Fundamental period of vibrations influencing characteristics of torsional irregularity in reinforced concrete buildings

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Abstract. This paper presents an analysis of irregular reinforced concrete buildings with respect to fundamental period of vibrations. During earthquake, reinforced concrete building with asymmetric building system experience extensive damage due to this torsional irregularity. Torsional irregularity of reinforced concrete buildings has been analysed with taking the strength and stiffness eccentricities as the main parameters of the rectangular in-plan building system. Displacement demand in reinforced concrete building has been determined in terms of fundamental period of vibrations and the behaviour of the building system was presented using the normalised displacement of buildings. The hypothetical model has been analysed has been set up using varies values of fundamental period of vibrations using Ruaumoko program and the lateral displacement of the building were extracted using Fortran program. The results indicated through the damage index showed that the fundamental period of vibration plays an important role in earthquake studies on reinforced concrete building since earthquake induced excessive displacement to the building system under the increment of the fundamental period of vibrations.

1.0 Introduction

Earthquake studies becoming vital nowadays in Malaysia after 2015 Ranau Earthquake hit Sabah on magnitude of 5.9 which was the largest to hit Malaysia since 1976. The damages of structural and non-structural elements due to 2015 Ranau Earthquake are reported in previous work [1,2]. Earthquakes also cause distress in building structures and one of the major causes of distress is the torsional motion induced during earthquake event. Torsional irregularity of building refers to a building system where the strength and stiffness are distributed unevenly in the building. During earthquake event, uneven strength and stiffness distributions induced excessive torsional movement of buildings. Damage analysis of reinforced concrete buildings has proven that torsion greatly produces additional displacements as reported by past researchers [3,4,5]. During seismic events, the vertical load resisting elements including walls and columns will vibrate back and forth. Torsion or twist in buildings will make different portions to move horizontally by different amounts; hence brings more damages in the walls and columns. Nowadays, the geometric form and dimension of building systems were not adequate parameters for defining the seismic irregularity of a building. In the seismic design, the correlation between performance and the distribution of mass, stiffness and strength in the building, also the environment, size and location of structural and non-structural building components are the most important factors that are established for defining the analysis procedure that should be used for the design of earthquake resistant buildings [6]. The seismic action on buildings is strongly dependent on their dynamic characteristics and on the fundamental period of vibration [7]. Fundamental period of vibrations is used predominantly for determining building seismic forces. The fundamental period of vibrations T_1 or the natural period is the rate at which the structure moves back and forth during vibrations. The fundamental period of vibrations T_1 is the global characteristic describing the behavior of building under seismic loads [8]. The fundamental period of vibrations of reinforced concrete buildings are affected by many factors such as structural regularity, number of story and bays, dimensions of member sections, infill panel properties and position and load level. A reliable estimation of the fundamental period of vibrations is not an easy task for designing new buildings or in analyzing of existing buildings. From studies that has been conducted by previous researchers, fundamental period of vibration is considered as the main parameter influence the behaviour of building structures during earthquake event. In CEN 2004 (Eurocode) for earthquake design, the fundamental period of vibration for moment resisting frames (MRF) has been derived from the Rayleigh's Method by assuming that the equivalent static lateral forces are linearly distributed over the height of the building and the base shear force is assumed to be proportional to $1/T^{2/3}$ and had been expressed as

$$T = 0.075H^{0.75} \text{ } (H \text{ in meter})$$

The objectives of this study are to determine the displacement demand in irregular reinforced concrete building in terms of fundamental period of vibrations and after that, the behaviour of the building system is also analysed using the normalised displacement under seismic excitations. Figure 1 shows an idealize building where the irregularity of the model is set to be depending on the stiffness eccentricity, es. Stiffness eccentricity is a distance from the center of mass CM and the center of stiffness CS. The CS position is calculated by determining the stiffness of the building whenever the sizes of wall is set to be differ in size. In the figure, wall 1 and 2 is not same in size where wall 3 and 4 has set to be the same size. These arrangement of wall sizes produces asymmetric building system as done by many researchers [9,10].

