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Article

Evaluating Seismic Performance of Steel Industrial Building with Different Bracing Type

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Abstract: Earthquakes are unpredictable natural events that release significant amounts of energy, often causing severe damage to structures. Traditionally considered safe from seismic activity due to its distance from active seismic zones, Malaysia has recently experienced notable seismic events, particularly in Sabah, East Malaysia. Cities like Lahad Datu, Ranau, and Tawau in Sabah have recorded over seven earthquakes with magnitudes greater than 5. This trend underscores the need for Malaysia to address and mitigate the impacts of earthquakes on structures. In response, Malaysia has adopted the British Standard for seismic resistance, incorporating Eurocode provisions for industrial buildings. Despite the region's proximity to low seismic zones, many industrial buildings in Sarawak, used for storage and manufacturing, lack of seismic resistance. This study investigates the potential impact of earthquakes on these structures. By using SAP2000, Nonlinear Pushover Analysis and Nonlinear Time History Analysis were conducted on steel industrial buildings to assess their behavior under lateral pushover forces and dynamic ground motions, scaled to local seismic intensities per Eurocode 8 (EC8). Various parameters, such as base shear, maximum displacement, and spectrum curves, were examined, along with the effects of different bracing configurations and building heights. The results indicate that seismic performance decreases with increasing building height, with maximum displacements of 36mm for a 10m building and 99mm for a 20m building. Additionally, 4 X-bracing configurations significantly improve performance, reducing lateral displacement from 36mm to 14mm (pushover analysis) and from 11mm to 0.3mm (time history analysis), and enhancing base shear from 146.617kN to 234.941kN. The findings demonstrate that incorporating bracing systems can effectively enhance the seismic performance of industrial buildings.

Keywords: Industrial buildings, seismic performance, non-linear pushover and time history analyses

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1. Introduction

Recently, structural steel construction has gained significant popularity worldwide [1]. In developed countries like Japan and China, structural steel is commonly used and widely implemented in construction projects [2]. In Malaysia, while steel construction is not yet the norm, it is increasingly being adopted [3]. Notably, most high-rise and mid-rise industrial buildings in Malaysia utilize structural steel. The performance in seismic of steel structure building is more suitable when compared to reinforced concrete structure building [4]. Earthquakes are natural disasters that can cause significant casualties and damage to buildings [5,6]. Typically, the majority of fatalities and injuries are not directly caused by the earthquake itself, but rather by the collapse of buildings [7]. Such collapses are generally due to the structural behavior of buildings during seismic events. The collapse of the building also depends on other factors such as architectural design, geometry configuration of structural elements in horizontal and vertical plans [8], earthquake zone, geographical location (distance to earthquake center), soil type, material quality, and construction quality [9].

Eleven provinces were affected by the Kahramanmaraş earthquake that occurred on February 6, 2023, in Turkey, leaving a path of destruction and suffering in its wake [10]. Due to the loss of life and damage to buildings and infrastructure, the provinces of Kahramanmaraş, Adıyaman, Hatay, Osmaniye, Gaziantep, Kilis, Malatya, and Adana in eastern Turkey were seriously damaged [11]. The damaged structures included reinforced concrete, masonry building, wood buildings, historical buildings, industrial building (Steel Structures) and bridge [12]. There are a huge number of industrial structures (steel structures) that damaged due the earthquake [13]. Although the steel is an excellent earthquake resistant material, the steel structure will also be destroyed by the strong earthquake and this may cause death and economic loss [14].

The massive destruction to townships and port infrastructure, along with the nearly 20,000 fatalities in the prefectures of Iwate, Miyagi, and Fukushima, are the most disastrous aspects of the 2011 Tohoku-Oki earthquake disaster [15]. The Fukushima nuclear accident was brought on by the same tsunami, and its effects will be experienced for many generations by the locals [16]. Many industries were made vulnerable when the earthquake and tsunami destroyed factories, resulting in an unexpected global disruption to the supply chain [17].

Many steel warehouse and steel industrial buildings were damaged during the Darfield earthquake in September 2010 [18]. These industrial buildings typically have light roofs and are built to withstand strong winds; light rod braces are commonly utilized in these situations [19]. Steel fabricators examined several warehouses after the earthquakes and retightened sagging braces that had stretched because of yielding during the earthquakes [20]. There have also been a few cases where tilt-up wall anchorages to steel structures have failed. Structural members of the steel warehouse destroyed, roof beams that have buckled under compression because of the tilt-up panels moving inward and the anchors failing as a result of their outward movement that caused by the earthquake [21].

