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Torsion Stability and Performance of Re-entrant Irregular Multistory Structures with Optimal Shear Wall Strengthening

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Abstract

This study aimed to reduce the torsion in the re-entrant corner structure that occurs due to the eccentricity distance between the center of mass and the center of stiffness. Three types of structures were modeled, namely regular structure (model A), re-entrant corner irregularity structure (Model B), and re-entrant cornet irregular structure with shear wall strengthening (B-SWA). The shear wall strengthening in the B-SWA model was designed for dimensional optimization using the Nelder-Mead Algorithm method with MatLab software. Running output from the fminsearch function on MatLab, the optimal shear wall dimensions for the B-SWA model are L1 = 2.2317 m, L2 = 1.1611 m.
The results of the structural analysis using the ETABS software show that the shear wall optimization carried out on the B-SWA model has succeeded in increasing the stability of the structure, namely the results of the mode mass ratio participation show a similar pattern to model A, namely in SumUX the value of 0.9019 has been reached in modal 7. Modeling optimal shear wall after performance review with pushover analysis shows that the performance of the B-SWA model has succeeded in increasing the performance seen from the Base Shear vs. Monitored Displacement value compared to models A and B.

Keywords: *Torsion Stability; Structure Performance; Re-entrant corner irregular Structure; Shear Wall; Pushover; Nelder Mead Algorithm.*

INTRODUCTION

Construction of high-rise buildings in Indonesia needs to consider earthquakes to ensure that the requirements of earthquake-resistant buildings are sufficiently met. Based on the shape of the structure, it is divided into two configurations, regular configuration and irregular configuration. Re-entrant corner irregularity is defined exists if inner corner projected is greater than 15% of the dimension of the structural plan of the direction (Badan Standardisasi Nasional, 2019).

Roeslin et al., (2018) in their research explained that at least 30% of irregular buildings were moderately damaged, while 40% were heavily damaged. As shown in Figure 1, based on the horizontal and vertical directions of configurations, half of the irregular building structures have torsion problems, but the configuration with the most damage is the re-entrant corner irregularity configuration.

Study on torsional analysis of re-entrant corner irregularity that were limited to simplified assumptions (Khatiwada & Lumantarna, 2021). Divyashree & Siddappa, (2014) in their research evaluate the structure of the re-entrant irregularities by conducting reinforcement experiments only at one position, but have not discussed the optimization of the reinforcement.

Federal Emergency Management Agency describe, one of the problems with re-entrant corner is the torsion due to the different locations of the center of mass and center of stiffness of floors in building which cannot geometrically coincide for all possible earthquake directions (FEMA, 2006).

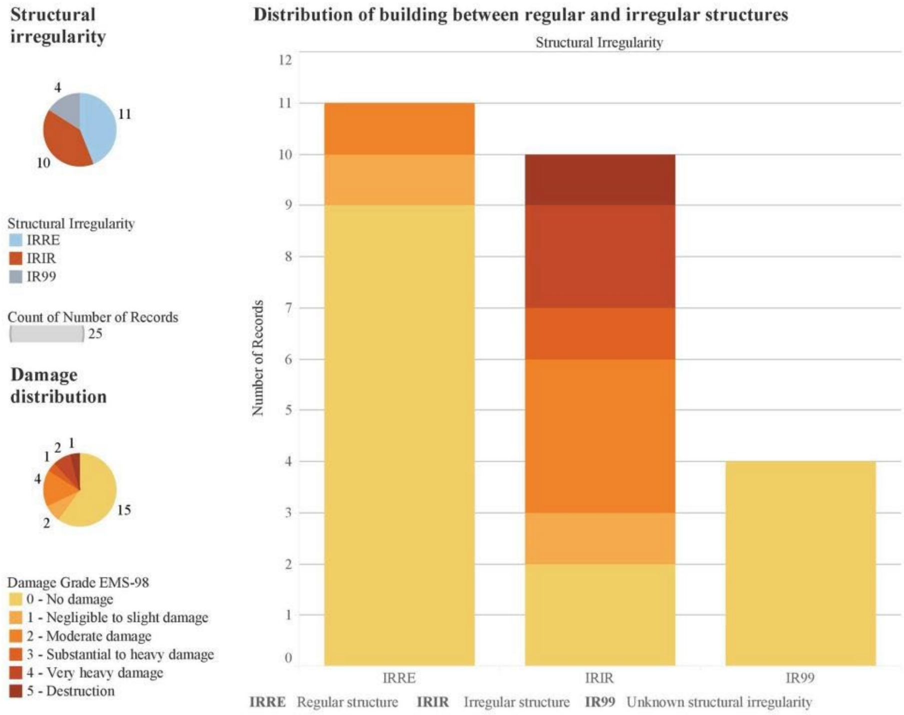


Figure 1. Distribution of damage between regular buildings and irregular building

Effects of moving a shear wall from the center of the building toward the outside of the building in a thirteen-story reinforced concrete frame-wall investigated using ETABS and SAP2000. Overall, the asymmetric model typically experienced torsional effects and larger displacement responses than the symmetric model (Bolander, 2014).

For this particular problem, Botis & Cerbu (2020) conducted an optimization of the dimensions of reinforced concrete walls using the Nelder - Mead Algorithm numerical method or also known as the Downhill Simplex method. The method aims to reduce or minimize the distance between the center of mass (CM) and the center of stiffness (CS). As has been widely known, reducing the eccentricity will prevent lateral joint - torsional movement of the structure.

Shear walls affect the stiffness and absorption of the structure. The location of the effective shear wall placement will vary depending on what percentage of the opening provides to absorption (Shahab & Gunawan, 2021).

