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Effects of Dynamic Characteristic on the 5-Storey Steel Tower with Different Orientations of Adjacent Structure

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Abstract: Many building in the world which are built-in direct contact close to each other. Interaction between two adjoining structures influence the dynamic characteristic. The construction of the building which direct contact or closer to each other without sufficient separation gap or expansion joint will modify the building dynamic characteristic such as natural frequency and mode shape. Modal analysis had been conducted in this study in order to investigate the effects of dynamic characteristic on 5-storey steel tower with different orientations of adjacent structures using STAAD Pro software. 5-storey steel tower was modelled with different orientations of adjacent structures according to the existing frame in Jamilus Research Centre (JRC). The dynamic characteristics of steel tower was investigated in terms of their relationship of natural frequencies, mode shape, maximum deflection amplitude and relative floor displacement amplitude. The output shows that the optimum natural frequency when the existing bare frame was restrained for all sides up to level 3. The percentage shows the natural frequencies increased up to 37.64%. As conclusion, it was found that the plan irregularity and unsymmetric adjacent structure contribute to significant change in natural frequencies to existing structure.

Keywords: Dynamic Characteristic, Adjacent Structure, Modal Analysis

1. Introduction

The construction of the multi-story building become complex because of there are many factors must be taken account that may be influence directly or indirectly to the building and their adjacent building because every structure has their structural dynamic response. The limited area of development giving them the alternative to building up the multi-storey building that made it compact and complex. There are many building in the world which are already built-in direct contact or extremely close to each other and it would be suffer pounding damage in future earthquakes or any unexpected event [1], [2]. Previous study [2] stated that, there has dynamic interaction between two adjoining structures, and it is significantly influenced the dynamic characteristic of each other. This was agreed by other study that

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has been performed on the other structure and their adjacent structure such as [3], [4], [5]. Because of that, it is significantly to investigate and identify about the effect of the adjacent building to the dynamic behavior of the structure. According to the previous study, the construction of the building which direct contact or closer to each other without sufficient separation gap or expansion joint will influenced the behaviour of the building and also will modify the building dynamic characteristic in term of natural frequency and mode shape [2], [4]–[6]. This is because it will affect the vibration mode of the building and their adjoining building. The actual condition of the building and their structural member should be assessed and monitored to ensure the safety and quality of the building.

To investigate the suitable orientation and configuration of adjacent or adjoining structure for multistorey building to make sure the structure can be performed as their desired function and behave well in term of dynamic behavior. Other than that, the adjoining structure also can be as supporting structure to improve the structure oscillation and their deformation shape. In this study, the modal parameter had been observed and investigated through the dynamic characteristic of the structural system when it is subjected to the different orientation with different level or storey (height) of the adjacent structure beside or surround of the structure. The effect of dynamic characteristic to the structure with multiple cases of the orientation of the adjacent structure had analysed and evaluated through the modal analysis by using STAAD PRO software. Thus, study are important in order to study the effects of vertical irregularity and plan irregularity due to various geometrical shapes could be investigated from the outcomes of this modal analysis. Besides that, it also can be identify the relationship on natural frequency and mode shape against the vulnerability of structure arrangement to provide better understanding for structural engineer about the dynamic behavior of the steel frame.

2. Dynamic Characteristics

The dynamic characteristic is the intensity and duration of oscillation and the amount of inertia force which induced in the building depend upon the features and properties of buildings [7]. The structural responses specifically describe the structural dynamic characteristics that are useful for understanding structural behavior and further assessing structural integrity [8]. In order to obtain the dynamic characteristic of studied structure, the effective way is by using the ambient vibration test and commonly used world widely. Meanwhile, the outcome from the testing which is the modal parameter can be identified and be as a baseline of properties for damage detection, response prediction and reliability assessment of the structure [4]. Thus, the effect of the adjacent structure on the dynamic characteristic is important to be analyse and investigate in order to study how significant the adjacent structure is influenced to other structure in term of their behaviour, stiffness and other parameters. The study on the effect of the seismic joint and separation joint of multi storey of adjacent structure by using ambient vibration field, there has significant dynamic interaction between the building and their adjacent structure, this are contributed by both of structural component and the non-structural component[2], [4]. Besides that, the study on the steel stairwell that attached at building found that there has a dynamic response from the adjacent building which is the structure where the stairwell is pinned on, that give the frequencies intrusion due to the testing [3].

