Study of inelastic behaviour steel structure of special moment frame (SMF) and eccentrically braced frame (EBF) with pushover analysis

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Abstract. High rise buildings should be made as sufficient seismic performance, so it won’t immediately collapse when an earthquake occurs. Therefore, lateral strengthened stories are required in high rise buildings to enhance the lateral rigidity of structure. The use of lateral strengthening has a great effect on the entire seismic performance. A 20-stories high rise steel structure building was evaluated on this research comparing the structures’ inelastic behaviour using two seismic force-resisting system, i.e., special moment frame and eccentrically braced frame. The analysis of inelastic behaviour in this research using static non-linear analysis, i.e., pushover analysis. By using pushover analysis, the inelastic behaviour of structures, including story drift, shear story, displacement, plastic joint formation, and ductility, were obtained. In the elastic condition, the shear story of the eccentrically braced frame system is smaller than the special moment frame system. While in plastic condition, the shear story of the eccentrically braced frame system is larger than the special moment frame system. The story drift and the displacement of the special moment frame system are indicated to be larger than the eccentrically braced frame system. These results show that the eccentrically braced frame system has better rigidity than the special moment frame system.

1. Introduction
Along with the rapidly growing population growth as well as the availability of the vacant land, is the cause of the increasing number of high rise building to provide maximum service for its user. But when an earthquake occurs, it will certainly cause the public to panic, while the objects most affected by the earthquake are infrastructures, including high rise buildings, houses, apartments, etc. If the high rise buildings are not strong enough, a large rift will definitely occur in the building or even collapsed when it struck by an earthquake, and it will also cause many fatalities. Therefore, one way to prevent fatalities caused by an earthquake is to build earthquake-resistant buildings.

An earthquake-resistant building here does not mean that the building will not be destroyed at all, but at least when there is an earthquake with large scale, then the building does not immediately collapse so the people inside could save themselves out of the building. In addition, earthquake-resistant building structures could also be interpreted as a building that capable of dampening the vibration of the earthquake so that the effect is not too big against the building. Basically, the earthquake resistance building implements some principle such as flexibility principle, rigidity principle, and resistance principal.

In the design and analysis of a high rise building, structures are influenced by the effect of lateral loads such as wind load and earthquake load, depending on which load is dominant. Lateral load, such as earthquake and wind load, are the main factor for high rise structures. Therefore, to reduce lateral deformation that would occur on the structures is to install some horizontal strengthened to each or some
stories of the high rise building [1]. In order for a high rise building could be an earthquake resistance building, the structure should be designed with seismic force-resisting system as one way to withstand lateral loads.

The function of a high rise building is also influenced by the tendency of the structure system to be used. That is not apart from the needs of its building and the efficiency of the building. Therefore, a better understanding of many seismic force-resisting that is available is required. This research has the objective of comparing two different steel seismic-force resisting systems, which are Special Moment Frame (SMF) and Eccentrically Braced Frame (EBF), with pushover analysis.

2. Research Methodology

This research was done by numerical modelling the 20-stories steel structure using STAAD Pro software to obtain the seismic response of the structure. The analysis used in this research was a non-linear static analysis, which is pushover analysis. Pushover analysis is a non-linear static structure analysis with a permanent vertical load and the lateral load that increased on an incremental basis [2]. Pushover analysis is carried out by applying a monotonic load to the structure with a pattern that continues to increase from the lateral load, which will show the force experienced by the structure when it receives a ground motion load [2]. The basic procedure of this method is to carry out a static elastic analysis in stages with an increase of lateral loading until the structure collapses. In the increase of loading, some structural elements would experience yielding sequentially [2]. At each stage of loading, there would be a decrease in the structure's stiffness. The pushover is performed in a force-controlled manner with a lateral force up to 50 times of the elastic equivalent static earthquake force.

With pushover analysis, response characteristics that could not be obtained through static and dynamic analysis and also the relation between non-linear force and displacement can be obtained. Through pushover analysis, we could find out the inelastic behaviour of the high rise building that was used in this research. The inelastic behaviour that was reviewed in this study includes story drift, shear story, displacement, plastic joint, and also ductility. The inelastic behaviour in steel structure is accommodated through the formation of plastic hinges in the beam at beam-column joint and column base.

When the structure receives an earthquake load at a certain level, a plastic hinge will occur on the beam. The plastic hinge works almost the same as shock breaker or springs which are useful to reduce the vibration, or in this case is to reduce the energy (energy dissipation) of the earthquake that occurs. The planned location of the plastic hinge must be designed to have a certain ductility in order to withstand the earthquake forces after the elastic condition of the structure is exceeded. The design of a building must also be in accordance with the design concept of strong column – weak beam. If there is a structural collapse, the beam will collapse first. While if the column is the one that first collapses, the structure will be immediately destroyed.

