Numerical study of two low rise eccentrically braced steel frames under Indonesia seismic load using ELM and DAM

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Abstract. Indonesia steel design code SNI 1729:2015 is a translation of AISC 360-2010 [1,2]. One of the significant revision of AISC 2010 is changing the stability analysis to Direct Analysis Method (DAM). DAM is an elastic analysis which includes second-order effect where P-delta and geometric imperfection are directly calculated during the analysis. Imperfection is modelled as notional load applied horizontally which is determined as 0.002 of gravity load. Numerical study using SAP software had been conducted to compare DAM and the previous method ELM on eccentrically braced frames (EBFs) under seismic load. It is known that EBF is one of earthquake resistant structural systems of steel structure. Numerical study was validated against experimental results performed by other researchers. Similar EBF frames used in the experiment were reanalyzed by ELM and DAM and coefficient of notional load is varied as 0.002 and 0.003. Seismic load applied in the analysis were varied based on three different seismic zones and soil conditions.

1. Introduction

Indonesia steel design code SNI 1729:2015 is a translation of AISC 360-2010 [1,2]. One of the significant revision of AISC 2010 is changing the stability analysis to Direct Analysis Method (DAM) substituting the preceding method Effective Length Method (ELM). The 2010 code uses DAM as its main analysis and ELM as an alternative. DAM is more accurate for stability analysis since second order effect is calculated explicitly in the analysis. Moreover, residual stress and out-of-plumbness effects may also be included in the analysis, therefore effective length factor can be omitted by taking effective length factor K as one.

As an alternative, ELM is still allowed to be used as explained on Appendix 7 of AISC 2010, if the ratio of maximum second-order drift to maximum first-order drift in all stories is equal to or less than 1.5 [1]. ELM includes the P-delta effect through amplification factor. To simplify the instability effect due to buckle, K factor is introduced as effective length where the value is determined according to relative rigidity between girder and column. Since the rapid development of ICT, P-delta effect and buckling can be directly calculated in the analysis. Hence, this method is named as direct analysis method, DAM.
Both ELM and DAM determine nominal capacity of individual column by using column interaction equations [3]. Initial imperfections, such as out-of-plumbness and fabrication tolerances, result destabilizing effects. As explained in Section 2.2 AISC 2010, it can be included in the analysis through direct modeling or represented as notional loads. Notional loads are applied as lateral loads at each level as an addition to other lateral loads. The load value shall be 0.002 of gravity load of each level. According to clausal 2.b of Section C AISC 2010, the coefficient of 0.002 equals nominal initial story out-of-plumbness ratio as 1/500. However, the load coefficient can be adjusted proportionally, if necessary.

Several study have been done to compare DAM and ELM to structural steel design results [5-7]. Analysis conducted on 1-storey with 1 bay structure result higher stress ratio when using ELM [3]. DAM has its advantages which are simpler to applied and more accurate for case which have significant second order effect. It is confirmed by study conducted on 1 story with 3 bays steel frame [5]. However, study which are compare DAM and ELM are rarely conducted on steel brace frame.

A numerical study to compare ELM and DAM on one and three-storey eccentric steel braced frame have been conducted. Preliminary research had been performed on one-story EBF, comparing flexural link and shear link [6]. The study was extended to three story EBF. Similar with former research, experimental study conducted by other researcher was reanalyzed using ELM and DAM. The frames were simulated against lateral loads represented seismic load from three seismic zones in Indonesia. Four stability methods were employed: ELM with first and second-order analysis, and DAM with notional load coefficients as 0.002 and 0.003.

2. Numerical Model of EBF and Validation

Numerical study was conducted using SAP2000 [8] software. Validation of numerical model was initially performed against two frames used in former experimental study conducted by other researcher, Shi [9] and Shujun [10] as shown in Figure 1 and 2. As described in AISC 341 [11] the two frames have the same link characteristics known as shear link.

![Figure 1. One-storey of EBF 1 [9].](image1)

![Figure 2. Three stories of EBF 3 [9].](image2)

Frame element are selected for beam, column and bracing. Following the experimental set-up, rigid and pin connections were assigned on connection of beam to column and brace connection, respectively. Moment curvature according FEMA 451 is assigned to link elements. [12]. To simulate the incremental loading, pushover analysis was carried out. Non linear of geometry and material were employed in the analysis. Plastic hinges were assigned on beam and column end, link and bracing.
The results are presented on load versus horizontal displacements. Both experiment and numerical results are plotted on the same graph as shown in Figure 3 and 4. As shown in Figure 3, experiment and numerical simulation of one storey frame is agree well. Furthermore, results from SAP analysis of three stories frame is not as good as one storey frame as presented in Figure 4. Initial stage of its load deflection curves agrees with experiment, where in the initial stage, the stiffness of SAP model is faintly higher compared to experimental result. After the plastic hinge was formed, the SAP result is above the test results. The maximum forces from SAP (365.85kN) is 10.9% higher than experiment (330kN). However, the first plastic hinge of SAP model occurred at 304.23kN which is late than experiment at 284.38kN.