Malaysia is surrounded with earth plates and the occurrence of earthquakes is driven by the movement of these tectonic crusts [22]. Peninsular Malaysia is located on the stable Sunda Trench as shown in Figure 1. In this table Sunda Trench, there are only got some low to moderate levels of seismic activity. Unfortunately, there will be some tremors that can be felt by the people that live on the west coast of Peninsular Malaysia and that tremors are produced by large earthquakes that centred in Sumatra and the Andaman Sea [23]. In East Malaysia especially Sabah State is unlike most of the other Malaysian states is characterized by common seismological activity. Generally, an earthquake of moderate magnitude is experienced at an interval of almost every 20 years. The source of the earthquake majorly from two major sources which are a local source as shown in Figure 1 (example: Ranau and Lahad Datu) seismicity map of Sabah shows the presence of two zones of distinctive seismicity, these zones are near Ranau (near Kota Kinabalu) and Lahad Datu in the southeast of Sabah [24]. Sabah shows extraordinary earthquake activities compared to other regions of Malaysia. The occurrence of a moderate earthquake with magnitude Mw = 6.0 in June 2015 which produce some damage to buildings and caused the death of some tourists near Mount Kinabalu [4], [7], [9], [15], [25].

Most structures are vulnerable to lateral stresses, particularly dynamic and unpredictable seismic loads. In previous earthquakes, a large number of seismically sensitive buildings have collapsed or suffered significant damage [26]. Safe methods of design and construction quality control can aid in avoiding damage to property and loss of life [27]. Earthquake analysis and design concepts were developed in response to the earthquake's consequences and structural damage [28]. There are 4 types of earthquake analysis methods which are seismic coefficients method (equivalent linear static analysis), pushover analysis (non-linear static analysis), response spectrum technique (linear dynamic analysis) and time history analysis (non-linear dynamic analysis) [29-34].

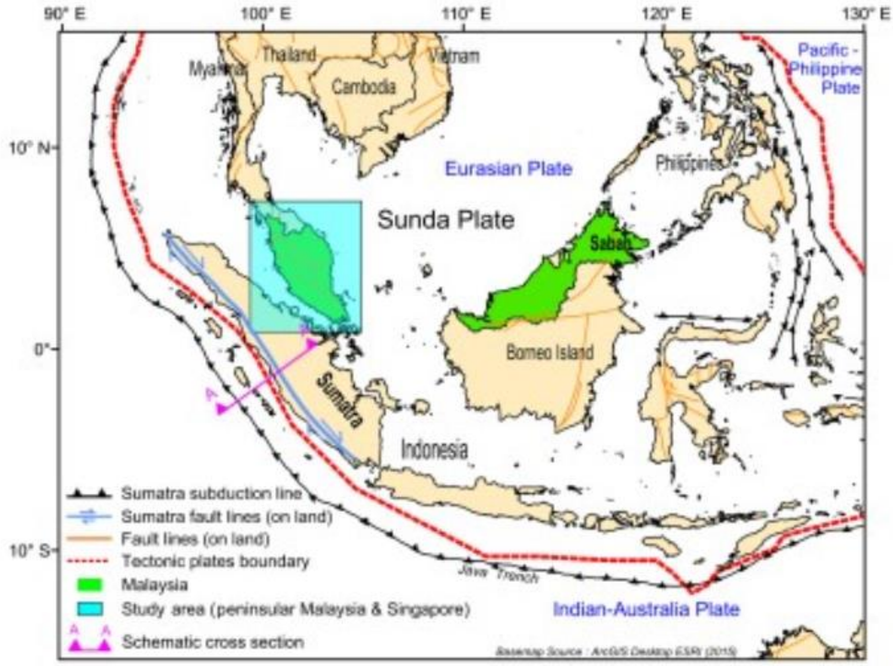

Fig. 1. The map of location of Peninsular Malaysia on the Suda Plate and the seismic sources around it

2. Materials and Methods

The height of structure and the type of bracing are the parameters that changed in the analysis. 21 models tabulated in Table 1 with different height and type of bracing are used in the nonlinear pushover analysis and time history analysis by using SAP2000. Moreover, there are several types of analysis, design standards, materials and properties that available in SAP2000 to choose. These parameters play a very important role in the upcoming modelling and analysis. Therefore, it is important to define the model information to the preferred settings first before proceeding to the modelling procedure. Material properties define the characteristics of the material which will be used in the model in terms of the region, material type, standards, and grade. Since there is no Malaysia available in the region tab, grade S355 steel materials from Europe and Eurocode 3, EN1993-1-1 is chosen. SAP2000 v25 has a pre-installed library that provides a wide range of steel sections to be chosen. The imported members can be categorized into a property, which allow the software to automatically chose the amend the insufficient member to ensure the frame is adequately designed to the applied loads without including earthquake loads. In this study, several types of steel sections, which are I Beam, I Column, and Equal Angles will be imported and categorized as Beams, Columns, and Bracing.