In analyzing performance, it is necessary to use methods. (Arifin & Widyaningsih, 2021) assessing passenger satisfaction with services and performance levels of the Jak Lingko 50 Transportation by using the importance Performance Analysis (IPA) method.

The purpose and objective of this research is to determine the optimal pattern of the shear wall building systems to increase the torsional stability of the structure. In other words, efforts were made to obtain the optimum shear wall dimensions in order to avoid torsional instability in irregular structures using Nelder - Mead Algorithm numerical method. This can be achieved by assessing the relationship between torsional stability and structural performance.

RESEARCH METHODOLOGY

In this study, the adopted numerical method was carried out by Botis et al., (2018) for the case of the re-entrant cornet irregular structure. As has been mentioned previously, the aim is to find out the optimal shear wall pattern for improving the performance of the re-entrant corner irregularity structure. The performance review has been processed using the Pushover method analysis. The research stages are depicted in Figure 2.

The building structure reviewed in this study is a reinforced concrete building (RC) with the addition of concrete shear walls. Table 1 and Table 2 show the parameter quality of the material used, both for concrete as the main component and steel as the reinforcing material.

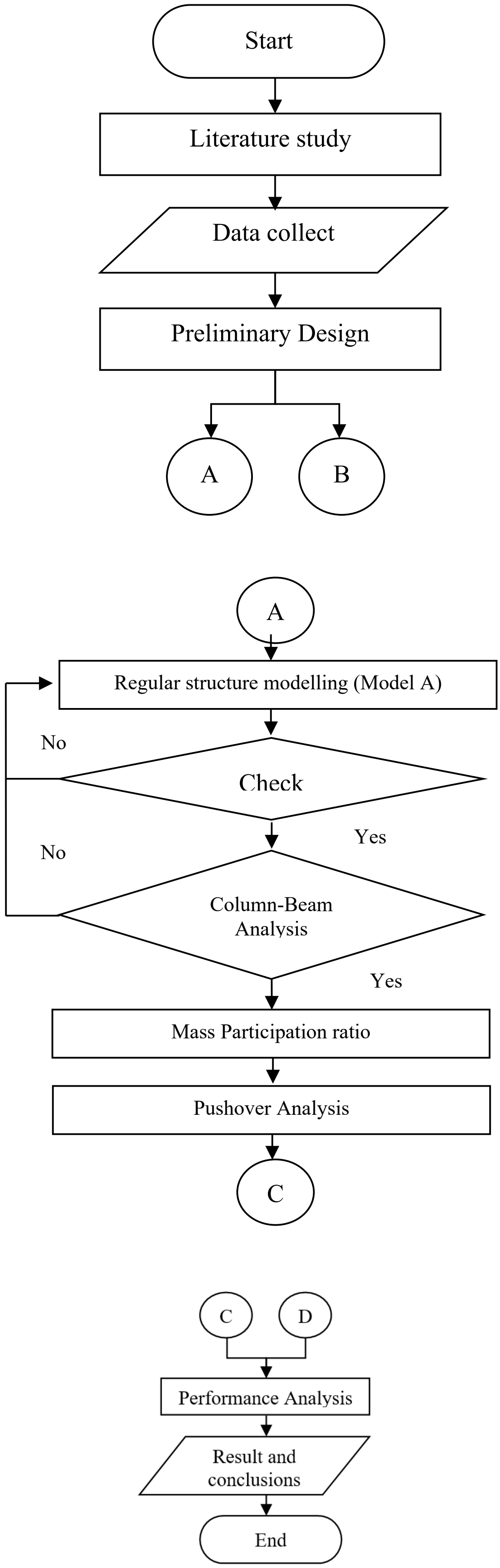


Figure 2. Research Flow Chart

Table 1. Concrete Material Data

Material	Quality	Material Quality
Concrete	Compressive strength of concrete (fc)	40 Mpa
	Elasticity modulus (ME)	29725.41 Mpa

Table 2. Steel Material Data

Material	Quality	Material Quality
Steel	Bending steel yield stress (fy)	410 Mpa
	Shear steel yield stress (fys)	240 Mpa
	Elasticity modulus (ME)	200000 Mpa

The load used in the calculation and input is in per metric unit. In Table 3 bellow is the data for each load based on SNI 1727:2020 (Badan Standardisasi Nasional, 2020).

Table 3. Load Data

Item	Definition	Reference
Dead load	The weight of all building construction materials installed.	SNI 17271:2020
Live load slab	2,4 kN/m	SNI 1727:2020
Live load roof slab	0,96 kN/m	SNI 1727:2020
Earthquake load	Using the Indonesian Spectra Design application http://rsa.ciptakarya.pu.go.id/2021/	SNI 1726-2019

Structural members and foudation elements shall be designed so that their design strength equals or exceeds the effect of factored loads with the following specified combinations in Table 4.

Table 4. Load Combination

Comb 1	1,4 D+1,4 SIDL
Comb 2	1,2 D+1,2 SIDL+1,6 LL
Comb 3	1,34D+1L+1,34SIDL+1.3DX+1,3 DY
Comb 4	1,34D+1L+1,34SIDL+1.3DX+0,39DY
Comb 5	1,34D+1L+1,34SIDL-1.3 DX+0,39DY
Comb 6	1,34D+1L+1,34SIDL-1.3DX-0,39DY
Comb 7	1,34D+1L+1,34SIDL+0,39DX+1,3DY
Comb 8	1,34D+1L+1,34SIDL-0,39DX+1,3DY
Comb 9	1,34D+1L+1,34SIDL+0,39DX-1,3DY
Comb 10	1,34D+1L+1,34SIDL-0,39DX -1,3DY
Comb 11	0,76D+0,76SIDL+1.3DX+0,39DY
Comb 12	0,76D+0,76SIDL+1.3DX-0,39DY
Comb 13	0,76D+0,76SIDL-1.3DX+0,39DY

