Comparative Study of DAM and ELM to One-Storey Eccentrically Braced Frames Subjected to Seismic Load in Indonesia

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Abstract. Indonesia is late in updating its structural steel building design code to AISC 360-10. Revision was done in 2015 replacing the 2002 code. The new version changes the method of steel stability analysis from effective length method (ELM) to direct analysis method (DAM). The 2015 code implements DAM, which is based on second-order elastic analysis which directly calculates P-delta effect in analysis. DAM takes into account geometric imperfection and strength reduction. Notional load as 0.002 of gravity load should be applied horizontally to represent geometric imperfection. It is allowed to adjust the notional load coefficient. Numerical study has been conducted to compare the use of DAM and ELM on eccentrically-braced frame subjected to Indonesian seismic load. Different values of notional load coefficient are considered. Experimental results conducted by other researchers were used as reference. The frames were reanalysed using four different stability methods: ELM first-order analysis, ELM second-order analysis and DAM with different notional load coefficients: 0.002 and 0.003

1. Introduction
The design code of steel structural building in Indonesia, SNI 03-1729-2015, is a revision of the former code of SNI 03-1729-2002. It is a translated version of AISC 2010. Revision was made in 2015, five years after AISC released AISC 360-10 in 2010 and replaced the former code AISC 2005. One significant change from AISC 2005 to 2010 was structure stability analysis. AICS 2010 uses direct analysis method (DAM) as the main method, as mentioned in Chapter C: Design for Stability [1]. As stated, the direct analysis method allows a more accurate determination of the load effects in the structure through the inclusion of the effects of geometric imperfections and stiffness reductions directly within the structural analysis. This also allows the use of K = 1.0 in calculating the in-plane column strength. The former code, AISC 2005, used effective length method (ELM) as the main method. As mentioned in Appendix 7, ELM is still permissible to be used if the ratio of maximum second-order drift to maximum first-order drift in all storeys is equal to or less than 1.5. ELM can be approached in two ways, first is second-order analysis, similar to DAM, but without stiffness reduction, and, secondly, first-order analysis where P-delta effect is counted through moment amplification.

Notional loads to represent geometric imperfection are described in section C2.2b AISC 2010. The loads shall be applied as lateral loads at all structural levels. The notional load coefficient of 0.002 is
based on a nominal initial storey out-of-plumbness ratio of 1/500 of column length and it is permissible to adjust the notional load coefficient proportionally.

Laid on seismic zones where earthquakes frequently occur, hence, structural building in Indonesia should be designed according to the SNI 1726:2012 design code for earthquake resistance. Eccentrically Braced Frame (EBF) is an earthquake resistant structural system for steel structure. It is a hybrid system, offering lateral stiffness from its concentric brace, and ductility from moment frame system. In addition, EBF has a link that serves as an element of energy dissipation as well as the place of plastic joints. The plastic joints occur away from the column so that, in the planning, EBF structure has a high endurance and security [2].

Several studies comparing ELM and DAM as regard structural stability have been conducted by other researchers [3, 4], but most have been carried out on moment resisting frames and none on varied notional loads coefficient. Therefore, a numerical study of different notional load coefficients has been conducted on a one-storey concentric steel braced frame. The study was performed using different stability methods, ELM and DAM. One-storey EBF was simulated against three different seismic loads in the Indonesian seismic zone. Experimental results conducted by other researchers were used as reference. The experiments were reanalysed with four methods: ELM first-order analysis, ELM second-order analysis and DAM with two different notional load coefficients: 0.002 and 0.003.

2. Numerical Study

2.1. Numerical Model of EBF with flexural and shear link

An experimental studies reported by Shi [5] and Shujun [6], as shown in figure 1, are used as a reference in modelling EBF using SAP software [7]. The two frames have different link characteristic, flexural and shear link. As described in AISC 341 [8], flexural link is known as long link whereas shear link is known as short link. Frame elements are assigned for all elements, column, beam and bracing. Nonlinearity of material and p-delta effect plus large displacement were conducted in the analysis. Rigid connections were applied on beam column joint whereas pin connections were used for brace element according to the experimental set-up. Pushover analysis was carried out to represent the experimental test where horizontal load was applied incrementally until the frames reached maximum capacity. Characteristics of links were modelled according to moment curvature as described in FEMA 356 [10]. Plastic hinges on both beam and column end, as well as on link and bracing, were assigned.

