Analytical Simulations of the Suspended Zipper Frames

Submitted By:

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Major points/topics:

- Simulations of the quasi-static tests for the suspended zipper frames conducted at Georgia Institute of Technology.
- Simulations of the shake table tests for the suspended zipper frames conducted at the University at Buffalo.
- Simulations of the hybrid simulation tests for the suspended zipper frames conducted at the University of Colorado at Boulder.
- Simulations of the hybrid simulation tests for the suspended zipper frames conducted at the University of California, Berkeley.

Abstract/Summary

This paper presents the analytical simulations of a 1/3-scaled suspended zipper frame prototype model that was tested under different experimental testing programs. The 1/3-scaled in-plan three-story prototype model was tested quasi-statically at the Georgia Institute of Technology (GT) and dynamically at the University at Buffalo (UB) NEES equipment site shaking table. In addition, the first story Chevron brace sub-assembly was tested with hybrid simulation testing method at the fast hybrid testing laboratory at University of Colorado at Boulder (UC) and at the nees@berkeley laboratory at University of California, Berkeley (UCB).

At Georgia Institute of Technology, the displacement loading history applied at the floor levels were obtained from a set of preliminary analytical simulations. The analytical simulation used the Open System for Earthquake Engineering Simulation (OpenSees) to model the system response of the suspended zipper frame. The analytical model consisted of a two- dimensional, three-story, 1/3-scaled suspended zipper frame, where the element response was modeled using the force beam column element in OpenSees. To properly model the buckling response of the brace, a slight imperfection is modeled at the mid-span of the brace and the boundary condition of the brace was modeled using rotational springs at the end of the braces.

After the experiments have been conducted, the parameter of the analytical model was adjusted. The yielding strength of the beams and columns was increased to R_yF_y, 55 ksi, instead of 50 ksi (R_y is 1.1 for A572 Gr. 50 steel), while the yielding strength of the brace and zipper struts was increased to 62 ksi rather than 46 ksi where R_y was set as 1.35 for A500 Gr. B steel, a little higher than the value 1.3 specified in the AISC Seismic Provisions. The initial imperfection ratios were increased to L_w/300 for the braces, where L_w denotes the distance between the working points. The end rotation spring stiffness for the braces was decreased to 500 in-kip/rad.

The comparisons between the experimental results and analytical simulation indicate that the analytical model can predict the behavior of the suspended zipper frame well until the brace starts to tear. This show with the current way of modeling the brace can not simulate the reduction of the brace cross-section after the brace tears. As for the yielding and initial buckling strength, the analytical results are in good agreement with the experimental data. The analytical results confirmed the experimental observation that the initial buckling strength of a brace subjected to tension first is smaller than the brace subjected to compression first. Furthermore, a three-dimensional model was established to simulate the out-of-plane buckling of the braces. There are two major differences between theses two analytical models. First, the initial imperfection for the three-dimension model is assigned in the out-of-plane direction, while the initial imperfection for the two-dimensional model is assigned in the in-plane direction. Second, the boundary condition for the three-dimension model is modeled as pin-pin, while rotation springs were used to model the boundary condition of the two-dimensional model. Comparisons between the simulation and experimental results indicate the three-dimension model can predict the trends of the trajectories but not the magnitude of the displacements.

At the University at Buffalo, the most important advantage of a shaking table test is its total independence of numerical models. It is then a good way to prove the accuracy of any analytical simulation. Before testing, an ideal model was built to predict some of the shaking table test results. The ideal model had hinge connections between braces and beams and between beams and columns. The model was subjected to the recorded base acceleration and the sequence of the tests was recreated. The braces show an enormous axial deformation and a very small compression capacity after buckling, therefore the zipper column carries a big tension force and the second story braces also buckle heavily. Results from actual test show, however, that the braces did not experience such big deformations; therefore the predicted and observed mechanisms are very different. In the specimen, the connections did transmit moments from braces to beams and from beams to columns. This example shows the importance of having a good analytical model when shaking table test is not available. Also, the fact that the braces buckled out of plane and its consequent torsion in the beam cannot be captured by a two-dimensional model. Efforts have been made by other sites to build better two-dimensional models. Those models were also subjected to the shaking table test sequence. The behavior is, in general, much closer to the test results. Details will be presented in the paper.

