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PERFORMANCE ANALYSIS OF ECCENTRIC PORTAL BRACING TO VERTICAL AND HORIZONTAL LINK CLASSIFICATION

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Abstract

Indonesia, which has tectonic conditions, makes the requirement for earthquake resistant buildings in Indonesia urgently needed. Eccentrically Braced Frames (EBFs) are a type of earthquake-resistant steel building structures that can limit inelastic behavior on the link elements. The use of these links, especially vertical link as replaceable links, can facilitate post-earthquake building repairs without having to reconstruct the main building. In this study, an analysis will be carried out regarding the behavior of the EBF structure that applies two different types of links. The behavior analyzed is related to stability, level of performance, and the ability of the structure to dissipate energy. The analysis will be carried out on six EBF portal structures with vertical and horizontal link types with different building height classifications, 3 floors, 6 floors and 10 floors respectively. The analysis was carried out using two methods, linear and nonlinear analysis. The outcome of the analysis exhibit that the performance of EBF with vertical links is comparable to EBF with conventional links, both in low-rise and high-rise buildings.

Keywords: EBF, Earthquake, Vertical Link, Horizontal Link, Replaceable Link

Introduction

Indonesia, which is located at the confluence of the world's large plates, makes Indonesia one of the areas with a high potential for earthquakes. (Fauzan et al., n.d.). BMKG are observed that 71.628 earthquakes are occurred start from 2009 to 2019 with average 6.512 per year, 543 per month, and 18 per day. Based on data that mention before, we can conclude that earthquake-resistant buildings are an absolute necessity in Indonesia (Nugraha et al., n.d.).

Steel structure is an earthquake-resistant structural system which has a satisfactory performance because it has high strength and ductility (Pangestuti & Suswanto, 2021). Steel structures also have the ability to dissipate earthquake energy and reduce the possibility of a building collapse (Bouwkamp et al., 2016), for that reason steel structures is suitable in the earthquake-prone areas. Eccentrically Braced Frames (EBF) is a type of earthquake resistant steel structure that can restrict inelastic behavior to occur in link beam elements that are between two eccentric stiffeners (David & Sarif, 2020). When an earthquake occurs, it is expected that plastification will occur in the link beams, so that if damage occurs it will be easier to restore (Vetr et al., 2017). The use of link beam is quite effective in increasing the performance of structures against earthquakes (Rofooei & Soleimani, 2023) and facilitating post-earthquake structural repairs without having to reconstruct the main building (Basavaraju & Kavitha, 2020).

Several studies related to the structure of the EBF have been carried out previously. The results of the study show that the link beam on the EBF will be a critical part if the structure is subjected to earthquake loads, so it is necessary to plan the beams with detailed planning (Susanti & Wijaya, 2022b). In addition, the type of bracing installed on the EBF also affects the ability of the structure to withstand earthquakes both in terms of stiffness and ductility (Manope et al., 2019) (Wilson et al., 2020). One type of bracing that has been analyzed in previous studies is the X-type bracing. This type of bracing has a good level of effectiveness in resisting earthquakes related to the stiffness and strength of the structure (Idris, 2017; Suryawanshi et al., 2020). Other research related to type X bracing also shows that type X bracing which is installed in two levels is able to produce a smaller story drift compared to conventional type X bracing (Fauzan et al., n.d.).

The configuration and properties of the EBF structure, especially the link beams also have an important role in the seismic energy dissipation process (Kumalasari et al., 2022; Tan & Christopoulos, 2016). Previous research stated that the use of high-strength steel in EBF structures was able to reduce the use of steel in structures (Lian & Su, 2017). In addition to the use of HSS material in the EBF structure, the use of vertical links is also able to reduce the weight of the EBF structure (Li et al., 2018; Muhammad & Suswanto, 2020). Regarding the link configuration, links that are included in the short link category have better stiffness and ductility when compared to medium and long link. (Wilson et al., 2017; Yao et al., 2020). Short links are also able to achieve inelastic rotation values beyond what is required (Ji et al., 2016).