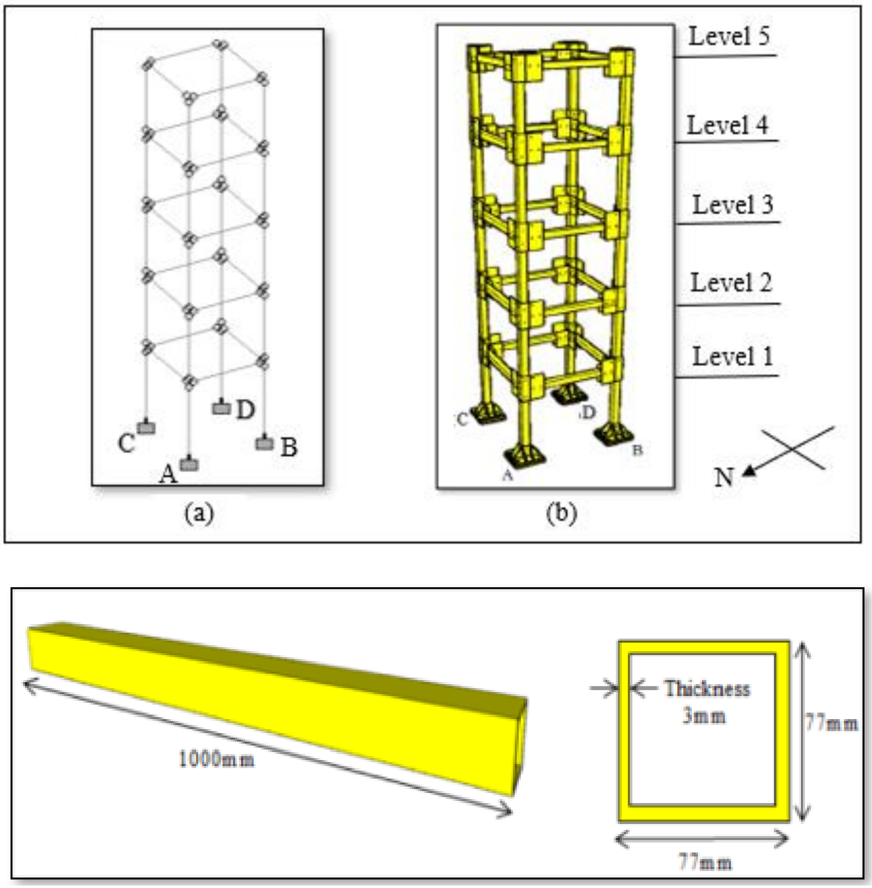
The natural frequency of the building are defined as a frequency at which the building sways as it returns to its original position after being excited and it is measured in Hertz [9]. Natural frequencies related to the deformation shape of building that create the natural mode of oscillations that caused from the external factor such as earthquakes and wind and internal factor such as mechanical component, applied mass etc. [7]. The self-weight, stiffness, and height of the building or structure will determine their natural frequency [9]. The natural frequency can be obtained from two modal parameter identification method and modal analysis results of finite element models by considering the dynamic interaction [4]. Mode shapes are associated by a natural frequency of the building, and it is the deformed shape of the building when it oscillated or shaken at the natural frequency. It is dependent on structural members of geometric and material properties, overall building geometry, and the connection between structural members and their building base at the ground [7]. Natural Frequencies and Mode Shapes could be used for the analysis of overall structural stiffness [8] and the stiffness of the building are mainly concern as a one of the factors that influence the natural frequency and mode shape as well [7], [9].

3. Materials and Methods

The materials and methods section, otherwise known as methodology, describes all the necessary information that is required to obtain the results of the study.

3.1 Stage 1: Description of structure and case study configuration

The steel frame modelled in the STAAD Pro software based on the existing steel tower in the Jamilus Research Centre (JRC), UTHM. All the detail of component and dimension are following the specification of that steel frame from TIER 1, 2017 which is use square hollow section with cross-sectional 77mm x 77mm and 3mm thickness of steel as shown in figure 1 (a), (b), (c). The steel with graded S275 used with overall length 1000mm. The detail specification of steel tower has stated in table 1. The steel frame consists of 5-storey which form as steel tower to be analyse with several configuration of the adjacent structure.