There are many different kinds of seismic-force resisting systems that could be used for high rise steel structure building. The seismic-force resisting system used in this paper are Special Moment Frame (SMF) and Eccentrically Braced Frame (EBF) system. Then the inelastic behaviour results from these two different systems were compared.

2.1. Special Moment Frame (SMF)

The structural steel special moment frame is made of beams, columns, and beam-column connections that are proportioned and detailed to resist flexural, axial, and shear actions that result in building sways because of multiple inelastic displacement cycle during an earthquake ground shaking [3]. This special proportioning aims to enabling the structure to resist earthquakes while experiencing inelastic behaviour safely [3].

The structure used in this analysis is a 20-story high rise steel structure building with 13 feet height of each story and a total height of 260 feet made from beams, columns, and beam-column connection. The numerical modelling in this research for the special moment frame structure could be seen in the image below as Figure 1.
2.2. Eccentrically Braced Frame (EBF)
An eccentrically braced frame that consists of columns, beams, stiffeners, and links, is a system to transfer the axial forces induced in the braces to a column or another brace through shear and bending in a critical beam segment called a link [4, 5]. In a split-K type structure, the link element is located in the middle of the span between two braces connected to the ends of the lower column on each floor [4]. Links are structural components that experience the greatest deformation due to lateral loads because they bear the most bending and shear moments among other structural components [4, 6]. These links act to dissipate a large amount of energy caused by a severe seismic activity by material yielding [4, 5].

In order to compare the response behaviour of special moment frame and eccentric brace frame, there are several types of modification made in the structure of eccentric brace frame in this study, i.e., eccentric brace frame structure on cores, eccentric braced frame structure on cores with cap truss, and eccentric brace frame structure on cores with outrigger. The cross-section of the numerical modelling for eccentric braced frame could be seen in the figure below. Figure 2 is the cross-section model for the eccentrically braced frame on its core on all floors. While in Figure 3 is the cross-section model for the eccentrically braced frame on its core in all floors with cap truss addition in top floors, and Figure 4 is the cross-section model for the eccentrically braced frame on its core in all floors with outrigger.
2.3. Cross Section & Material Property
A 20-story building in this study uses steel material with the yield strength is 50 ksi. The tensile strength is 65 ksi. The column, beam, and bracing properties for the structure are outlined in Table 1 and Table 2 below. The beam cross-section that was used in this research is W12x27 for all beam in this building. While different columns and bracing are used where the cross-section became smaller the more story it increased that is in line with less load it received.

### Table 1. Beam Cross-Section

| Floor | 1-2   | 2-3   | 3-4   |
|-------|-------|-------|-------|
| 20    | -     | W12X27| -     |
| 2-19  | W12X27| W12X27| W12X27|
| 1     | -     | -     | -     |

### Table 2. Column and Bracing Cross-Section

| Floor | Column 1  | Column 2  | Column 3  | Column 4  | All Columns |
|-------|-----------|-----------|-----------|-----------|-------------|
| 19-20 | W14x211   | W14x211   | -         | -         | W14x132     |
| 18-19 | W14x61    | W14x211   | W14x211   | W14x61    | W14x132     |
| 17-18 | W14x61    | W14x211   | W14x211   | W14x61    | W14x133     |
| 16-17 | W14x90    | W14x211   | W14x211   | W14x90    | W14x134     |
| 15-16 | W14x90    | W14x211   | W14x211   | W14x90    | W14x135     |
| 14-15 | W14x132   | W14x211   | W14x211   | W14x132   | W14x136     |
| 13-14 | W14x132   | W14x211   | W14x211   | W14x132   | W14x137     |
3. Results and Discussion

3.1. Story Drift

The fundamental period of the structure in the elastic and the inelastic condition could be seen in Table 3. It shows that the plastic period of all the system structure that used in this study is much greater than during the elastic condition. While the plastic period of the SMF model is greater than the plastic period of the EBF model.

Table 3. Fundamental Period

| Structural System Model                          | Fundamental Period (second) |
|------------------------------------------------|----------------------------|
|                                                 | Elastic | Plastic |
| Steel Moment Frame (SMF)                        | 0.188   | 9.731   |
| Eccentric Brace Frame at Core                   | 0.194   | 1.955   |
| Eccentric Brace Frame at Core + Cap Truss       | 0.191   | 1.878   |
| Eccentric Brace Frame at Core + Outrigger       | 0.190   | 1.721   |

The story drift was calculated based on the difference in deflection of the centre of mass at the roof level and bottom level, according to SNI 03-1726-2012 [7]. The story drift between the building level due to the influence of an earthquake needs to be limited in yielding to prevent damage to the non-structure and the discomfort of occupants.

