Effect of Hinge Properties on Nonlinear Analysis of Eccentrically Steel Braced Frames

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Abstract. Eccentrically Braced Frame (EBF) is one of seismic resistance of steel structures. Dissipation of seismic energies is designed by allowing plastic hinges to form in link element. Design of link elements allow plastic hinge to form due to shear or flexural failure. Structural analysis using finite element software require shear plastic hinges to be modelled. It is found that hinge properties proposed by two references, FEMA 356 and Richards & Uang are different. Study of effect of hinge properties on non-linear analysis of EBF was performed. The research is limited to hinge properties of shear link of EBFs. Numerical study was conducted on one and three storey of EBFs in two and three dimensional geometric of EBFs. Two different hinge properties from FEMA 356 and Richard-Uang were compared each other. Results show that hinge properties affect the structural response. It is found that EBFs modelled by hinge properties according to Richards-Uang has close result to experimental result than modelled built by FEMA 356. The difference between FEMA 356 and Richard-Uang to experiment are 34,54% and 15,55%, respectively.

1. Introduction
Eccentrically Braced Frame (EBF) is one of earthquake resistant structural systems for steel structure. It is a hybrid system, offering lateral stiffness from its concentrically brace, and ductility from moment frame system. EBF has a link that serves as an element of energy dissipation as well as the place of plastic joints. The link is intended to provide weaker section to allow plastic deformation so that energy from earthquake can be absorbed. Longer link will experience flexural yielding while shorter link will experience shear yielding. According to Bruneau [1], shear yielding allows the development of plastic deformation without an excessive amount of local strain, a phenomenon that appears with flexural yielding. According to Kasai [2], shear yielding provides larger dissipative energy capacity than flexural yielding. Hence, brace configuration, link length and link section properties are three important factors in EBF design. Shear link EBFs are more stable and more ductile than flexural link.

An analytic model of the shear link was proposed by Ramadan and Ghobarah [3] in 1995. It is modelled by three translational and three rotational sub-spring in each ends of the link. The stiffness and yielding of the link are determined by the force-deformation relationship of the sub-springs. Revised model was proposed by Richards and Uang in 2006 [4].

An earlier research by Inel [5] found that different parameters of hinge property could affect the structural response to earthquakes. Study conducted to RC structures showed that displacement capacity of structure was affected by plastic hinge length and the amount of transversal reinforcements in the hinge region. Therefore, bear in mind to conduct similar studies on EBF structure. This research aims
to compare the effects of the two hinge properties used in FEMA 356 and Richard-Uang. The study conducted by using OpenSEES software.

OpenSEES (Open System for Earthquake Engineering Simulation) is an open source software that is largely used by researchers. OpenSEES provides various materials, elements and algorithm. Each behaves differently and affects the results of the analyses. Results of the analyses conducted by OpenSEES can closely resembles the results of an advanced analysis. Thus, the results can be considered as advanced analysis. However, structural analysis using OpenSEES are considered costly since it is difficult to use. For that purpose, commercial software such as ETABS remain to be favoured instead of OpenSEES. However, there needs to be an adjustment in ETABS so that the analysis results can closely resemble advanced analysis. Hence, this research also aims to find out the best way to modelled EBFs with shear link in ETABS so that the result can be identical as the OpenSEES.

2. Numerical Model of EBF and Validation

As mention, the research objectives are to study the differences of hinge properties modelling on EBFs using the guidelines in FEMA 356 [6] and in Richard-Uang [4]. Then it aims to find out the strategy to model EBFs frame in ETABS so that the results are closed to OpenSEES. Pushover analysis was performed on EBFs using both software. Prior to this research, model validations need to be done to ensure that numerical model can represent the real condition. The reference are EBFs used by Shujun [7] who conducted experimental and numerical study of EBFs. Figure 1 show the EBFs used in Shujun’s study. It is Inverted-V EBF with a shear link as shown in in figure 1. The frame used H350x350x10x16 for columns, H300x150x6.5x9 for beams and \( \varnothing 150 \times 8 \) for braces. Steel has yield stress as 235 MPa.

Figure 2 shows EBF model used in openSEES. The shear link refers to Richards-Uang hinge property where link is presented as 3 rotational and 3 translational springs where each has different stiffness presented as multi-linear graph as shown in figure 3. Stiffness of each linier line can be determined based on Richards-Uang theory [4]. The equations are as follows:

\[
K_{V1} = \frac{2AE_{\text{shear}}}{e} \\
K_{V2} = 0.030 K_{V1} \\
K_{V3} = 0.015 K_{V2} \\
K_{V4} = 0 \\
V_p = 0.6 F_y A_{\text{shear}}.
\]

Steel02 is selected for steel material which is a uniaxial Giuffre-Menegotto-Pinto model with isotropic strain hardening. Truss element is assigned for bracing since it only receives axial loads. Beam and column use the NonlinearBeamColumn element, an element that assumes plastic deformation to be distributed along the element. Link is defined with BeamWithHinges command, where the plasticity is...
concentrated at the end of link. Each uses the ElasticPP command, which represents an elastic-perfectly plastic material. This allows the three springs are parallel to each other.

