into consideration. In this model, the reinforcement in the model was modeled as 1D spring. Figure (6) shows the reinforcement details in the ELS. The number of elements used in the model was 15100 elements.

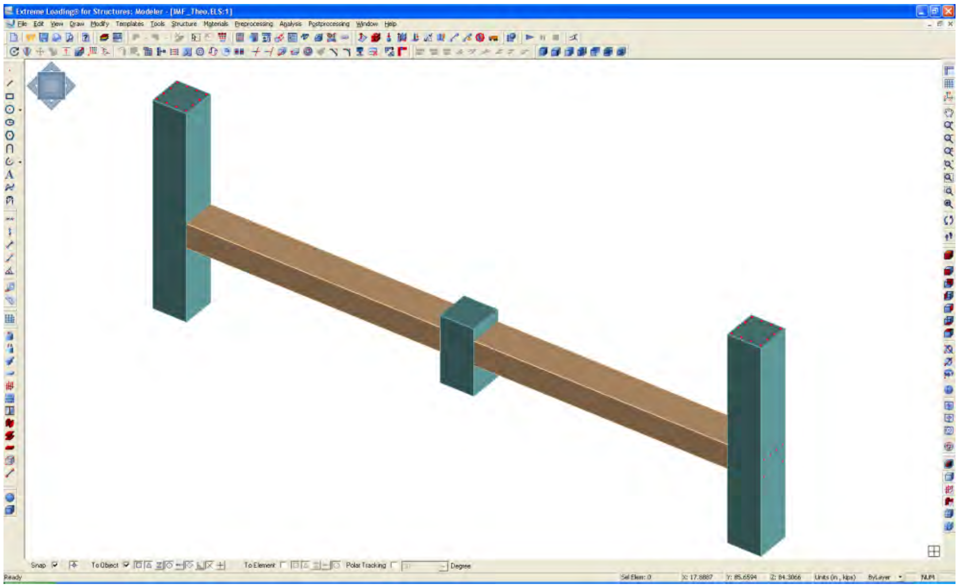

Fig. 5 ELS Model (Case 2)

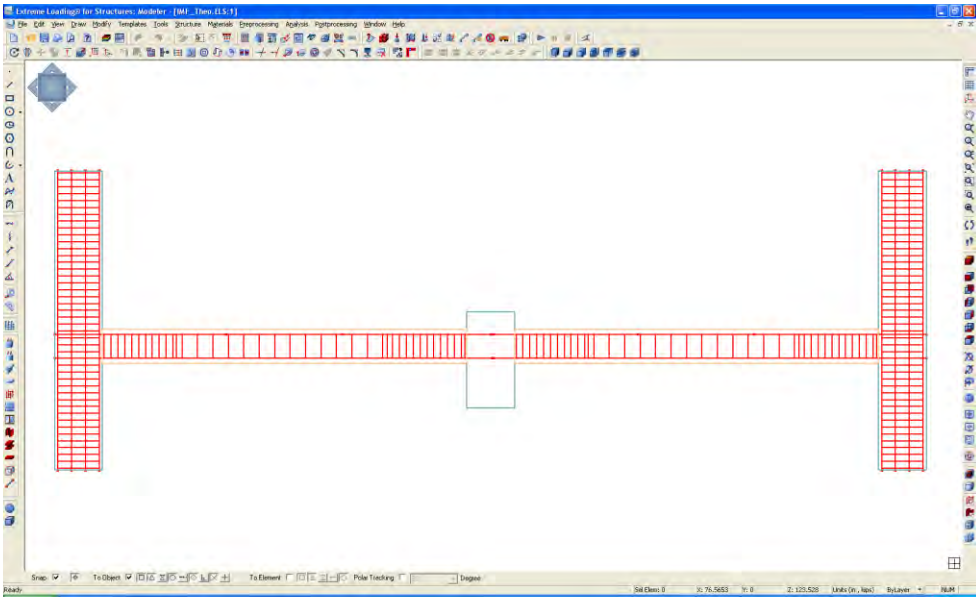

Fig. 6 ELS Model Reinforcement Details (Case 2)

2.2. Material Properties:

Table (1) shows the material properties used in the analysis.

