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Performance Analysis of Typical Soft Story Infill Wall Frame Structure

I Ketut Sudarsana[1*], Ida Ayu Made Budiwati[2], Made Sukrawa[3], I G. A. Maheswari Alma Widhyatni[4]
[1,2,3,4]*(Civil Engineering Department, Engineering Faculty, Udayana University, Indonesia)*

Abstract: *Non-continuity of infill walls is one of the causes of soft stories in a structural system. In densely populated areas, the first level of a typical building is used as a parking lot, creating a typical soft story plan where the first floor has fewer walls than the floors above so the walls are not continuous. Modeling of infill walls as one of the load-bearing elements must be done in buildings with a typical soft story plan. This study aims to determine the design results and performance of the four stories existing structure that was analyzed as a structural system of infill wall frame (SRDP) and to compare it with the existing building using SAP 2000 software. The model was analyzed to produce displacement, drift ratio, and reinforcement of slabs, beams, columns, and structural performance. The results showed that the existing building modeled as an SRDP system yields a drift ratio of more than 1.3 at the ground level so it was strengthened by enlarging the dimensions of the ground floor column and reducing the dimensions of the second to fourth floors. It was found that the area of longitudinal reinforcement in the SRDP building was less than in the existing building. On the second-floor column, the flexural reinforcement area is only 20% of the existing reinforcement area, on the third to fourth-floor columns, the flexural reinforcement area is only 30% of the existing reinforcement area. In the beams, the flexural reinforcement area was found to be only 38% to 52% of the existing reinforcement area. The performance level of the SRDP after strengthening is Collapse Prevention (CP) in the x direction and Collapse (C) in the y direction with hinge formation occurring firstly in the beam.*

KeyWord: *Analysis; Infilled Frame; Soft Story.*

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I. Introduction

Infill walls are generally installed and constructed after the main structure has been completed, therefore they are treated as architectural elements where in planning, the structural analysis is carried out as an open frame and the infill walls are only analyzed as loads. The presence of infill walls in reinforced concrete frame structures can significantly change the mechanism of the structure in response to earthquake loads [1installed and constructed after the main structure has been completed, therefore they are treated as architectural elements where in planning, the structural analysis is carried out as an open frame and the infill walls are only analyzed as loads. The presence of infill walls in reinforced concrete frame structures can significantly change the mechanism of the structure in response to earthquake loads [1].

In congested areas, the first level of a typical building is used as a parking lot, creating a typical plan where the first floor has fewer or no walls compared to the floors above. The presence of non-continuous infill walls at the first level causes the levels above to be stiffer than the first level, potentially causing the building to experience a soft story mechanism [2].

The police dormitory building located in Denpasar Bali with moderate soil conditions is a four stories structure with brick wall partitions. The building is categorized as an infill wall frame structural system. The majority of first-level buildings are not walled because they function as parking lots and access roads. On levels two to four, there is a continuous infill wall because it functions as a residence. Therefore, the building structure has a soft story due to non-continuous walls. This building uses a bored pile foundation and a steel roof truss.

In this study, the building is designed and analyzed as an infill wall frame structural system (SRDP) by taking into account the openings in the walls, so that the actual structural behavior can be evaluated. A performance analysis is then carried out on the structure that has been designed as an infill wall frame structural system. The performance analysis method used is pushover nonlinear static analysis. This is done to determine the performance of the building and further evaluate the potential for soft stories due to non-continuous walls at the first level, which will then be used as a basis for mitigating soft stories in the building.

II. Material And Methods

Infill Wall Frame Structural System

Infilled frame structural system is formed through the interaction between the infill wall and the frame that binds it due to lateral loads. Infill walls usually consist of brick or concrete blocks built between reinforced concrete beams and columns [3]. The behavior of a frame structure with infill walls will be different from that of an open frame structure. The interaction between the infill wall and the reinforced concrete frame can increase the strength and stiffness of the structure, as the infill wall contributes structurally to resist deformation and internal forces due to lateral loads up to its capacity limit. The presence of infill walls in a reinforced concrete portal changes the lateral load-receiving mechanism of the structure to predominantly behave as a truss.