From the results of previous research where it is still infrequent to analyze the effect of building height on the performance of EBF portals, this research conducted an analysis related to the effect of building height on the performance of EBF portals. The results of this study are expected to provide insights regarding earthquake resisting elements that are suitable for building height types, namely low, medium and high buildings, especially regarding the application of EBF portals to these structures.

Research Methodology

The EBF structure is modeled using a V-Inverted bracing type, where the two diagonal beams are expected to be able to withstand horizontal loads and also axial loads due to gravity loads. With the implementation of inverted-V type bracing

(Susanti & Wijaya, 2022a), there are two types of links that are modeled, a vertical link and a horizontal link, which are located in the middle of the floor beam. The link beam elements to be modeled are included in the short link beam category where the link beam should meet the requirements e<1.6(Mn/Vn). The structures observed are 3-storey, 6-storey and 10-storey buildings which represent low, medium and high-rise buildings as depicted in Figure 1. Meanwhile the properties of the steel profiles used are as listed in Table 1.

Table 1. Structure properties

Storey	Column	Beam	Bracing	Link
3 Storey	KC 400x200x8x13	WF 500x200x10x16	WF 350x350x12x19	WF 350x175x7x11
6 Storey	KC 500x200x10x16	WF 500x200x10x16	WF 350x350x12x19	WF 350x175x7x11
10 Storey	KC 600x200x11x17	WF 500x200x10x16	WF 350x350x12x19	WF 350x175x7x11

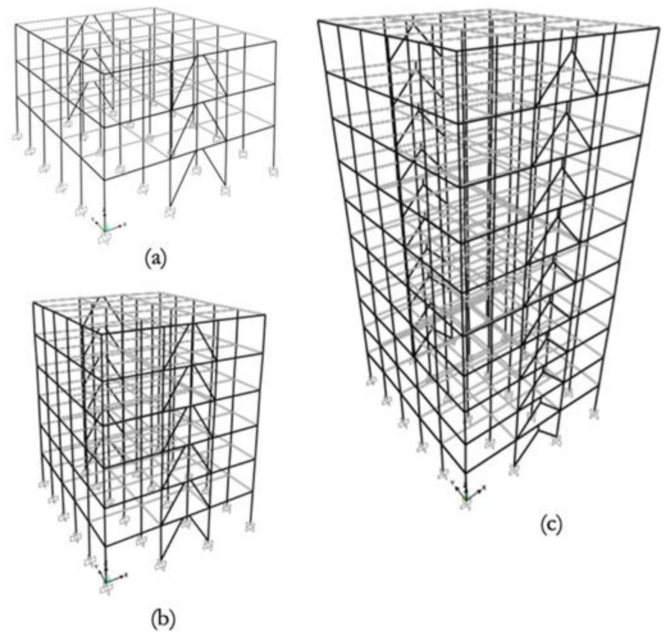

Figure 1. EBF with (a) 3 storey, (b) 6 storey, (c) 10 storey

Research Results and Discussion

Structure Drift, Drift Ratio, and Interstory Drift

On a structure, the installation of braces on the structure is able to reduce the drift that occurs so that the possibility of collapse of the structure can be minimized. (Akbar & Candra, 2018). The parameters that affect the drift that occurs in a building include building height, number of building spans, cross sectional length and width of the column, shear value of column and girder (A. Rahman, 2012). Drift that occurs on the structure, especially in the main direction, is proportional to the building height. The maximum drift always occurs at the top floor or roof. From the results of the analysis, it was found that regarded from the height of the building, a conventional EBF structure with 3 floors has a drift value of 0.35 mm. Whereas the EBF structure with the same height but applying the use of vertical links has a drift of 0.48 mm where this value is 1.37% greater than conventional EBF.

