Rigid, Semi Rigid, and Flexible Diaphragms for Horizontally Asymmetric Building

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***Abstract*—The development of architectural design has increased numerous types of irregularities in structures, one of them is a T-shape building. The asymmetrical plan structure can induce a more unstable response due to earthquake loads. Buildings are generally designed using a rigid diaphragm rather than a semi rigid and flexible diaphragm. This study aimed to analyze the effects of diaphragm flexibility on structural response such as natural period, deformation, and base shear forces. The gravity and seismic loads on the buildings were based on SNI 1727:2013 and SNI 1726:2019. The finite element software program was used for modeling and running the analysis of structure. The results reveal that the rigid diaphragm structure has higher stiffness and generates smaller story displacement and base shear force than semi rigid and flexible diaphragm structures. The flexibility on irregular structure also affects the structural mode shape significantly.**

Keywords*—*diaphragm flexibility, structural irregularities, structural response

I. INTRODUCTION

Earthquakes are uncertain natural disasters which cause casualties due to structural collapses. In order to minimize the risk of damage, the design of building structure should consider the factors for earthquake-resistant structural design with performance based design.

The development of architectural design has increased numerous types of irregularities in structures, one of them is a T-shape building. The variation of structural types can affect the stiffness and performance of the buildings due to earthquake loads and induce a more unstable response than symmetrical structures. In most previous designs on irregular buildings, fully rigid diaphragm has been considered as a basic assumption rather than a semi-rigid and flexible diaphragm. Similar analysis has been carried out previously but on L-shape building with shear wall structure [1]. The conclusion of that analysis is still limited thus more extensive researches are required with more variation of floor plans and structural types.

The purpose of this study was to investigate the structural responses of rigid diaphragm, semi rigid diaphragm, and flexible diaphragm on T-shape buildings. For the comparison, parameters taken were natural periods, story displacements, and base shear forces of structures generated from the finite element software program.

II. LITERATURE REVIEW

A. Irregular Building Structure

Building structures as per SNI 1726:2019 can be classified into regular and irregular buildings. The classifications are based on the horizontal and vertical configurations of the building structure. Example of irregular building is a C, T, U, Z, H, or L shape building as illustrated in Fig. 1.

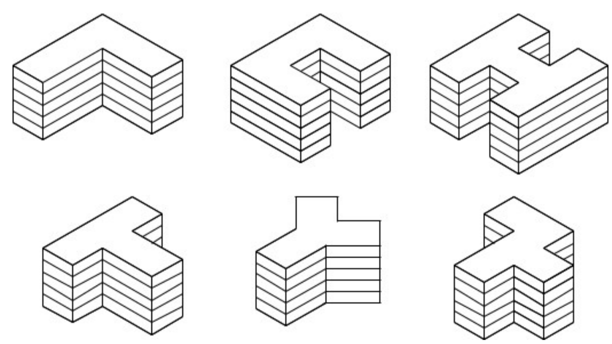

Fig. 1. Asymmetrical building plan (Fajar Nugroho, 2015) [2]

B. Structural System

The structural system based on SNI 1726:2019 is divided into four types.

- The bearing wall system is a structural system that does not have a complete gravity load resisting frame, where most or all of the gravitational load is resisted by the bearing walls. Eearthquake load resistance is provided by shear walls or bracing.
- The building frame system consists a complete gravity load resisting frame, while the earthquake load resistance is provided by shear walls or bracing.
- The dual system provides a complete gravity load resisting frame, while the earthquake load resistance is provided by a combination of a moment-resisting frame system and shear walls or by a combination of a moment-resisting frame system and bracing.

- The shear wall-frame interactive system is a structure with a combination of ordinary reinforced concrete shear walls and ordinary reinforced concrete moment frames system to resist lateral loads according to the ratio of its stiffness, regarding the interaction between shear walls and frames at all levels of the building.

C. Gravity Load Resisting System

The slabs form the floor system which resist gravity loads and transmit them to beams and columns. Floor slabs also act as diaphragm and provide lateral support to the lateral load resisting system. The floor system is basically divided into two types, namely one-way slab and two-way slab as shown in Fig. 2.