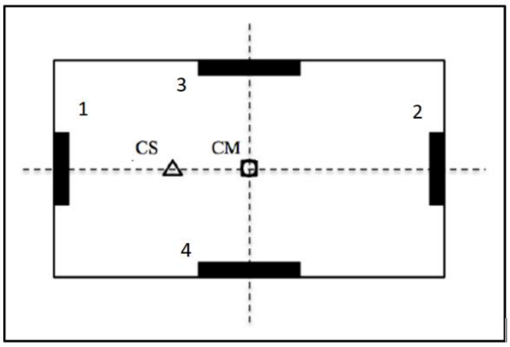

Figure 1 Building model idealization considering stiffness eccentricity

2.0 Methodology

In the present study, the building model is analysed by using RUAUMOKO 3D program. This is well-known program to be used in analysing building behaviour and characteristics under seismic excitation. The program is a Fortran-based program built in year 2008 by Professor Autor J. Carr from University of Canterbury, Christchurch. The research procedure can be summarized in Figure 2.

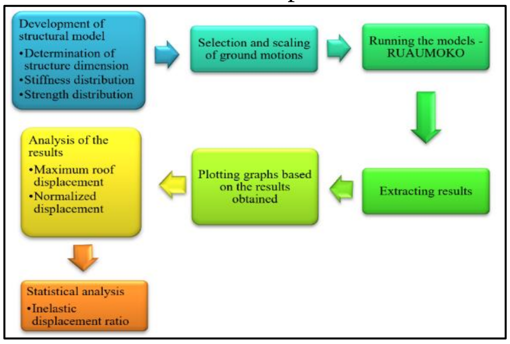

Figure 2 Step by step processes for the present study

2.1 Modelling of the building systems

All building model have been set as an in-plan single storey asymmetric reinforced concrete building. The building is asymmetric building by modelling the system having varies center of stiffness CS. Beside CR, other parameter considered is the position of the center of strength CV, fundamental period of vibration T_1, behaviour factor q and post-yield stiffness ratio r. The present study will only focus on the effect of varies stiffness eccentricity e_s and fundamental period of vibration T_1, whereas other parameter has been fixed to a certain value only. The Eurocode 8 was used as a guide in analyzing and designing all the building models. The stiffness eccentricy, e_s have been set in various locations in order to represent the real building system. The e_s is the distance between the center of mass CM located at the geometric center GC of the building and the position of CS.

$$e_s = e_{sx} = \frac{1}{L}\frac{\sum_{i=1}^{N} k_{yi} x_i}{K}$$

The analysis and design of one-story reinforced concrete buildings have been started using a hypothetical building model as shown in Figure 4 below. The buildings were modeled as extremely torsional building system, adopted system as used in DeStefano and Pintucchi [4] by using wall system located at perimeter of building model. In order to determine the results of torsion, the lateral displacements were determined at five locations labeled as node number as shown in Figure 3. For the system chosen in the present study, nodes 5, 6, 7 and 8 were labeled at the center of each side to represent the wall system labeling. Node number 9 was used in the model as the compulsory requirement in modeling 3-dimensional buildings using RUAUMOKO-3D since the behavior of the building under torsion can be determined by the ratio of the maximum lateral displacement at nodes divided by the maximum lateral displacement at node 9. The building models proposed by DeStefano and Pintucchi [4] was used with various positions of center of strength CV and center of stiffness CS make total models equal to forty due to strength and stiffness distributions. DeStefano and Pintucchi [4] have set the positions of CS and CV coincides for all models they used giving the same position of CS and CV for the model discussed, whereas the present study was due to the varying positions of stiffness eccentricities for each fifteen building models.

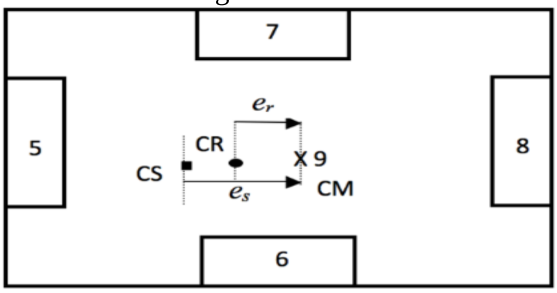

Figure 3: Node locations on top of building

Table 1 shows the variation position of stiffness eccentricities e_s. These variations are considered in the present study in order to represent real building conditions since there are no building is symmetric in real. The diagrams are drawn along x-axis with the distance 26 m. The center of mass CM is located at the geometric center GC i.e. 13 m from edge. From the table, wall number 5 is set varies due to the eccentricity have been set. Height of the building h is also varying since it relates with fundamental period of vibration T_1.