The story drift for each steel seismic-force resisting system in this study is presented in Table 4. The story drift of the SMF system on the top floor is 0.0762 mm. In comparison, the story drift of the EBF system on core, EBF system on core + cap truss, and EBF system on core + outrigger are almost close to zero.

Table 4. Story Drift

| Story | SMF Drift X (mm) | EBF Core Drift X (mm) | EBF Core + Cap Truss Drift X (mm) | EBF Core + Outrigger Drift X (mm) |
|-------|------------------|-----------------------|----------------------------------|----------------------------------|
| 1     | 0                | 0.0000                | 0.0000                           | 0.0000                           |
| 2     | 0.0178           | 0.0025                | 0.0025                           | 0.0025                           |
| 3     | 0.0457           | 0.0025                | 0.0025                           | 0.0025                           |
| 4     | 0.0635           | 0.0025                | 0.0025                           | 0.0025                           |
| 5     | 0.0737           | 0.0025                | 0.0025                           | 0.0025                           |
| Story | SMF Drift X (mm) | EBF Core Drift X (mm) | EBF Core + Cap Truss Drift X (mm) | EBF Core + Outrigger Drift X (mm) |
|-------|----------------|----------------------|-------------------------------|-------------------------------|
| 6     | 0.0813         | 0.0025               | 0.0025                        | 0.0025                        |
| 7     | 0.0838         | 0.0025               | 0.0025                        | 0.0025                        |
| 8     | 0.0864         | 0.0025               | 0.0025                        | 0.0000                        |
| 9     | 0.0889         | 0.0025               | 0.0025                        | 0.0000                        |
| 10    | 0.0889         | 0.0051               | 0.0025                        | 0.0025                        |
| 11    | 0.0914         | 0.0051               | 0.0025                        | 0.0000                        |
| 12    | 0.0914         | 0.0051               | 0.0025                        | 0.0000                        |
| 13    | 0.0914         | 0.0051               | 0.0025                        | 0.0000                        |
| 14    | 0.0914         | 0.0051               | 0.0025                        | 0.0000                        |
| 15    | 0.0914         | 0.0051               | 0.0025                        | 0.0000                        |
| 16    | 0.0889         | 0.0051               | 0.0025                        | 0.0000                        |
| 17    | 0.0889         | 0.0051               | 0.0025                        | 0.0000                        |
| 18    | 0.0889         | 0.0051               | 0.0000                        | 0.0051                        |
| 19    | 0.0864         | 0.0051               | 0.0000                        | 0.0051                        |
| 20    | 0.0762         | 0.0051               | 0.0000                        | 0.0051                        |

From the table above, the relationship between the story height and the story drift on the SMF model is more linear, where the higher the story, the higher its drift. On the EBF core model, the relationship between the story height and the story drift is similar to the SMF model, but the value of the story drift on the EBF core model is much smaller than on the SMF model. While on EBF core with an additional lateral brace, the story drift at the floor that is given the cap truss or the outrigger has almost zero drift. The drift on the EBF structural system in the core with cap truss is almost zero in level 18 to 20. This nearly zero drift is caused by the truss cap on the floor 18 to 20. While on EBF structural system in the core with outrigger has almost zero drift on levels 8 to 9 and level 15 to 16. This is because of the outrigger that was given between levels 8 to 9 and 15 to 16.

3.2. Shear Story
One of the observed behaviours during the structure is graded loading through pushover analysis is the shear story behaviour, which represents the occurrence of shear forces at each story and at each stage of loading. The behaviour of the shear forces of each story for the steel moment frame (SMF) and eccentric brace frame (EBF) structural systems is described in Figure 5 below. Figure 5 shows the shear story behaviour of the structural system in the final stage loading in the pushover analysis. The base shear on all the variation of the eccentrically braced frame (EBF) structural system is greater than the steel moment frame (SMF) structural system. While it also showed that the steel moment frame (SMF) structural system would provide shear stories with a relatively even distribution at each story floor. The effect of bracing on the type of eccentric brace frame structure system could also be seen from the distribution of shear stories in the figure above.