Figure 3. Validation of Numerical Model on one storey EBF.

Figure 4. Validation of Numerical model on three stories EBF.

Figure 5 shows collapse mechanism of both frames. As shown, similar mechanism was detected as the plastic hinge form at shear link. The results confirm numerical results conducted by Shi et al. [9] where shear yielding occurs in mid-link. It can be concluded that numerical simulation using SAP software can simulate the experiment. Therefore, numerical models are considered valid and further study can be carried out using those models. The test results are used as reference in comparing ELM and DAM and named as advanced analysis. Advanced analysis is known as non-linear inelastic analysis where non-linearity in geometric and material are considered in the analysis.

Figure 5. Plastic hinge on One-story and three stories EBF.

3. Results and Discussions

3.1. Comparison of DAM and ELM
Comparison study between DAM and ELM as steel stability analysis is conducted according to SNI 1729:2015 which accord to AISC 2010. ELM is the method adopted in the preceding design code, SNI
03-1729-2002. DAM was initially introduced as an alternative method besides ELM in AISC 2005. Refer to AISC 2010, DAM is the main method in SNI 2015 and ELM is one of alternative methods. Unlike SNI 2002 where ELM with first order elastic analysis is the only method used, SNI 2015 introduces second order elastic analysis of ELM. The difference between first and second order analysis is in determining the P-delta effect. As described on Appendix 8 AISC 2010, first order analysis calculates P-delta effect through amplification factor whereas second order analysis includes the effect in the analysis. Requirement details of DAM and ELM can be found on Chapter C and Appendix 8 of AISC 360-10, respectively. In addition, besides imperfection, DAM can also consider reduction of stiffness as 20% than initial condition, except for displacement calculation.

As explain in Section C2.2b, initial imperfections of column can be directly modeled in the analysis or represented as notional loads [1]. The loads are determined as follow:

\[ Ni = 0.002aY_i \]  \( \text{where} \ a = 1.0 \ (LRFD); \ a = 1.6 \ (ASD) \)

\[ Ni = \text{notional load applied at level } i, \text{ kips (N)} \]

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

The constant of 0.002 in equation (1) is determined based on amount of nominal initial story out-of-plumbness ratio of 1/500L and is allowed to adjust proportionally [1]. Two EBFs shown in Figure 1 and 2 were reanalyzed by two different approach of ELM, first order and second order approach. DAM with two notional load constant number of 0.002 and 0.003 were used. The loads were laterally applied according to equation 1. Hence, four stability methods named as ELM first order, ELM second order, DAM_0.002 and DAM_0.003 are compared.

The study aims to evaluate different notional load values which represent the column plumbness. The second objective is to see how effective the amplification moment factor can represent the P-delta effect on ELM analysis. Pushover analysis were carried where the maximum force is limited to ratio of second-order to first-order analysis as 1.5. Henceforth, one-story and three-stories EBF were loaded by 1940.09 kN and 1043.25 kN, respectively.

![Figure 6. Comparison Results of one-storey EBF analyzed by ELM and DAM.](image)
Figure 6 and 7 shows results of pushover analysis. As shown, stability analysis using ELM or DAM is not significant on one-storey EBF as can be seen from the four graphs that close each other. Slightly different are found on three-storey EBF as can be seen on Figure 7. At the same base shear, DAM_0.003 has the highest drift followed by DAM 0.002 and ELM. The results are due to lateral forces applied at DAM 0.003 is higher since it is added by notional loads. The difference is not significant since the loads is a function of gravity loads which come from EBF’s selfweight. Thought that the effect is not significant, ELM second order is less stiff than ELM first order. The result is predicted since ELM second order include the effect of P-delta in the analysis.