Drift or sway generated by a structure due to lateral forces is a fundamental seismic demand parameter that can be used to assess performance levels and calculate structural damage in performance-based designs (Özsoy Özbay & Gündeş Bakır, 2021).In buildings with the same height, the EBF Building which has 6 floors shows that the structure that applies vertical links has a greater drift value compared to EBF with horizontal links, which are 2.31 mm and 1.98 mm respectively. From these results it can be concluded that structures with vertical links have a lower stiffness level compared to structures with conventional link types.

From previous researches, high-rise buildings will have a greater drift structure than other building that has a smaller height (Islam & Islam, 2013; Prof et al., n.d.; Sharapov et al., 2021). The maximum drift always occurs at the top floor or roof. As in a 10-storey building, the EBF with a vertical link experiences a drift of 7.55 mm. The drift that occurs in the 10-floor structure is greater than the structure with horizontal links, where the structure with horizontal links experiences a drift of 6.84 mm, or 1.1% less than the structure with vertical links. From these results it was found that as the building heights increased, the greater the drift that occurred (A. Rahman, 2012) . At the same building height, the drift on the H-EBF portal is relatively smaller than the drift on the V-EBF portal. Several studies have identified how to deal with large drifts in building structures. Based on previous research, the way to overcome the large drift in buildings, one of which is in high rise buildings, is to add an Energy-Dissipative Column (EDC) element (Y. W. Li et al., 2022). The results of the structure drift in the main direction of the entire EBF portal structure at each building height can be shown in Figure 2.

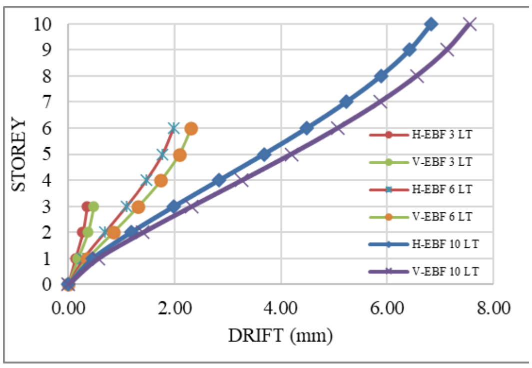

Figure 2. Structure drift at the main direction of EBF portal

The drift ratio between floors is the difference in drift between two consecutive stories divided by the floor height. Previous research has shown a correlation between drift ratio and structural damage that occurs after an earthquake. Therefore, a designer should initially check the floor drift ratio to obtain a safe structural design. (Mishra1 et al., 2018) (Dev Bhatt, 2020). In a 3-storey structure, the EBF with vertical links has a drift ratio value of 3.98. This outcome is 34.5% greater than the 3-storey building with horizontal links which produces 2.96. Just like a structure with 3 floors, a 6-storey structure with vertical links has a drift ratio value of 16.89% greater than the same structure but uses horizontal links, where each structure has a drift ratio of 9.63 and 8.24. While the results of the analysis related to the drift ratio in a 10-storey building show that the EBF structure with vertical links produces a ratio of 18.89 which is 10.53% greater than buildings with horizontal links, specifically 17.09. The results of the drift ratio of the entire EBF portal structure with the height of each building can be seen in Figure 3.

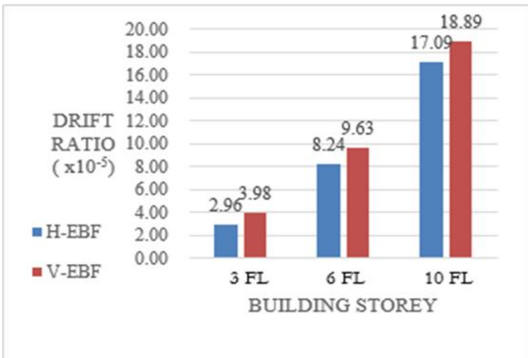

Figure 3. Drift ratio of the building

Column size has an impact on the outcome drift storey (Basavaraju & Kavitha, 2020). Predecessor studies have shown that the unsuitable column size can cause a soft-story mechanism (M., 2014). In addition, the building plans that are asymmetrical at each level also have an influence on the resulting Inter-storey drift (Rumimper & Dapas, 2013). Based on the analysis, the comparison of drift storey on EBF portals are shown in Figure 4. From the differences in the types of links in buildings with the same height, the value of drift stores with vertical links is always greater than that of drift stores on horizontal links, with a difference of 34.5% for portals 3-floor EBF, 17.8% for 6-floor EBF portal, and 11.2% for 10-floor EBF portal.