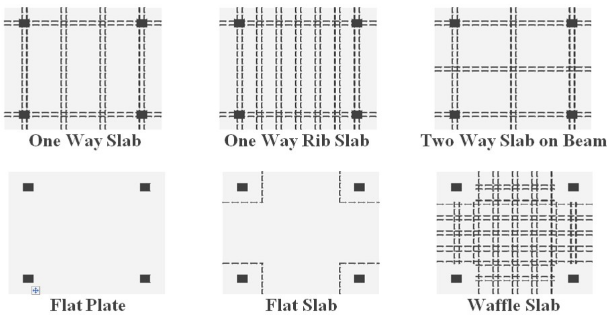

Fig. 2. Floor system (Mc. Cormak, 1995) [3]

D. Lateral Load Resisting System

Lateral loads in structures are including wind loads and earthquake loads. The building strength should be adequate to provide comfort for its occupants, especially in the upper floors. Lateral deflections which occur in a structure are greater on the top floor (Mc. Cormak, 1995) [3]. The spaces between columns, story height, and structural element dimensions significantly affect the stiffness of a frame structure.

The lateral load resisting system is divided into several types which are Moment-Resisting Frame Systems, Bearing Wall Systems, and Dual Systems (a combination of Moment Frames and Shear Walls).

E. Diaphragm Flexibility Modelling

According to SNI 1726:2019 as illustrated in fig. 3, diaphragms with span-to-depth (S/D_e) ratios of 3 or less are permitted to be idealized as rigid diaphragm. On the contrary, the diaphragm is flexible if the ratio of maximum deflection of diaphragm (DDM) to average deflection of vertical element (SREV) is more than two .

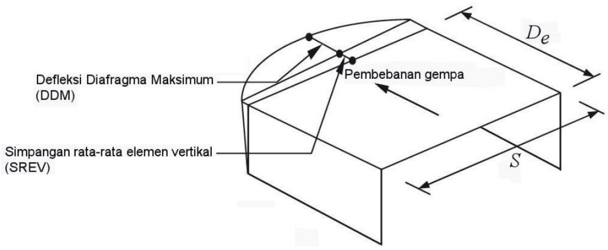

Fig. 3. Diaphragm flexibility (SNI 1726:2019) [4]

Diaphragm must be able to resist the shear and bending stress due to the design seismic force from the vertical elements on each floor. It also has struts to distribute the anchoring force from walls. The diaphragm joint must be a mechanical or welded joint. The use of a diaphragm on the floor structure will be considered as infinite stiffness so that it will be able to help resist the seismic loads (Devi Arsyana, 2016) [5].

III. Methodology

Literature study was conducted on previous journals, articles, research and books related to research. The referred codes were SNI 1726:2019 concerning earthquake-resistant design concepts and SNI 1727:2013 regarding minimum design loads for buildings.

The purpose of preliminary design was to determine the dimensions of beams, columns, and slabs on an office building. The finite element software was used for modeling three types of structures which are rigid, semi rigid, and flexible diaphragm systems.

The loads were assigned on these building structure including dead load (DL), live load (LL), super imposed dead load (SDL), and seismic load (EQ). The dead load or self-weight of structures was generated automatically by the software, while other loads were determined based on SNI 1727:2013 [6]. Dead load, super imposed dead load, and live load were assigned on the shell area while the wall load was assigned on the beam.

The results of the structural analysis such as natural period, story drift, and base shear would be investigated and compared with allowable limit value.

IV. Design and Modeling

The data of structures in this study are as follow.

- The building was a special reinforced concrete moment frame which located in Bandung, Indonesia, with medium soil condition (SD).
- The building was a T-shape asymmetrical structure with 6 stories which used as an office.
- There were three structure models which were rigid, semi rigid, and flexible diaphragm systems as illustrated in fig. 4, fig. 5, and fig. 6.
- The data of reinforced concrete material i.e.:
  - Concrete grade (f'_c) : 35 MPa
  - Steel grade (f_y) : 400 MPa
  - Concrete density : 24 kN/m^3

