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EXTENDED ABSTRACT

Investigating Geometric Imperfection Effects on Failure of Steel Angles Under Compressive Force in Power Transmission Line Lattice Towers

Ali Asghar Zekavati, Karim Abedi *, Mohammad Reza Chenaghlou, Mohammad Charkhtab Basim

Faculty of Civil Engineering, Sahand University of Technology, Tabriz 5331811111, Iran

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Steel angle, Power transmission line lattice tower, Geometric imperfection, Eccentricity, Joint slippage, Initial crookedness.

1. Introduction

This paper presents a study of the behavior of single-angle compression members connected through one leg only with single and double-bolted connections. Non-linear finite element simulations with OpenSees software have been performed, and the results are compared with experimental tests conducted by other researchers. A comparison is also made with the strength predicted by major code provisions. The investigation aims to assess the effect of geometric imperfections, such as eccentricity, joint slippage, and initial crookedness, on the failure of steel angles under compressive force. This will be achieved by presenting a straightforward modeling method for the angle elements.

2. Methodology

2.1. Experimental tests of Kettler et al. (2019)

This study aims to investigate the effect of geometric imperfections on the compressive strength of steel angles using a finite element model based on experimental data from Kettler et al. (2019), who conducted 27 experimental tests on bolted steel angles, including 14 with two-bolt connections and 13 with single-bolt connections, at Graz University of Technology. The samples consisted of 24 L80×8 hot-rolled steel angles and three L120×12 hot-rolled steel angles, fastened with grade 10.9 M20 and M27 bolts, respectively. The study also provides detailed dimensions, member length, system length, and other pertinent test specifications. Additionally, various boundary conditions were outlined, including clamped support, knife-edge support, and fully hinged support with specific rotational restraints.

2.2. FE modeling

In this section, finite element models have been developed based on geometric imperfections. The same specimens made by Kettler et al. (2019) are analyzed by means of the finite element method in the present study. In the numerical model, each member with an equal-angle section was defined as shown in Fig. (1-a). Each part of a member with an equal-angle section was modeled by the force-based beam-column element in Open Sees. The eccentricity at two ends of the member was defined based on an elastic beam-column element

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* Orcid Cod Corresponding Author: 0009-0003-4021-8389
E-mail addresses: a_zekavati99@sut.ac.ir (Ali Asghar Zekavati), k_abedi@sut.ac.ir (Karim Abedi), mrchenaghlou@sut.ac.ir (Mohammad Reza Chenaghlou), basim@sut.ac.ir (Mohammad Charkhtab Basim).

with an elasticity modulus 100 times that of steel to behave rigidly. Corotational and linear geometry transformations were used for the major members and elements, respectively, to represent eccentricity. Using zero-length elements, six nonlinear springs at the terminal node of each member were defined by translational and rotational stiffness values along the local axes x, y, and z. The steel material properties were based on the tensile test results from Kettler et al. (2019), and displacement-control static pushover analyses were carried out to reach the failure load.

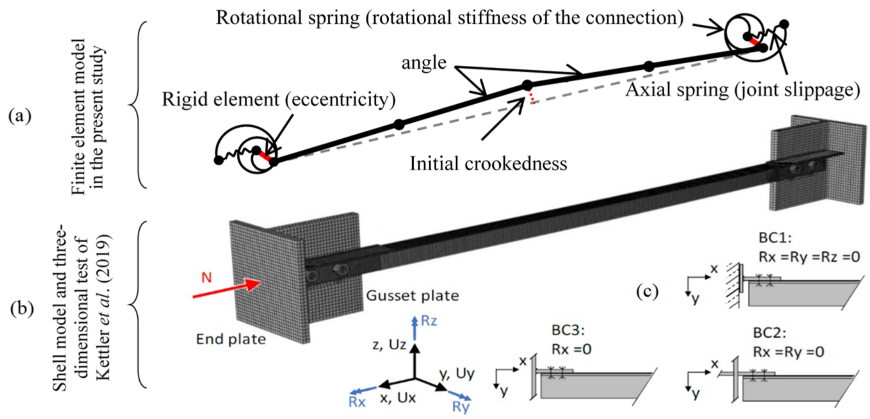

Fig. 1. a) Finite element (FE) model, **b)** 3D experimental test of Kettler et al. (2019), **c)** Boundary conditions