Comb 14	0,76D+0,76SIDL-1.3DX-0,39DY
Comb 15	0,76D+0,76SIDL+0,39DX+1,3DY
Comb 16	0,76D+0,76SIDL-0,39DX+1,3DY
Comb 17	0,76D+0,76SIDL+0,39DX-1,3DY
Comb 18	0,76D+0,76SIDL-0,39DX-1,3DY

Where:
D : Dead Load
Dx/y : Earthquake Load
L : Live Load
SIDL : Superinposed Dead Load

Two-building structures were modeled, first model is the regular structure (model A) as shown in Figure 3, and the second is re-entrant cornet irregular structure (model B) as shown in Figure 4. The re-entrant of model were made on the sides based on the projection value of the angle of both x and y direction projections that are greater than 15%. Irregular buildings with reinforcement are made in two models, Figure 5 and Figure 6 show booth models, first is model (B SW-1), with reinforcement at the bend angle, and the second is model (B SW-2) with reinforcement at the end of the projection.

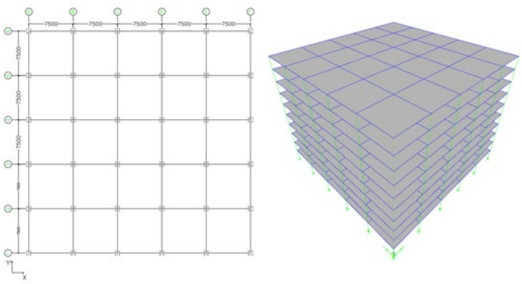


Figure 3. Regular Structure Model A Plan

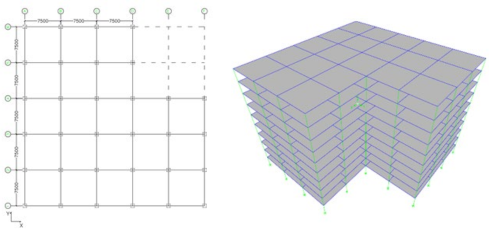


Figure 4. Irregular Structure Model B Plan

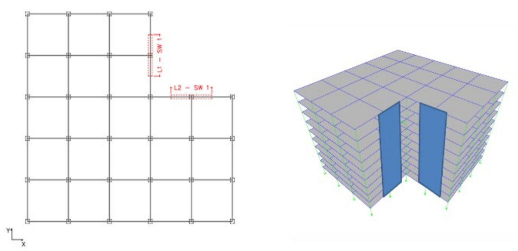


Figure 5. Model B Shear Wall Modeling Plan SW-1

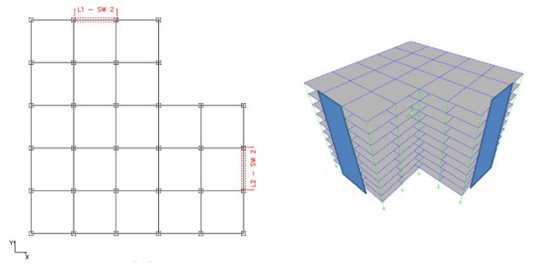


Figure 6. Model B Shear Wall Modeling Plan SW-2

Structural modeling was carried out in several stages, the results of the preliminary that have been carried out, a floor plan modeling are carried out to review its eccentricity and whether it is effective to be reviewed in this study. If it is effective enough, proceed to the next stage, while if it is not effective, a new plan is made. Then calculation of stiffness and strength was carried out using ETABS software to get the dimensions of the structure as shown in Table 5. If it meets the requirements of limit for stiffness and strength, it can be proceed to the analysis of the ratio of mass participation mode.

Table 5. Structure Dimension

Object	Floor	New dimension (mm)
Column	2	800 x 800
	3	800 x 800
	4	800 x 800
	5	800 x 800
	6	650 x 650
	7	650 x 650
	8	650 x 650
	9	550 x 550
	10	550 x 550
	roof	550 x 550
Beam	2 – 9	400 x 800
	10 – roof	350 x 700
Slab	2 – 10	180 mm

As has been mentioned previously, this study discusses the regular structure and horizontal irregular structure. In this study, torsion was observed in irregular buildings by calculating on a floor that is being reviewed as a multi-story building system. In this study, a structural model was made on the stiffness of the diaphragm using ETABS software. Manual calculation of the center of stiffness by reviewing structural properties does not depend on loading. Eccentricity was obtained by identifying the center of mass and center of stiffness in each structural model made. The eccentricity of model A as shown in the Figure 7 and Table 6 while model B as shown in Figure 8 and Table 7.

The modeled regular and irregular structures are then checked for their eccentricity based on the center of mass and the center of stiffness that occurs. The results of coordinate Center of Mass, Center of Stiffness in metric unit (m) and Eccentricity X,Y directions are described in Table 6 and Table 7.