Upon the generation of load cases and load combinations, appropriate wind, dead, and live loads are applied onto the model to show realistic results. MS EN 1991-1-1:2010, MS EN 1991-1-4:2010 MS 1553:2002 are the codes that used to calculate the dead load, live load and wind load that acting on the models. After providing loads onto the member, the model is first analysed to check the deformation of the model. SAP2000 allows the animation to show how the model shall deform. From the analysis result, green lines are observed in the structural members indicating that the member provided are adequate to resist the given loads. Meanwhile, purlins are shown in red colour, indicating that members are failed. However, these purlins are not considered as structural members as they are used to hold metal roof sheet. The adequate member will be designed and provided by SAP2000 and tabulated in Table 2. Weak beam-strong column (WBSC) concept implies that beams in a structure will tend to fail by forming plastic hinges before columns. This is to prevent the progressive collapse of a structure due to cascade effect created by column failure in the lower levels. In order to obtain Weak Beam-Strong Column, Grade 355 steel is chosen for both beams and columns so that it can be checked using Equation 1, where Eq1 is used to check for nodes where 2 beams and 2 columns are intersecting.

$$\sum' W_{pl,Col} \geq 1.3 \sum' W_{pl,Beam}$$

After getting the horizontal force from the previous calculation, it can be added into the model in SAP2000 as seismic load. The horizontal load of 314.184 kN point load is added to the joints of the columns where wind loads are applied. As the horizontal force is added onto the model, the analysis is then conducted. After the completion of analysis, the estimated deformed shape of the model can be observed in either three-dimensional view or elevation views. The pushover analysis will be conducted for several different models that configured for seismic fragility assessment. Each model will be conducted pushover analysis in X and Y directions to determine the direction that gives the most critical effect to the building.

Table 1 Tabulation of the model that used for analysis

Model	Height of structure (m)	Type of bracing	Model	Height of structure (m)	Type of bracing
Model 1	10	Without bracing	Model 12	15	X-bracing (2B)
Model 2	10	V-bracing (2B)	Model 12	15	X-bracing (4B)
Model 3	10	V-bracing (4B)	Model 13	15	Diagonal bracing (2B)
Model 4	10	X-bracing (2B)	Model 14	15	Diagonal bracing (4B)
Model 5	10	X-bracing (4B)	Model 15	20	Without bracing
Model 6	10	Diagonal bracing (2B)	Model 16	20	V-bracing (2B)
Model 7	10	Diagonal bracing (4B)	Model 17	20	V-bracing (4B)
Model 8	15	Without bracing	Model 18	20	X-bracing (2B)
Model 9	15	V-bracing (2B)	Model 19	20	X-bracing (4B)
Model 10	15	V-bracing (4B)	Model 20	20	Diagonal bracing (2B)
			Model 21	20	Diagonal bracing (4B)

Note: B is stand for braces

Ground motion record is important for the time history analysis. There are various sources to obtain ground motion records. In this study, online ground motion data from 'PEER Ground Motion Database' will be adopted. From PEER online ground motion database, ground motion of earthquake in Tokat and Aydin are adopted. The downloaded ground motion record is unscaled. Thus, it is required to plot the ground motion record to scale before import into SAP2000. The earthquake data need to be rescaling into 0.05g, 0.10g, 0.15g, 0.20g, 0.25g and 0.30g by using the formula below:

$$Scale\ factor = \frac{Required\ PGA}{Current\ PGA}$$

After scaling, all the ground motion record will be save in text file. All the saved files is to be imported into SAP2000 by several procedures. While creating the non-linear time history analysis load cases, it is important to pay sufficient on the load applied in each load case. In this study, each time history analysis load case has acceleration load applied in either X or Y direction with a scale factor of 9.81 m/s2 for each ground motion record inserted into the model. Time history analysis is then performed. Prior to time history analysis, it is suggested to check the model thoroughly making sure that there is no mistake or information inconsistency as the analysis takes relatively longer time to conduct compared to pushover analysis.

