Comparative Study on the Nonlinear Behavior of Steel Shear-Links

Y. Kızıldağ[1], A. Sarıtaş[2]

[1]Department of Engineering Science, METU, Ankara, Turkey, yophieey@yahoo.com
[2]Department of Civil Engineering, METU, Ankara, Turkey, asaritas@metu.edu.tr

Abstract

The use of advanced finite element programs provides opportunity for the assessment and simulation of the nonlinear behavior of shear-links under various loading and boundary conditions. Such a study has been undertaken in this paper, and the shear links are modeled and analyzed in finite element program ANSYS with 2-D and 3-D elements. First, a verification study is conducted by comparison of the results of past experimental data and the numerical analysis carried out in this work by using a realistic cyclic material model for steel. Then, a detailed comparative finite element study has been conducted, where the links are analyzed not only with the proposed finite element modeling approach, i.e. the utilization of 2-D and 3-D elements and cyclic calibration of steel material through the use of ANSYS, but also with a frame element that can capture spread of plasticity both along element length and section depth. In the first part of the comparative study, the contribution of flange to the overall shear force carrying capacity of shear-links is assessed through both finite element modeling approaches. With this comparison, a realistic description of flange shear strain for the frame finite element model is suggested. In the second part of the comparative study, the influence of unsymmetrical loading protocols on the nonlinear behavior of shear-links is studied through the use of both finite element modeling approaches, and the results are compared to each other and the accuracy of the frame finite element model is assessed.

Keywords: *eccentrically braced steel frames, shear-links, finite element method, cyclic material behavior, nonlinear structural analysis*

1 Introduction

Eccentrically braced frame (EBF) is developed by Professor Popov and his associates at University of California, Berkeley as an alternative to concentrically braced frame and moment resisting frame. EBFs have large energy dissipation capacity and sufficient stiffness to resist lateral cyclic loads in ductility limits. In this kind of bracing system, an active link (called as shear-link) is located as a part of the beam. The purpose of this link is to transfer the shear and bending forces on the beam to the bracing strut as axial force. Thus, the maximum force that can be conveyed to the brace depends on the shear capacity of the shear-link. Yielding of the shear-link limits the axial force on braces and prevents buckling of the braces.

Researches that are generally focused on experimental studies show that behavior of shear links are fairly complicated and affected by various parameters. Experimental studies are usually limited in terms of loading and boundary conditions as well as material and geometric properties of tested specimens. Therefore, development of finite element models or the use of already available finite element programs could provide means for this purpose. However, the reliability of a finite element model should be checked attentively.

In this paper, a comparative numerical study on the estimation of the nonlinear behavior of steel shear-links subjected to cyclic loading will be carried out through the use of 2-D (shell) and 3-D (solid) finite element models and also through the use of 1-D (frame) finite element model. In order to check the validity of the modeling and analyses in ANSYS, first, a validation study with the experiments conducted in literature is undertaken, where the experimental specimens are selected from the studies of Kasai (1985) and Hjelmstad (1983). Then, the influence of the flange thickness on the shear carrying capacity is investigated. Also, unsymmetrical cyclic loading protocols, which are called as “near-fault loading protocol” in literature are also applied to the same finite element models. The results obtained from ANSYS are compared with the numerical results obtained from a frame finite element model developed by Saritas and Filippou (2009).

2 Verification Study

Experiments conducted on shear-links by Hjelmstad (1983) and Kasai (1985) are considered for verification of the calibrated material parameters and finite element modeling approach. In this paper, the results from only Specimen 5 from Kasai will be presented, but for interested readers, please refer to the thesis by Kizildag (2013) for complete presentation of the modeling part and the results from both studies.

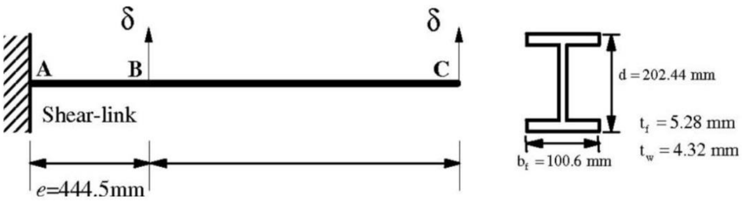

Figure 1. Geometry of Specimen 5 of Kasai (1985)

The boundary conditions of specimens used in experiments of Kasai (1985) is shown in Figure 1 and defined as fixed connection at the column connection end and at the other end connected to the long beam behaves like pin connection. Also, at the other end of the long beam, rotation is allowed. Specimen 5 is modeled with 2d surface (shell) elements in ANSYS. The material properties of web and flange are calibrated to fit the cyclic stress-strain values as suggested by Kaufmann et al. (2001), and multi-linear kinematic hardening material model in ANSYS is used for this purpose. For detailed presentation of the calibration method, please refer to the thesis by Kizildag (2013).