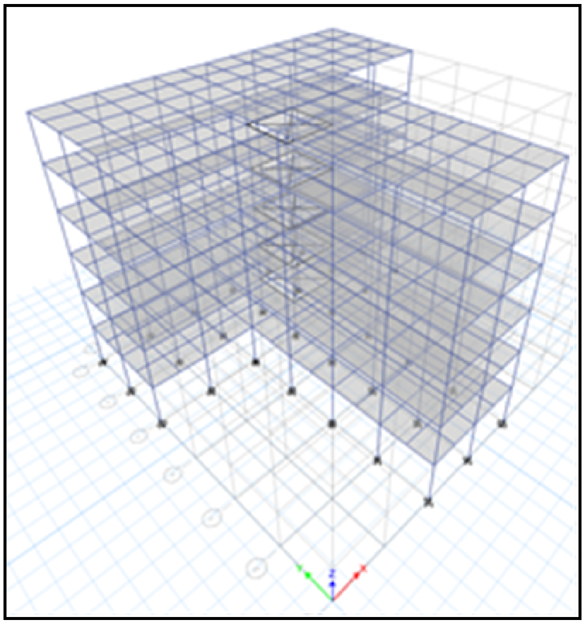

Fig. 4. 3D modeling of building structure

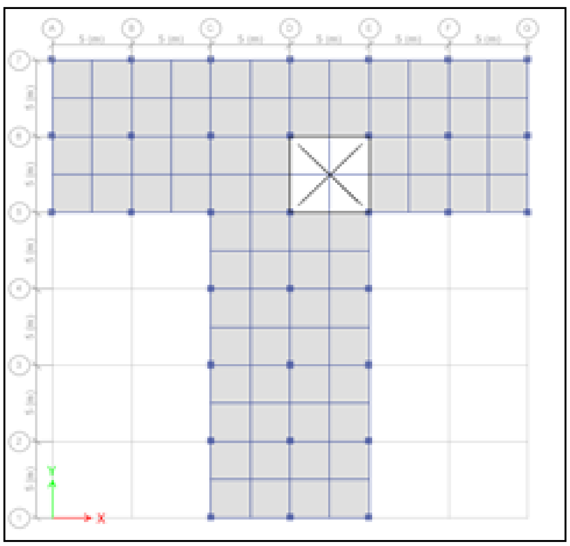

Fig. 5. Typical floor plan

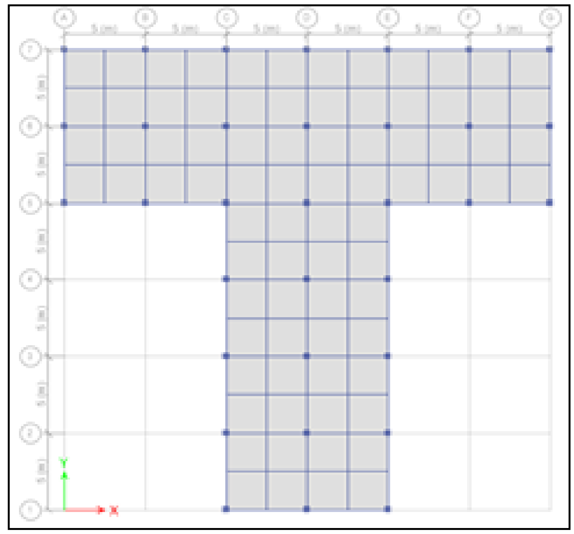

Fig. 6. Roof plan

V. Results and Discussion

Preliminary design and structural analysis generated dimensions of structures output as shown in Table 1. The structure weight result for each floor is revealed in Table 2.

TABLE I. STRUCTURAL ELEMENTS DIMENSIONS

Structural Elements	Width (mm)	Height (mm)	Thickness (mm)
Longitudinal main beam	0.30	0.45	
Transversal main beam	0.30	0.45	
Longitudinal secondary beam	0.25	0.30	
Transversal secondary beam	0.25	0.30	
Story 1-3 Column	0.40	0.40	
Story 4-6 Column	0.35	0.35	
Floor Slab			0.10
Roof Slab			0.12

TABLE II. WEIGHT OF THE STRUCTURE

Story	Mass X (kg)	Mass Y (kg)
6	397558.19	397558.19
5	506620.61	506620.61
4	517346.57	517346.57
3	522334.72	522334.72
2	534913.22	534913.22
1	535355.33	535355.33
Cummulative	3014128.64	3014128.64

A. Natural Period and Mode Shape

Two of the structural analysis outputs are mode shape and natural period of structure. The first mode of rigid and semi rigid structures exhibit a high relative modal mass in Y direction, while the second mode is in X direction. On the contrary, the first mode shape of flexible structure is along the x direction and the second mode shape is along y direction. Based on the result, it is also found that the flexible diaphragm has higher stiffness than other types, revealed by a lower natural period than other structures which can be seen in Table 3 until Table 5.

