Analysis of Extended End-Plate Connections Under Cyclic Loading Using the LS-DYNA Implicit Solver

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Abstract

Moment-Resisting Frames (MRF's) are widely used as lateral-force resisting systems in buildings. Their successful performance depends on the behavior of their moment-resisting beam-column connections. In regions at risk for earthquakes, MRF's need to resist large cyclic forces and displacements. A variety of beam-column connections are used in practice. Most, including end plate connections, are designed assuming the MRF seismic capacity is based on the ability of the connection to allow inelastic rotation through the development of plastic hinges within the beam elements of the structure. In this paper, Finite Element (FE) computer analysis is used to simulate the behavior of the joint region of an MRF. A computer model of the MRF's extended end plate beam-column connection was created and its performance was analyzed under cyclic loading condition. The LS-DYNA implicit solver was used in this study. Results from these simulations were compared to previously conducted physical tests. The results show good correlation with the measured test data. The work demonstrates the ability of LS-DYNA to simulate the cyclic behavior of this type of beam-column connection and is a step toward using physically calibrated computational model to complement physical testing for the future evaluation of this type of structural detail.

Introduction

Moment-Resisting Frames (MRF's) are widely used as lateral-force resisting systems in buildings located in regions with high seismic activity. When properly designed and constructed, they dissipate energy to control the seismic response of steel-framed structures. Successful performance of MRF's depends on the capacity of their moment-resisting beam-column connections to allow inelastic rotation through the development of the plastic hinges within beam elements of the moment-resisting frame. Weak-beam/strong-column philosophy is used in seismic design of a moment-resisting connection to ensure that plastic hinge forms in the beam element rather than in the column element to have enough redundancy and prevent collapse.

During the Northridge earthquake of January 17, 1994, there was widespread damage and unanticipated brittle fractures in welded steel beam-to-column connection. There was no complete collapse or loss of life, but the economic damage was considerable. The brittle nature of fractures observed invalidated the design approaches and code provisions existing at that time. As a result, extensive laboratory testing was done to study the poor performance of beam-to-column joints and to develop improved connection details and methodologies [1]. The results of these studies indicate improved performance of extended end-plate moment connections under cyclic loading. An extended end-plate connection (Figure 1) has a plate that extends beyond the beam flanges, which provides the moment resistance and makes the connection less susceptible to cracking under repeated loads.

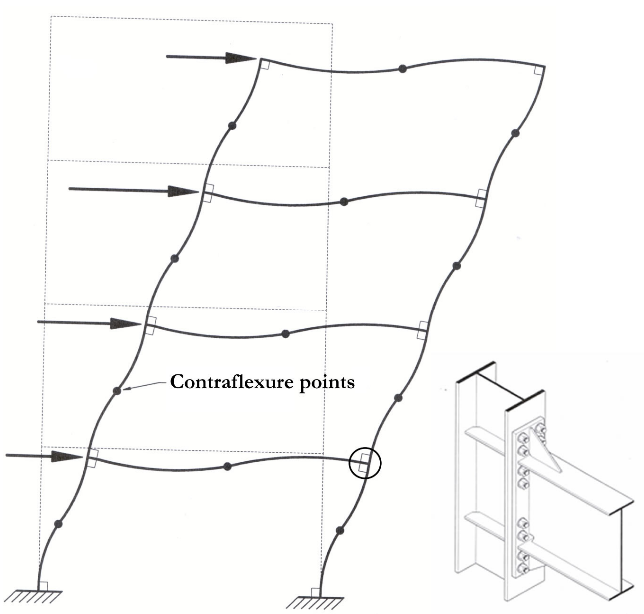

Figure 1: Deflected shape of a MRF subjected to lateral loads.

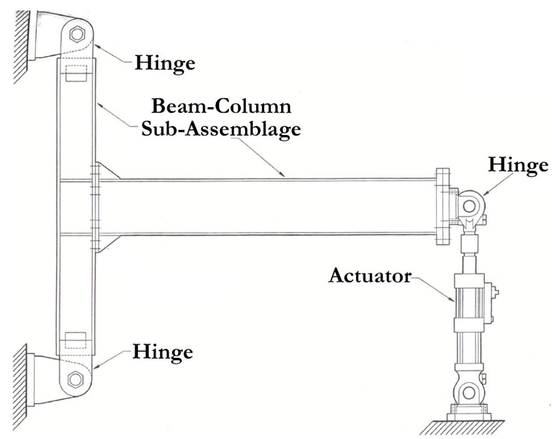

Figure 2: Schematic of test set-up for cyclic testing of a beam-column sub-assemblage.