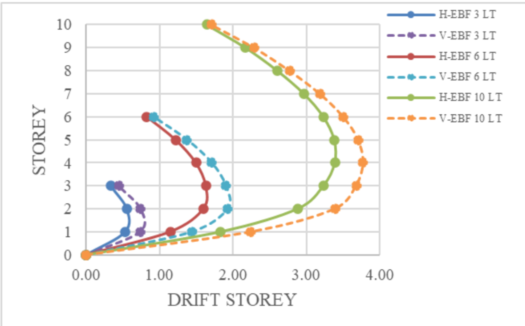

Figure 4. The result of drift storey of the structure

Stress Ratio

The maximum stress ratio that occurs are shown in Table 2 to Table 4. The stress ratio in all models has a value below 1.0, which means that the cross sections of each structural element are still in a safe condition and strong enough to withstand structural loads. As in previous studies, the stress ratio permitted is ≤ 1, which means that the external load must be smaller than the cross section of the structure, especially beams and columns. If the stress ratio is > 1, then the dimensions must be enlarged (Rani et al., 2019).

One of the parameters that affect the magnitude of the stress ratio that occurs in a building structure is the height of the building (Erizal et al., 2023). In addition, there is the same tendency where the largest stress ratio is occurred on the link elements and then continues to the column, beam, and bracing elements in the 3-floor, 6-floor, and 10-floor EBF portals as in previous research (Kaffah & Suswanto, 2021),. The results of the stress ratio on the V-EBF portal have a greater value than the stress ratio on the H-EBF portal, although the results are not very significant.

Table 2. Stress ratio on 3 floor building

Element	**Properties**	**Maximum Stress Ratio**			
		H-EBF	Loc	V-EBF	Loc
Link	WF 350x175x7x11	0,041	1st floor	0,042	1st floor
Bracing	WF 350x350x12x19	0,010	1st floor	0,013	2nd floor
Beam	WF 500x200x10x16	0,016	1st floor	0,020	1st floor
Column	KC 400x200x8x13	0,037	1st floor	0,039	1st floor

Table 3. Stress ratio on 6 floor building

Element	**Properties**	**Maximum Stress Ratio**			
		H-EBF	Loc	V-EBF	Loc
Link	WF 350x175x7x11	0,085	1st floor	0,086	2nd floor
Bracing	WF350x350x12x19	0,014	1st and 2nd floor	0,022	2nd floor
Beam	WF500x200x10x16	0,034	1st floor	0,039	1st floor
Column	KC 500x200x10x16	0,066	1st floor	0,072	1st floor

Table 4. Stress ratio on 10 floor building

Element	**Properties**	**Maximum Stress Ratio**			
		H-EBF	Loc	V-EBF	Loc
Link	WF 350x175x7x11	0,143	2nd floor	0,146	2nd floor
Bracing	WF 350x350x12x19	0,020	2nd floor	0,033	2nd floor
Beam	WF 500x200x10x16	0,057	2nd floor	0,061	2nd floor
Column	KF 600x200x11x17	0,106	1st floor	0,116	1st floor

Base Shear

The ground floor of the structure is the place where the movement of the ground due to the earthquake acts on the structure (Idris, 2017). Meanwhile base shear is the force that occurs on the base of the structure mainly caused by seismic forces (Sarvade et al., 2022). Based on previous research, it was established that high-rise buildings tend to have substantial base shear (Bolouri Bazaz et al., 2021). Identical as something that occur to the results of the analysis. The 6-storey EBF structure using horizontal and vertical links has a base shear value of 4770.85 kN and 3569.91 kN, respectively. The 10-storey EBF structure, both having vertical and horizontal links, has more substantial base shear contrast to other lower structures. The outcome of the analysis in previous studies exhibit that the higher a structure is, the longer it will take to reach its first yield. The results of this analysis exhibit that the 10-storey EBF structure with horizontal links has a base shear of 4868.65 kN. Whereas on the vertical link, the base shear is 29% smaller than the horizontal link which is equal to 3654.84 kN. The base shear occurred in the entire structure can be seen on Figure 5.