Table 1: Material Properties

Material	Property	Value
Concrete	Compressive Strength	4 ksi
Longitudinal Reinforcement	Tensile Yield Strength	60 ksi
	Ultimate tensile Strength	90 ksi
	Rupture Strain	21%
Lateral Reinforcement	Tensile Yield Strength	76 ksi
	Ultimate tensile Strength	103 ksi
	Rupture Strain	15%
Interface Material	Young’s Modulus	3,800 ksi
	Shear Modulus	80 ksi
	Rupture Strain	0.1

2.3. Loading and Boundary Conditions:

The loading is applied in two stages to match the loading conditions in the experiment.

In the first stage, the own weights of the assembly are applied statically. The second stage is also a static loading case, where the middle column is removed from the analysis and replaced by applying a displacement loading. Figure (7) shows the loading setup and the boundary conditions in the ELS model. The loading was applied as a static displacement load of 60" over 2000 loading increments.

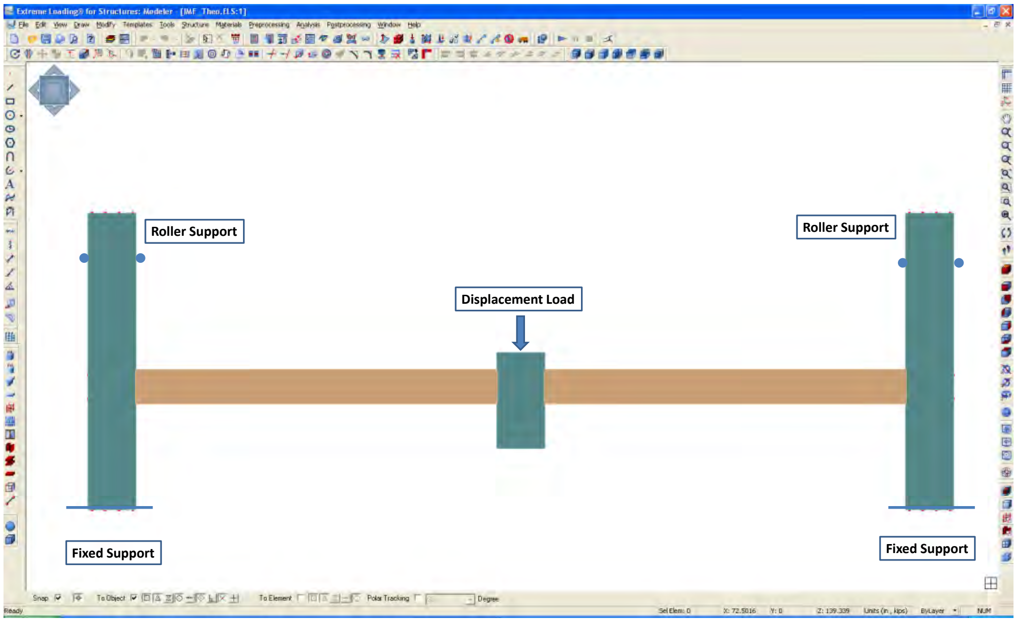

Fig. 7: Loading Setup and Boundary Conditions

3. Results and Discussion:

3.1. Case (1):

As mentioned before, reinforcement bars are modeled using 3D solid elements. The interface between the reinforcement bars are modeled using an interface model. The analysis took 2 hours of running on a quad-core processor PC with 32 GB RAM. A monotonic vertical displacement was applied at the center column. The failure sequence observed in the experimental results was concrete crushing followed by flexural cracks and then rupture of the bottom longitudinal bars. The ELS software was able to capture the same behavior. In the following section, the analytical results were compared to the experimental results in terms of load deflections curve, crack propagation and sequence of failure.

3.1.1. Force-Displacement Relationship:

Figure (8) shows the force versus displacement relationship of the lower center column obtained from the experimental results compared to the results obtained from the ELS analytical results.