Diagonal Strut Modeling

Infill walls can be modeled with macro modeling, using diagonal struts as an approach to idealizing the behavior of infill walls in a structure. Beam and column elements will deform when receiving lateral loads, which causes the wall to receive compressive axial forces at the contact area between the beam, column, and infill wall elements. The force is resisted by the wall diagonally and then the interaction is idealized as a diagonal strut.

Diagonal Strut Width

The diagonal strut width is one of the important parameters for analyzing the behavior of infill wall frames, where it represents the contact area between the infill wall and the frame that binds it. Sukrawa & Budiwati [4] proposed the diagonal strut width equation to analyze centric and concentric hollow infill walls with practical beam and column reinforcement around the holes with the following correction factor.

$$w_{sco} = \frac{d}{20 tan\theta} fc'^{0.5} C \quad (1)$$

$$C = 1{,}1262r^2 - 2{,}212r + 1{,}0971 \quad (2)$$

Soft Story

A soft story is a condition where a level in a particular structure has a much smaller stiffness than other levels, causing the level to be weaker. Soft stories can be caused by uneven wall distribution. One of the most common cases of the soft story is at the first level, which is due to discontinuity in the distribution of lateral earthquake forces [5].

Structure Performance Analysis

Nonlinear static pushover analysis is one of the analytical methods that can predict the collapse mechanism and detect possible locations of premature collapse [6]. Pushover analysis is an analytical procedure to estimate the strength capacity of a structure beyond its elastic limit to its ultimate limit and aims to estimate the largest force and deformation in the structure and identify critical components in the structure. The pushover analysis procedure is performed by applying gradually increasing loads at the center of mass of each floor until the structural components reach the yield point.

Property Data and Geometry

The study was conducted on an existing dormitory building. Structural data were obtained from as-built drawings and material specifications provided by the contractor. Using SAP 2000 software, the building (SRDP) was modeled in 3D and loaded with structural loading in the form of dead, live, and earthquake loads. Furthermore, the 3D model was analyzed to produce displacement and story drift ratio, reinforcement of slabs, beams, and columns, and structural performances. Two buildings were modeled in which the second model was the strengthened building (by enlarging the column dimension on the first floor).

The ground floor of the building functions as a parking area and access road as shown in Figure 1. The height of each floor level is 3.6 m. The span length between columns is 6 m and 7.2 m. The material data used was adjusted to the existing building material specifications. The concrete compressive strength, f'c, was 29.05 MPa. The wall thickness was 150 mm and its compressive strength, f'm, was 3.84 MPa [7]. The dimensions of the structural elements of the existing building and after strengthening by enlarging the columns are presented in Table 1.

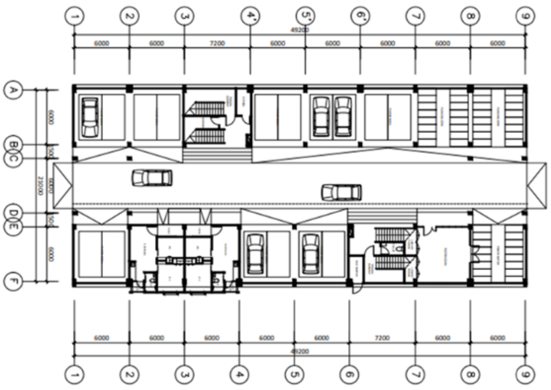

Figure 1. Ground Floor Plan

Table 1. Structure Dimensions

Existing Building (SRDP)				**Strengthened Building**			
Column (cm)		***Beam (cm)***		***Column (cm)***		***Beam (cm)***	
K1	35/50	B1	30/50	K1	40/55	B1	30/50
K2	40/50	B2	30/60	K2	40/60	B2	30/60
		B3	25/50	K3	50/60	B3	25/50
				K4	35/35		
				K5	30/30		

Structure Modeling

The structural modeling of the existing building (SRDP) was carried out following the architectural and structural drawings, where the beam-column and slab dimensions were adjusted to the actual dimensions with the addition of a compressed diagonal strut on the model as a representation of the infill wall. The diagonal strut is assumed to have no weight as the weight of the wall is defined separately as an additional dead load in SAP 2000. The diagonal struts are released from the influence of moments and tensile forces. The length of the compressed diagonal strut corresponds to the length of the hypotenuse of the beam-column frame, the thickness of the strut is the thickness of the wall while the width of the strut is calculated based on Equation 1 where the correction factor C is calculated based on Equation 2. The width dimensions of all types of diagonal struts can be seen in Table 2. The 3D model of the structure is shown in Figure 2. The strut representation is shown in Figure 3.