The shear story for the upper level in the EBF structural system is smaller compared to the SMF structural system due to the effect of the cap truss and the outrigger that could also be seen in Figure 5 above. There is a negative shear story value due to the cap truss and the outrigger. While in the figure 5 also shows that the base shear of the steel moment frame are smaller that the eccentrically braced frame structure.
3.3. Displacement

The displacement behaviour observed in this study represents the amount of displacement at each story and at the final stage of loading using pushover analysis. The displacement behaviour for each of the steel moment frame (SMF) and eccentric brace frame (EBF) structural systems is shown in Figure 6 below.

Figure 6 above shows the displacement behaviour of the structural system in the final loading level. It shows that the displacement on the lower level has a similar value with each structural system variation in this study. From level 6, the SMF structural system began to have a bigger displacement compared to other structural systems. Meanwhile, the steel moment frame (SMF) structural system has a greater roof displacement result compared to all variations in the eccentric brace frame (EBF) structural system. The displacement value on the roof for each structural system could be seen in Table 4 where the roof displacement for the steel moment frame (SMF) structural system is 2187 mm, for the eccentric brace frame (EBF) structural system is 1412 mm, and for EBF with a cap truss of 1131 mm. The smallest roof displacement occurs in the EBF structural system with an outrigger of 1017 mm.
The result in Figure 6 and Table 5 shows that buildings using the EBF structural system have a better displacement than those using the SMF structural system. And among the EBF structural systems, the EBF structural system with the outrigger has the smallest displacement value. This is because there are additional stiffeners in the form of braces which have a link that is located in the middle of the span as in Figure 2, Figure 3, and Figure 4 so that it could withstand loads compared to buildings with an SMF structural system that do not have additional stiffeners. In other words, the EBF structural system has a greater stiffness than the SMF structural system so that it has a smaller elastic displacement and drift.

**Table 5.** Roof Displacement

| Structure System                  | Roof Displacement (mm) |
|-----------------------------------|------------------------|
| Steel moment frame (SMF)          | 2188                   |
| Eccentric Brace Frame (EBF)       | 1412                   |
| EBF with cap truss                | 1131                   |
| EBF with outrigger                | 1017                   |

**3.4. Plastic Hinge Formation**

The formation of plastic hinge at the final pushover stage for the steel moment frame and eccentrically braced frame and each its variations is described as in the figure below on the state performance point deformation. In figure 8 to 11, there are small dots that indicate the status of the beam. A white dot indicates that the block is still linear. When the dots become colored, this indicates that plastic hinges have started to occur in the beam. The green dots indicate that the beam is experiencing an immediate occupancy regime (IO). The blue dot indicates that the beam is experiencing a regime that is between immediate collapse and life safety (IO-LS). The purple dots indicate that the beam is experiencing a regime that falls between life safety and collapse prevention (LS-CP). While the dots in red indicate that the beam has failed, or in other words, there is regime above the collapse prevention (≥ CP). The different stages of the plastic formation could be seen in figure 11.
Figure 7. Degree of Damage to Structure Due to Plastic Joints

Letter B indicates a linear boundary, which is followed by the first yielding of the structure. Letter IO or Immediate Occupancy indicates there was little or no significant damage to the structure, and the stiffness of the structure was almost the same before the earthquake [8]. Letter LS or Life Safety indicates damage occurred ranging from small to moderate levels and reduced structural stiffness but still had a fairly large threshold for collapse value [8]. Letter CP or Collapse Prevention indicates there was severe damage to the structure resulting in strength and stiffness that decreases a lot [8]. Letter C indicates the maximum limit of the shear force that the building can hold [8]. Letter D indicates there was a great degradation to the structural strength that the condition of the structure became unstable and almost collapsed [8]. And the last, letter E indicates the structure is no longer able to withstand shear and destroyed [8].

In the steel moment frame structure, plastic hinge began to occur at loading stage 4 with a displacement control at 2000 mm. The beam on the 5th floor experiencing an elastic regime which was under the immediate collapse regime. While the beam on floor 6 to 10, there was a regime between immediate collapse and life safety (IO-LS). Plastic hinge also occurred at loading stage 5 with a controlled displacement of 2500 mm. The beam on the 4th floor underwent an elastic regime which was under the immediate collapse regime. The beams on floors 11 to 12 experience a regime between...
immediate collapse and life safety (IO - LS). The beams at levels 5 and 10 experience a regime that falls between life safety and collapse prevention (LS-CP). As well as beams on floors 6 to 9 were failing or experience a regime above collapse prevention (CP).