(c)

Figure 1(a): free body diagram of steel tower. (b) 3D diagram of steel tower. (c) Details cross-sectional of the member

Table 1: Steel tower specification details

No.	Component/Parameter	Details
1	Standard	BS EN 1993-1-8:2005
2	Properties	Steel grade 275 fy: 275 x $10^{-3} kN/m^2$ E: 205 kN/m^2
3	Structural element (Beam and column)	Square hollow section (SHS) Length, L = 1000 mm Width, B = 77 mm Height, H = 77 mm Thickness, t = 3 mm
4	Connection/Joint	Partially rigid Using high tension bolt grade 8.8 with diameter 10 mm and 25 mm
5	Support	Fixed end support Connected at reinforced concrete base floor
6	Loading	Self-weight of structure

3.2 Stage 2: Modelling and modal analysis:

Input of the steel tower bare frame parameter was key in by using STAAD editor that has been constructed from the existing specification coding of bare frame to ensure the steel tower bare frame will be modelled exactly and standardized with the actual one in the laboratory with their specific direction and connection of the beams and column. The customized section properties used because of the steel used for steel tower are custom made and the section size are not in the British Standard table list in the software. There is no external loading subjected to the steel tower except their own self-weight and was assigned as load cases to the section. Partial release moment is important to be considered because every frame structural member at their end joint is not rigid joint, so that the bending moment at the joint should be release. This is because the software is set up to assumed it is completely continuity at their end joint which is rigid joint. But on the actual steel frame the connection of the members may be not able to develop the full of continuity of the connecting member because it just slotted in with bolt. Thus, the partial moment release will provide the section to transfers a certain of percentage of forces and will cause the reduction in design force. Partial moment release was assigned on the modelled steel frame structure in the STAAD Pro with percentage value of 80% and 28% for beam and column, respectively. The value assign in STAAD Pro software on the specification is 0.80 and 0.28 for beam and column, respectively.

3.3 Stage 3: Output data and result from modal analysis

3.3.1 Verification result of 5-storey steel tower

The output of the natural frequency and mode shape of the steel tower bare frame has been compared with the previous laboratory result [10]. It was used verification of the modelled in STAAD Pro software to make sure the output from the modal analysis are approximately equal with the existing steel tower in laboratory. The result comparison has been made as shown in Table 2.

Table 2: Percentage difference for frequency data from STAAD Pro modal analysis and previous laboratory testing

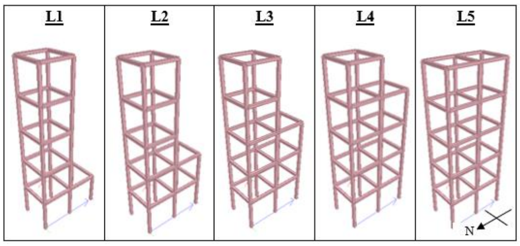
Mode	1	2	3
STAAD Pro modal analysis (Hz)	5.55	5.55	7.17
Ambient vibration testing (Hz) (Khairul *et al.*, 2019)	5.24	5.49	7.23
Percentage difference (%)	5.80	1.00	0.86

There are increment on the value of the natural frequencies from modal analysis compared from the laboratory testing. The percentage of different between both output has been calculated for mode 1, mode 2 and mode 3 which is 5.8%, 1.0% and 0.86% respectively. The studies that conducted by Pachla et al. [11] and Andresen et al. [12] obtained with similar percentage of differences based on result comparison between modal analysis and laboratory result. The percentage of differences between first three modes was less than 10% of different. Thus, the model of the steel tower in modal analysis of STAAD pro is acceptable.

3.3.2 Configuration and parametric studies of adjacent structure

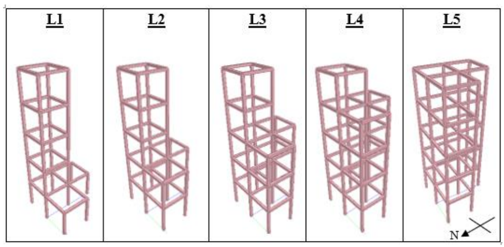
Adjacent structures were added with similar properties and structural configuration of bare frame. There are four cases of adjacent structures were applied at different orientations. The orientations were grouped as single annex, double annex, triple annex, and surrounded annex. For every case, the annex were modelled with different height starting from the first storey denoted as level 1 (L1) until the fifth storey denoted as level 5 (L5). The effects of respective orientations of adjacent structures and its height to the existing steel tower were evaluated against the dynamic characteristic and lateral displacement amplitude.