TABLE III. NATURAL PERIOD AND MODAL MASS PARTICIPATING RATIOS OF RIGID DIAPHRAGM STRUCTURE

Mode	Period (second)	UX	UY	RZ
1	1.918	0.2155	0.3162	0.2708
2	1.823	0.5196	0.2771	0.0054
3	1.655	0.0675	0.2077	0.5262
4	0.678	0.0362	0.0424	0.0412
5	0.639	0.0676	0.0507	0.0002
6	0.579	0.0142	0.0268	0.0754
7	0.395	0.0122	0.0125	0.0132
8	0.371	0.0200	0.0178	0.0001
9	0.335	0.0056	0.0075	0.0252
10	0.273	0.0081	0.0073	0.0078
11	0.256	0.0115	0.0118	0.0000
12	0.230	0.0036	0.0041	0.0161

TABLE IV. NATURAL PERIOD AND MODAL MASS PARTICIPATING RATIOS OF SEMI RIGID DIAPHRAGM STRUCTURE

Mode	Period (second)	UX	UY	RZ
1	1.914	0.2278	0.3583	0.2164
2	1.832	0.5111	0.2895	0.0016
3	1.642	0.0639	0.1532	0.5849
4	0.676	0.0376	0.0485	0.0337
5	0.642	0.0677	0.051	0.0000
6	0.574	0.0128	0.0204	0.083
7	0.394	0.0124	0.0145	0.011
8	0.374	0.0204	0.0174	0.0000
9	0.333	0.0049	0.0059	0.0274
10	0.273	0.0081	0.0085	0.0066
11	0.258	0.012	0.0112	0.0000
12	0.23	0.0031	0.0034	0.0173

TABLE V. NATURAL PERIOD AND MODAL MASS PARTICIPATING RATIOS OF FLEXIBLE DIAPHRAGM STRUCTURE

Mode	Period (second)	UX	UY	RZ
1	1.864	0.7457	0.0000	0.0623
2	1.855	0.0000	0.8087	0.0000
3	1.781	0.0630	0.0000	0.7455
4	0.633	0.1082	0.0001	0.0044
5	0.631	0.0001	0.1125	0.0000
6	0.604	0.0043	0.0000	0.1082
7	0.363	0.0363	0.0001	0.0006
8	0.362	0.0001	0.0367	0.0000
9	0.345	0.0005	0.0000	0.0369
10	0.253	0.0229	0.0003	0.0001
11	0.253	0.0003	0.023	0.0000
12	0.241	0.0001	0.0000	0.0233

B. Story Drift

Based on Fig. 7 and Fig. 8, it is revealed that the resulting interstory drift should be limited to a maximum allowable value of 0.08 m. For each model, the maximum drift which located on the different floors can be seen in both directions. It can be concluded in Table 6 that the smallest maximum drifts are occurred in rigid model which are 0.072 m in X direction and 0.078 m in Y direction.

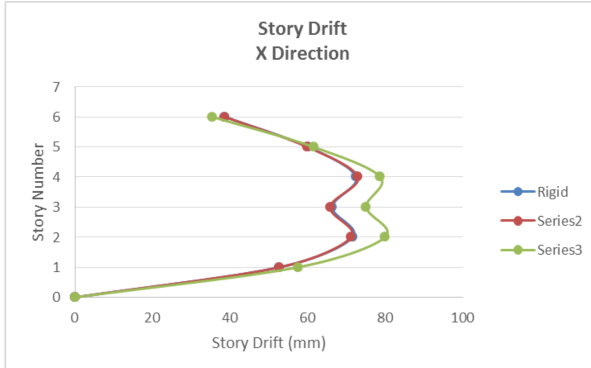

Fig. 7. Interstory drift diagram (x-direction)