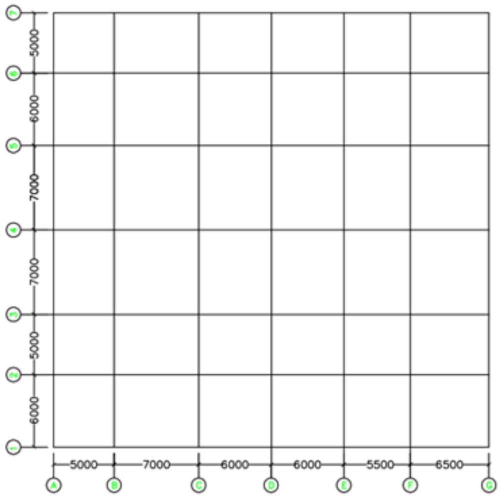


Figure 7. Model A Plan

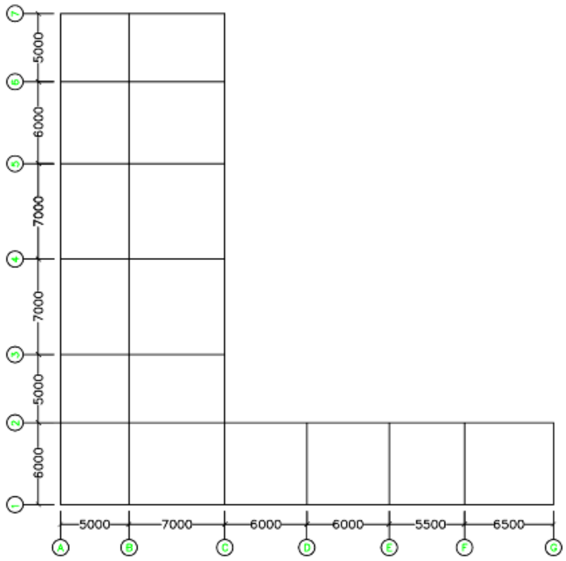


Figure 8. Model B Plan

Table 6. Model A

Story	C.M (m)		C.R (m)		Ecc. (m)	
	x_m	y_m	XCR	YCR	e_x	e_y
1 - Roof	18	18	17.71	18.14	0.29	0.14

(the Center of mass and Stiffness)

Table 7. Model B

Story	C.M (m)		C.R (m)		Ecc. (m)	
	xm	ym	XCR	YCR	ex	ey
1 - Roof	10.5	14.2	11.48	13.97	0.98	0.28

(the Center of mass and Stiffness)

RESULTS AND ANALYSIS

After checking that model A and model B meet the displacement requirements as shown in Figure 9 and Figure 10, then the structural reinforcement was modeled with two conditions. Model B SW-1 is reinforcement at the bent corner, and Model B SW-2 is reinforcement at the end of the projection side as shown in Figure 11.

Table 8 is the formula used to get the optimal value of the shear wall based on the eccentricity of each model as Figure 11. Where L_1, L_2 are the optimal length of the shear wall. The sear wall optimization obtained with Nelder - Mead algorithm method or downhill simplex method, which is a commonly used to find the minimum or maximum of an objective function in a multidimensional space.