i) Case 1: Single annex adjacent structure



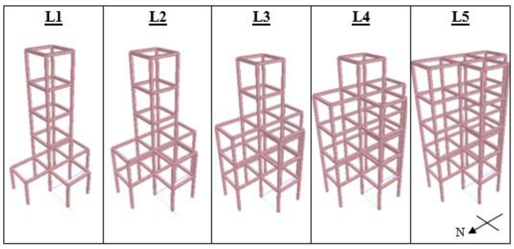
(a)

ii) Case 2: Double annex adjacent structure



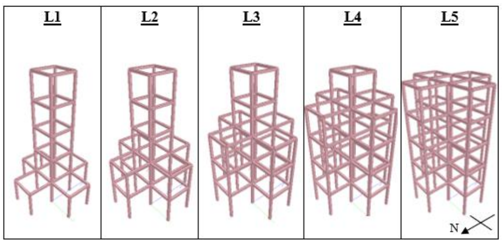
(b)

iii) Case 3: Triple annex adjacent structure



(c)

iv) Case 4: Surrounded annex adjacent structure



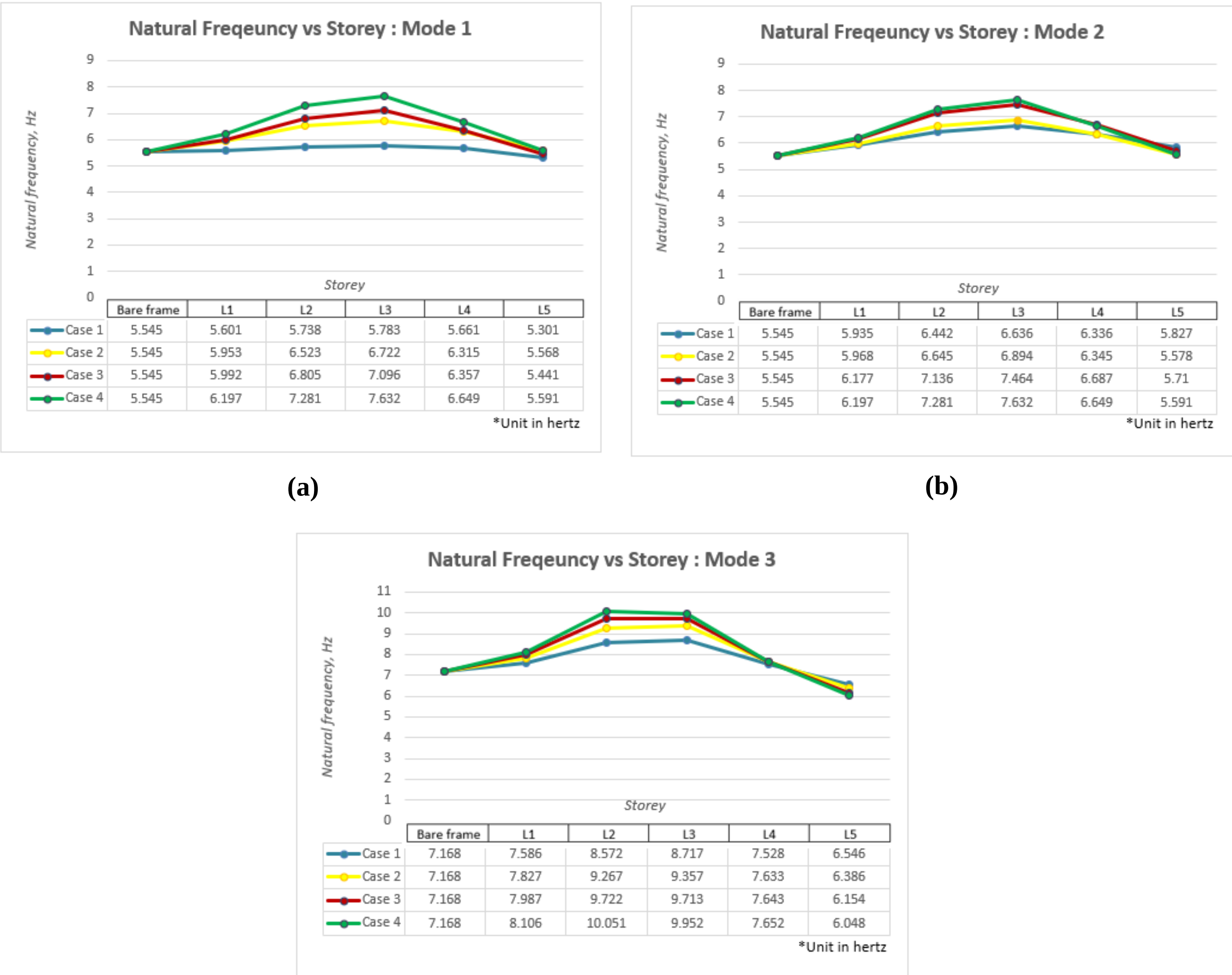
(d)