Table 2. Diagonal strut widths

Type1	**d (mm)**	**tanθ**	**r (%)**	**C**	**Wsco (mm)**
S1	8050	0,5	0%	1	4339
S2	8050	0,5	13%	0.83	3668
S3	6997	0,6	0%	1	3143
S4	6997	0,6	12%	0,84	2647
S5	6997	0,6	19%	0,72	2260
S6	6997	0,6	62%	0,16	500

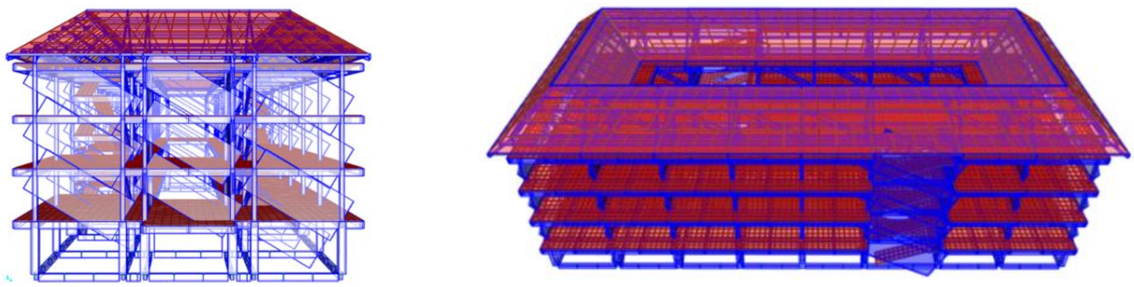

Figure 2. Ground Floor Plan

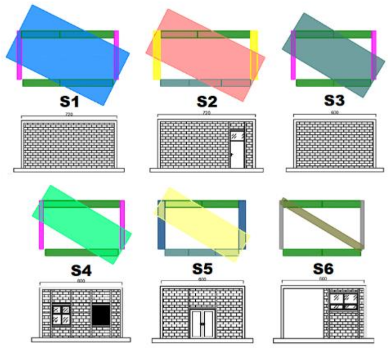

Figure 3. Representation of Each Type of Wall with an Opening

Structure Loading

The loading given to this structure consists of dead loads [8], live loads [9], and earthquake loads [10]. The additional dead load on the floor slab was 145 kg/m^2, the roof slab was 121 kg/m^2, the wall load was 250 kg/m^2, the slab live load was 1.92 kN/m^2 for private spaces, and 4.79 kN/m^2 for public spaces, and the roof live load was 20 kg/m^2.

Calculation of earthquake loads in SAP2000 uses the auto lateral earthquake loading feature based on ASCE 7-16 which was adjusted to SNI 1726: 2019. The structural risk category was II, the earthquake primacy factor was 1, the seismic design category was D, Ss was 0.959, S1 was 0.397, the system strength factor was 3, the deflection magnification factor was 3.5, and the response modification coefficient was 6.

III. Results

Lateral Displacement

The inter-story drift ratios of the SRDP and the strengthened building are shown in Table 3 and Table 4 respectively. The inter-story drift of the structure has met the requirements of allowable inter-story drift.