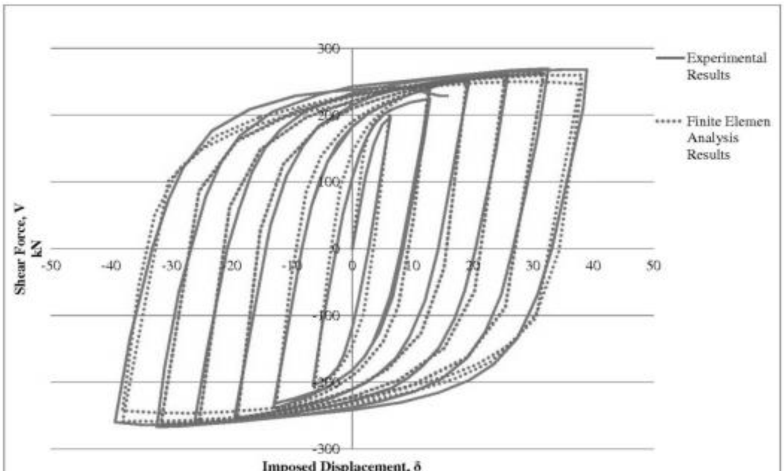

Figure 2. Comparison of the shear-imposed displacement curves of experiment and finite element analysis for specimen 5 of Kasai (1985)

The experimental data and results reported by Kasai (1985) on Specimen 5 provided not only the link shear force versus displacement plots but also the variation of link end moments through cyclic loading. The comparison of results of Specimen 5 in Fig 2 and Figure 3 shows excellent agreement between finite element model and the experimental results. The comparisons of the moments at the ends of the links at A and B show that similar stiffness values are captured in both hysteretic diagrams. Variation of moment through cyclic loading obtained from analysis shows slight differences when compared with experimental results.

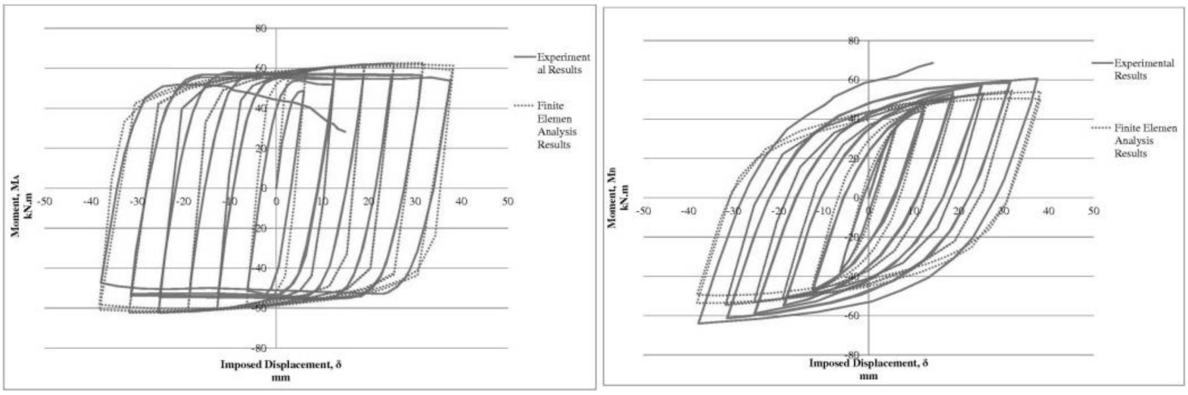

Figure 3. Comparison of the moment at column end of the link (left) and the moment at beam joint end of the link (right) versus imposed displacement curves of experiment and finite element analysis for Specimen 5

Furthermore, Kasai (1985) presented the deformed shapes of the specimens during the tests. At same cycles and displacement values, the deformed shapes of the finite element model are captured to compare with the deformed shapes of the tested specimen in Figure 4, where close match between the numerical and experimental results can be observed.