Table 1: Variation of stiffness eccentricity distribution

Model	Wall size		Moment of inertia, I (m^4)	Position of CS from CM (m)
	l (m)	h (m)		
1a	7.72	2.152438	0.4155093	0.05L = 1.3
1b	8.1	2.31692	0.5182292	0.1L = 2.6
1c	8.34	2.4990473	0.6502976	0.15L = 3.9
2a	11.12	2.152438	0.4155093	0.05L = 1.3

2c	11.8	2.4990473	0.6502976	0.15*L* = 3.9
3a	13.62	2.152438	0.4155093	0.05*L* = 1.3
3b	14	2.31692	0.5182292	0.1*L* = 2.6
3c	14.5	2.4990473	0.6502976	0.15*L* = 3.9
4a	15.72	2.152438	0.4155093	0.05*L* = 1.3
4b	16.2	2.31692	0.5182292	0.1*L* = 2.6
Model	Wall size		Moment of inertia, I (m^4)	Position of CS from CM (m)
4c	16.74	2.4990473	0.6502976	0.15*L* = 3.9
5a	17.58	2.152438	0.4155093	0.05*L* = 1.3
5b	18.1	2.31692	0.5182292	0.1*L* = 2.6
5c	18.72	2.4990473	0.6502976	0.15*L* = 3.9

2.2 Ground motions selection

Since the torsional behavior of one-story asymmetric building is to be analyzed, the 3-dimensional generic model used in this study to accommodate the irregularity issues in plan. It is mainly intended to incorporate the bi-directional seismic action with considering the near-field ground motion (NFGM). 7 sets of ground motions data have been selected from PEER (Pacific Earthquake Engineering Research Center) for the NFGM and FFGM as listed in Table 2.

Table 2: Near field ground motion (NFGM)

Year	Earthquake	Mag	Distance (km)	Station
1989	Loma Prieta	6.9	9.96	Gilroy - Gavilan Coll.
1994	Northridge-01	6.7	5.43	Jensen Filter Plant
1994	Northridge-01	6.7	5.43	Jensen Filter Plant Generator
1999	Kocaeli, Turkey	7.5	10.92	Gebze
1999	Chi-Chi, Taiwan	7.6	3.78	TCU049
1999	Chi-Chi, Taiwan	7.6	0.66	TCU052
1999	Chi-Chi, Taiwan	7.6	2.76	TCU076

For all seven sets of ground motions, the displacements due to these seven ground motions were converting to one value by using the average value of all ground motions separately. Despite, the program used the motion of the building model using RUAUMOKO-3D for Loma-Prieta Earthquake is used in the verification model as shown in Figure 4.

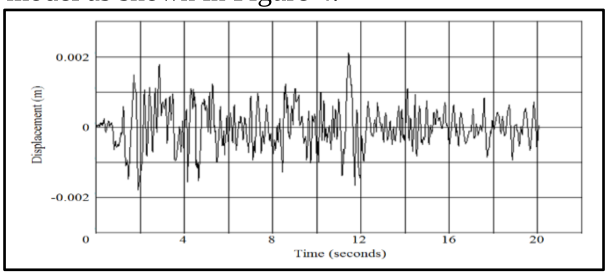

Figure 4: Building motion in RUAUMOKO-3D

3.0 Results and discussions

Irregular building systems induced torsion during earthquake event. Despite the fact that many earthquakes studies have disregard this effect due to lack of information, such as the strength and stiffness eccentricities occurred in the building system, the present study decided to take into consideration the effect of these irregularities in building system. The study had been done to reinforced concrete building system in conjunction with several fundamental period of vibrations, T_1 values starts from 0.3s to 1.5s with increment of 0.3s for each time step. Due to fundamental period of vibration T_1, the lateral displacement at flexible side of building increase with the increment of T_1. This is occurred due to the relationship between the building height and the fundamental period of vibration.

3.1 Lateral displacement of reinforced concrete building model

In order to analyze the building behaviour subjected to ground motion, the lateral displacements were extracted out from the RUAUMOKO 3D programme. Displacement on *z*-axis will be used to analyze the severity of the impact due to the ground motion. This delta-*z*, Δ_z represents the displacement of the building. Figure 5 to 7 show the lateral displacement vs fundamental period of vibration for node 5, 8 and 9. Node 5 and node 8 refer to the stiff side and flexible side of building, respectively, whereas node 9 is located at the center of building representing the diagphragm. The figures show that the top displacement of building.