Table 3. Inter-story drift ratio of the existing building

Story	SRDP		
	Δ_i/L	Δ_{i+1} /L	Ratio
4	0,0008	-	-
3	0,0014	0,0008	1,78
2	0,0018	0,0014	1,26
1	0,0026	0,0018	1,45

Table 4. Inter-story drift ratio of strengthened building

Storey	Strengthened Building		
	Δ/L	D/L	Ratio
4	0,0008	-	-
3	0,0009	-	-
2	0,0017	0,0009	1,78
1	0,0020	0,0017	1,19

Comparison of Reinforcement Results

The reinforcement bars of structural elements of the existing building and infill walled building structure (SRDP) are presented in Table 5. The beams of the SRDP model resulted in a smaller reinforcement area. The dimensions of the second to fourth-floor main beams and sub-beams were the same as the actual dimensions, but the reinforcement area required for structures designed as SRDPs was smaller than that of the existing structures. On the second to the fourth floor, the main beams with dimensions 300/600 had a flexural reinforcement area of only 38% of the existing reinforcement area. While on the second to fourth-floor main beam with dimension 300/500, it was only 34% of the existing reinforcement area. On the second to the fourth floor, the secondary beams with dimensions 250/500 had a bending reinforcement area of only 52% of the existing reinforcement area. The shear reinforcement area required was smaller, and the shear reinforcement spacing was larger.

The design results on columns with SRDP on the second floor was the cross-section of 350x350 mm with 10D13 main bars, on the third to fourth the dimensions were 300x300 mm with 8D12 main bars in which the dimensions and reinforcement area were less compared to the existing structure. On the ground floor, the columns as a whole have larger dimensions than the existing structure because most of the ground level area is used for parking, so larger column dimensions are needed to increase the strength and stiffness of the ground level due to the absence of walls as well as to meet the requirements for the inter-story drift ratio and to avoid soft-story failure. The column shear reinforcement area required by the SRDP columns is relatively smaller than the existing one, and the overall column shear reinforcement spacing is larger. On the second floor column, the bending reinforcement area was only 55% of the existing reinforcement area. On the third to fourth-floor columns, the bending reinforcement area was only 50% of the existing reinforcement area.

Table 5. Comparison Results of SRDP with Existing

	SRDP		**Existing**	
	Main Beam story 2-4			
	300x600		300x600	
	Negative moment	Positive moment	Negative moment	Positive moment
Top reinforcement	3D16	2D16	5D22	3D22
Bottom reinforcement	2D16	3D16	3D22	3D22
Stirrup	D10 – 200	D10 – 250	D13 - 100	D13 – 150
	Main Beam story 2-4			
	300x500		300x500	
Top reinforcement	3D16	2D16	5D22	3D22
Bottom reinforcement	2D16	2D16	3D22	3D22
Stirrup	D10 – 150	D10 – 150	D13 - 100	D13 – 150
	Secondary beam			
	250x500		250x500	
Top reinforcement	3D13	2D13	2D19	2D19
Bottom reinforcement	2D13	2D13	2D19	2D19
Stirrup	D10 - 200	D10 - 200	D10 – 100	D10 - 150

	SRDP		**Existing**	
	Column First Floor Parking Area			
	550x400		350x500	
Main Bar	8D20		12D22	
	Negative moment	Positive moment	Negative moment	Positive moment
Stirrup	D13 – 100	D13 – 150	D13 - 100	D13 – 120
	Column First Floor Stair Area			
	600x400		400x500	
Main Bar	8D20		12D22	
	Negative moment	Positive moment	Negative moment	Positive moment
Stirrup	D13 – 100	D13 – 150	D13 - 100	D13 – 120
	Column First Floor Parking Area			
	600x500		350x500	
Main Bar	12D22		12D22	
	Negative moment	Positive moment	Negative moment	Positive moment
Stirrup	D13 – 100	D13 – 150	D13 - 100	D13 – 150
	Column Second Floor			
	350x350		350x500	
Main Bar	8D20		12D22	
	Negative moment	Positive moment	Negative moment	Positive moment
Stirrup	D13 – 100	D13 – 150	D13 - 100	D10 – 150
	Column story 3-4			
	300x300		350x500	
Main Bar	8D19		12D22	
	Negative moment	Positive moment	Negative moment	Positive moment
Stirrup	D13 – 100	D13 – 150	D13 - 100	D10 – 150