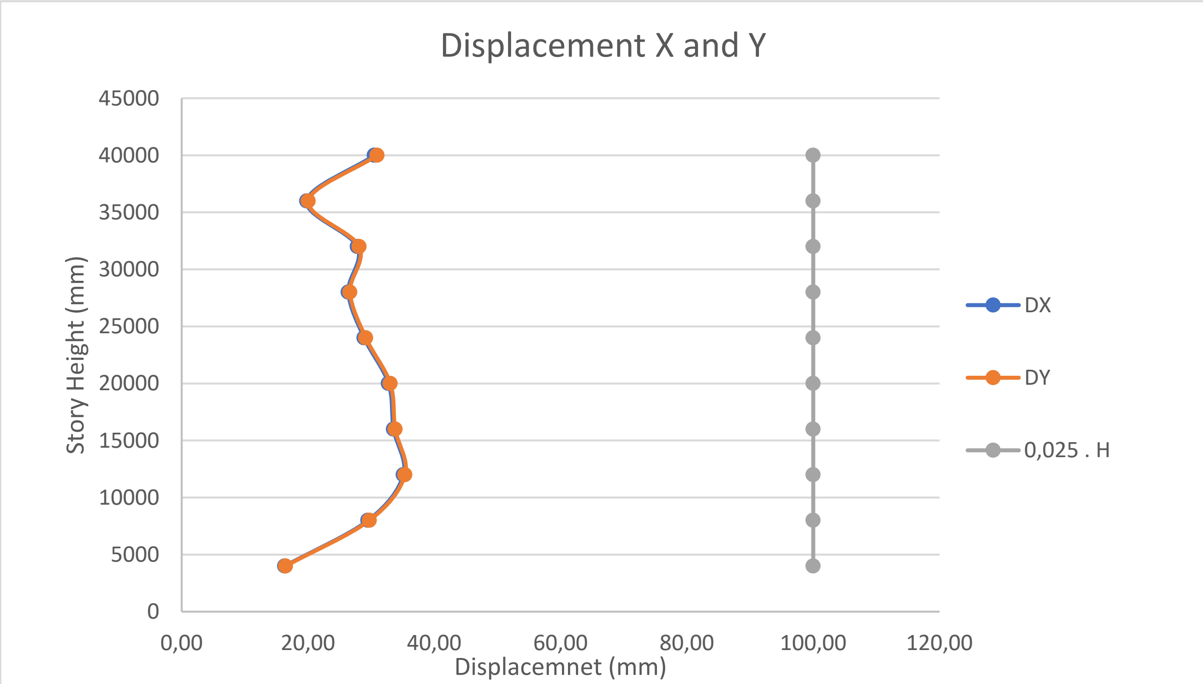


Figure 9. Model A Displacement

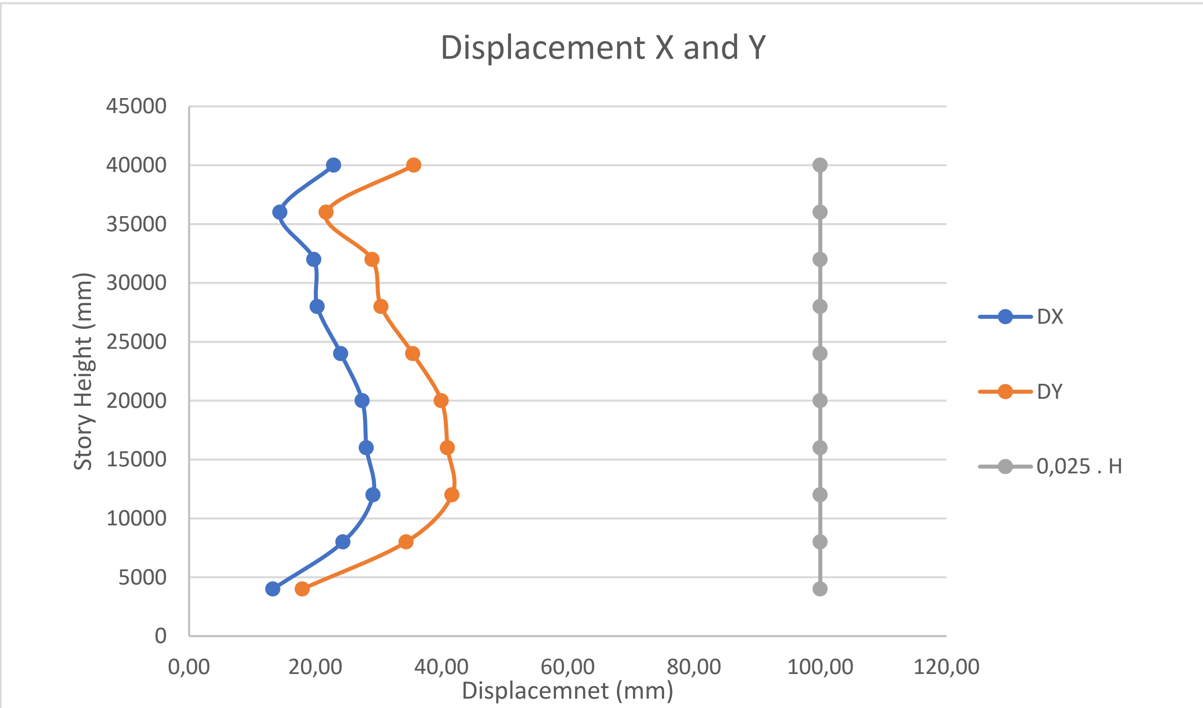


Figure 10. Model B Displacement

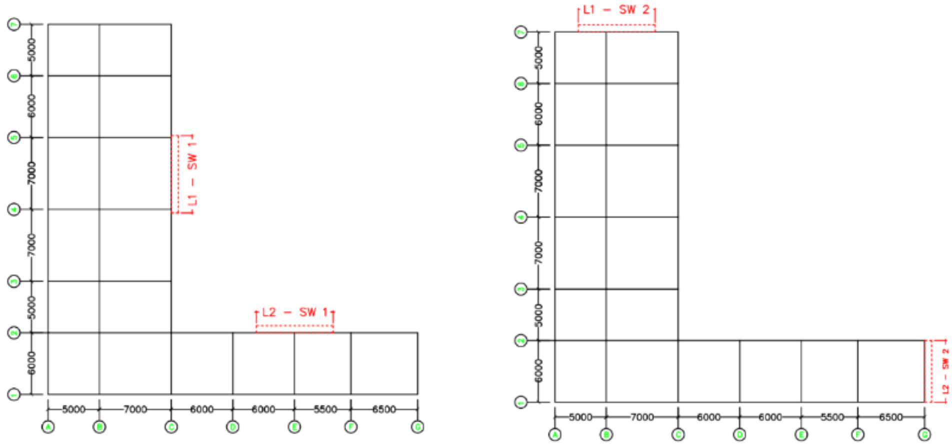


Figure 11. Modeling B SW-1 and B SW-2

Table 8. Eccentricity optimization formula Model B SW-1 and B-SW2

Model	Equation
B SW-1	$\begin{cases} f_1(L_1, L_2 = 10{,}5 - \left(\dfrac{\left(\frac{0{,}1.L_1{}^3}{12}.12\right) + \left(\frac{0{,}1^3.L_2}{12}.21{,}5\right) + 11{,}3664}{\left(\frac{0{,}1.L_1{}^3}{12}\right) + \left(\frac{0{,}1^3.L_2}{12}\right) + 0{,}9899} \right) = 0 \\ f_2(L_1, L_2 = 14{,}25 - \left(\dfrac{\left(\frac{0{,}1^3.L_1}{12}.24\right) + \left(\frac{0{,}1.L_2{}^3}{12}.6\right) + 13{,}824}{\left(\frac{0{,}1^3.L_1}{12}\right) + \left(\frac{0{,}1.L_2{}^3}{12}\right) + 0{,}9899} \right) = 0 \end{cases}$
B SW-2	$\begin{cases} f_1(L_1, L_2 = 10{,}5 - \left(\dfrac{\left(\frac{0{,}1^3.L_1}{12}.8\right) + \left(\frac{0{,}1.L_2{}^3}{12}.36\right) + 11{,}3664}{\left(\frac{0{,}1^3.L_1}{12}\right) + \left(\frac{0{,}1.L_2{}^3}{12}\right) + 0{,}9899} \right) = 0 \\ f_2(L_1, L_2 = 14{,}25 - \left(\dfrac{\left(\frac{0{,}1.L_1{}^3}{12}.36\right) + \left(\frac{0{,}1^3.L_1}{12}.3\right) + 13{,}824}{\left(\frac{0{,}1.L_1{}^3}{12}\right) + \left(\frac{0{,}1^3.L_2}{12}\right) + 0{,}9899} \right) = 0 \end{cases}$