Figure 2: Adjacent structure configurations (a) Case1, (b) Case 2, (c) Case 3. (d) Case 4

4. Results and Discussion

4.1 Predominant frequency

From the graph in Figure 3, it was clearly showed the highest natural frequency was found at L3 in all cases. Meanwhile, the trendline of natural frequency for L5 in Case 1 (single annex) and Case 3 (triple annex) was lesser than the natural frequency of the bare frame. This result shows the adjacent structure was significantly influence the dynamic characteristic of the existing structure. It has significant interaction among the structure that affected the natural frequency of both adjoining structures [2], [4], [5].



(a) **(b)**

(c)

Figure 3: Natural frequency vs Storey (a) mode 1, (b) mode 2 and (c) mode 3

According to the study conducted by Bhatt & Lamichhane [13], the adjoining building with unequal height has low different of time period of structure oscillation. Meanwhile, for adjoining building or structure with equal story height, it was high different time period of oscillation by comparing both structures. This result shows the adjoining building with different storey height are more rigid by referring the different period of oscillation that produce high natural frequency when the period of oscillation was short. The outcomes of the natural frequency trendline pattern for all cases can had proven the irregularity in plan and vertical are one of the main factors could influence the output of the result. The vertical irregularity in term of height for adjacent structure provide improvement to existing structure. The structure rigidity has directly improved by structure oscillation and natural frequency. Thus, the self-weight, stiffness, and height of the building or structure will determine their natural frequency [9]. The improvement natural frequency will influence the stiffness of the structure. Thus, when the natural frequency increased, the stiffness will also increase.

4.2 Percentage of natural frequency improvement

Figure 4 shows the percentage of natural frequencies increase when the 5-storey steel tower were subjected to the multiple orientations of adjacent structures at different level for the first mode of natural frequency. Mode 1 was taken as a reference because the first mode of vibration is the one of primary interest. The first mode usually has the largest contribution to the structure motion. The period of first mode is the longest for structural building [14]. Most of the level for all cases of application of adjacent structure had increased the natural frequency except for L5 for Case 1 and Case 3.

The natural frequency has been increased to 37.64% of the bare frame model based on the Case 4 at L3 and the worst when the natural frequency was decreased to -4.40% based on Case 1 L5 model. This is because of the buildings become laterally flexible as their height increases and it will result to the natural period of buildings increase with increase in height [7]. The adjacent structure was acting as a restrained structure. This can be shown when natural frequency of structure was increased and reduced the displacement amplitude compared to the bare frame model.