Table 2 Tabulation of selected sizes for each structural member

Height of structure (m)	Column	Rafter	Purlin
10	UC 203x203x52	UB 305x165x46	C15010
15	UC 305x305x118	UB 305x165x46	C15010
20	UC 356x368x129	UB 305x165x46	C15010

3. Results

Results of pushover analysis will be presented in several ways: (1) comparison of steel industrial building with different heights, (2) comparison of steel industrial building with different types of bracing, and (3) comparison the height of the steel industrial building and the type of bracing in terms of seismic performance. The deformed shape and the hinge formation will be record. The deformation shape and the formation of hinge of Model 1 (10m without bracing) as shown in Figure 2

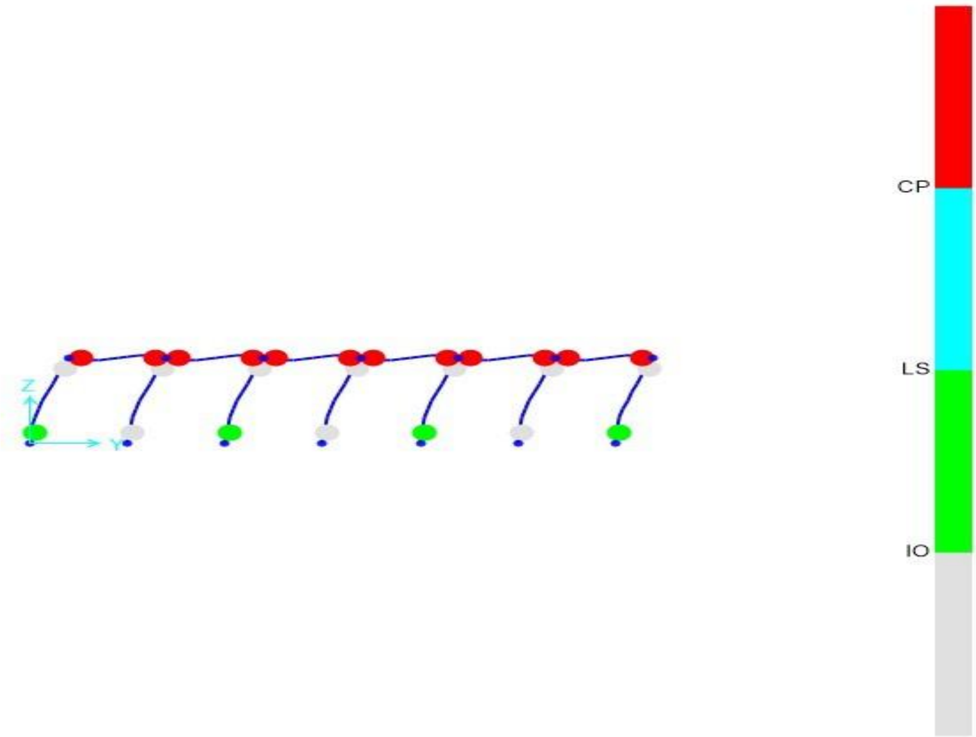

Fig. 2 .The deformation shape of the Model 1

Since this model without any horizontal force resisting system such as bracing, most of hinges in columns is in the safe stage while there are 4 hinges in column in IO stage. However, all the hinges in the steel beam in CP stage which means the steel warehouse without any horizontal force resisting system cannot withstand the horizontal force such as seismic force.

The static pushover curve or the graph of base shear against displacement is the result of the pushover analysis on the selected structure. The static pushover curve of every will be used to do comparison based on the height of structure and type of bracing. Figure 3 illustrates the relationship between base shear and displacement for a steel warehouse of different heights (10 meters, 15 meters, and 20 meters) without bracing, obtained through pushover analysis. The 10-meter structure exhibits the highest base shear values, indicating that it is the most resistant to lateral loads. In contrast, the 20-meter structure shows the lowest base shear values, suggesting it is the least resistant. As the height of the structure increases, its resistance to lateral loads decreases, resulting in lower base shear values for a given displacement. This highlights the importance of bracing in taller structures to improve their stability and resistance to lateral forces.