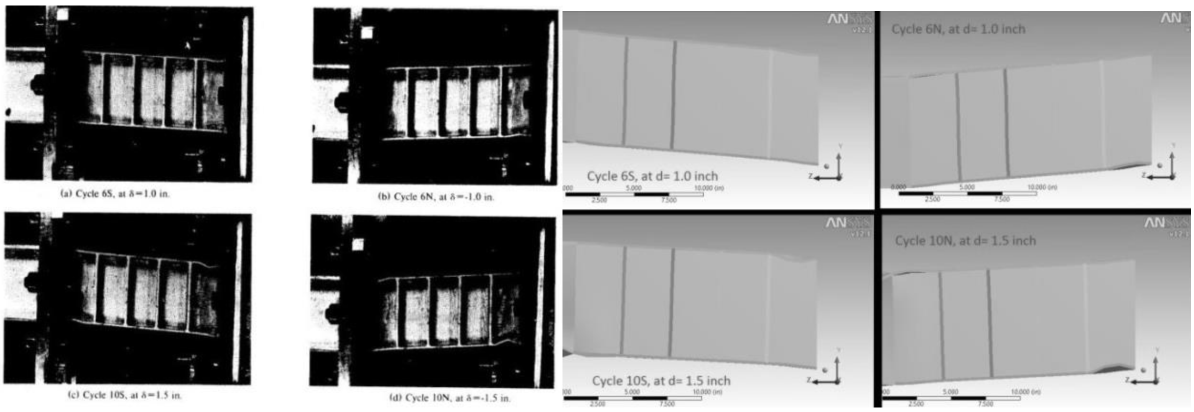

Figure 4. Photos of Specimen 5 during the test by Kasai (1985) and Deformed shapes of Specimen 5 at different steps of the analysis

3 Comparative Studies

3.1 Influence of Flange Thickness

For typical wide flange sections used in eccentrically braced frames, most of the shear force is resisted by the web; however, as the flange thickness increases, shear force carried by the flange under inelastic loading conditions may overstrength the response of a shear-link. In order to assess this increase, Specimen 4 of Hjelmstad (1983) is considered for a comparative finite element study. As part of this numerical study, solid finite element models available in ANSYS are considered in modeling Specimen 4. The same specimen is also modeled with the frame finite element proposed by Saritas and Filippou (2009), where the material model is the same as employed in the numerical study by Saritas and Filippou (2009). In this regards, there is not only a difference in terms of finite element modeling approach, but also in terms of material modeling approach, as well. In order to conduct the comparative finite element study on Specimen 4 of Hjelmstad (1983), the flange thickness of this specimen is increased with by 20%, 50%, 80%, and 100% by keeping the depth of web constant. The right end of this specimen is monotonically loaded until reaching 3 inches (76.2 mm) displacement.

Verification study conducted for Specimen 4 of Hjelmstad (1983) was done through the use of shell elements instead of solid finite elements. However, while increasing the flange thickness, shell elements may not be sufficient to illustrate the response of the specimen. Therefore, a solid model with single layer discretization along flange thickness directions is chosen for the parametric analysis. The parametric analysis is conducted also with frame finite element model. Figure 5 represents the over-strengthening in shear capacity as flange thickness increases with solid and frame models. The ratio of the shear capacities of each model to the original model are shown in Figure 6. As shown in Figure 5, the frame finite element model estimates 15% increase with respect to the original specimen's shear force capacity as the flange thickness increases 100% with respect to the original specimen dimension, while the solid finite element model estimates 12% increase. While including flange shear strain is important as flange thickness increases, Figure 6 also shows the fact that flange shear strain may be neglected in the original specimen's response.

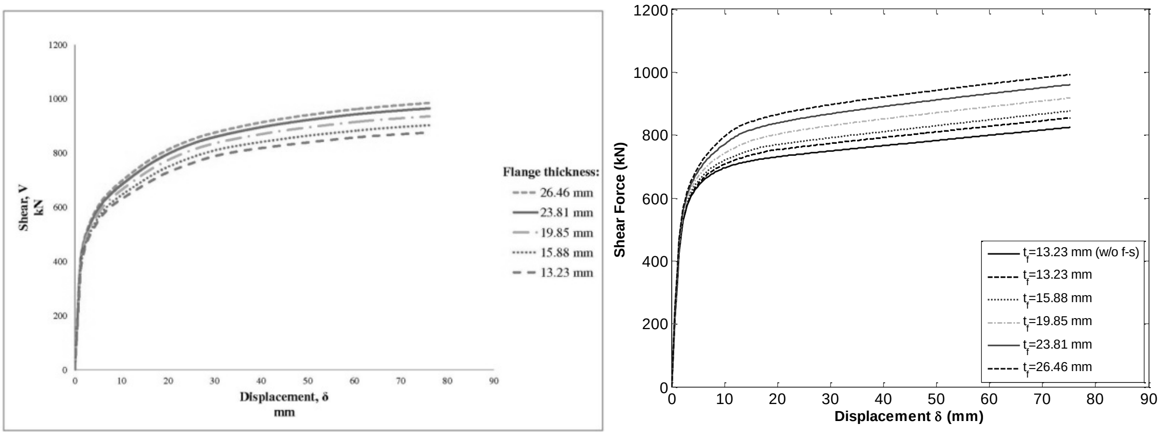

Figure 5. Comparison of solid models created in ANSYS (left) and frame models (right) with different flange thicknesses