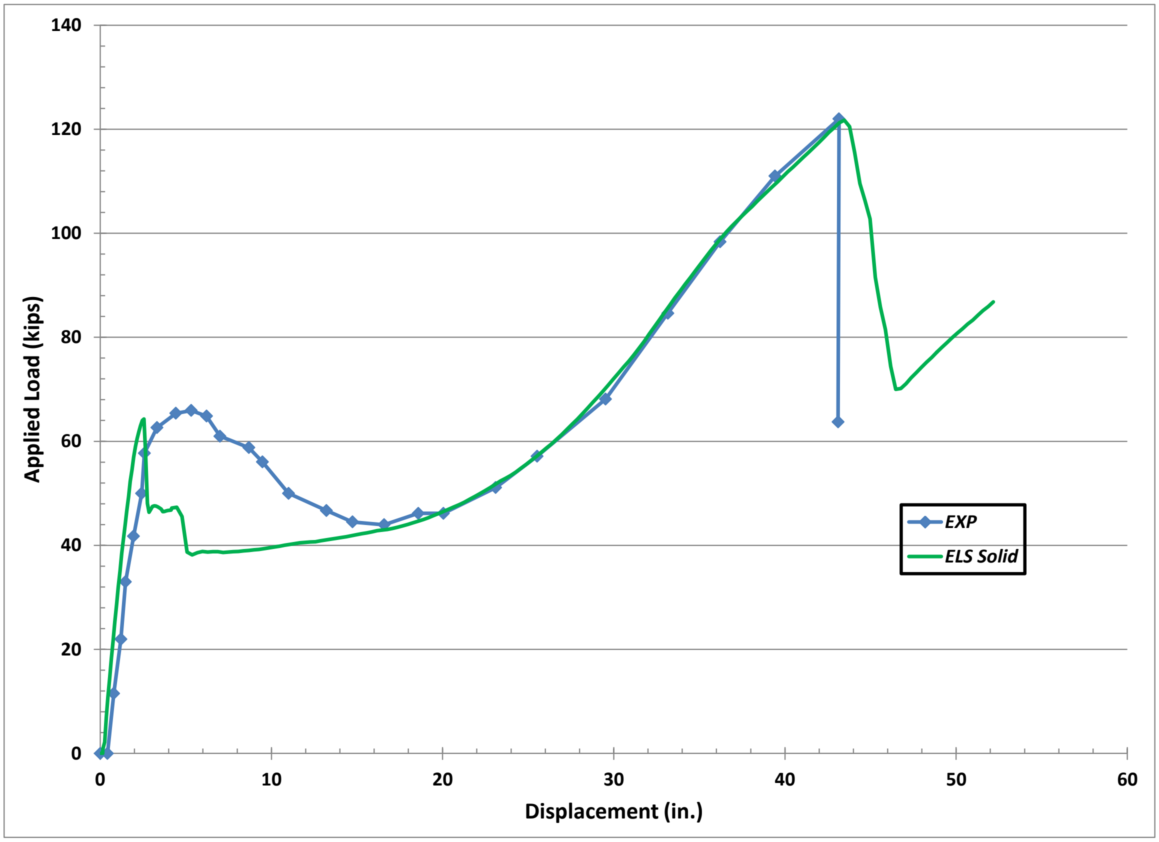

Fig. 8: Load Deflection Curve

3.1.2. Cracks:

Figure (9) shows a comparison between the experimental cracks and the tension principal strain contours. The tension principal strain contours is very good indication for the cracks. Figure (10) shows the location of the ruptured bar in the experiment in comparison with the ELS analytical results.