Pushover Analysis Results

The pushover analysis results are presented in Table 6 and Table 7 and the capacity curves can be seen in Figure 5. Based on the results of the x-direction pushover analysis, the building was in the Collapse Prevention (CP) phase, which means that the structure has more than 30% damage but the structure has not collapsed. The behavior of the building when receiving earthquake loads showed that the beams yielded first compared to the columns. This shows that the condition of the building concern to safety so that casualties due to the earthquake can be avoided. The plastic joints were formed on 5 columns at the ground level of the parking area, which is an area where there are no infill walls, which means that 5 columns on the ground floor suffered structural damage of more than 30% in the x-direction.

Based on the results of the y-direction pushover analysis, the building was in the Collapse (C) phase. The beam yielded first when receiving earthquake loads is that the. This means that the building conditions concern safety so that casualties due to earthquakes can be avoided. Collapse Prevention (CP) plastic hinges are formed on 5 columns at the ground level of the parking area which is an area where there are no infill walls and on 4 diagonal struts on the ground floor, which means that 5 columns have more than 30% structural damage and 4 walls have cracks on the ground floor. Collapse plastic joint (C) was formed at 1 column, which means that 1 column on the ground floor collapsed.

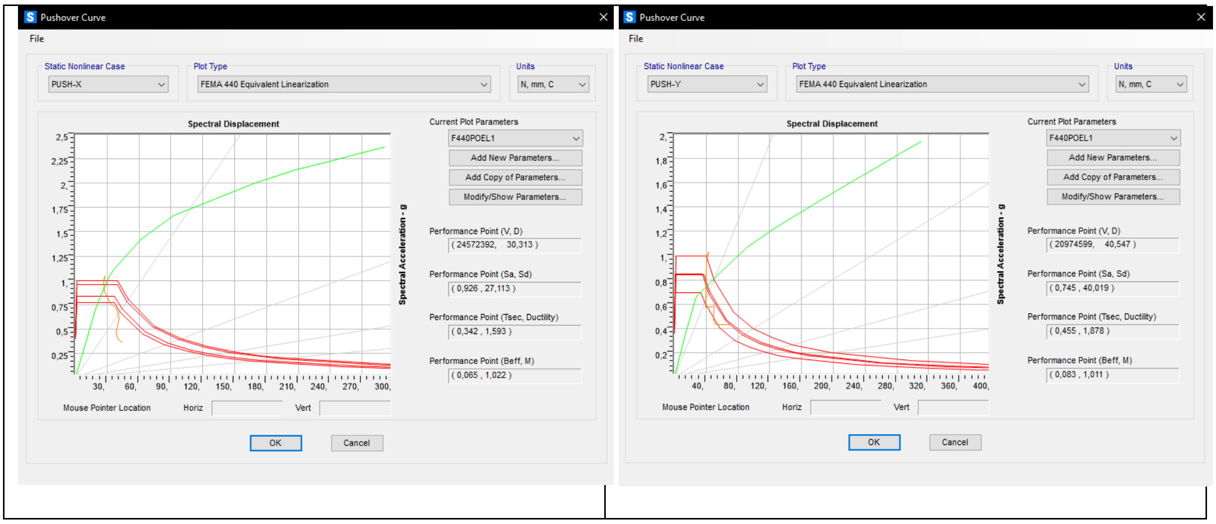

Figure 4. Pushover Capacity Curves in X and Y Directions

Table 6. Results of X-direction pushover

Step	Displacement (mm)	Base Force (N)	A to B	B to IO	IO to LS	LS to CP	CP to C	C to D	D to E	Beyond E	Total
0	-1,49	0	3143	0	0	0	0	0	0	0	3143
1	10,02	10.428.554	3131	12	0	0	0	0	0	0	3143
2	18,58	17.907.059	3082	60	0	0	1	0	0	0	3143
3	18,74	17.930.252	3081	61	0	0	1	0	0	0	3143
4	23,90	21.440.072	3044	97	0	0	2	0	0	0	3143
5	**23,99**	**21.417.160**	**3044**	**97**	**0**	**0**	**2**	**0**	**0**	**0**	**3143**
6	**34,94**	**26.881.233**	**2992**	**144**	**1**	**0**	**6**	**0**	**0**	**0**	**3143**
7	36,44	27.317.872	2989	140	8	0	6	0	0	0	3143