3. Results and discussion

3.1. Failure behavior of angle sections vs. experimental test results

The performance of the FE model in reasonably predicting the axial capacity of single angles is discussed here by comparing the corresponding test results of Kettler et al. (2019). Fig. (2-a) presents a graphical comparison between experiments and FE models based on the non-dimensional reference parameters N_R / N_{pl} and $N_{R,FEM} / N_{pl}$. It can be verified that the finite element calculations describe the ultimate loads of the experiments fairly accurately. Fig. (2-b, c, d) presents a comparison of the load-deformation curves up to the ultimate axial forces N_R. The joint slippage phase in the experimental and FE models is different, which is due to the type of connections. The majority of connections in the experimental specimen are of the prestressed type, and the connections in the FE model are bearing connections based on Ungkurapinan et al. (2003).

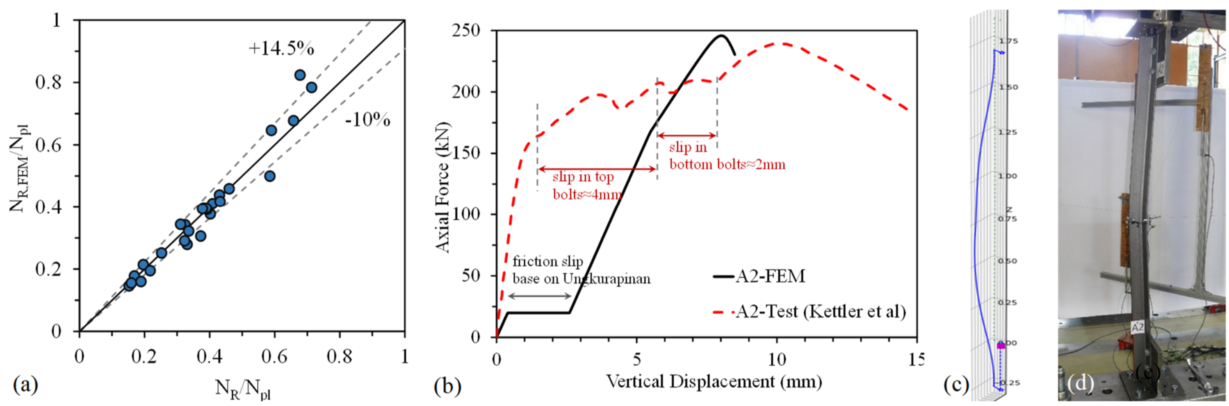

Fig. 2. a) Comparison of ultimate axial forces from experimental tests NR with numerical results NR, FEM, **b)** Comparison of axial force and vertical deformations at top between numerical and experimental tests: specimen A2 **c)** buckling behavior of an angle section in FE Model, **d)** Compression test on an angle section by Kettler et al. (2019).

3.2. Parametric study on imperfection sensitivity

Based on the finite element model, a numerical parametric study has been carried out in order to investigate the influence of geometric imperfections on the ultimate loads. The additional finite element models were developed and covered the following three cases:

1) Ultimate capacity load from the FE model without initial crookedness ($N_{R,\,noicr}$);

2) Ultimate capacity load from the FE model without eccentricity ($N_{R,\,noecc}$);

3) Ultimate capacity load from the FE model without joint slippage ($N_{R,\,noslip}$).

In Fig. 3, the results of these numerical models are compared with the comprehensive FE model ($N_{R,\,FEM}$). In this figure, a normal curve is fitted on the histogram of the data obtained from the numerical analysis. The median difference in the model without any eccentricity shows the important effect of this type of imperfection compared to joint slippage and initial crookedness.