Figure 1 shows the deflected shape of a MRF subjected to equivalent static lateral forces, which are representative of the inertial effects of an earthquake. The point of contraflexure is located at the mid-span of all the frame members. A beam column connection can be isolated by truncating the frame at these inflection points. This truncated portion of the frame is called beam-column sub-assemblage. In a cyclic test a beam-column sub-assemblage is subjected to several elastic and inelastic cycles. The ends of the test specimen are hinged for consistency with the frame behavior under seismic loads. Figure 1 shows a schematic of a typical test set-up. If the sub-assemblage is able to sustain a large number of inelastic cycles, it indicates that the connection has desirable characteristics of energy dissipation.

A finite element (FE) simulation of a full-scale cyclic test of a beam-column sub-assemblage is carried out to assess the ability of LS-DYNA to predict cyclic behavior of a connection. The physical testing was done at the campus of University of Kansas [2]. The numerical simulation is done using LS-DYNA implicit solver. The analysis was quasi-static, simulating the cyclic quasi-static nature of the test. The implicit solution procedure reduces the analysis run time compared with the explicit time integration procedure. Comparison of the test results with the simulation results is presented in this paper.

Finite Element Simulation

FE Model

The FE model of the sub-assemblage is constructed from fully integrated (type 16) shell elements. Typical element size is 1 inch x 1 inch. To reduce modeling and computational effort, only half of the assembly is modeled by identifying a plane of symmetry at model's centerline parallel to the longitudinal axis. Figure 3 shows the FE model, the elements are hidden for clarity. Important components of the model, the end-plate, the end-plate stiffener, and the continuity plates are also highlighted in the figure. In the figure the x-y plane is the symmetry plane.