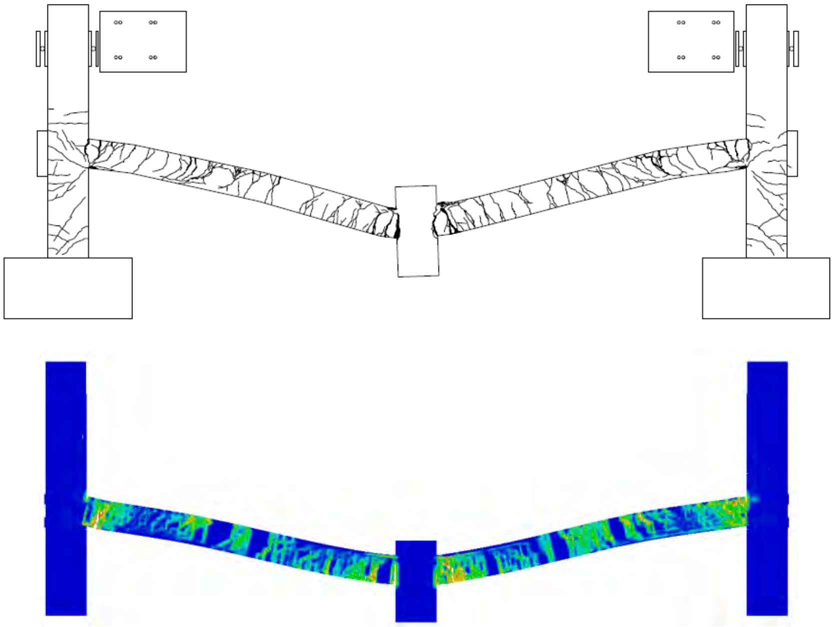

Fig. 9 Experimental Cracks Compared to the Principal Strain Contours

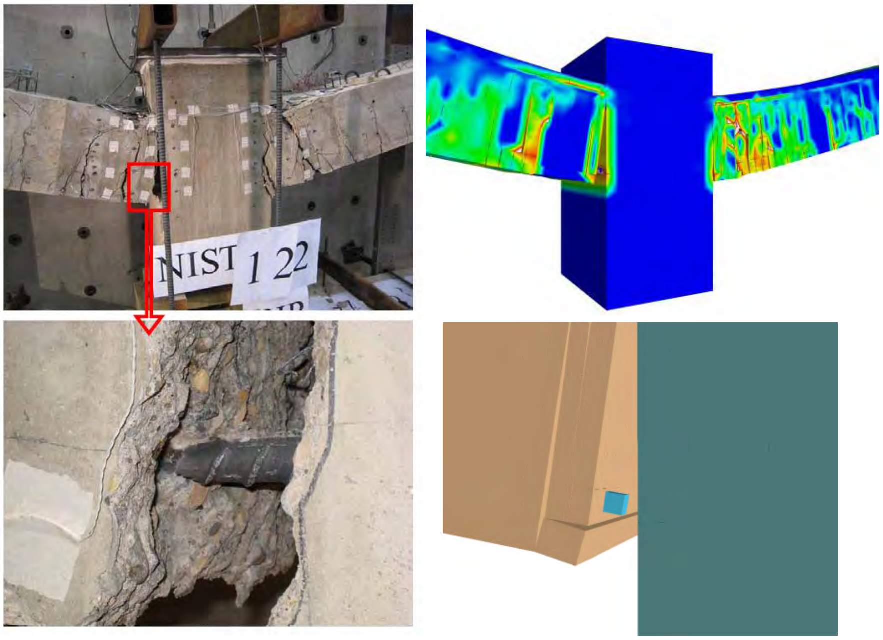

Fig. 10: Experimental Results Compared to the Analytical Bar Rupture

3.2. Case (2):

In this model, the reinforcement bars are modeled using one-dimensional springs between the element surfaces. There is an assumption of full bond between the concrete and the reinforcement. The analysis took 10 minutes of running on a quad-core processor PC with 32 GB RAM.

3.2.1. Force-Displacement Relationship of Falling Column:

Figure (11) shows the force versus displacement relationship of the center column obtained from the experimental results compared to the results obtained from the ELS analytical results. At the beginning of loading, the relation was linear up to point (1) when cracking occurred near the supports. The loading then dropped to point (2) where the catenary action begin developing leading to the increase in the load until the reinforcement bars raptured leading to losing the loading carrying capacity at point 3.