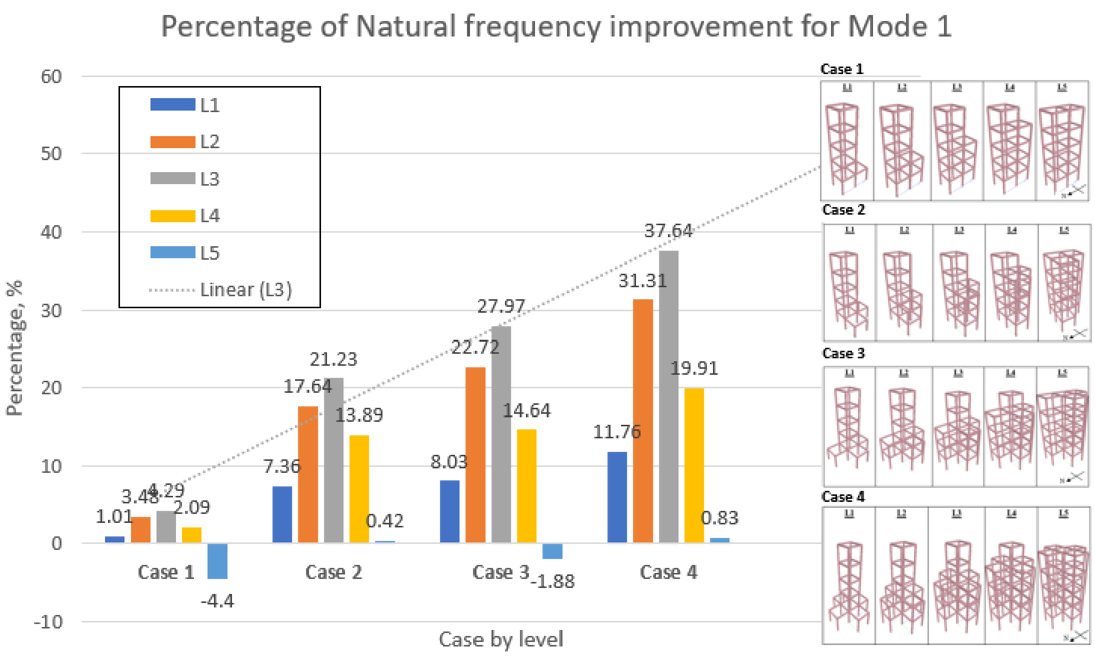


Figure 4 Percentage of natural frequency improvement

The result from analysis conducted by Bhatt & Lamichhane [13] shows the adjoining building with different storey height are more rigid by referring the different of time period of oscillation that will produce high frequency among other cases or model. This study also shows, the lower the height of building the more rigid of structure according to period of oscillation. In addition, the steel frame model with 8 story having period of oscillation less than the building with 13 storey [1]. The shorter the storey height, the period of oscillation will be low. The different orientation and storey height of adjacent structure applied has shown significant improvement to the structural bare frame natural frequency or their rigidity except for L5 for Case 1 and Case 3.

4.3 Deflection Amplitude

Figure 5 has illustrated the deflection amplitude for steel tower bare frame and the application of adjacent structure for every case at L3. L3 was taken to intensive parametric studies because of the optimum natural frequency was found with its adjacent structure. The deflection amplitude against the storey level for every case was compared with steel tower bare frame to investigate their effect. The graph is clearly illustrated the increment of adjacent structure application to the existing structure are directly proportional to the improvement of the deflection amplitude. It can be seen the trendline of the deflection curve are improved, especially in the middle height of the structure. The graph pattern was shrink substantially compared to the bare frame when it subjected to adjacent structure from Case 1 until Case 4. The pattern of the deflection amplitude has significant improvement for all cases with respective mode.

The deflection amplitude for Case 1 and Case 2 in mode 1 indicate that column deflection for node B and D are overlapped with node A and C. The column deflection amplitude for node B and D are less than node A and C. This because the column node B and D are at side where it attached or connected with the adjacent structure. Thus, when translational on NS direction occurs column position at node B and D are smaller than column at node A and C. Meanwhile, in mode 2 the trendline pattern of deflection amplitude are uneven especially for Case 2. The deflection amplitude on column node A, node B and node D are moving together but for column node C are split apart from others. The deflection amplitude on column node C are less than column node A, node B and node D. From the observation for case 2, the adjacent structure is connected beside the original structure (at column node B and node D side) and at front of original structure (at column node A and column node D side).

According to Murthy et al., [7] the lateral deflection is affected by the lateral stiffness of the structure. Thus, the lateral deflection can be used to observe and investigate the lateral stiffness of the building. Besides that, it is clearly showing the case 4 pattern of graph was linear. This indicate that the regularity of structure plan and the symmetrically of structure geometry significantly influence the behaviour of structure and their deformation shape of structure. The irregularity shows a great effect on the deflection shapes. The effect of vertical irregularities was reduced and weakening the stiffness of the tower, based on the reduction of natural frequency and increasing in deflection amplitude [15].