![Figure 1. Two Eccentrically Braced Frames as a reference for numerical studies.](image1)

![Figure 2. The first plastic hinge and the final stage of EBF with Flexural Link.](image2)

![Figure 3. The first plastic hinge and the final stage of EBF with Shear Link.](image3)
Numerical simulations detect different collapse mechanism between the two frames, as can be seen on figures 2 and 3. The first plastic hinge at EBF with flexural link is formed at edge link and a subsequent plastic hinge is formed at beam segment outside of the link, as can be seen in figure 2. The SAP result agrees with numerical results obtained by Shi et al. [7]. For EBF with shear link, the shear yielding occurs in mid-link and is the only plastic hinge which is formed, as shown in figure 3.

Figure 4 and 5 show load – displacement curve based on SAP and experimental results. As can be seen, in the linear stage, the test results are slightly above the numerical results. After the first plastic hinge is formed, results of SAP have close agreement with the test result. Moreover, the numerical model can accurately predict the maximum capacity of EBF. It can be concluded that SAP can represent the test well and, hence, the model can be used for further numerical study.

2.2. Results and Discussion

The effect of initial imperfections should be taken into account, either by direct modelling of imperfections in the analysis or by the application of notional loads, as specified in Section C2.2b [1]. The magnitude of the notional loads shall be:

\[
N_i = 0.002\alpha Y_i \tag{1}
\]

where \(\alpha = 1.0\) (LRFD); \(\alpha = 1.6\) (ASD)

\(N_i\) = notional load applied at level \(i\), kips (N)

\(Y_i\) = gravity load applied at level \(i\) from the LRFD/ASD load combination, kips (N)

The notional load coefficient of 0.002 in equation (1) is based on a nominal initial storey out-of-plumbness ratio of 1/500L and it is permissible to adjust the notional load coefficient proportionally [1]. ELM can be referred to as a first-order elastic analysis where moment due to P-delta effect is calculated based on amplification factor [2]. ELM can also be analyzed as second-order analysis if the P-delta and P-\(\delta\) effect are included in the analysis. In order to see the difference in the ELM approaches of first-order and second-order analysis, the EBF frames were reanalyzed by both method. Meanwhile, different notional coefficients were used for the direct analysis method, which are DAM_0.002 and DAM_0.003.

Pushover analysis were carried out on both eccentrically braced frames. The maximum force is based on the limitation of ELM, where the ratio of second-order to first-order analysis is less or equal to 1.5. Hence the maximum pushover forces are: 1940.09kN for EBF with flexural links and 414.27kN for EBF with shear link. Results of pushover analysis are plotted on figure 6 and 7. Load-displacements curves resulting from different stability analysis methods are compared to experimental tests performed by Shi et al. and Shujun et al. The curves of the four methods are almost similar for EBF with flexural link, whereas slightly different results are observed on EBF with shear link. It can be concluded that using ELM or DAM as stability analysis of EBF with single storey leads to similar structural responses in term of force – displacement value.
Further study was carried out by taking into account seismic load. The EBF were simulated in three different seismic zones in Indonesia, from the lightest and medium to the strongest seismic load, which are Samarinda, Jakarta and Padang, respectively. Seismic simulation also considered three different soil conditions: hard, medium and soft soil, which are named as SC, SD and SE, respectively. Horizontal forces presenting earthquake load are determined based on SNI 1726:2012 [13] using linear elastic seismic analysis, as follows:

\[ F_x = C_{vx} V \]  

where: 
- \( F_x \) : Seismic load for x-storey
- \( C_{vx} \) : Distribution factor for each floor
- \( V \) : Base shear of structure, where \( V = C_s W \)
- \( W \) : Effective Weight of the structure, and \( C_s \) : Seismic response factor

Table 1. PM Interaction of EBF.

| Seismic Zone | Soil Type | Earthquake Loads (kN) | PM Interaction of EBF with Flexural Link | PM Interaction of EBF with Shear Link |
|--------------|-----------|------------------------|------------------------------------------|--------------------------------------|
|              |           |                        | Advanced Analysis | ELM 1st Order | ELM 2nd Order | DAM 0.002 | DAM 0.003 | Advanced Analysis | ELM 1st Order | ELM 2nd Order | DAM 0.002 | DAM 0.003 |
| Samarinda    | SC        | 12.54                  | 0.016            | 0.016         | 0.016         | 0.016      | 0.016      | 0.007   | 0.007 | 0.007 | 0.007 |
|              | SD        | 16.73                  | 0.022            | 0.022         | 0.022         | 0.022      | 0.022      | 0.009   | 0.009 | 0.009 | 0.009 |
|              | SE        | 26.13                  | 0.034            | 0.034         | 0.034         | 0.034      | 0.034      | 0.014   | 0.014 | 0.014 | 0.015 |
| Jakarta      | SC        | 72.74                  | 0.095            | 0.094         | 0.094         | 0.094      | 0.094      | 0.040   | 0.040 | 0.040 | 0.040 |
|              | SD        | 82.77                  | 0.108            | 0.107         | 0.107         | 0.107      | 0.107      | 0.046   | 0.046 | 0.046 | 0.046 |
|              | SE        | 94.06                  | 0.122            | 0.122         | 0.122         | 0.122      | 0.122      | 0.052   | 0.052 | 0.052 | 0.052 |
| Padang       | SC        | 145.68                 | 0.190            | 0.188         | 0.189         | 0.189      | 0.189      | 0.081   | 0.081 | 0.081 | 0.081 |
|              | SD        | 145.68                 | 0.190            | 0.188         | 0.189         | 0.189      | 0.189      | 0.081   | 0.081 | 0.081 | 0.081 |
|              | SE        | 131.30                 | 0.171            | 0.170         | 0.170         | 0.170      | 0.170      | 0.073   | 0.073 | 0.073 | 0.073 |