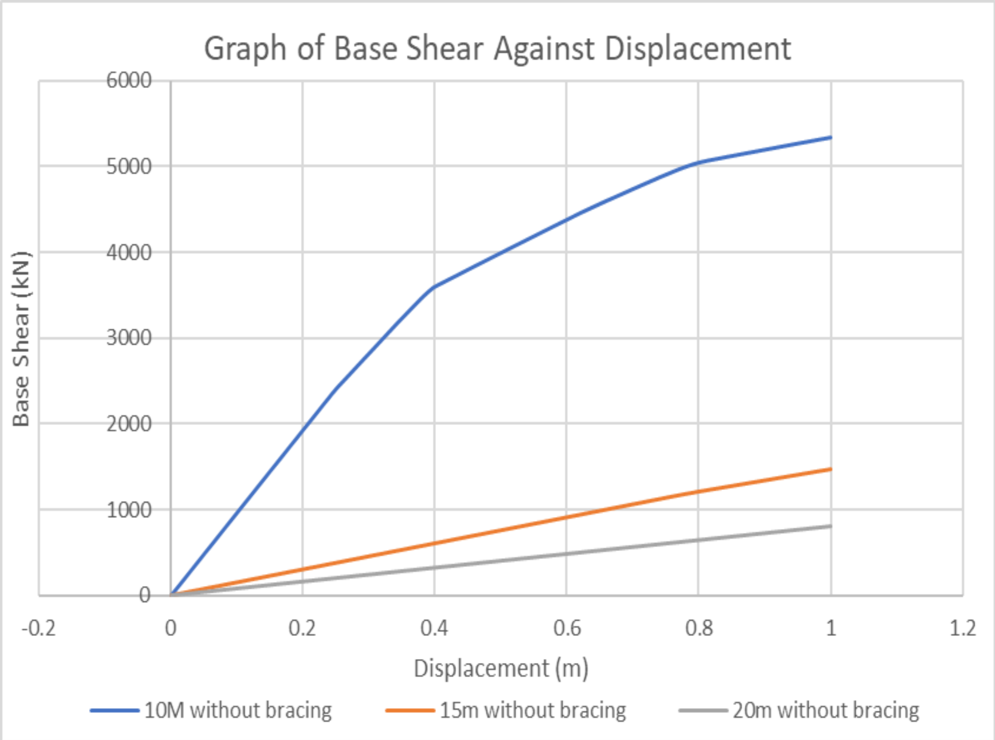

Fig. 3. The graph of base shear against displacement for the model with different height (without bracing)

Type of bracing will also affect the seismic performance of the structures. Figure 4 shows that different bracing configurations affect the base shear and displacement behavior of the structure. For the model of 10m with 4 X- bracing, this configuration shows the highest base shear for a given displacement, indicating it provides the greatest resistance against lateral loads. This means it's the most rigid and can withstand higher forces before displacing significantly. Next, for the model with 10m and 2 X-bracing and model of 10m with 4 diagonal bracing, these configurations also show relatively high base shear values but less than the 4 X bracing. They provide substantial resistance but are slightly less stiff. Other than that, for the model of 10m with 2 diagonal bracing and the model of 10m with 4 V-bracing, these configurations provide moderate resistance, with lower base shear values compared to the above configurations. Apart from that, for the model of 10m with 2 V bracing, this configuration shows lower base shear values than the above configurations, this indicating less resistance to displacement. Moreover, for the model of 10m without bracing, this configuration shows the lowest base shear values, indicating it provides the least resistance to lateral loads and is the least stiff. All curves show a positive relationship between base shear and displacement. As displacement increases, the base shear also increases, which is typical in pushover analysis where higher lateral loads lead to greater structural displacement. In summary, the graph indicates that adding more bracing, especially X bracing, significantly increases the base shear capacity of the structure, making it more resistant to lateral loads and less prone to large displacements during events like earthquakes. The structure without bracing is the least resistant, showing the importance of bracing in enhancing structural performance.

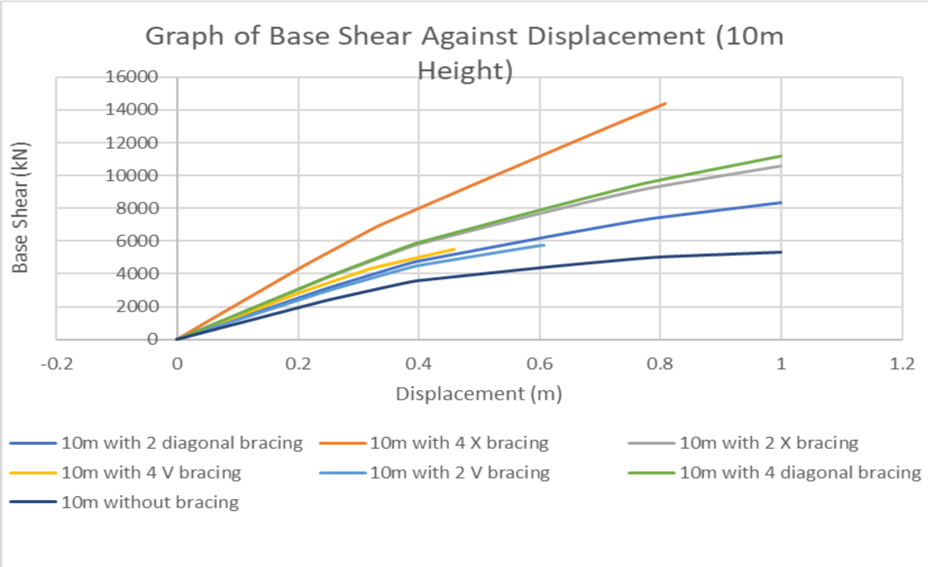

Fig. 4. The graph of base shear against displacement (10m with different bracing)