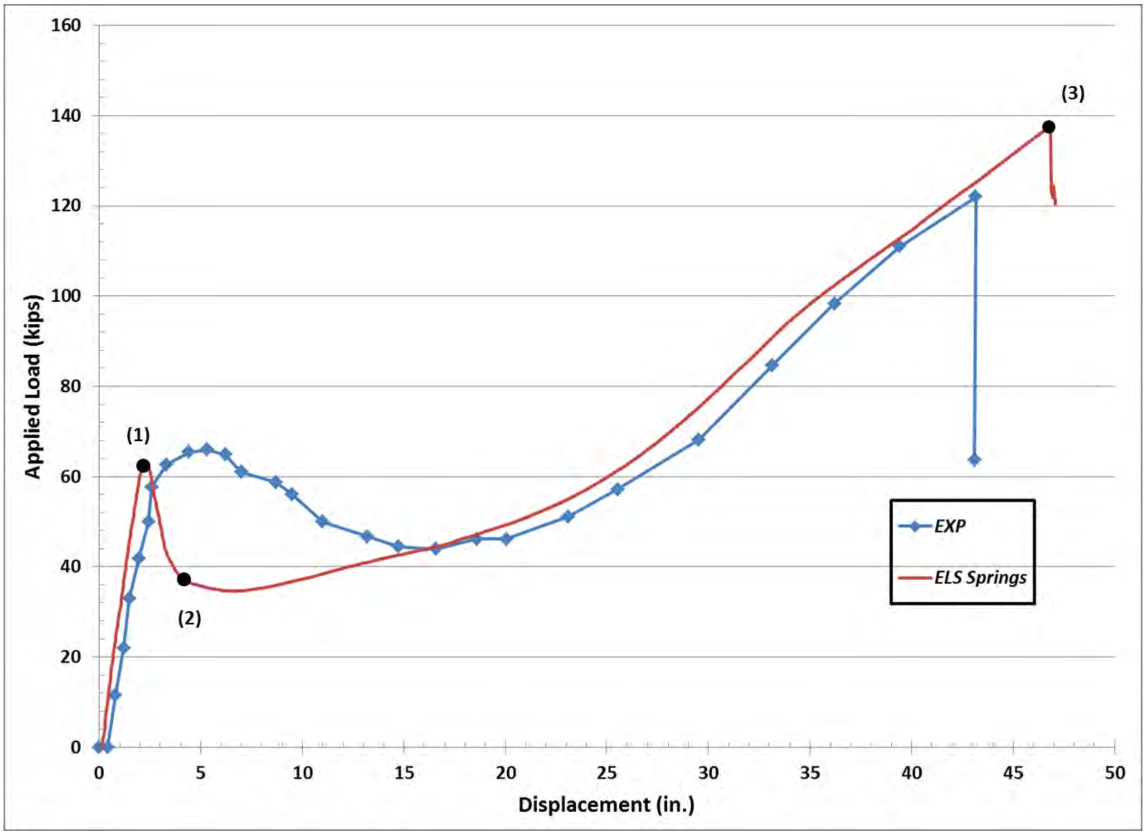

Fig. 11: Load Deflection Curve

3.2.2. Cracks:

Figure (12) shows a comparison between the experimental cracks and the tension principal strain contours. The tension principal strain contours is very good indication for the cracks. Figure (13) shows the location of the ruptured bar in the experiment in comparison with the ELS analytical results.