Results of the analysis are presented on PM interaction and drift. PM is determined based on interaction formula where factored axial force Pu and bending moment Mu are compared to each’s nominal strength, ΦPn and ΦMn, multiplied by their resistance factors. Drift is top lateral displacement of the frames. Table 1 and 2 present PM interaction results and drift. Advanced analysis based on numerical simulation as mentioned in Section 2 is used as a reference. As presented, similar PM values are found for both EBF with flexural or shear links, which means that stability analysis using ELM and DAM gives the same results. Moreover, there is no effect of different value of notional load coefficient to the PM ratio.

Different results are found at drift, as shown in table 2. Although ELM and DAM do not give significant results, ELM second-order analysis gives closer results to advanced analysis than other
methods for EBF with flexural links. DAM with notional load coefficients as 0.002 or 0.003 has similar drift. Meanwhile, similar drift is also detected on EBF with shear link when it is analyzed with ELM second-order and DAM. Again, changing notional load coefficient from 0.002 to 0.003 does not change the drift. In addition, the value of PM interaction and drift is far below the allowable value. The allowed drift of EBF with flexural links and shear links is 2.675mm and 7.5mm, respectively.

Table 2. Drift of EBF.

| Seismic Zone | Soil Type | Earthquake Loads (kN) | Drift of EBF with Flexural Link | Drift of EBF with Shear Link |
|--------------|-----------|------------------------|---------------------------------|------------------------------|
|              |           |                        | Advanced Analysis | ELM 1st Order | ELM 2nd Order | DAM _0.002 | DAM _0.003 | Advanced Analysis | ELM 1st Order | ELM 2nd Order | DAM _0.002 | DAM _0.003 |
| Samarinda    | SC        | 12.54                  | 0.39              | 0.31          | 0.40          | 0.52        | 0.52        | 0.18             | 0.18          | 0.18          | 0.18      | 0.18       |
|              | SD        | 16.73                  | 0.51              | 0.42          | 0.53          | 0.69        | 0.69        | 0.23             | 0.24          | 0.24          | 0.24      | 0.24       |
| Jakarta      | SE        | 26.13                  | 0.80              | 0.65          | 0.83          | 1.08        | 1.08        | 0.37             | 0.37          | 0.37          | 0.37      | 0.37       |
|              | SC        | 72.74                  | 2.32              | 1.82          | 2.31          | 3.02        | 3.01        | 1.02             | 1.04          | 1.02          | 1.03      | 1.02       |
|              | SD        | 82.77                  | 2.54              | 2.07          | 2.63          | 3.43        | 3.42        | 1.16             | 1.18          | 1.17          | 1.17      | 1.17       |
| Padang       | SE        | 145.68                 | 4.47              | 3.64          | 4.63          | 6.04        | 6.03        | 2.04             | 2.07          | 2.05          | 2.05      | 2.05       |
|              | SC        | 131.30                 | 4.03              | 3.28          | 4.17          | 5.45        | 5.43        | 1.84             | 1.87          | 1.85          | 1.85      | 1.85       |

3. Conclusion

The effect of different methods of steel stability analysis, ELM and DAM, to one-storey EBF is not significant. This is because of the study is only limited to one-storey structure where the instability do not appear significantly. Hence the buckling factor “K” between ELM and DAM seems similar. Two different notional load coefficients also do not significantly change the EBF response. This is due to less gravity load worked on structure. However, notional load is a function of gravity load. The finding is confirmed by PM interaction and drift results when the frames are loaded by seismic load according to the seismic design code in Indonesia. The EBF has enough strength against seismic loads in all seismic zones in Indonesia. Further study should be conducted on multi-storey EBF with gravity load.

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