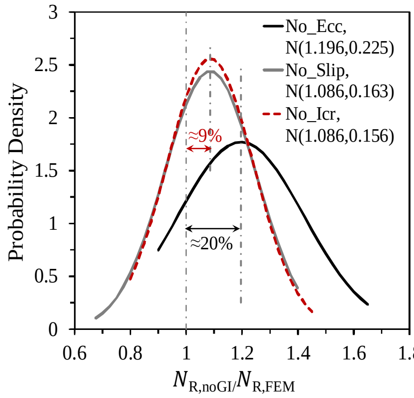

Fig. 3. Comparison of fitted normal distributions based on a parametric study of sensitivity to geometric imperfections

3.3. Failure behavior of angle sections vs. code provisions

In this section, the FE model and test results of Kettler et al. are compared with several relevant design standards by means of N_R/N_{pl} over λ_v diagrams. Fig. (4-a, b) compares the L80×8 test results with design standards and FE model results.

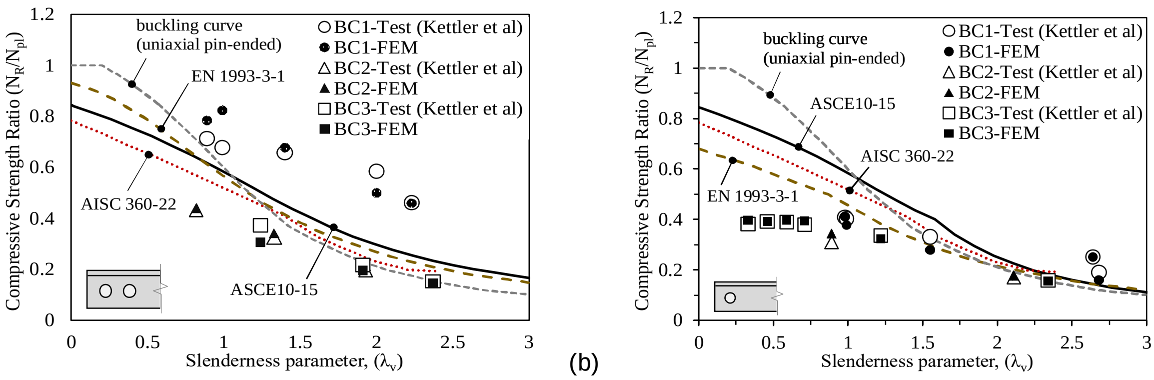

Fig. 4. Comparison of L80×8 test results with design standards and FE Model results: **a)** two-bolt connections, **b)** one-bolt connections

4. Conclusion

The results of the FE Model on single steel angles in compression with bolted connections and comparing them with the experimental studies and code provisions provide the following outcomes:

- The analytical results from the FE models show good agreement with the experimental results conducted by other researchers. This modeling method can consider the effects of geometric imperfections (eccentricity, joint slippage, and initial crookedness). More importantly, unlike the complexity of shell and solid modeling, the FE model is simple and improves the speed of modeling and analysis.
- Comparing the comprehensive FE model ($N_{R,\,FEM}$) and the FE model without initial crookedness ($N_{R,noicr}$) indicates that in some cases, this imperfection has a significant impact on predicting failure behavior. In some other cases where the difference is insignificant, it has been due to the very small geometric imperfections of the test specimen.

- Taking into account the eccentricity of single steel angles with one leg connected has a significant effect on the correct prediction of the ultimate capacity because eccentricity creates a concentrated moment and changes the internal forces of the member.
- While joint slippage has little effect on the prediction of ultimate capacity, it will have a significant effect on the prediction of member displacement.
- Based on the comparison of the ultimate loads between the tests and the numerical simulations, the effects of residual stresses are very small.
- The code provisions for boundary conditions BC1 (clamped end support) yield conservative predictions for the member buckling resistance, and their ultimate compressive strength is significantly higher than the current code requirements.
- There is a significant difference for members with low slenderness, especially for conditions BC2 (knife edge support) and BC3 (hinged support) in most code provisions. This issue is caused by the failure of connections in single-bolt samples with low slenderness, which causes the system capacity to decrease despite the high ultimate capacity of the angle members.