At the University of Colorado at Boulder, a series of numerical simulations was conducted to obtain an analytical model for the three-story suspended zipper frame. The analytical model uses OpenSees to model the response of the suspended zipper frame. The parameters of the analytical model was initially calibrated using the results of shake table tests conducted at University at Buffalo and then fine tuned with initial hybrid simulation tests conducted at the University of Colorado, Boulder. The tuning of the model involved the investigation of the influence of the loading history, the damping formulation, the material properties, the initial imperfection, the modeling of the structural mass, and the connection stiffness of the braces on the numerical results.

The analytical model was subjected to a sequence of six base motion time histories that were recorded during the shaking table test conducted at University at Buffalo. The analytical simulation accounted for the cumulative damage developed in the sequential excitations. The damping of the structure was modeled with Rayleigh damping, however, different combination of mass and stiffness proportional damping was studied.

The material property was modeled with the Menegotto–Pinto model that was calibrated to match the coupon tests conducted at University at Buffalo. The geometric nonlinearity was accounted using the corotational transformation in OpenSees and initial imperfection that was introduced at the mid-span of each brace. For the initial tests, the brace-to-gusset plate connections were considered pinned.

The analytical model was modified to conduct the hybrid simulation tests, where the first story Chevron brace sub-assembly was replaced with physical elements in the laboratory. The table acceleration recorded during the shaking table test conducted at University at Buffalo was used as the input motion to the hybrid simulation model. The hysteretic behavior of the first story braces was used to fine tune the analytical brace model. The refined analytical brace was then used for the second and third story braces in the next hybrid simulation test. The final model included a slightly lower damping coefficient for the stiffness proportional damping and rotational springs to account for the flexibility of the gusset plates at the ends of the braces. Additionally, the initial offset at the mid-span of the brace was altered and the material model was re-calibrated with the brace behavior obtained in the tests. The test results from the fourth specimen show good correlation to the numerical simulation results up to the fracture of a brace in the specimen which was not modeled in the analysis.

At University of California, Berkeley, a quasi-static test has been conducted to calibrate the brace hysteresis model developed in OpenSees. A Chevron brace sub-assembly with controlled and well-know boundary condition was tested using a quasi-static incrementally increasing symmetric displacement history. The results of the quasi-static test were used to calibrate the OpenSees analytical element to recapture the brace hysteresis of the Chevron brace sub-assembly.

The analytical model used to replicate the brace hysteresis, is a two-dimensional (in-plane) OpenSees model. Even though the buckling phenomenal happens in three dimensions, the brace hysteresis only accounts the brace axial force and axial deformation in the direction between the two ends of the brace. Since both ends of the brace stay in plane, the hysteresis of the brace can be modeled using a two-dimensional OpenSees model.

The analytical model uses a fiber sections with uniaxial Menegotto-Pinto steel material to model the cross sections of the braces. Each brace was modeled using two flexibility-formulation nonlinear beam-column elements, with five fiber cross sections along the length of each element.

Geometric imperfection of the brace was modeled using a slight misalignment of the middle node of each brace. The corotational transformation was used to capture the second-order geometry effects. To account for the rotational stiffness at the ends of the braces, three zero-length elements were used to model the gusset plate. Two rigid springs (elastic material with high stiffness) were used to restrain the translation degrees of freedom while the rotational degree of freedom is modeled using an elastic spring whose stiffness is calibrated to match the quasi-static test data.

The results of the quasi-static test and the analytical simulation shows with the appropriate selection of initial imperfection, rotational spring stiffness and the material properties used in the analytical model, the flexibility-formulation nonlinear beam-column element in OpenSees can be used to model the hysteresis behavior of the Chevron brace sub-assembly very well.