Table 7. Results of Y-direction pushover

Step	Displacement (mm)	Base Force (N)	A to B	B to IO	IO to LS	LS to CP	CP to C	C to D	D to E	Beyond E	Total
0	-0,61	0	3143	0	0	0	0	0	0	0	3143
1	14,56	9.722.421	3139	4	0	0	0	0	0	0	3143
2	28,15	17.806.685	3023	117	0	3	0	0	0	0	3143
3	30,05	18.616.427	3005	133	0	5	0	0	0	0	3143
4	30,06	18.608.154	3003	135	0	5	0	0	0	0	3143
5	**30,35**	**18.730.371**	**3002**	**136**	**0**	**0**	**5**	**0**	**0**	**0**	**3143**
6	**59,15**	**25.066.558**	**2924**	**119**	**82**	**0**	**17**	**1**	**0**	**0**	**3143**
7	87,95	30.827.696	2789	251	0	14	88	0	0	0	3143

IV. Discussions

The existing building designed as an infilled framed structure (SRDP) shows that the story drift meets the requirements of the allowable story drift required in Table 20 Article 7.12.1 SNI 1726: 2019. However, the inter-story drift ratio of the existing SRDP has a soft-story failure at the ground level. This can be seen from the inter-story drift ratio of 1.45 at the base level which exceeds the maximum allowable value of 1.3. This shows that in the existing SRDP dimensions, the base level will fail first compared to the level above it, so it is necessary to enlarge the column dimensions [11]. After the base level column dimensions were enlarged, the value of the inter-story drift ratio was 1.07. This shows that the enlarged column dimensions at the base level can increase the strength of the base level so that it does not fail when receiving the earthquake load.

The beams of SRDP that were modeled using the same dimensions as the existing ones resulted in a smaller reinforcement area of up to 50% and even when the size was reduced. This indicated that the infill walls contribute to the strength and stiffness of the building. However, larger column dimensions were needed on the ground level to avoid a soft story due to the absence of infilled walls.

Based on the results of non-linear static analysis, it was found that the collapse pattern of the existing dimension building modeled as SRDP experienced column yielding first (strong beam weak column), and after strengthening the ground floor, it was found that the collapse pattern of the building experienced beam yielding first (strong column weak beam). The performance point obtained by the SRDP building with reinforced ground floor columns with enlarged column dimensions is better than the performance of the existing building.

The above results indicated that typical SRDP buildings that visually have the potential for soft failure should be re-evaluated to take into account the influence of infill walls so that if a soft failure occurs after evaluation, the structure can be mitigated immediately. The base level should be reinforced to obtain a better level of structural performance.

The resulting strut width exceeds the floor level. A single diagonal strut used may not be appropriate, it is necessary to try modeling using a double diagonal strut considering that the infill wall panels have a span width much greater than 3m. It is suggested to study the effect of infill wall modeling with double strut to accommodate wide spans, to obtain a more suitable strut width.

V. Conclusion

From the results of the performance analysis and design of the dormitory building as SRDP, it can be concluded that:

1. Based on the story drift ratio the existing dimensional structure experiences a soft story on the ground floor. Strengthening the ground floor column by increasing the dimensions can increase the strength of the ground level so that it does not experience a soft story.
2. The SRDP generally produces less flexural reinforcement area than the existing structure. In the second to fourth-floor columns, the flexural reinforcement area is only 20% to 30% of the existing flexural reinforcement area. In beams, the flexural reinforcement area is only 34% to 52% of the existing flexural reinforcement area.
3. The performance level of the SRDP after strengthening is Collapse Prevention (CP) in the X direction where CP plastic joints are formed in 5 columns, and Collapse (C) in the Y direction where C plastic joints are formed in 1 column, with plastic joint formation occurring in the beam first. The overall structure has not collapsed but has suffered significant structural damage.

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