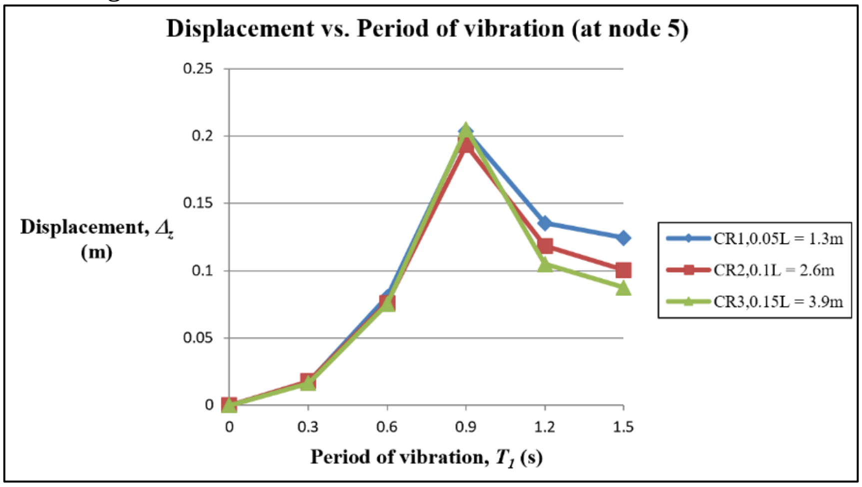

Figure 5 Displacement vs. Fundamental period of vibration T_1 (at node 5)

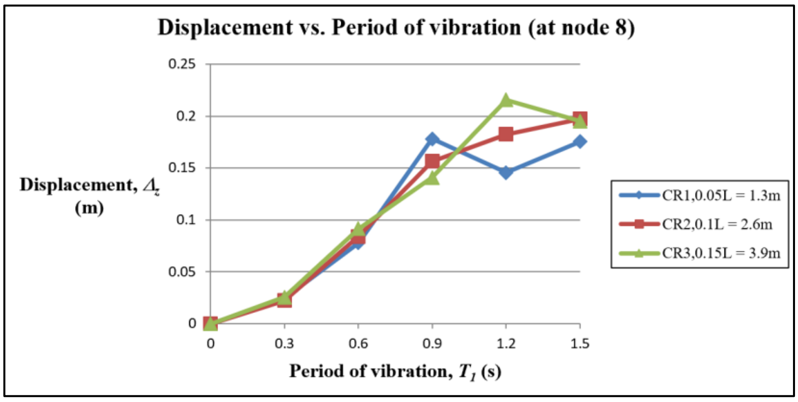

Figure 6 Displacement vs. Fundamental period of vibration T_1 (at node 8)

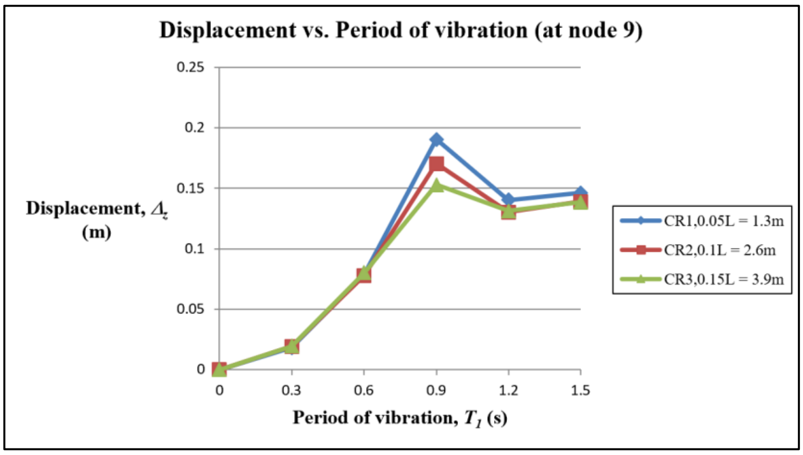

Figure 7 Displacement vs. Fundamental period of vibration T_1 (at node 9)

As seen in the three figures, as the displacement change with changing of T_1 for stiff side, flexible side and the center of the building model. The displacements can be seen increased by fundamental period of vibration increase until at T_1 = 0.9s the displacement also increase. The optimum displacements are found occur at T_1 = 0.9s because the displacement start tu decrease for T_1 = 1.2s and T_1 = 1.5s. This is occur due to many factors such as ground motions effect and soil types that is not considered in the present study. It is also can be seen that at each node, the displacement recorded does not exceed 0.25 m. The models with position of CR at 3.9 m from the CM give mostly the smallest displacement values compared to other models with the other two position of CR.