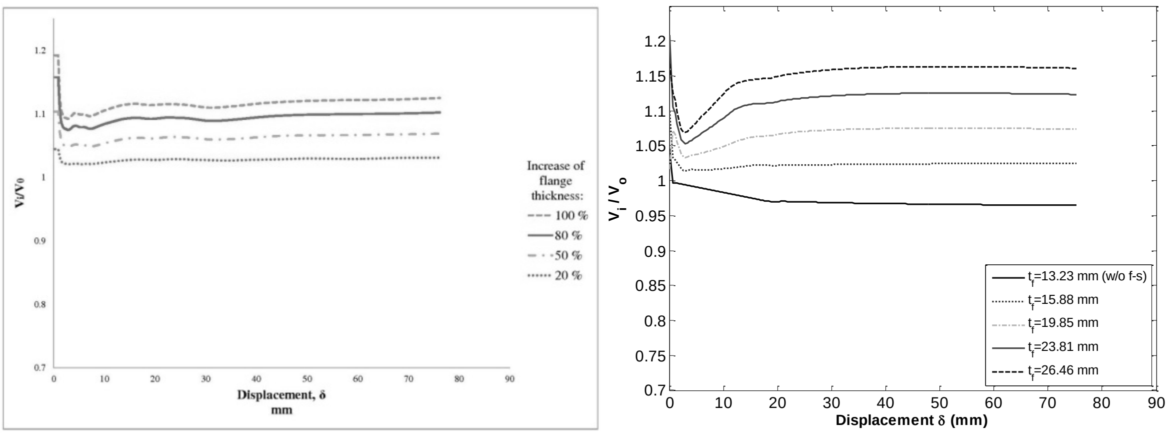

Figure 6. Increase in shear capacity where V_i is the shear capacity of each model, V_o is the shear capacity of the original specimen (solid models created in ANSYS (left) and frame models (right))

3.2 Near-Fault Loading and Nonlinear Behavior of Shear-Links

The near-fault loading protocol considered in this study was originally proposed by Krawinkler et al. (2000) for the evaluation of performance of steel moment resisting frames subjected to near-fault ground motions. The loading histories used in the current study are constructed based on SAC and CUREE near-fault loading protocols, and modifications are introduced in order to reduce the amount of computation time by eliminating some of the cycles of displacements.

The modified loading histories are applied on both Specimen 4 of Hjelmstad (1983) and Specimen 5 of Kasai (1985). The loadings are applied both on the finite element model constructed in ANSYS Workbench and on the frame finite element model. Detailed discussion with regards to the loading protocols is available in the thesis by Kizildag (2013).

Shear force versus imposed displacement responses obtained from SAC and CUREE loading protocols for Specimen 4 of Hjelmstad and Specimen 5 of Kasai are presented in Figure 7 and Figure 8, respectively. Despite the fact that the scale of finite element models are totally different and with the fact that the implemented material models and calibration of cyclic material parameters are not the same, the eventual shear force versus imposed displacement responses obtained from all near-fault loading protocols provide fairly close match between the frame and shell finite element models.

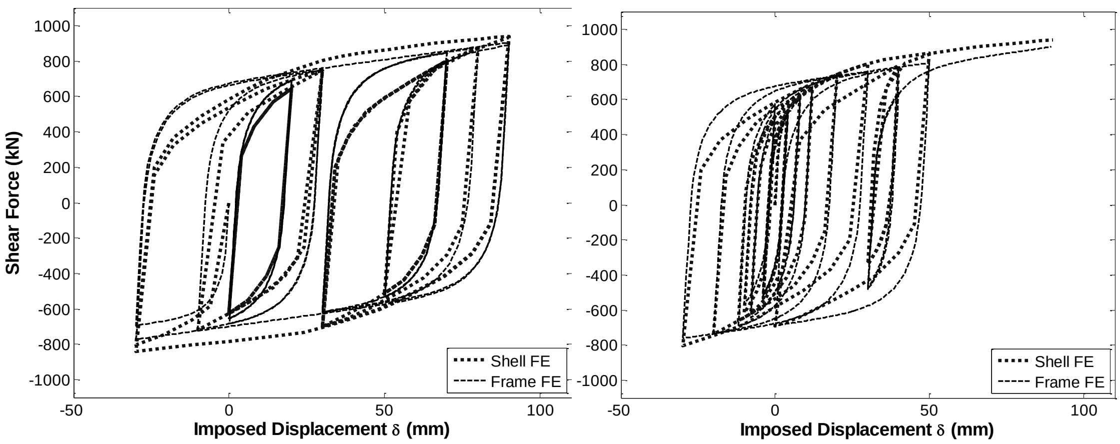

Figure 7. Responses of Specimen 4 of Hjelmstad under SAC loading protocol (left) and CUREE loading protocol (right)