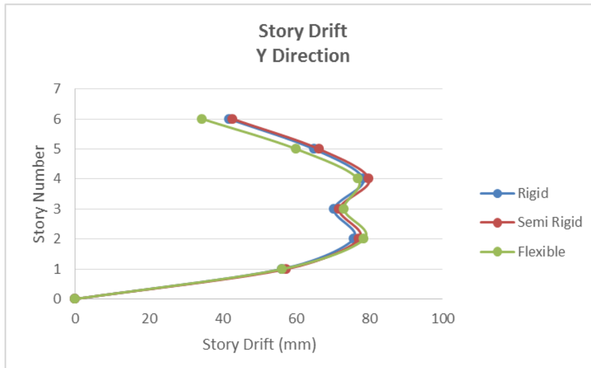

Fig. 8. Interstory drift diagram (y-direction)

TABLE VI. MAXIMUM INTERSTORY DRIFT

Type	Story Drift (m)			Allowable Drift (m)	Check	
	Location	X	Y		X	Y
Rigid	4th Floor	0.072	0.078	0.08	OK	OK
Semi Rigid	4th Floor	0.073	0.080	0.08	OK	OK
Flexible	2nd Floor	0.080	0.079	0.08	OK	OK

C. Seismic Base Shear

The seismic story shear forces which occurred in the structures are plotted in Fig. 9 and Fig. 10. The graphs reveal that the smallest base shear is occurred in rigid diaphragm building.

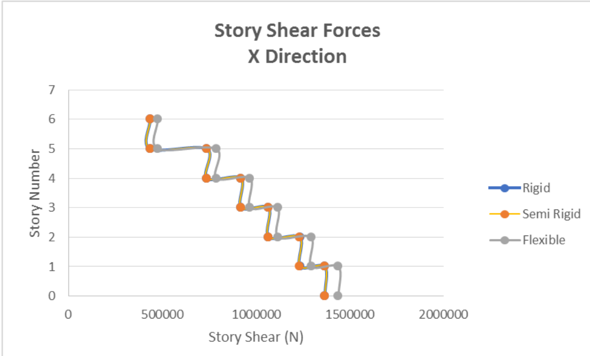

Fig. 9. Seismic shear force diagram (x-direction)

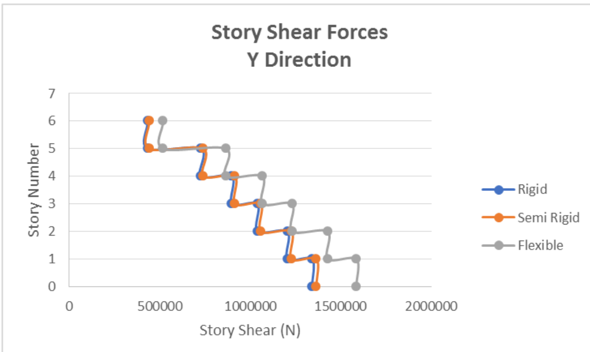

Fig. 10. Seismic shear force diagram (y-direction)

VI. Conclusions

Based on the analysis and comparison of three diaphragm flexibility types of asymmetric buildings, the following conclusions can be drawn:

- The level of diaphragm flexibility and plan irregularity could affect the natural period and mode shape of structures. For the first mode, the rigid and semi rigid diaphragm buildings have 2.9% and 2.7% higher periods than the rigid diaphragm building, while for the second mode the periods of semi rigid and flexible diaphragm buildings are 0.49% and 1.76% higher than the rigid diaphragm building. It is also clearly seen that the flexibility of diaphragm could affect the mode shapes of structures.
- The story drift results for all of the buildings have fulfilled the code allowable limit. Rigid diaphragm building generates higher stiffness among them. The story drift of rigid type along x-axis is 0.58% and 10.3% smaller than semi rigid and flexible types, while along y-axis is 2.04% and 0.35% smaller.
- Higher flexibility of diaphragm could increase the story shears of structure. Rigid diaphragm has 0.01% and 5.35% smaller base shear for the first mode than semi rigid and flexible diaphragm. Likewise, the base shear of rigid building is also 1.76% and 18.21% smaller than semi rigid and flexible building for the second mode.

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