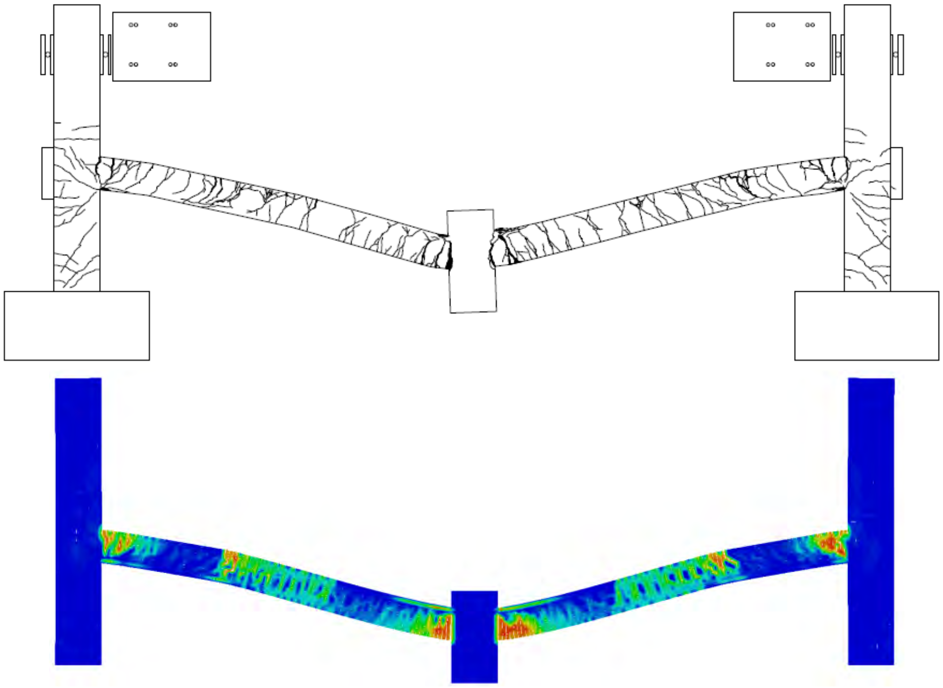

Fig. 12: Experimental Cracks Compared to the Analytical Strain Contour

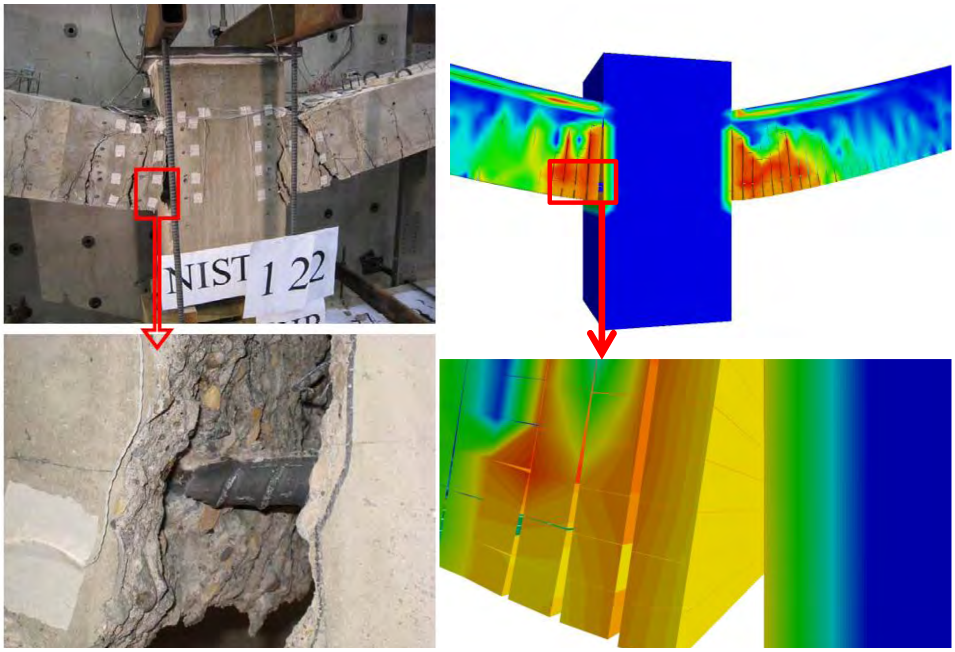

Fig. 13: Experimental Cracks Compared to the Analytical Cracks

3.3. Effect of Modeling Choices:

In Case (1) the reinforcement bars were modeled explicitly using three dimensional elements, while in Case (2) the reinforcement bars were modeled as springs. Comparison of the results of the two types of modeling shows that both types of modeling yield reasonable results that agree with experimental results. The main difference between the two techniques is the ability to model bond slip. This suggests that in the studied case there is limited bond slip between the steel bars and the concrete. In such cases using the simpler model described in Case 2 is more computationally efficient without affecting the accuracy of the results.