Table 9. Eccentricity optimization formula Model B SW-1 and B-SW2

Model	Equation
B SW-A	$\begin{cases} f_1(L_1, L_2 = 10{,}5 - \left(\dfrac{\left(\frac{0{,}1.L_1{}^3}{12}.0\right) + \left(\frac{0{,}1^3.L_2}{12}.8{,}5\right) + 11{,}3664}{\left(\frac{0{,}1.L_1{}^3}{12}\right) + \left(\frac{0{,}1^3.L_2}{12}\right) + 0{,}9899} \right) = 0 \\ f_2(L_1, L_2 = 14{,}25 - \left(\dfrac{\left(\frac{0{,}1^3.L_1}{12}.3\right) + \left(\frac{0{,}1.L_2{}^3}{12}.36\right) + 13{,}824}{\left(\frac{0{,}1^3.L_1}{12}\right) + \left(\frac{0{,}1.L_2{}^3}{12}\right) + 0{,}9899} \right) = 0 \end{cases}$

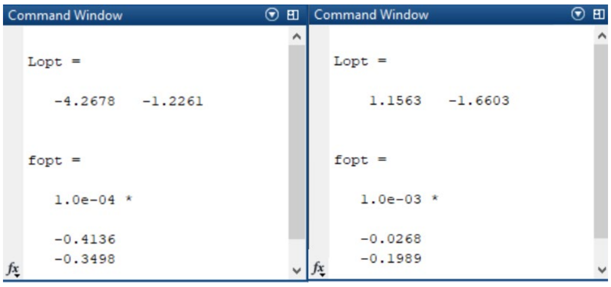


Figure 12. Result MatLab model B SW-1, B SW-2

Figure 12 show the results of the analysis optimum shear wall length dimension (L opt) for model B SW-1 and B SW-2 models of the proposed configuration, that not effective to reviewed further. So it is necessary to analyze the optimal alternative configuration model. To obtain the optimal shear wall dimensions, it is necessary to identify an alternative model by referring to the position of the center of mass and the center of stiffness that occurs, this alternative model is called the B SW-A model as shown in Figure 13 then the optimization solution was calculated in Table 9.

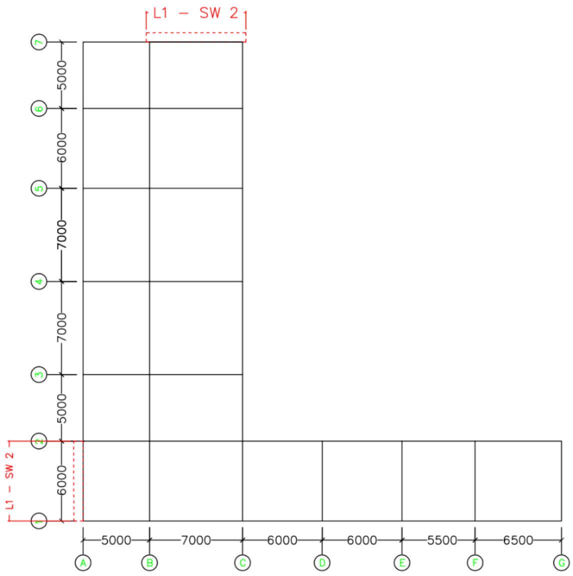


Figure 13. Modeling B SW-A

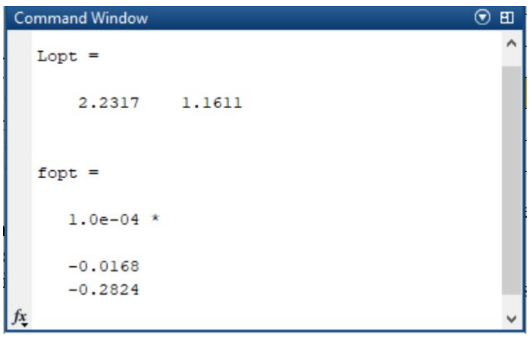


Figure 14. Result MatLab model B SW-A

The shear wall dimension optimization was carried out using the fminsearch function ('func', [1 1]) in MatLab software, fminshearch uses the simplex search methode, therefore it can be used in this observation. From the results of the MatLab software data processing of model B SW-A as shown in Figure 14, the optimal value solution of shear wall length is obtained L_1=2.2317 m and L_2=1.1611 m.

Torsion stability is considered regarding the minimum amount of model to achieve a combined variance mass of 90% of the actual mass in each orthogonal horizontal direction of the response considered by the model. The results of Table 10 show a similar pattern in Models A and B SW-A, the ratio value of participation Mass model in SumUX reaches a value of 0.9187 and 0.9019 on modal 7, while model B a value of 0.9131 only occurs when modal 8. It can be interpreted that the strenghtening of shear walls in model irregular B SW-A can approximate the variance in the model A as regular structure.

Table 10. Mass Participation Ratio Mode Results Recap SunUX

Mode	Model A	Model B	Model B-SWA
	SumUX	SumUX	SumUX
1	0.737	0.3024	0.3479
2	0.7666	0.6622	0.7313
3	0.7672	0.7622	0.7626
4	0.8709	0.8138	0.8218
5	0.8733	0.8589	0.8679
6	0.8734	0.8709	0.8737
7	0.9187	0.898	0.9019
8	0.9192	0.9131	0.9175
9	0.9193	0.9172	0.9196
10	0.9425	0.9342	0.9351
11	0.9429	0.9398	0.9427
12	0.9429	0.9416	0.9548

The three models that have been made previously will each be subjected to a Pushover analysis to assess the performance of the building structure. Pushover analysis made with ETABS software. The results of the pushover analysis illustrate the comparison curve of the base shear vs. monitored displacement value on the X axis (PUSH X) and Y axis (PUSH Y) of each structural model in Figure 15 for Model A, Figure 16 for Model B, and Figure 17 for model B SW-A. From each curve, the maximum total deviation and maximum inelastic deviation values are calculated to identify the structure performance level.