4. Discussion

The Table 3 displays the results of a pushover analysis, focusing on the displacement (in meters) of structures of varying heights (10m, 15m, and 20m) with different types of bracing. The types of bracing include: no bracing, X bracing (2 braces and 4 braces), V bracing (2 braces and 4 braces), and diagonal bracing (2 braces and 4braces). Generally, the data shows that structures without bracing exhibit the highest displacements, indicating the least resistance to lateral loads. For instance, a 20m structure without bracing has a displacement of 0.099m. In contrast, structures with X bracing (4 braces) have the lowest displacements, suggesting better performance under lateral loads, as seen with a 15m structure having a displacement of just 0.004m. Overall, the displacement decreases as the type of bracing changes from without bracing to various forms of bracing, highlighting the effectiveness of bracing in enhancing structural stiffness and reducing lateral displacements.

Table 3. Tabulation of performance points

Model	Height	Bracing	D (m)	Base Shear (kN)
Model 1	10m	Without bracing	0.036	346.617
Model 2	10m	X bracing (2B)	0.014	204.982
Model 3	10m	X bracing (4B)	0.011	234.941
Model 4	10m	V bracing (2B)	0.017	204.974
Model 5	10m	V bracing (4B)	0.014	205.082
Model 6	10m	Diagonal Bracing (2B)	0.016	205.233
Model 7	10m	Diagonal Bracing (4B)	0.013	205.114

Model 8	15m	Without bracing	0.068	102.714
Model 9	15m	X bracing (2B)	0.007	237.774
Model 10	15m	X bracing (4B)	0.004	241.692
Model 11	15m	V bracing (2B)	0.018	237.823
Model 12	15m	V bracing (2B)	0.010	242.759
Model 13	15m	Bracing (2B)	0.013	235.178
Model 14	15m	Diagonal Bracing (4B)	0.008	244.137
Model 15	20m	Without bracing	0.099	80.428
Model 16	20m	X bracing (2B)	0.020	272.901
Model 17	20m	X bracing (4B)	0.010	280.580
Model 18	20m	V bracing (2B)	0.054	269.080
Model 19	20m	V bracing (4B)	0.031	276.873
Model 20	20m	Diagonal Bracing (2B)	0.032	247.270
Model 21	20m	Diagonal Bracing (4B)	0.019	273.480

All of the models were analysed using Dynamic Analysis or Time History Analysis. Two of the ground motion record (Aydin Earthquake and Tokat Earthquake) will be used to analysis all the models. The result of the time history analysis will be plotted in the graph of displacement against time as shown in the Figure 5. From the graph, it shown that the structure witn 10m without bracing has the highest displaemnt when compared to other structure.

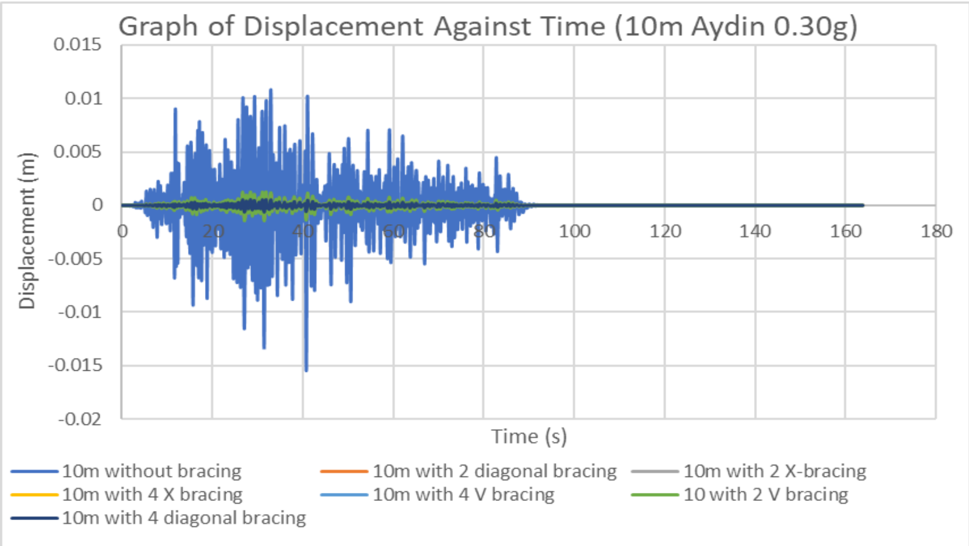

Fig. 5. Graph of Displacement Against Time (10m Aydin 0.30g)