From the figure, it appears that the building in SMF structure shows a very safe condition where until the third step, there has not been a plastic joint. In comparison, the building in the EBF structure shows that the plastic hinge occurs in step 3, where the performance point has exceeded, but the behaviour of the plastic hinge still in the Immediate Occupancy regime. This means that when the greatest earthquake force occurs in the design according to the earthquake load planned in step 3 is exceeded, according to SNI 03-1726-2012, the building is still safe and can be used without making repairs [7]. Even with the decrease in capacity to a Life Safety condition, the condition of the building structure is still very safe and without any repairs to the maximum design earthquake force.

Figures 8 also shows that the plastic hinge of the steel moment frame structural system will occur in the main component of the structure, which is beams. Whereas in Figure 9 to 11 shows the result of pushover analysis of the eccentric brace frame structural system where the plastic hinges will occur first in the braces and panel beams. It also shows that in the EBF structural system, links play a very important role in the process of melting beams and columns because the links will undergo plastification before the beams and columns. The more rigid the eccentric brace frame structure system, the less plastic hinges that occur in the main components of the beam structure.

3.5. Ductility
The behaviour of the structure in receiving multilevel loading with pushover analysis can be represented by a capacity curve. The displacement behaviour and the size of the base shear for each loading level are described in Figure 12 for each steel moment frame (SMF) and each variation of eccentric brace frame (EBF) structural system.

The figure above shows the behaviour of the structural system capacity in the final stage of loading in the pushover analysis. The capacity curve of the SMF system structure as shown in figure 12 is due to the SMF system structure has a longer plastic period than the EBF system structure that shown in table 3.

In the final pushover stage, the steel moment frame system produces very large deflections with a relatively small base shear compared to other structural systems. While all the variation of EBF structure are relatively the same. The EBF system with the outrigger seems to have the highest base shear value.
and the smallest displacement. It shows that the higher the base shear value and the smaller the displacement that occurs, the more rigid the building is.

Ductility is calculated based on the ratio between the target displacement and the peak displacement in the final pushover stage. To calculate the target displacement could be seen in equation 1. While the ductility is calculated in the equation 2. The ductility of each variation of the structural system could be seen in the table 6.

\[
\delta_t = C_0 C_1 C_2 S a \frac{T^2_e}{4\pi^2 g}
\]  \hspace{1cm} (1)

\[
\mu = \frac{\delta_u}{\delta_y}
\]  \hspace{1cm} (2)

Table 6. Ductility

| Structural System                      | Calculated Target Displacement (mm) | Displacement at Failure (mm) | Ductility |
|----------------------------------------|-------------------------------------|-----------------------------|-----------|
| Steel Moment Frame (SMF)               | 2188                                | 1976                        | 1.107     |
| Eccentric Brace Frame (EBF) at the core| 1412                                | 462                         | 3.056     |
| EBF Core + Cap Truss                   | 1131                                | 355                         | 3.186     |
| EBF Core + Outrigger                  | 1018                                | 318                         | 3.210     |

Table 7 above shows that the ductility of Steel Moment Frames (SMF) is 1.107, while the ductility of the Eccentrically Braced Frame (EBF) are all above 3. The ductility of EBF structure at the core, EBF structure with the cap truss, and EBF structure with the outrigger respectively are 3.055, 3.186, and 3.210. Therefore, the Steel Moment Frames (SMF) structural system has less ductility compared to the eccentric brace frame structural system.

4. Conclusion

a. The story drift of the steel moment frames (SMF) system is bigger than the eccentric brace frame (EBF) structural system. On the EBF structural system, the almost zero drift was due to the additional lateral brace, which are cap truss and outrigger.

b. The base shear of the EBF structural system is greater than the SMF structural system under plastic conditions. Meanwhile, the base shear of the EBF structural system is smaller than the SMF structural system. Among the EBF structural systems, the base shear forces that are more stable are the EBF Core structural system and the EBF + Cap Truss structural system.

c. The effect of bracing on the type of eccentric brace frame structure system was making the shear story in the EBF structural system is smaller at each level compared to the SMF structural system. And the EBF structural system with the outrigger has the smallest displacement value because of the additional stiffeners in the form of braces, which have a link that is located in the middle of the span so that it could withstand loads. While the effect of the cap truss is a negative shear story value due to the cap truss.

d. In the SMF structural system, the plastic hinge will occur in the main component of the structure, which is beams. While in the EF structural system, the plastic hinges will occur first in the braces and panel beams. In the EBF structural system, links play a very important role in the process of melting beams and columns because the links will undergo plastification before the beams and columns. The more rigid the eccentric brace frame structure system, the less plastic hinges that occur in the main components of the beam structure.
c. The EBF structural system has a greater stiffness than the SMF structural system so that it has less elastic displacement and drift. The EBF structural system also has better ductility than the SMF structural system.

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