The performance level of the structure is determined based on the ATC-40 shown in Table 11. Performance level was obtained from the ratio of the roof drift value at the performance point to the total building height.

Table 11. Performance Level

Interstory Drift Limit	Performance Level Immediate Occupancy (IO)	Damage Control (DC)	Life Safety (LS)	Structural Stability
Maximum Total Drift	0,01	0,01 – 0,02	0,02	0,33 $\frac{V}{P_i}$
Maximum Inelastic Drift	0,05	0,05 – 0,015	No limit	No Limi

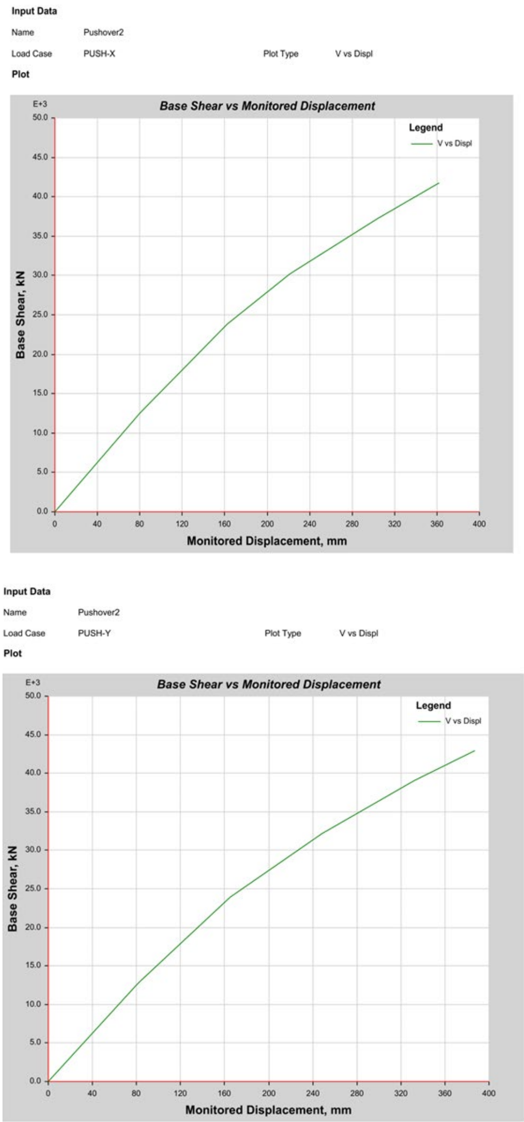


Figure 15. Base Shear vs Monitored Displacement PUSH X & PUSH Y model A

Maximum total displacement

Dir. X–X = $\frac{D_t}{H_{total}} = \frac{362{,}323}{40.000} = 0{,}009058$ (IO)

Dir. Y–Y = $\frac{D_t}{H_{total}} = \frac{386{,}877}{40.000} = 0{,}009672$ (IO)

Maximum inelastic displacement

Dir. X–X = $\frac{D_t - D_1}{H_{total}} = \frac{362{,}323-80}{40.000} = 0{,}007058$ (IO)

Dir. Y–Y = $\frac{D_t - D_1}{H_{total}} = \frac{386{,}877-80}{40.000} = 0{,}007672$ (IO)