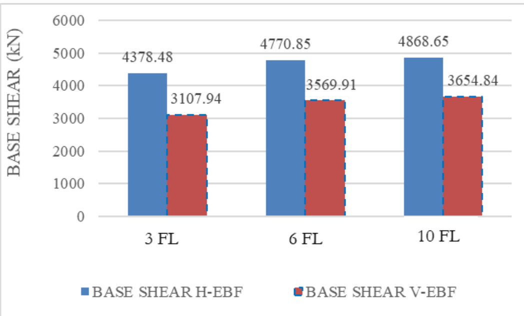

Figure 5. Base shear occurred in the structure

Structure Ductility

The ductility achieved in the 3-storey EBF building exhibit that structures with vertical links have 10% greater ductility, where for vertical links the ductility value is 12.12 while for horizontal links the ductility value is 10.92. The results obtained from the analysis of the ductility of the 6-storey building are different from the 3-floor and 10-floor structures. If the other two types of structures show that the EBF structure with links has higher vertical ductility when compared to horizontal links, then at this height the results show otherwise. EBF with horizontal links is 5.2% more ductile than vertical links, which are 9.34 and 8.85 respectively.

The ductility that can be achieved by the two 10-storey EBF structures is 6.59 for conventional structures and 8.36 for structures with vertical links. From the results of structural modeling, the higher a structure, the less ductility it has, when compared to low-rise structures. The results of the analysis of the ductility of the structure are illustrated in Figure 6.

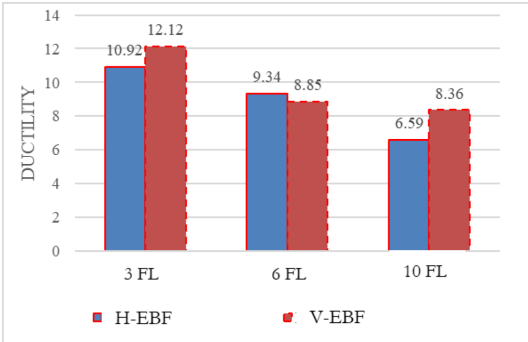

Figure 6. Ductility of the structure

Structure Stiffness

In a 3-storey structure, EBF with horizontal links has a stiffness of 199148.73 kN/m. This result is 21.2% higher than the vertical link which has a stiffness of 156974.7 kN/m. The structural stiffness of the vertical link modeling in the 6-storey EBF building is 78948.89 kN/m. the result is 14.9% smaller when compared to the same structure but with a horizontal link, which is equal to 92803.71 kN/m. The modeling results also show that the structural rigidity of a high-rise building is smaller than that of a low-rise building. The structural stiffness of the 10-storey EBF with horizontal links is 21% greater than that of vertical links which are 199148.73 kN/m and 156974.7 kN/m respectively.

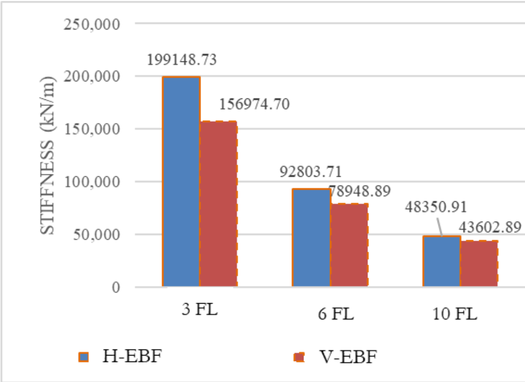

Figure 7. Structure stiffness

Performance Level

The results of structural analysis related to post-earthquake performance levels are shown in Figure 8. The structural performance levels for all models based on ATC-40 displacement fall into the Immediate Occupancy (IO) category which indicates that the structure is still in a similar condition as the initial condition when it was not given earthquake loads so that the structure can be reused (Handana et al., 2018; Hassaballa et al., 2014; Widyaningrum et al., 2019).