The graph in Figure 6 illustrates the results of a time history analysis performed on a steel warehouse with different heights (10m, 15m, and 20m) subjected to two different earthquake records: the Aydin Earthquake (A) and the Tokat Earthquake (T). The displacement of joint of the warehouse is plotted against time, showing how the structure's lateral displacement evolves during seismic events.

The data shows distinct patterns of displacement for the different heights and earthquake records. For the 10m structure, the displacement curves for both the Aydin and Tokat earthquake records show relatively small increases over time, with the Aydin record resulting in slightly higher displacements than the Tokat record. This suggests that the 10m structure experiences moderate lateral movement under both earthquake conditions, with a marginally greater impact from the Aydin Earthquake.

For the 15m structure, the displacement curves for the Aydin and Tokat records demonstrate more pronounced increases in displacement compared to the 10m structure. The Tokat record results in higher displacements, indicating that the 15m structure is more significantly affected by this earthquake. The increasing trend in displacement highlights the greater susceptibility of taller structures to seismic forces.

The 20m structure exhibits the highest displacements among the three heights, with the Aydin and Tokat records showing steep increases in displacement over time. The Aydin Earthquake induces the largest displacements, reaching up to approximately 0.45 meters, suggesting that the tallest structure undergoes substantial lateral movement and deformation during this seismic event. Overall, the graph clearly shows that the displacement of the steel warehouse increases with height, with taller structures experiencing greater lateral movement during earthquakes. Additionally, the Aydin Earthquake generally results in higher displacements than the Tokat Earthquake, indicating a more severe impact on the structural performance. This analysis underscores the importance of considering both the height of structures and the characteristics of different earthquake records in seismic design and assessment.

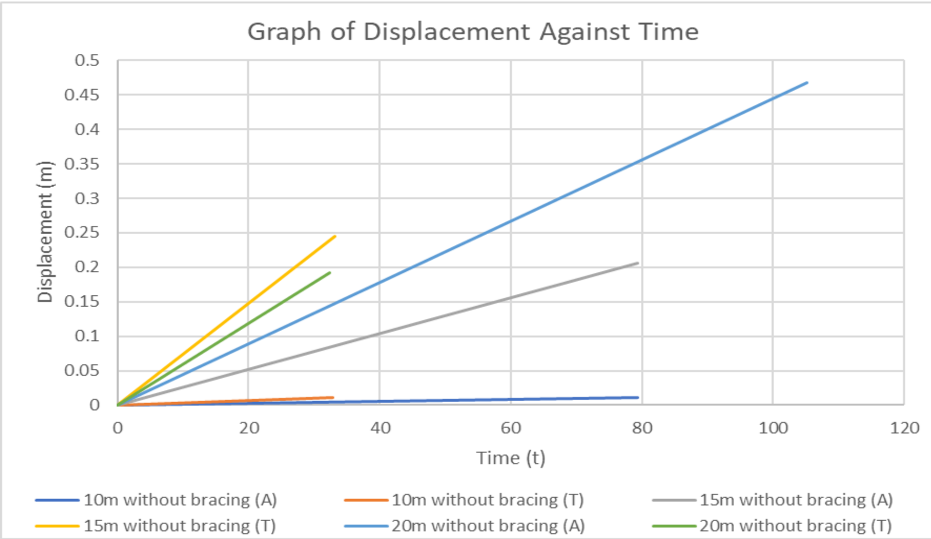

Fig. 6. Graph of Displacement Against Time (For structure with different height)

The graph in Figure 4.7 illustrates the displacement over time for a 10-meter steel warehouse subjected to the Aydin Earthquake with a peak ground acceleration of 0.30g. The analysis compares the effectiveness of various types of bracing in mitigating structural displacement during seismic activity.

The warehouse without any bracing, which experiences the highest displacement, reaching approximately 0.012 meters by the 80-second mark. This indicates that the absence of bracing results in significant structural movement under seismic forces, making it the least effective in resisting earthquake-induced displacements.