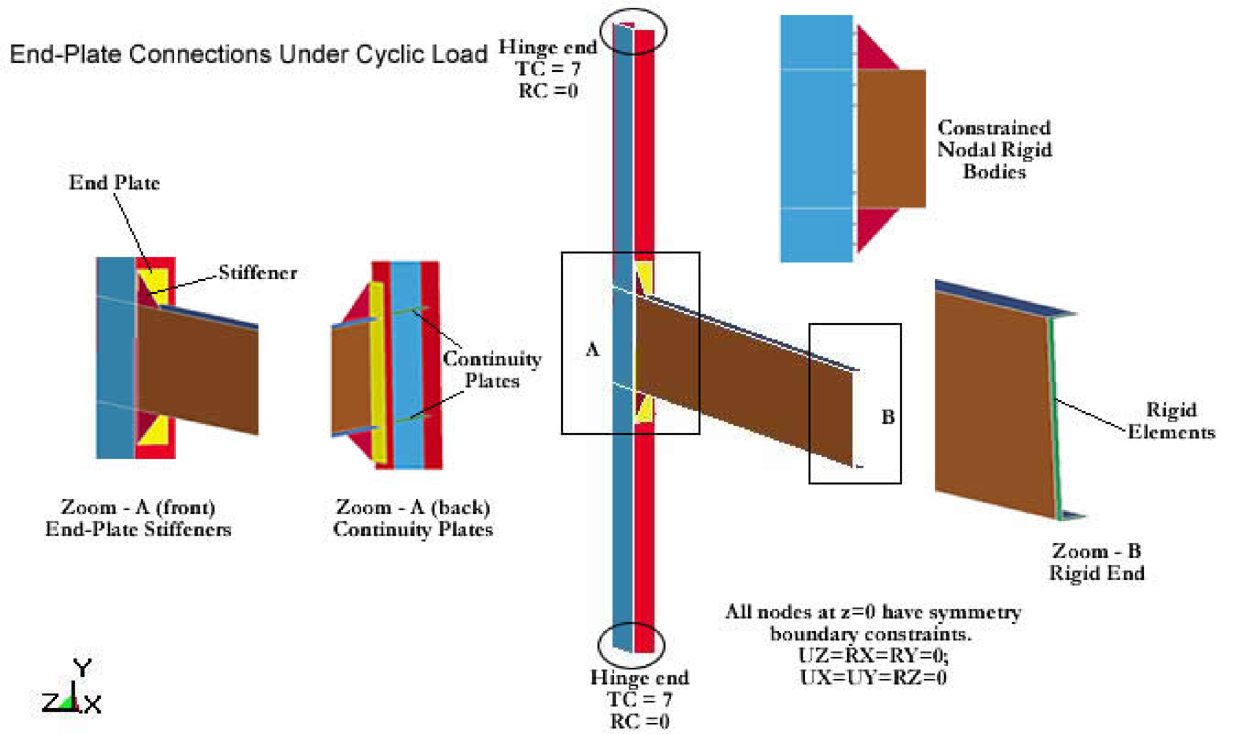

Figure 3: FE model of beam-column sub-assemblage.

All the welded connections in the FE model are fully meshed together. The bolts were modeled as *constrained nodal rigid bodies* between a node of the end-plate and the column flange at the specified location. The pre-tension present in the bolts during the test is not represented in the FE model. The end-plate and column flange interface is assumed to be frictionless and the contact between the interface is not modeled.

End Restraints

To represent true frame behavior, consistent boundary conditions must be imposed. The column ends were hinged by allowing rotations and restricting translation. The beam/actuator connection in the physical test is like a ball and socket joint which allows rotations. In the FE model the beam tip is modeled as a rigid body to which motion is applied and so its rotation is in a way restricted. In light of St. Venant's principle in elasticity, it can be assumed that such a boundary condition will not have any influence on the global behavior. The area of influence will be restricted to a distance equal to the characteristic length that is the depth of the beam from the beam tip.

Material Model

Member properties and dimensions were obtained from the results of material testing conducted for the experiment. The keyword *MAT_PLASTIC_KINEMATIC was used and isotropic strain hardening was assumed.

Loading Protocol

Deformation history applied for the test consisted of a total of 37 cycles. The peak displacement was 4.56 inches which corresponds to a peak rotation of 0.03 radians. Figure 4 shows the displacement history used for the simulation. The motion is applied to the rigid tip of the beam using the keyword *BOUNDARY_PRESCRIBED_MOTION_RIGID.

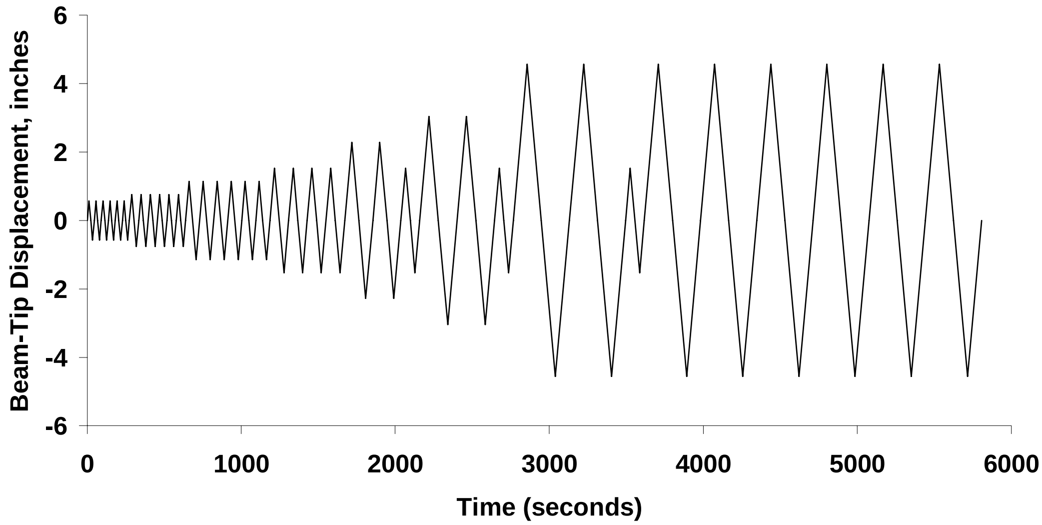

Figure 4: Applied Displacement Time-History

Implicit Control Cards

Following are the implicit control cards used for the simulation:

*CONTROL_IMPLICIT_AUTO
*CONTROL_IMPLICIT_GENERAL
*CONTROL_IMPLICIT_SOLUTION
*CONTROL_IMPLICIT_DYNAMICS

Default values were used for the above cards except for IAUTO, ITEOPT, and DTMAX. Automatic time stepping is used by setting IAUTO at 1, ITEOPT was increased to 100 to aid convergence, and a load curve was specified for DTMAX. There are two advantages of using a load curve for DTMAX. First, if it is known *a priori* that at a particular state more detailed output is required, user can specify a lower DTMAX to ensure information is not missed. Second, if a load curve is defined for DTMAX, LS-DYNA ensures that a state is created at every key point in the load curve; thus it can be ensured that no part of the load curve is missed during the simulation.

Results

Location of Plastic Hinge

Severe yielding in the form of local flange buckling was observed during the test (Figure 5). The test specimen was coated with a brittle coating of lime and water to indicate local yield lines and plastic hinge formations. The analysis results agreed well with the test results as observed from the contour plot of plastic strains at the final state of simulation. Considerable yielding can be observed from the plots in the stiffener and in the beam element near its base. The maximum value of plastic strain occurs in the stiffener and is approximately 42.1% and the maximum value of plastic strain in the beam element is approximately 21.0%. Significant yielding of beam's web around the stiffener base can also be observed from the plots indicating a full-depth plastic hinge.

The plastic hinge is observed approximately at a distance of 13.2 inches from the column face, which matched well with that in the test.

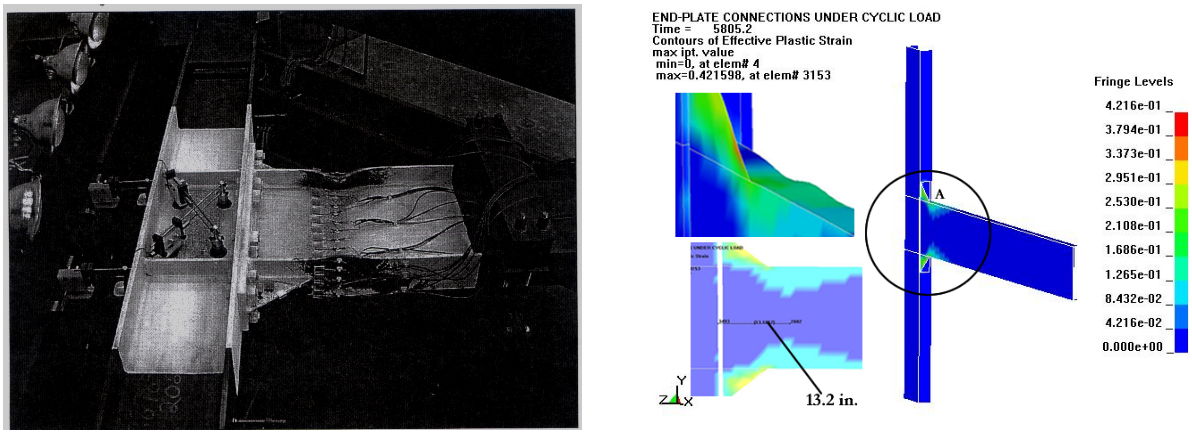

Figure 5: Comparison of Plastic Deformation

Moment vs. Rotation

Performance of beam-column connection is best characterized by its moment-rotation behavior which is determined by multiplying the load-values and dividing the total displacement values by the length of the moment-arm. The maximum moment applied to the finite element model is 6714 kip-inch which shows a good correlation with the test data, where the maximum applied moment was 7049 kip-inch (Figure 6). The maximum total beam rotation was 0.03 radian for the simulation and it was 0.0322 radians during the test. These extreme values occurred in cycle number 37 and 33 for the simulation and the test, respectively. The plots have good match for a loading sequence but simulation results tend to differ from test results in unloading sequence. They match well with respect to the extent and the spread of the hysteretic curve, which is indicative of the energy dissipated by the joint.