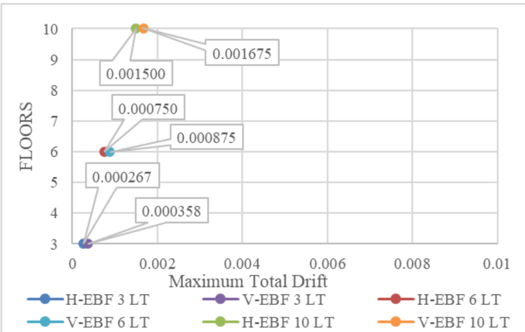

Figure 8. Structure performance level

Energy Dissipation

Some of the parameters that can affect the ability of the structure, especially the link beams on the EBF, to dissipate earthquake energy are the dimension of the cross section, the thickness of the web section, and the spacing of stiffeners (Xu et al., 2021). The energy dissipation in a structure can be assessed from its hysteresis curve. Hysteresis itself refers to the path-dependence of the structure's restoring force versus deformation. EBF portals with horizontal link for 3-story buildings have a smaller hysteresis energy value compared to EBF portals with vertical link with the same height. A 3-storey building with horizontal links is capable of dissipating 892.1 kNm of earthquake energy. Likewise with a 3-storey building with a vertical link, the specimen is able to dissipate 1028.7 kNm of earthquake energy, where the EBF-V capability in a 3-storey building is 0.87% greater than a 3-story building with a conventional link.

For medium-rise buildings, which is 6-story building, the hysteresis energy of EBF portals with horizontal link is greater than that of EBF frames with vertical link. A 6-storey building with a conventional link is able to dissipate energy of 2146.62 kNm, whereas a building with a vertical link has an energy dissipation capacity 0.88% less than other structures with 1894.86 kNm.

The largest hysteresis energy is found in high-rise buildings for each type of link in the EBF portal compared to another structure with different height. For H-EBF and V-EBF, the structures are able to dissipate energy with 2713.20 kNm and 3013.69 kNm respectively. This condition is occurred because high-rise buildings have a higher number of links, which means that there will be an increasing number of plastic hinges formed in the structure when an earthquake load is applied. All of the outcome related to energy dissipation of the structure can be observe at Figure 9.

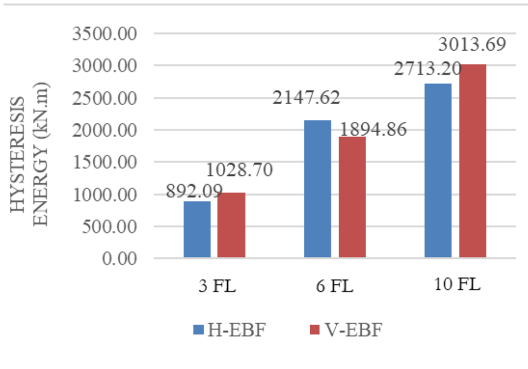

Figure 9. Hysteresis energy of the structure

Conclusion

Based on the research that has been done, it can be concluded that the link configuration has an influence on the structural performance related to structural displacement, displacement and stress ratio, base shear, ductility, and stiffness. Structures with horizontal link configurations provide better performance, but the results also exhibit that the applied of vertical links is still comparable when applied to a structure. Whereas in terms of ductility and the ability of the structure to dissipate the energy, vertical links exhibit higher performance when compared to horizontal links. Therefore, it can be stated that vertical links are able to dissipate earthquake better than conventional links.

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