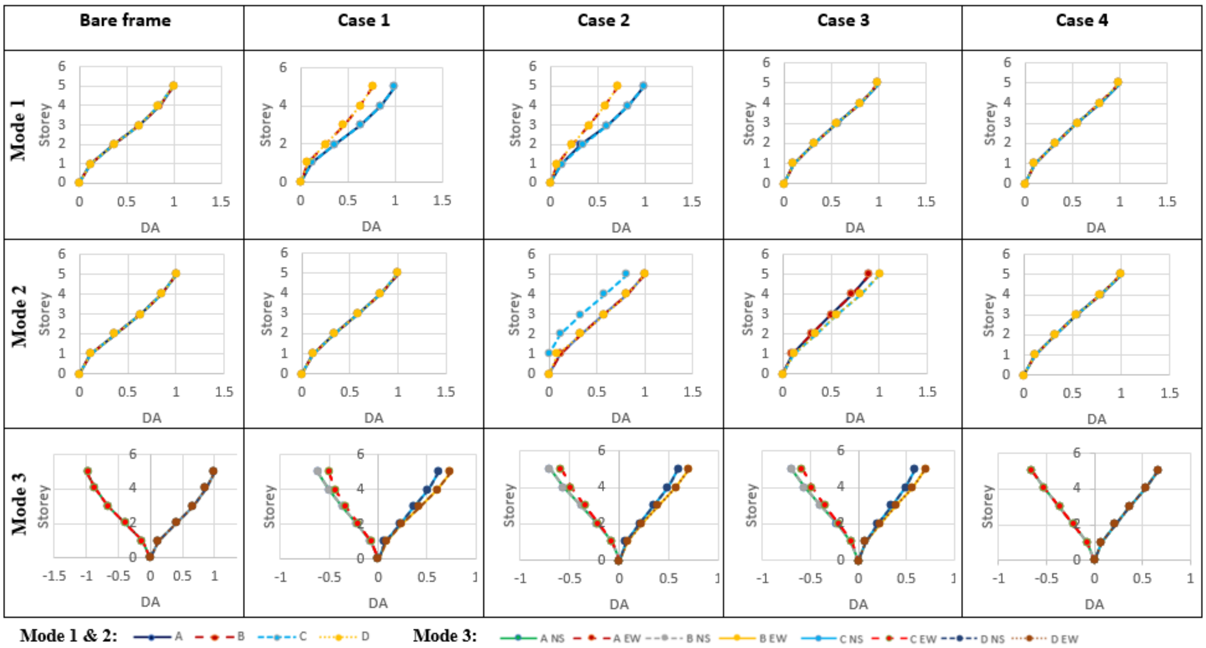


Figure 5 Deflection amplitude of steel tower bare frame and with adjacent structure

4.4 Relative Floor Displacement Amplitude (RFDA)

Figure 6 shows the RFDA of the bare and four cases of adjacent structure for the respective mode. Weak level can be identified at the center of a structure. Overall, bare frame and all cases experienced weak level of displacement at ranging from L3 and L4 which located at the mid-high of the steel tower. According to the Shah & Vyas [16] the maximum relative floor displacement was took place in the mid-height of structure for all frame formations in terms of inter-storey drift. For this study, the maximum displacement for all columns in bare frame were located at L3. For overall cases shows significant improvement of relative floor displacement amplitude for steel tower when subjected to adjacent structure. The relative floor displacement is increase together with increasing the storey height but after reached to L3 the displacement fluctuated to drop back. There has significant improvement on side where the adjacent structure has been attached which where column that connected with adjacent structure.

For the first mode it can be seen the trendline pattern of RFDA were not similar for case 1 and Case 2. For Case 1 the trendline pattern were overlapped together for column node A dan C and column node B and D, respectively. The RFDA of column node B and D are below 0.2000 which is the displacement occurred are lesser than column node A and C. This happen because of the attachment of column node B and D to the adjacent structure that can be as a support or brace to the column. Meanwhile, for the Case 2 the trendline pattern of RFDA are more complex which are the highest displacement occurred on L3 for column node A with displacement amplitude 0.2747 that higher than the RFDA for bare frame at same point with value 0.2630. Besides that, for Case 3 and Case 4 the improvement of structure RFDA were occurred evenly and uniformly for every single column and move as one unit of structure.

For the second mode, the trendline for case 3 were overlapped for column node A and B to each other and similar to column node C and D. This is because of the adjacent structure was applied in a few sides was connected both on their side and in front of existing structure. It becomes more rigid and less displaced for columns node C and D compared to the columns node A and B.