3.2 Normalized displacement of reinforced concrete building model

From the displacements obtained, normalized displacement graphs can be plotted. In engineering and mathematics, normalized displacement is a tool to visual the behaviour of the building models under seismic action and this is done by rationalizing the maximum displacement at all nodes with the maximum displacement at the mass centre, the normalized displacement can be developed. Comparisons are made by observing the models at different fundamental period of vibrations T_1. Figures 8 to 12 show the normalized displacement of building plotted at stiff side, flexible side and at center for each fundamental period of vibration T_1. The normalized displacement shows the trend of the building behaviour and the fundamental period of vibration T_1. The normalized displacement at the flexible side of building are shown to have larger value compared to the stiff side of building.

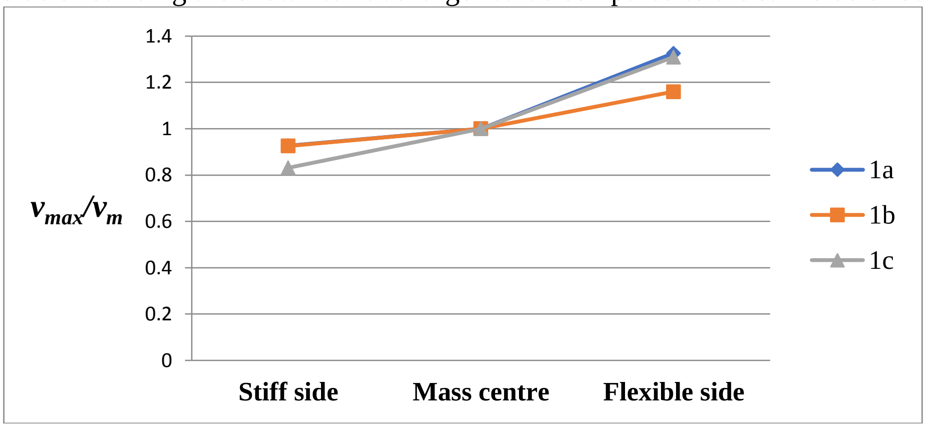

Figure 8 Normalized displacement at T_1 = 0.3 s

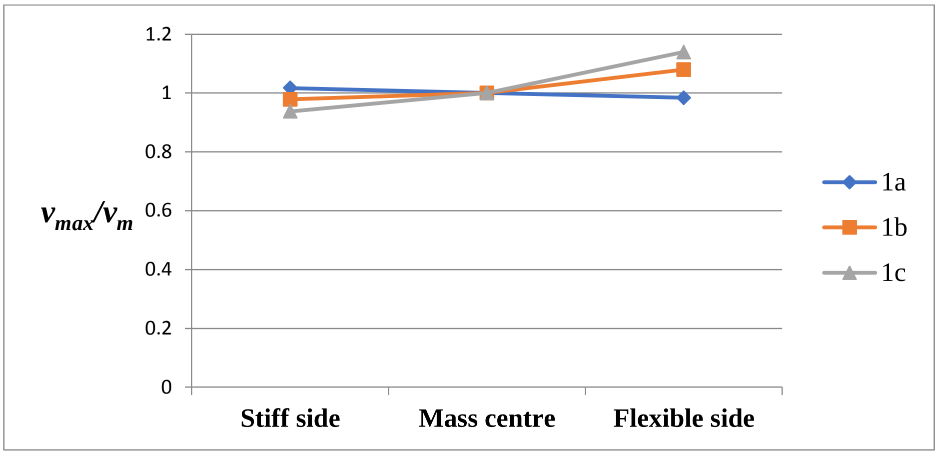

Figure 9 Normalized displacement at T_1 = 0.6 s

