Response of Steel Buildings Subjected to 3D Seismic Motion

Blind Prediction Contest

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This article describes the numerical simulation of a four-story steel moment frame building subjected to three-dimensional time history acceleration at the base. The simulation was performed in response to a competition call for the blind prediction of numerous kinetic and kinematic parameters of a full scale structure, which was subjected to incipient and collapse-level shaking on the world's largest earthquake simulator – the E-Defense shake table facility in Hyogo, Japan.

The goal of this study was to create a realistic and practical model using commercial software. The authors chose SAP2000 for this purpose, and their modeling effort placed first in the Three-Dimensional Researchers' category in the worldwide Blind Prediction Contest.

Experimental Program

Full-scale testing of the building occurred on the shake table located at Miki City, Hyogo Prefecture, Japan, in September 2007 by applying a scaled version of near fault motion recorded during the Kobe earthquake in 1995. The design of the experiment addressed various issues, including possible collapse scenarios and the selection of the appropriate ground motion for shaking. Prior to testing, the researchers in Japan used several methods of analysis, including a two-dimensional model of the structure with members as line elements and a three-dimensional model using numerous shell elements.

The researchers provided extensive data pertaining to the test structure, including the structural plans, elevations, member properties, and details of connections and non-structural components. The loading on the structure consisted of the weights of structural and non-structural components. The research team also provided information from its preliminary analysis results, which included pushover analysis, modal analysis and time history analysis; components such as beam, column, and composite beam and anchor bolt test results; and material test properties of steel and concrete. Finally, the researchers provided two types of time histories of the seismic motion, namely a) idealized acceleration for pretest analysis and b) actual acceleration history for post-test analysis.

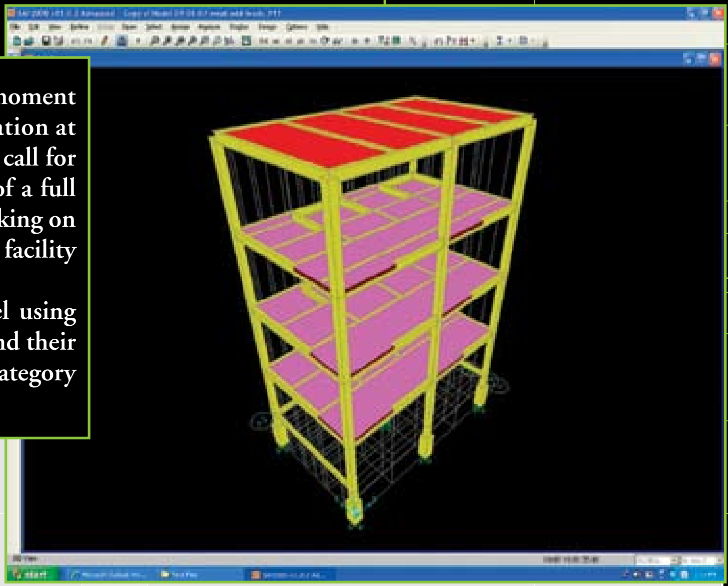

Figure 1: Schematic of the Model using SAP 2000.

The building was made of steel moment-resisting frames consisting of square tube columns and wide flange beams with concrete slab floors. The building footprint had two 5-meter-long bays in the X-direction and a single 6-meter-long bay in the Y-direction. The first floor height was 3.875 meters and other floors were each 3.5 meters high. The concrete floor slabs were 175 millimeters thick, and the roof slab thickness was 150 millimeters. In addition to the dead load, 800 Pa of the total 1800 Pa live load was considered as a part of the seismic mass. Non-structural components included autoclaved aerated concrete wall panels, sash window, partition wall and ceilings. The researchers provided the Japanese-specific member designations and properties, as well as the details of connections and other non-structural components. Moment connections and special welding details precluded premature failure of connections.

Other details of the specimen and pictures of the construction of the building and its placement in the shake table test bed can be found at the website of the Hyogo earthquake engineering research center at **www.bosai.go.jp/hyogo/ehyogo/**.

