

CHAPTER 9 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FOR FURTHER WORK

Until now, moment end-plate connections have been used primarily to resist only wind and gravity loading. Due to the failure of the “pre-Northridge” connection, they are becoming much more attractive for seismic design. However, design procedures for large moment end-plate connections that meet seismic detailing requirements are not currently available. In particular, for numerous practical beam sizes, moment end-plate connections can not be designed to be stronger than the plastic moment capacity of the adjoining beam. As a result, engineers are not able to utilize the benefits that this type of connection can provide. This research examined the seismic response of previously conceived end-plate configurations, and proposed a design procedure for a new end-plate configuration called 16-bolt extended stiffened (16ES) that can satisfy current code requirements. The results of this computational study were validated by direct comparison with numerous experimental tests performed at Virginia Tech. These tests are part of the SAC Steel Project, the most influential study of steel moment frame structures ongoing in the United States. Some of the results and design recommendations of this research will be included in SAC publications.

The finite element method was used to develop local models of moment end-plate connections. Since the structure is three-dimensional, solid eight-node brick elements that include plasticity effects were used to model the beam and the rigid column flange. The bolts and end-plate were modeled using twenty-node solid elements. Contact elements were included between the end-plate and the column flange to represent the nonlinear behavior of this problem. Prying forces and plastic behavior in the bolts were tracked throughout the loading process.

After determining that the models could effectively predict the response characteristics (e.g., bolt forces, plate separation, plastic rotation) of the moment end-plate connections, models of SAC steel project specimens were developed. These included a four-bolt extended, a four-bolt wide, and an eight-bolt extended stiffened connection. The finite element results obtained by static loading were compared to the experimental results of the SAC steel project specimens under cyclic loading and the following conclusions were made:

- The finite element method can be used to accurately predict the envelope of the behavior of moment end-plate connections under cyclic loading.
- Finite element analysis is an excellent tool for justifying specific connections designed by interpolation of results from similar connections that have been tested experimentally.

Next, a parametric study of the four-bolt wide moment end-plate connection was performed. No design procedure is currently available for this “large” connection, and the brittle limit state of plate shearing/tearing has occurred in some experimental tests. For a specific W30x173 beam-to-column connection, bolt pitch, bolt gage, and end-plate thickness were varied one at a time to determine how each of these variables affected the response of the connection. The following conclusions were reached:

- The horizontal distance g_o from the outside bolt centerline to the beam flange tip is the primary factor in determining the effectiveness of the outside bolts. For strength and to avoid the brittle limit state of plate shearing/tearing, this value should always be positive. The larger this value is, the more effective the outside bolts become.
- The bolt to beam flange pitch should not be increased to obtain larger inelastic rotations of the end-plate. Such an increase may significantly decrease the overall strength of the connection and can cause the brittle limit state of plate shearing/tearing to occur.
- The end-plate thickness is the only variable of concern for this connection. Decreasing the thickness of the end-plate effectively increases the inelastic rotation capability of the connection, but also reduces the strength of the connection due to increased prying forces. Increasing the plate thickness decreases prying forces and results in a stronger connection.

Based on the above conclusions, a design procedure was obtained for the 16ES connection. The limit states of end-plate yielding and bolt rupture were considered. To meet the current code requirements of designing the moment end-plate connection stronger than the plastic moment capacity of the adjoining beam, a thick plate design

procedure was obtained using yield line analysis. Using a thick plate, prying forces were minimized and a relationship between outside bolt gage and connection capacity was obtained. This relationship can be used to determine the size of bolts needed to ensure that a connection is stronger than the plastic moment capacity of the adjoining beam. Conclusions for this study include the following:

- The 16ES connection can be used to design connections stronger than the plastic moment capacity of the adjoining beam.
- Minimum bolt pitch, bolt gage, and bolt spacing should be utilized to obtain the maximum strength of the connection.
- The design procedure for this connection is particularly appropriate for ordinary moment frames where experimental testing is not required.

The rigid column flange assumption used in all the local models of the moment end-plate connections was justified by considering a flexible column flange. It was found that the column flange should be at least as thick as the end-plate, or a stiffener should be provided. This ensures that a premature failure of the connection via bolt rupture does not occur. For strength, a design procedure for the limit state of column flange bending was provided.

The results (applied moment vs. plastic rotation) of the local models were used as nonlinear springs representing the connections of the global system (i.e., two-story frame). Both beam hinging and end-plate yielding mechanisms were considered to determine which form of inelastic rotation provides better energy dissipation characteristics. Hysteretic behavior, period shift, and moment redistribution characteristics of the connections were obtained by performing a nonlinear time history analysis of two-story frames under earthquake excitation. Conclusions from this study include the following:

- Both beam hinging and end-plate yielding can provide significant energy dissipation during seismic loading.

- For the same applied loading, a beam hinging (thick plate) connection requires considerably less plastic rotation capacity than the same end-plate yielding (thin plate) connection.
- Period shift can reduce earthquake induced forces, but relative to hysteretic behavior, its contribution is negligible.

Two additional topics indirectly related to moment end-plate connections were considered. Based on finite element studies, welding guidelines were provided for doubler plates used to strengthen the panel zone. This study was two-dimensional and eight-node solid elements were used to model the assembly. It was determined that for cases when the doubler plate is sized to fit between stiffeners, a minimum size fillet weld can be used for the horizontal welding. When the doubler is extended beyond the stiffeners, horizontal welding is not required. Also, some important findings deal with the seismic design of metal building systems. It was found that these lightweight buildings need not follow the stringent detailing requirements that current building codes have established. Their lightweight roofing and wall systems generate small inertia forces that can be resisted elastically by a lateral force-resisting system designed for wind and gravity loading.

Several topics should still be considered in future research. The same connection model can be used to examine the response characteristics of numerous end-plate configurations. Simplified design procedures should be established using the thick plate assumption made for the 16ES design. This will ensure that all currently utilized configurations can be used safely and in accordance with current design philosophies. Also, other large end-plate configurations should be considered with stiffeners between bolts so that more bolts can resist the flange force. In regards to metal building design, a more complete study should be performed for all types of structural systems (e.g., gabled frames, tapered members). Finally, cases should be considered to determine if end-plate yielding can be coupled safely with beam hinging to increase system ductility.