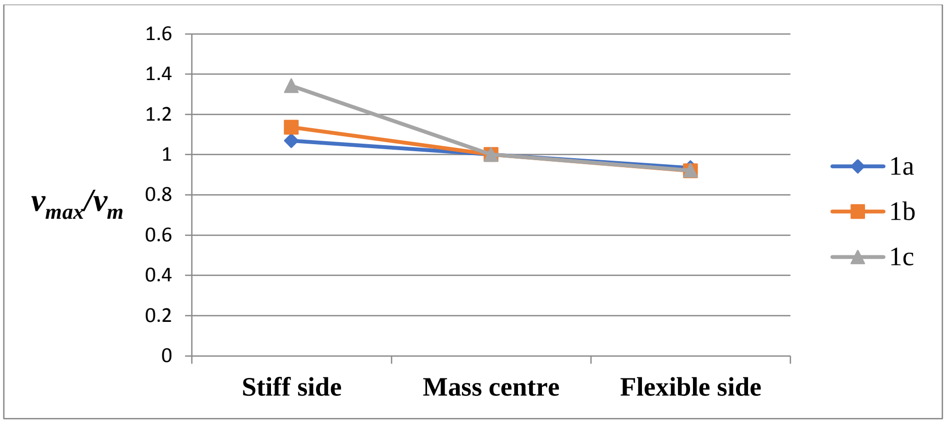

Figure 10 Normalized displacement at T_1 = 0.9 s

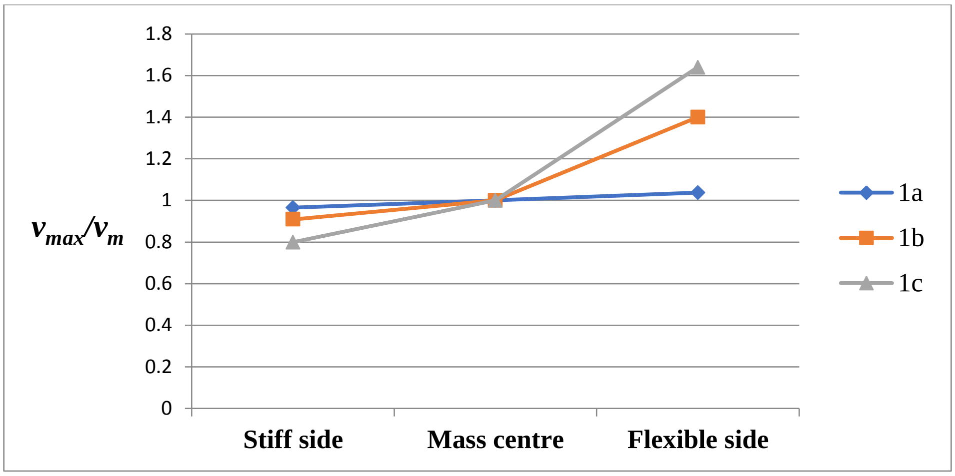

Figure 11 Normalized displacement at T_1 = 1.2 s

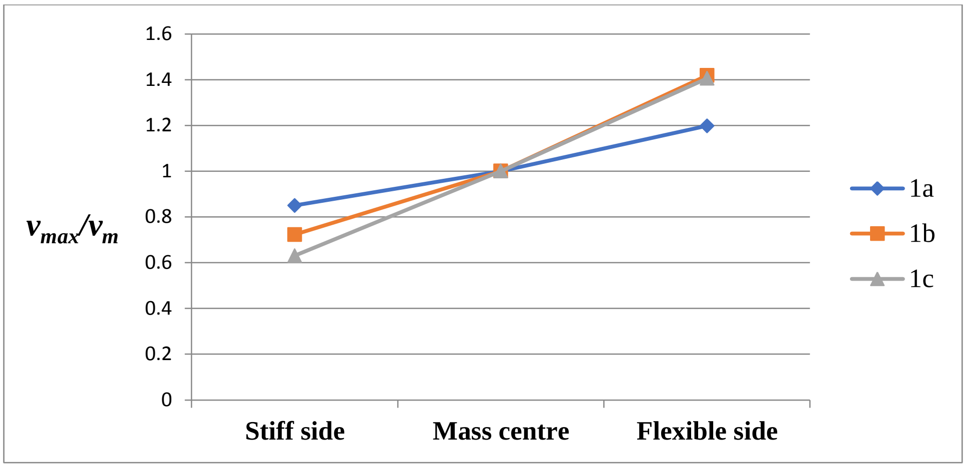

Figure 12 Normalized displacement at T_1 = 1.5 s

4.0 Conclusions

Through the present study of irregular building system of single story reinforced concrete building, the displacement demand and normalized displacement have been analysed with considering one important parameter called fundamental period of vibration T_1. From the result, the displacement increases with increment of fundamental period of vibration T_1. Anyway, the optimum value of displacement is found occurred at 0.9s fundamental period of vibration T_1. For the normalized displacement figures, the larger displacement occurs at the flexible side of building and in terms of fundamental period of vibrations T_1, the values displacement also increases. It can be concluded that the irregular building models in the present study are directly influence by the fundamental period of vibrations T_1.

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