The value of maximum RFDA for overall cases of adjacent structure were less than the bare frame. It was indicated the adjacent structure give significant effect to the RFDA of the original structure, that can reduce the floor displacement of the structure. It was clearly shown the adjacent structure for Case 3 and Case 4 had brough significant change and improved the weak level of existing structure. The highest RFDA of steel tower bare frame has found at level 3 but when it subjected to the adjacent structure Case 2, Case 3, and Case 4, the RFDA was improved substantially. The highest level of RFDA had changed from L3 (bare frame) to the L4 and the value of RFDA for adjacent structure (L4) are less than L3 in bare frame.

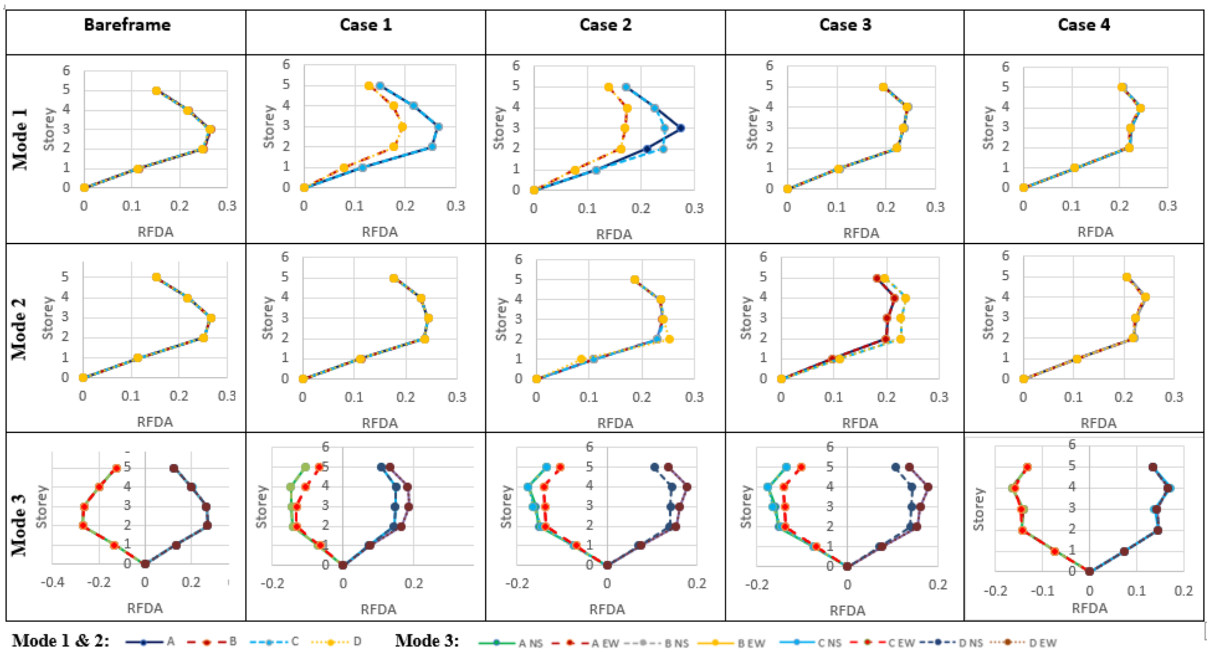


Figure 6: RFDA of steel tower bare frame and with adjacent structure

5. Conclusion

There are two main objectives has been addressed in this study. The modal analysis of 5-storey bare frame steel tower STAAD Pro has been successfully verified with less than 6.0% of different to the ambient vibration testing result conducted by Khairul et, al. (2019). Different orientations of adjacent structure which are single annex (one side), double annex (two sides), triple annex (three sides) and surrounded annex (all sides) was found significantly affected the dynamic characteristic of the steel tower. Most of cases at every level of storey (except level 5 for case 1 and 3) had improvement for natural frequency, mode shape or deformation shape of structure, the behavior of deflection amplitude and relative floor displacement amplitude. But in some level of storey and case, the effect of adjacent structure orientation for level 5 of case 1 and case 3 that behave worse than the original structure. The effect of adjacent structure on the dynamic characteristic of 5-storey steel structure depending on the several factor such as the regularity of structure plan and height. It was found that, the improvement of modal parameter was happened when it was regular in plan and irregular in height which mean the plan regularity and vertical irregularity can improved the structure oscillation and behavior. Furthermore, the structure geometrical shape, and adjacent structure configuration and orientation also influenced significantly to the structure deformation and behavior.

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