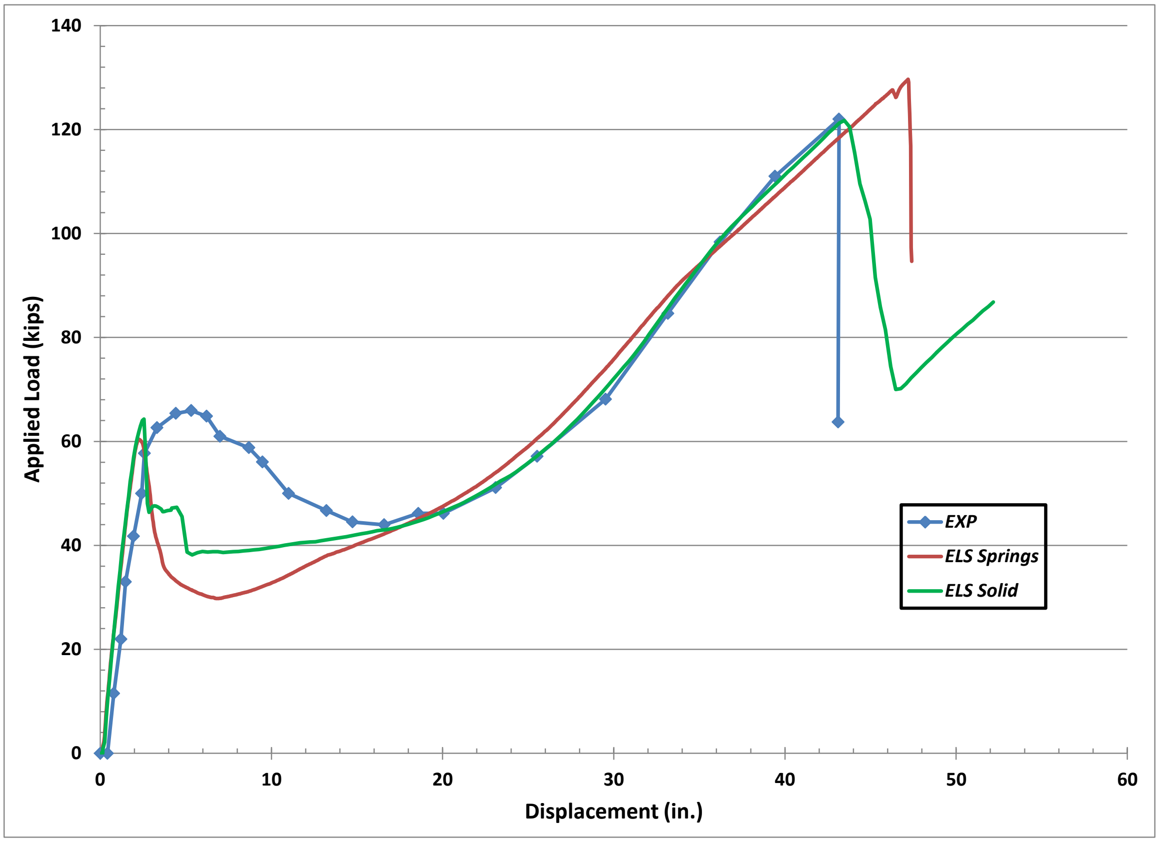

Fig. 14: Evaluation of the Results of Different Modeling Techniques

4. Conclusion:

The results of the ELS analysis match the results of the load deformation analysis observed in the experiment. The mode of failure observed in the analysis results matches the mode of failure in the experiment. The results of the numerically efficient ELS analysis using springs to model the reinforcement bars were just as good as the results using the more sophisticated ELS analysis using three dimensional applied elements.

5. References:

1. H.S. Lew, Yihai Bao, Fahim Sadek, Joseph A. Main, Santiago Pujol, and Mete A. Sozen, "An Experimental and Computational Study of Reinforced Concrete Assemblies under a Column Removal Scenario." NIST Technical Note 1720. October 2011.
2. Applied Science International, LLC www.appliedscienceint.com