3.2. EBF subjected to Indonesian Seismic Zone

Study of ELM and DAM is proceeded by comparing PM ratio of EBFs as a results of seismic simulation. The EBFs were loaded by earthquake load according to Indonesia design code: SNI 1726-2012 [13]. The frames were simulated in 3 seismic zones, Samarinda, Jakarta and Padang which considered as light, medium and strong seismic zone, respectively. Soil types were varied as hard, medium and soft soil which were denoted as SC, SD and SE, respectively. Earthquake loads applied are determined as follows [14]:

\[ F_x = C_{vx} V \]  

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

As discusses earlier, two EBFs used in this study are those tested by Shujun where the frames were loaded horizontally. Similar load case was applied in this study where horizontal load consisted of earthquake and notional load. Hence, combination of loads according to ASCE [15] are: (C1) 1.4D + 1.4ND; (C2) 1.2D + 1.0E and (C3) 0.9D + 1.0E, where D is dead load, ND is notional dead load, and E is earthquake. Combination C2 result the highest PM interaction for both EBFs, hereafter, only that combination result is discussed here. Structural responses are presented as PM interaction where it is determined based on ultimate load of axial and flexural compared to its each nominal capacity as follow:
For ratio of $P_u / \phi P_n \geq 0.2$ PM interaction : $P_u/\phi P_n + 8M_u/(9\phi P_n) \leq 1$ (3)

For ratio of $P_u / \phi P_n < 0.2$ PM interaction: $P_u/(2\phi P_n) + M_u/(9\phi P_n) \leq 1$ (4)

Results of numerical simulation modeled based on experimental test is assumed as advanced analysis since the model can simulate the experimental test. Advanced analysis is a non-linear inelastic analysis considering non-linearity in geometric and material. Hence it can be used as reference to compare ELM and DAM.

Table 1 and 2 shows PM interaction results of EBFs. The value presented here were taken from column at the lowest floor. Similar with previous result, ELM and DAM have no different effect in term of PM ratio of one story EBF. As presented on Table 1, PM ratio of ELM and DAM are same. Minor effect of ELM and DAM is observed on PM ratio of three stories-EBF. The four methods, ELM first order, ELM second order, DAM_0.002 and DAM_0.003, have ratio below advanced analysis. PM-interactions obtained for all methods are below 0.5.

### Table 1. PM Interaction of One-Storey EBF.

| Seismic Zone | Soil Type | Earthquake Loads (kN) | PM Interaction of One-Storey EBF |
|--------------|-----------|------------------------|---------------------------------|
|              |           |                        | Advanced Analysis | ELM 1st Order | ELM 2nd Order | DAM _0.002 | DAM _0.003 |
| Samarinda    | SC        | 12.54                  | 0.007              | 0.007        | 0.007        | 0.007      | 0.007      |
|              | SD        | 16.73                  | 0.009              | 0.009        | 0.009        | 0.009      | 0.009      |
|              | SE        | 26.13                  | 0.014              | 0.014        | 0.014        | 0.015      | 0.015      |
| Jakarta      | SC        | 72.74                  | 0.04               | 0.040        | 0.04        | 0.04       | 0.040      |
|              | SD        | 82.77                  | 0.046              | 0.046        | 0.046       | 0.046      | 0.046      |
|              | SE        | 94.06                  | 0.052              | 0.052        | 0.052       | 0.052      | 0.052      |
| Padang       | SC        | 145.68                 | 0.081              | 0.081        | 0.081       | 0.081      | 0.081      |
|              | SD        | 145.68                 | 0.081              | 0.081        | 0.081       | 0.081      | 0.081      |
|              | SE        | 131.30                 | 0.073              | 0.073        | 0.073       | 0.073      | 0.073      |

### Table 2. PM Interaction of Three-Stories EBF.

| Seismic Zone | Soil Type | Earthquake Loads (kN) | PM Interaction of Three-Storey EBF |
|--------------|-----------|------------------------|---------------------------------|
|              |           |                        | Advanced Analysis | ELM 1st Order | ELM 2nd Order | DAM _0.002 | DAM _0.003 |
| Samarinda    | SC        | 123.69                 | 0.066              | 0.057        | 0.057        | 0.057      | 0.057      |
|              | SD        | 164.97                 | 0.088              | 0.076        | 0.076        | 0.076      | 0.076      |
|              | SE        | 257.73                 | 0.138              | 0.119        | 0.118        | 0.118      | 0.118      |
| Jakarta      | SC        | 717.38                 | 0.384              | 0.330        | 0.329        | 0.329      | 0.328      |
|              | SD        | 816.33                 | 0.437              | 0.375        | 0.374        | 0.374      | 0.374      |
|              | SE        | 927.65                 | 0.497              | 0.427        | 0.425        | 0.425      | 0.425      |
| Padang       | SC        | 1436.77                | 0.769              | 0.661        | 0.658        | 0.659      | 0.658      |
|              | SD        | 1436.77                | 0.769              | 0.661        | 0.658        | 0.659      | 0.658      |
|              | SE        | 1295.00                | 0.693              | 0.595        | 0.593        | 0.594      | 0.593      |
Table 3. Drift of One-Storey EBF.