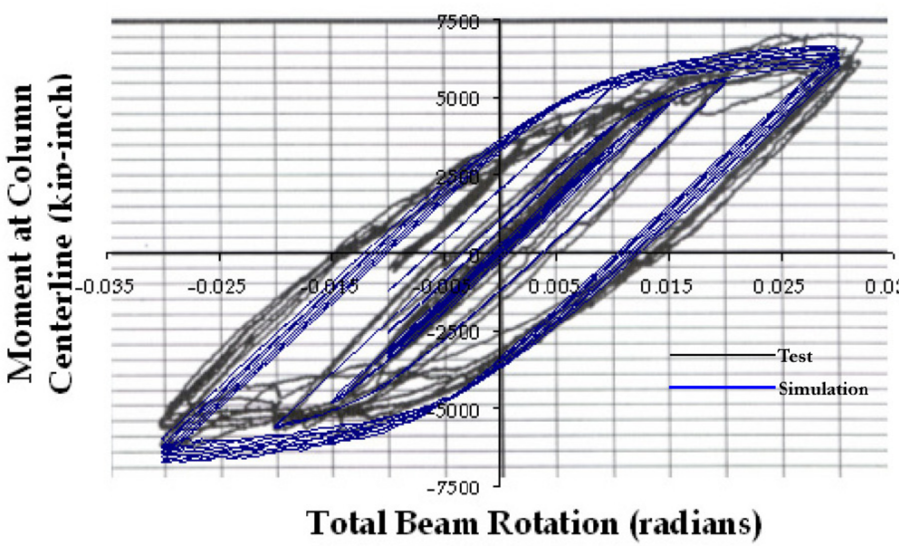

Figure 6: Comparison of Moment vs. Total Beam Rotation Hysteretic Behavior

Energy Dissipation

The key to performance of a connection during a seismic event lies in its ability to absorb or dissipate energy fed into the system by the ground shaking. In a FE analysis this absorption is indicated by the internal strain energy value of the FE model at the end and during the simulation. The strain energy of the FE model at the end of the simulation is approximately 2126 kip-inches. For the test specimen this value is approximately 3231 kip-inches. Flexural stresses transferred from the beam flanges create complex state of stress and strain in the portion of the column web between the continuity plates (see Figure 3), called the panel zone. Under the action of forces panel zone deforms primarily in shear mode causing web crippling with significant shear yield. The FE model is a symmetric half-model of the actual specimen which will not be able to capture these shear deformations. The column behavior thus is not represented well and the difference in absorbed energy values is expected. During the test the panel was also instrumented to measure the shear deformations. The contribution of panel zone to the overall energy dissipation was about 29%. If the panel zone contribution is subtracted from the overall dissipated energy of the test specimen, the absorbed energy is approximately 2290 kip-inches, which matches well with the predicted value from the simulation.

Conclusions

The simulation results have a good match with the test results. The beam side behavior of the sub-assemblage is well represented by the symmetric FE model. To improve upon prediction of the column behavior a full FE model should be analyzed. The simulation successfully predicts the formation of a full-depth plastic hinge and its location matches well with that in the test. The hysteretic plot of moment vs. total beam rotation has a good correlation with the test results with respect to the extent and spread of the plot. The major contribution to energy dissipation comes from the inelastic deformations in the beam and the amount of energy dissipated through this mode matches well with the test results. The study gives confidence in the implicit procedure implemented in LS-DYNA. The application allows completing quickly a pseudo static nonlinear analysis, compared to an explicit analysis, which is time-consuming. The work demonstrates the ability of LS-DYNA to simulate the cyclic behavior of this type of beam-column connection and is a step toward using physically calibrated computational model to complement physical testing for the future evaluation of this type of structural detail.

References

1. SAC Joint Venture, *Interim Guidelines: Evaluation, Repair, Modification, and Design of Welded Steel Moment Frame Structures,* Report No. SAC-95-02, Sacremento, California, August 1995.
2. Jon K. Lindsey, Master’s Thesis, *Moment-Rotation Behavior of Extended End-Plate Connections Under Cyclic Loading, Phase One,* University of Kansas, Lawrence, Kansas 2000.