		3-Dimensional Analysis		Plane Frame Analysis	
		Researchers	Practitioners	Researchers	Practitioners
Software Type	Commercial	6	8	3	1
	Research	9	2	8	1
	Personal	2	2	1	3
	Unknown	1	0	0	0
Modeling Beams and Columns	Line	5	2	2	3
	Line+hinge	3	6	4	2
	Line+fiber	6	0	5	0
	Line+hinge+fiber	2	0	1	0
	Shell	0	3	0	0
	Lumped Mass	1	0	0	0
	Others	1	1	0	0
	Unknown	1	0	0	0

Table 1: Analysis Methods and Frame Models used by the participants.

Modeling Details and Limitations

The first challenge was the choice of the platform in which to model the building and run the experimental time histories. The choices were limited, as was the time to perform the simulations and submit the results. The authors chose SAP 2000 due to their previous experience with the software in other similar projects. The main question was which details furnished during the experimental program to eliminate, and which ones to retain and implement in the model. The decisions were based on the options a practicing engineer would have upon beginning to work on such a project.

The modeling details are shown in *Figure 1*. The beams and columns were modeled as frame elements with properties specific to Japanese sections. The connections were modeled as simple moment connections. Both the floor and roof slabs were modeled using membrane elements. Hence, the model contained 168 frame elements and 48 shell elements. Due to the connectivity of the slab to the frame, there were 8 constraints formed by the program in the process. All columns were considered fixed at the base. These details resulted in a total of 105 joints and 306 equilibrium equations. Hence, the computer time required for the model was relatively low, with a typical analysis for all the modal and time history computations taking two to three minutes. The low computational demand, for a relatively simple structure, allowed for numerous trials prior to the submission of results. The authors decided to exclude the effect of connection-specific test data, because it was impractical to gage its effectiveness given the short response time for the results. Floor subsystems, such as the collapse prevention structure and the walls, were taken as a lumped mass at the center of the floor area.

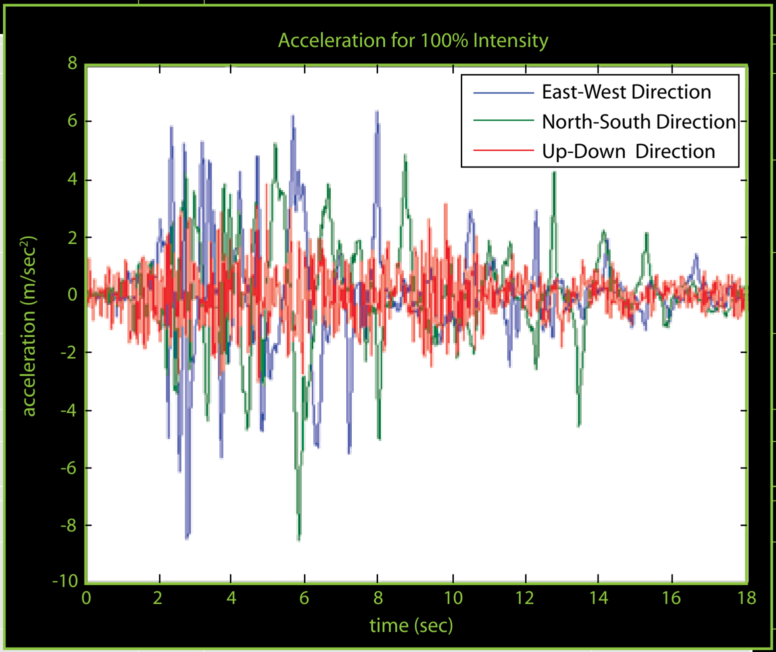

Figure 2: Input acceleration time histories in the three directions at the incipient collapse level.

Table 1 shows a comparison of the modeling efforts of various participants in the contest, in which there were four different categories of participants, namely researchers and practitioners using either three-dimensional frame analyses or a plane frame analysis methodology.