Push over analysis with P-delta effect was carried to represent loading stage conducted in the experiment and to allow the non-linearity in geometric. Results are presented on base shear and lateral displacement as shown in figure 3. As can be seen, result of openSEES agrees well with Shujun’s. It can be concluded that model built by openSEES is valid since it can represent the real structure, thus the openSEES model can be used for further study.

3. Research Methodology

Since the numerical model built by openSEES is valid, further study was continued to three-storey EBF. The frames were also built in three dimensional (3D) to see the geometric effect. Hence there are four EBF models investigate in this study; one-storey EBF in 2D geometric (1S-EBF2D) as presented in figure 1, one-storey EBF in 3D geometric (1S-EBF3D), three storey EBFs in 2D (3S-EBF2D) and 3D model (3S-EBF3D) as shown in figurer 5. The 3D model is an extension of the 2D model, thus having the same dimensions and specifications. The 3S-EBF3D is a single system where EBFs are only at grid A and D and frame on grid B and C have pin connection on each joint.

The different of FEMA 356 and Richard-Uang in modelling the hinge on link element is described in figure 6. As shown, the main difference is hinge location. FEMA assume that hinges are located on both link-end whereas Richard-Uang put hinges not exactly on link-end with an eccentricity as 5% of link length. This assumption affects force-deformation curve to represent the plastic hinge properties as shown in figure 7. As shown, point A, B, C, D, and E depends on value of a and b. The parameters are required when defining hinge properties in ETABS and modelling springs in OpenSEES. The different value of those parameters used in numerical model is presented on Table 1.
Figure 6. Link Model Based on Richards-Uang and FEMA 356.

Figure 7. Force-Deformation Curve on FEMA 356.

Table 1. Hinge Property of shear spring in OpenSEES and ETABS model.

| Point | OpenSEES model | ETABS model |
|-------|----------------|-------------|
|       | FEMA 356       | Richard-Uang| FEMA 356       | Richard-Uang| Force (N) | Displacement (mm) | Force (N) | Displacement (mm) | Force/SF | Displacement/SF | Force/SF | Displacement/SF |
| A     | 0              | 0            | 0              | 0              | 0          | 0            | 0              | 0              | 0         | 0         | 0         |
| B     | 258453         | 0.795493682  | 284298.3       | 0.62           | 1          | 0            | 0              | 0              | 0.916     | 0         |
| C     | 284298.3       | 25.71428571  | 335988.9       | 4.38           | 1.27       | 25.714       | 1.3            | 4.0153         |
| D     | 206762.4       | 25.71428571  | 387679.5       | 11.9           | 0.8        | 25.714       | 1.5            | 10.9           |
| E     | 206762.4       | 29.14285714  | 387679.5       | 27.43          | 0.8        | 29.143       | 1.5            | 25.002         |

Figure 8. Comparison Results of 2D 1 Bay 1 Storey EBF.

Figure 9. Comparison Results of 3D 1x1 Bay 1 Storey EBF.

Figure 10. Comparison Results of 3D 3x5 Bay 3 Storey EBF.
4. Results and Discussions

Results of comparative study of hinge properties proposed by Richard-Uang and FEMA 356 are shown in figure 8 to figure 10. Figure 8 present analysis results based on OpenSEES and ETABS software. Using the same hinge property proposed by Richard-Uang has slightly different results when analysis conducted by OpenSEES and ETABS. As shown, results of openSEES has closer results to Shujun’s experiment than ETABS. Results based on Richards-Uang’s model is 15.55% higher than Shujun’s whereas FEMA 356 are 34.54% higher. The difference is explained by figure 5. The Richards-Uang has rotational and linear springs at the ends of the link while the FEMA 356 has rotational springs with eccentricity as 5% from link-ends and put linear spring at the midpoint of the link. Modelling EBFs with ETABS using Richards-Uang hinge model results close agreement with advanced analysis. It can be concluded that the Richards-Uang shear link model is more accurate in modelling shear links in EBF steel structures.

Based on above results it can be concluded that hinge property greatly affects the analysis results. Hinge property use in FEMA 356 results result higher structural response than those model use with Richards-Uang’s hinge property. Therefore, it is suggested to adopt Richard-Uang model in defining hinge properties for EBF in order to get closer results to real structure.

5. Summary

Hinge properties proposed by Richards-Uang result a Point B displacement as 33% smaller than that of FEMA 356, thus earlier yielding occur. During the elastic stage, model with FEMA and Richard-Uang show the same behaviour since hinge properties only affect post-yield behaviour. Using OpenSEES software, hinge properties based on Richards-Uang and FEMA 356 have almost similar results. However, it is suggested to use Richard-Uang hinge since its closer to experiment results than FEMA 356.

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