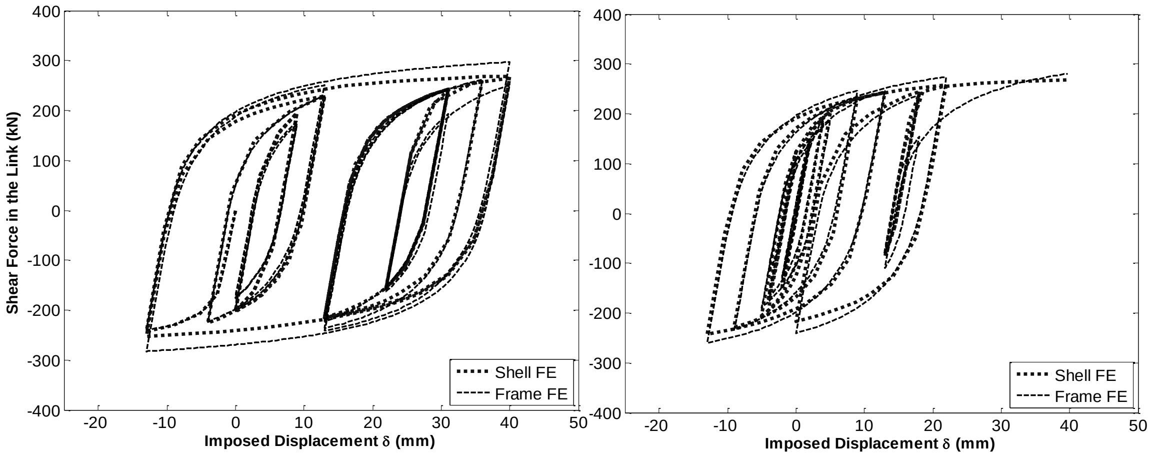

Figure 8. Responses of Specimen 5 of Kasai under SAC loading protocol (left) and CUREE loading protocol (right)

4 Conclusion

The result of the verification study shows that the proposed calibration technique to represent cyclic behavior of steel in ANSYS by the use of multi-linear kinematic hardening material model gives very close estimation of the nonlinear behavior of shear-link members when compared with experimental data.

The frame finite element with proposed flange shear strain assumption provides very close match when compared with the solid finite element results for shear-link specimens with thicker flanges. After the parametric study for flange thickness, it can be said that, influence of shear strain acting on the flanges of a thin flanged shear-link member is on the order of 3% of total shear force carried by the member. Thus, for a frame finite element formulation of a shear-link member, it is safe to assume the sandwich beam theory assumptions, i.e. the web carries all of the shear force.

Under unsymmetrical loading conditions, the results attained by the frame finite element closely matches with the results obtained with the use of shell finite elements. Despite this close match, experimental specimens tested under more complex loading histories are needed in order to verify the reliability of finite element models in capturing the energy dissipation characteristics of structural members. Further work may be necessary especially in using a more complex steel material model that captures monotonic loadings, as well as various symmetrical and unsymmetrical loading conditions.

References

Hjelmstad, K. D. (1983). Seismic Behavior of Active Beam Links in Eccentrically Braced Frames Ph.D., University of California.

Kasai, K. (1985). A Study of Seismically Resistant Eccentrically Braced Frame Systems Ph.D., University of California.

Kaufmann, E., B. Metrovich and A. Pense (2001). Characterization of Cyclic Inelastic Strain Behavior on Properties of A572 Gr. 50 and A913 Gr. 50 Rolled Sections. ATLSS Rep (01-13).

Kizildag, Y. (2013). Finite Element Modeling Approaches and Comparative Study on the Nonlinear Behavior of Steel Shear-Links. M.S., METU.

Krawinkler, H., A. Gupta, R. Medina and N. Luco (2000). Development of loading histories for testing of steel beam-to-column assemblies, Stanford University.

Saritas, A. and F. C. Filippou (2009). "A Frame Element for Metallic Shear-Yielding Members under Cyclic Loading." Journal of Structural Engineering, ASCE **135**(9): 1115-1123.