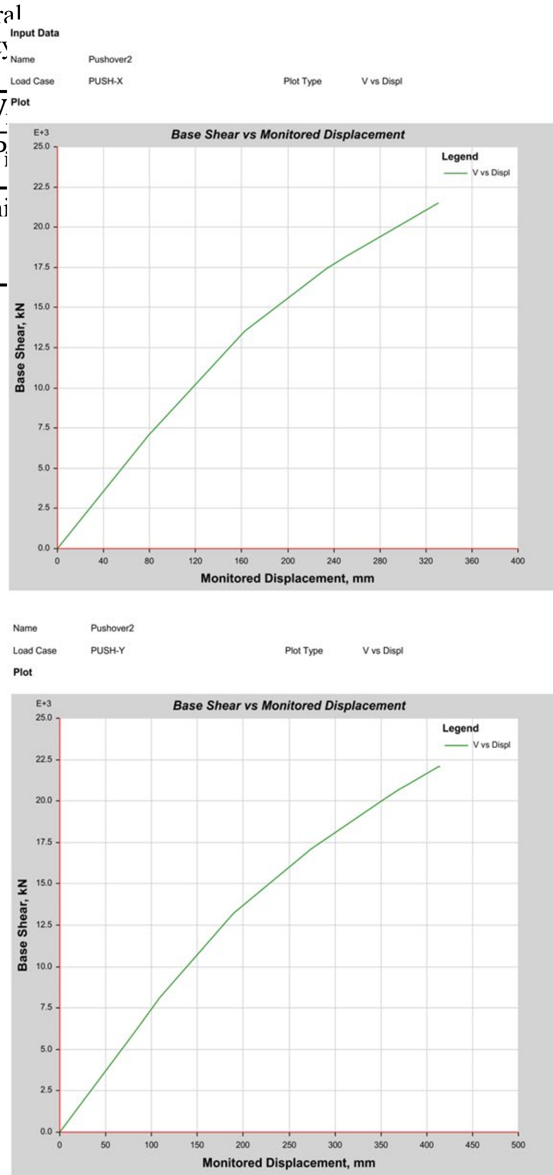


Figure 16. Base Shear vs Monitored Displacement PUSH X & PUSH Y model B

Maximum total displacement

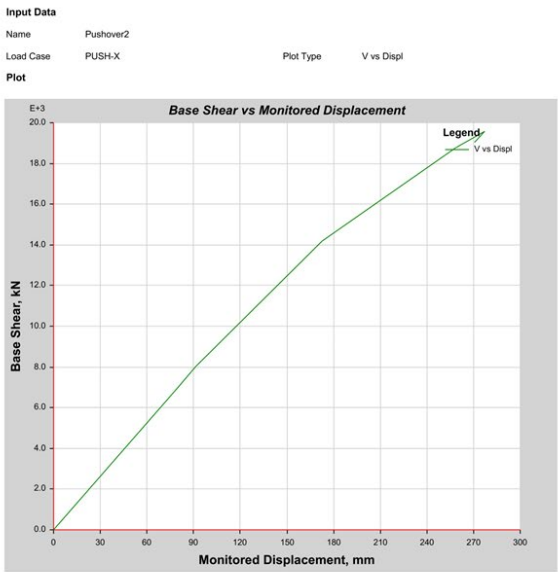
Dir. X–X = $\frac{D_t}{H_{total}} = \frac{331{,}118}{40.000} = 0{,}008278$ (IO)

Dir. Y–Y = $\frac{D_t}{H_{total}} = \frac{414{,}51}{40.000} = 0{,}010363$ (DC)

Maximum inelastic displacement

Dir. X–X= $\frac{D_t - D_1}{H_{total}} = \frac{331{,}118-80}{40.000} = 0{,}007479$ (IO)

Dir. Y–Y = $\frac{D_t - D_1}{H_{total}} = \frac{414{,}51-80}{40.000} = 0{,}008363$ (IO)



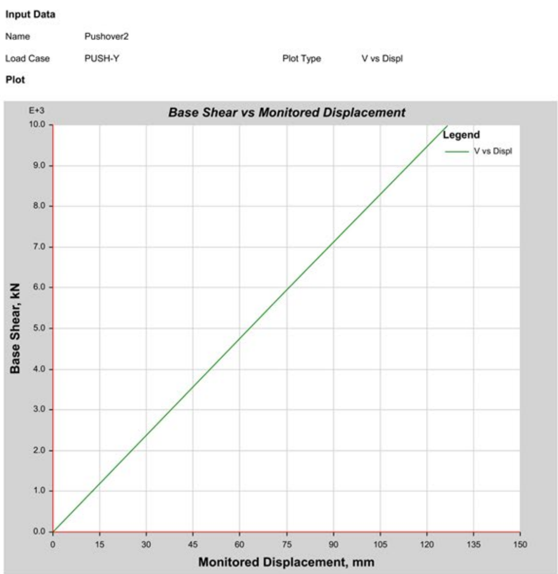


Figure 17. Base Shear vs Monitored Displacement PUSH X & PUSH Y model B SW-A

Maximum total displacement

Dir. X–X = $\frac{D_t}{H_{total}} = \frac{270{,}718}{40.000} = 0{,}00677$ (IO)

Dir. Y–Y = $\frac{D_t}{H_{total}} = \frac{126{,}594}{40.000} = 0{,}00316$ (IO)

Maximum inelastic displacement

Dir. X–X = $\frac{D_t - D_1}{H_{total}} = \frac{270{,}718-80}{40.000} = 0{,}00477$ (IO)

Dir. Y–Y = $\frac{D_t - D_1}{H_{total}} = \frac{126{,}594-80}{40.000} = 0{,}00116$ (IO)

CONCLUSION

Based on the analysis that has been done, the results obtained as an answer to the formulation of this research problem. Three different types of buildings are modeled, regular structures (model A), irregular structures without reinforcement (model B), and irregular structures with shear wall reinforcement (B SW-1, B SW-2). The following are the results obtained in this study.

1. The four structural models made in this research method, then the formulation of the ideal shear wall reinforcement position for the re-entrant irregular structure is model B SW-A, with the position of the shear wall on the coordinates of the X axis and Y axis (0; 3) m, and (8.5; 36) m, with 0.1 m thickness. The results of the Nelder-Mead algorithm with MatLab software for model B SW-A, obtained the optimal shear wall width L1 = 2.2317 m and L2 = 1.1611 m.
2. The results of mass participation for model A, the ratio of 0.9187 occurred in mode 7. Then in model B, the ratio of 0.9192 occurred in mode 8. While in model B SW-A, the ratio of 0.9019 occurred in mode 7. These results show the 90% ratio in B SW-A occurs faster than model B. Thus the optimal shear wall reinforcement effect modeled as model B SW-A is able to increase the torsional stability of the re-entrant irregularity structure.
3. Three structural models that are further reviewed (Model A, Model B, and Model B SW-A) to be analyzed using the Pushover method, the maximum total drift rasio of the model A direction X = 0.009058, direction Y = 0 ,009672. In model B, direction X = 0.008278, direction Y = 0.010363, then in model B SW-A direction X = 0.00677, direction Y = 0.00316. In terms of performance level based on ATC-40, the optimal shear wall reinforcement can improve the performance of the re-entrant irregularity structure based on the maximum total drift value in the Y direction of 0.010363 categorized as Damage Control (DC) to 0.00316, categorized as Immediate Occupancy (IO).

From the results of the research that has been done, it can be submitted recomendation that can be done in further research to develop previous research.

The shear wall analysis which has a relatively large size in this study has not considered the effect of shear deformation and rotational inertia, as discussed in a previous study regarding the analysis of the frequency of natural vibrations in cantilever beams using Timoshenko's theory. (Bestari & Nasution, 2010).

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