| Seismic Zone | Soil Type | Earthquake Loads (kN) | Advanced Analysis | ELM 1st Order | ELM 2nd Order | DAM _0.002 | DAM _0.003 |
|--------------|-----------|-----------------------|-------------------|---------------|---------------|------------|------------|
| Samarinda    | SC        | 12.54                 | 0.18              | 0.18          | 0.18          | 0.18       | 0.18       |
|              | SD        | 16.73                 | 0.23              | 0.24          | 0.24          | 0.24       | 0.24       |
|              | SE        | 26.13                 | 0.37              | 0.37          | 0.37          | 0.37       | 0.37       |
| Jakarta      | SC        | 67.94                 | 1.02              | 1.04          | 1.02          | 1.02       | 1.02       |
|              | SD        | 82.77                 | 1.16              | 1.18          | 1.17          | 1.17       | 1.17       |
|              | SE        | 94.06                 | 1.32              | 1.34          | 1.32          | 1.32       | 1.32       |
| Padang       | SC        | 145.68                | 2.04              | 2.07          | 2.05          | 2.05       | 2.05       |
|              | SD        | 145.68                | 2.04              | 2.07          | 2.05          | 2.05       | 2.05       |
|              | SE        | 131.30                | 1.84              | 1.87          | 1.85          | 1.85       | 1.85       |

allowable drift = 60mm

Table 4. Drift of Three-Stories EBF.

| Seismic Zone | Soil Type | Earthquake Loads (kN) | Advanced Analysis | ELM 1st Order | ELM 2nd Order | DAM _0.002 | DAM _0.003 |
|--------------|-----------|-----------------------|-------------------|---------------|---------------|------------|------------|
| Samarinda    | SC        | 123.69                | 5.950             | 5.670         | 5.858         | 5.770      | 8.551      |
|              | SD        | 164.97                | 7.936             | 7.562         | 7.813         | 7.793      | 11.405     |
|              | SE        | 257.73                | 12.399            | 11.815        | 12.207        | 12.338     | 17.819     |
| Jakarta      | SC        | 717.38                | -                 | 32.886        | 33.977        | 34.857     | 49.598     |
|              | SD        | 816.33                | -                 | 37.422        | 38.663        | 39.705     | 56.439     |
|              | SE        | 927.65                | -                 | 42.525        | 43.935        | 45.159     | 64.135     |
| Padang       | SC        | 1436.77               | -                 | 65.865        | 68.048        | 70.102     | 99.334     |
|              | SD        | 1436.77               | -                 | 65.865        | 68.048        | 70.102     | 99.334     |
|              | SE        | 1295.00               | -                 | 59.365        | 61.333        | 63.156     | 89.532     |

allowable drift = 254mm

Comparison of horizontal displacement at top story called as drift are displayed on Table 3 and 4. The value of allowable drift are determined based on SNI 1729-2012 and ASCE 7-16, section 12.12. The EBFs are categorized as all other structures and classified in risk category II. Thus allowable drift is 0.02h where the limit for one storey is 60mm and 254mm for three stories. The EBFs drift are meet the requirement which is below the maximum value. Similar results are also found that ELM and DAM do not results significant effect to drift of both EBFs.

As presented on Table 4, DAM with notional load factor as 0.003 have the highest drift followed by DAM _0.002, ELM second order and ELM first order. As discussed earlier, this is due to addition of horizontal forces comes from notional loads and second order effect. EBFs with ELM analysis were only loaded by earthquake without notional load.

4. Conclusions
Comparing different methods of steel stability analysis, ELM and DAM, to two EBFs gives almost similar results on one storey frame. The difference of instability calculated by the two methods does not appear significantly. Hence, the buckling factor “K” between ELM and DAM
seems similar. In term of PM ratio, three stories EBFs also have similar results. The effect of ELM and DAM appears evidently on three stories where DAM_0.003 has the highest drift. Initial imperfections of column as 0.002 (1/500L) and 0.003 that represented on notional loads slightly change the EBF responses. This is because of less dead load load worked on the structures. However, notional load is a function of gravity load. Both EBFs have enough strength against seismic loads in three seismic zones in Indonesia.

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