Time History Analysis of the Frame

Three sets of time histories (J1, J2 and J3) were input in SAP 2000 as user-defined data. Each set consisted of a scaled version of the final time history intensity. J3 (collapse level) represented the 100% intensity, while J2 (incipient level) and J1 represented 60% and 40% of J3, respectively. *Figure 2* shows the details of the J3 level input acceleration. The peak intensities were more than 0.85g in the east-west and north-south directions, while the up-down accelerations had a peak value of about 0.4g. Each of the three intensities were run as load cases in which the results from one run were transferred to the other. However, the analysis did not explicitly account for any loss of stiffness in the structure due to cracking and damage after each step. The analysis was run using the nonlinear modal time history analysis method with a constant damping for both mass and stiffness of 0.02.

Results and Discussion

The periods of the four lowest modes were 0.869, 0.821, 0.623 and 0.284 seconds. The first three corresponded to the lateral, longitudinal, and torsional modes, and the fourth mode is the second lowest in the longitudinal direction. *Table 2* shows the

Measure	X-direction		Y-direction	
	Numerical	Experimental	Numerical	Experimental
Max. Relative Displacement [mm]				
d_5	195	160	209	205
d_4	169	135	177	160
d_3	129	90	134	134
d_2	81	50	82	75
Max. Absolute Acceleration [mm/s²]				
a_5	10875	8750	9820	9500
a_4	8850	7000	7955	8700
a_3	7529	7900	7277	7000
a_2	5752	7800	6388	6500
Max. Story Shear [kN]				
V_5	728	560	680	720
V_4	1118	840	998	1000
V_3	1548	1100	1235	1260
V_2	1835	1160	1371	1420
Max. Relative Drift Angle [radians]				
R_5	0.007	0.006	0.0092	0.0075
R_4	0.011	0.0115	0.0127	0.0125
R_3	0.014	0.0135	0.0149	0.0175
R_2	0.021	0.0125	0.02125	0.0190

Table 2: Comparison of the predicted and experimental values and provides the following observations.

a. *The maximum relative displacements were predicted very accurately in the Y-direction, but overpredicted in the X-direction by about 18 percent.*
b. *The maximum absolute accelerations were predicted reasonably well in the Y-direction, while in the X-direction they were underpredicted by 25 percent at the second floor level and overpredicted by as much as 25 percent at the fourth and fifth floor levels.*
c. *The story shears were predicted accurately in the Y-direction, but overpredicted by up to 30 percent in the X-direction.*
d. *The maximum relative drift angles in the X- and Y-directions were predicted very closely.*

comparison of the predicted and the observed experimental values; the subscripts represent the floor at which the measurement was taken.

As frame elements were used for columns, the authors could not submit a prediction for the axial strain in them at the base level. Two other parameters – namely the maximum overturning moment and the residual drift angles – are not shown in *Table 2*, as they closely reflected some of the observations made above.

One observation that stands out is that the predictions were very close in the Y-direction, but off in the X-direction. There are two reasons to which the authors attribute this, namely a) damping effects due to mass and stiffness were not given very careful consideration, and b) panel zone effects at beam-column junctions were not incorporated. Further study of the damping effects is underway. It was observed from the final collapse mechanism of the experimental structure that the failure was probably due to plastic hinge formation in the X-direction at the base of the structure. Hence, inclusion of the panel zone and plastic hinge effects could have resulted in a more accurate collapse prediction.

Conclusions

With the stated objective of keeping the numerical simulation effort as practical as possible by a) using commercial software, b) keeping modeling assumptions relatively general and easy to implement by any engineer, and c) not considering in-depth data which may either be impractical to implement or unavailable to an engineer, it is possible to simulate, with reasonable accuracy, the behavior of steel moment frame structures subjected to time history base acceleration. From this research-oriented study, in which the experimental observations were compared with the numerical predictions, it can also be seen that, while the response of the structure during the ground motion was predicted very well, the actual collapse mechanism was not predicted well. Further studies are underway to gain a better understanding of the issues involved with the numerical modeling of the response of structures subjected to a seismic motion.▪

References

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