Next, the warehouse with four X bracings, which shows one of the lowest displacement values over time. This suggests that the 4 X bracings provide substantial resistance to seismic forces, effectively minimizing displacement. Similarly, the dark green line represents the warehouse with four diagonal bracings, also demonstrating low displacement values. This indicates that both X and diagonal bracings are equally effective in reducing seismic displacement.

Apart from that, the warehouse with two X bracings, which experiences slightly higher displacement than the one with four X bracings but still maintains relatively low values. This configuration, while effective, is less resistant compared to its counterpart with four X bracings. The light green line represents the warehouse with two diagonal bracings, showing slightly higher displacement than the four diagonal bracings but remaining effective in minimizing movement. This provides a moderate level of seismic resistance.

Furthermore, the warehouse with four V bracings, displaying low displacement values similar to the four X and four diagonal bracings. This demonstrates that V bracings are also highly effective in reducing seismic-induced displacements. The orange line, corresponding to the warehouse with two V bracings, shows slightly higher displacement compared to the four V bracings but remains relatively low. This indicates that while two V bracings offer good resistance, increasing the number of bracings enhances structural stability. Overall, the graph reveals that the presence of bracing significantly reduces displacement in a steel warehouse during an earthquake. Among the various bracing types, configurations with four bracings (X, diagonal, or V) show the most effective performance, maintaining the lowest displacement values. In contrast, the absence of bracing results in the highest displacement, underscoring the critical importance of bracing in seismic design to ensure structural stability and safety.

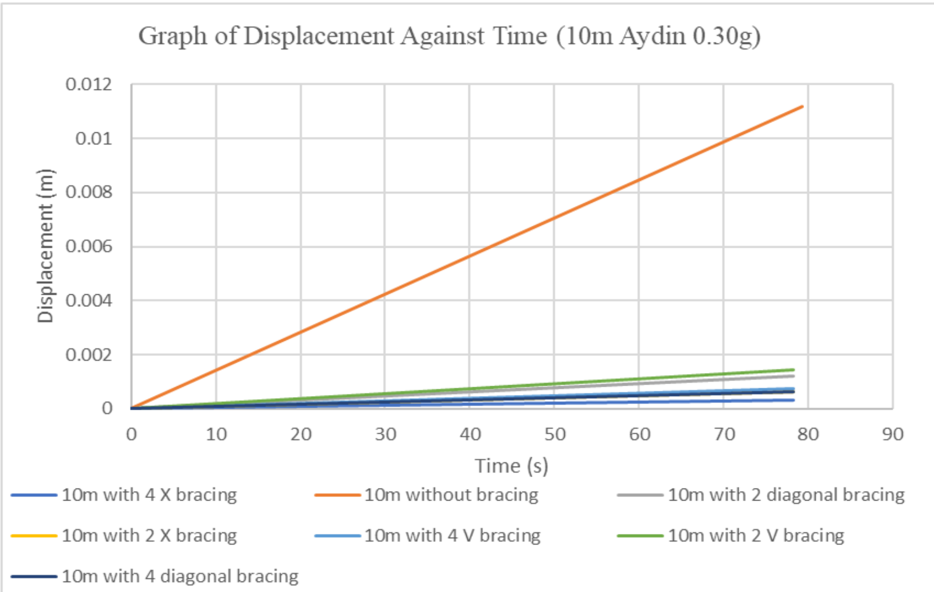

Fig. 7. Graph of Displacement against Time (For structure with different height)

5. Conclusion

For the pushover analysis, the maximum displacement increases from the structure with 10m height to 20m height (Maximum displacement of Model 1 is 0.036m, maximum displacement of Model 8 is 0.068m, maximum displacement of Model 3 is 0.099m). The low structure has strong seismic performance while high structure has weak structure performance which proved in term of the maximum interstory displacement during seismic condition based on Eurocode 8. However, for the time history analysis by using record of Aydin 0.30g and Tokat 0.30g, the maximum displacement also increases when the height of the structure increases.

From both the pushover analysis and time history analysis, 4 X-bracing provide the better seismic performance to the structure. The maximum displacement of the structure with 4 X-bracing is 0.011m which is the lowest when compared to other type of bracing.

Adding bracing to a structure (regardless of height) dramatically reduces displacement. The tenfold reduction in displacement highlights the dominant role of bracing. While the displacement increases with height for unbraced structures, the increase is marginal when effective bracing is applied. This is showing that the height impact is secondary to the bracing effect. So, the bracing system's ability to significantly enhance stiffness, strength, and energy absorption makes it a critical factor in controlling seismic displacements. While the height of a structure influences its behavior under seismic forces.

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