Appendix

Modeling Options

Tables A.1. and A.2. summarize the modeling and analysis options used in OpenSees. The beam-end hinges are modeled using *zeroLength* elements. Two independent nodes were created at the top of each column. One of the nodes served as a column top node. The degrees-of-freedom (DOFs) with respect to U, V, Z and Θ were confined to the corresponding DOFs of the column top node using *equalDOF* command. The rest of DOFs were fixed, and a *zeroLength* element was inserted between the two nodes. Thus, the shear forces of the roof beams were not added to the columns to maintain the consistency with the theory. *Steel01* material was used to model the bilinear property of the hinges.

The two pairs of interstory shear springs were modeled using *zeroLength* elements with *Elastic* material properties. An Euler–Bernoulli element designated *elasticBeamColumn* in OpenSees was used to model the columns. The area, second moments of the areas about the weak and strong axes, and torsional moment of inertia of the cross-section of the column elements, are given sufficiently large values for representing a rigid bar. The areas and second moments of the areas about the vertical axis of the *elasticBeamColumn* elements that connect the column tops were given sufficiently large values to render the in-plane stiffness of the roof level rigid and to ensure that the roof slab acts as a rigid diaphragm. The second moments of the area and moment of inertia of the cross-section of these elements were given very small values. To consider the P-Delta effect, the *PDelta* option was applied to the column members whereas the *Linear* option was applied to the rest of beam-column members (Denavit and Hajjar, 2013).

Table A.1. Modeling options on OpenSees

Members	**Element type**	**Options**
Beams-end hinge and horizontal elastic shear springs	*zeroLength* elements (implemented with dummy nodes)	**Beam-end hinges**: - *Steel01* material **Horizontal shear springs**: - *Elastic* material
Columns (rigid bars) and rigid diaphragm	*elasticBeamColumn* elements with a sufficiently large/small stiffness	**Columns**: - A, I_c, and J_x are sufficiently large. - *PDelta* option was applied for geometrical transform (*geomTransf*). **Components of the rigid diaphragm**: - The element connects the main node and each column top. - A and I_z are sufficiently large. J_x and I_y are sufficiently small. - *Linear* option was applied for geometrical transform (*geomTransf*).

Table A.2. Analysis options on OpenSees

Commands	**Options for gravity loading**	**Options for horizontal loading**
Constrain	Penalty 1.0e+15 1.0e+15	Penalty 1.0e+18 1.0e+18
Numberer	RCM	RCM
System (solver)	SparseGEN(SuperLU)	Full General
Test	NormDispIncr 1.0e-8 100	NormDispIncr 1.0e-6 1000
Algorithm	NewtonLineSearch -maxIter 10000	Broyden -count 50
Integrator	Load Control	Load Control
Analysis	Static	Static

Reference

Denavit, M. D., and Hajjar, J. F. (2013). *Description of geometric nonlinearity for beam-column analysis in OpenSEES, department of civil and environmental engineering reports (No. NEU-CEE-2013-02)*. Boston, Massachusetts: Department of Civil and Environmental Engineering, Northeastern University. https://repository.library.northeastern.edu/files/neu:376268 (Accessed October 18, 2023).