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BEHAVIOR OF BUILDING STRUCTURES RETROFITTED USING SHEAR WALLS WITH OPENINGS

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ABSTRACT: School buildings are a crucial component of educational infrastructure. Adequate school facilities significantly influence the effectiveness of the teaching and learning process; therefore, their structural performance must comply with applicable building codes. SDN 08 Campago Ipuh, an elementary school located in Bukittinggi City, Indonesia, consists of a three-story reinforced concrete structural system constructed in multiple phases. By 2020, only the foundation and column structures up to the second floor had been completed. Field inspections identified deterioration in several structural components, including concrete bulging, segregation, and visible cracking. Furthermore, the measured compressive strength of the concrete elements fell below the minimum requirement specified in the Indonesian concrete code (SNI 2847:2019). In this study, a structural evaluation was conducted in accordance with current national standards. The results revealed that several critical structural elements, particularly beams and columns, lack sufficient capacity to resist the applied loads. Therefore, strengthening measures are required prior to continuing construction. Among the retrofitting methods evaluated, the use of shear walls was found to significantly improve the load-bearing capacity of the building.

Keywords: School Building, Visual Assessment, Structural Analysis, Retrofitting, Shear Wall

1. INTRODUCTION

School buildings are an important component of educational infrastructure [1]. Adequate school facilities play a vital role in ensuring that teaching and learning activities run effectively, thereby supporting the achievement of educational quality. To guarantee this, building structures must comply with established safety and serviceability requirements. During structural design and analysis, reference must be made to the latest Indonesian codes, including SNI 1726:2019 for seismic design of buildings and non-buildings, SNI 2847:2019 for structural concrete provisions, and SNI 1727:2020 for minimum design loads and associated criteria for buildings and other structures.

SDN 08 Campago Ipuh is an elementary school located in Bukittinggi City, West Sumatra Province, Indonesia. The building is designed as a three-story reinforced concrete structure, constructed in successive phases. By 2020, construction had only covered the foundation and the column structures up to the second floor.

A field survey was conducted to assess the structural condition of the SDN 08 Campago Ipuh building in Bukittinggi City. The assessment involved visual observations of all structural elements and concrete quality evaluation using Schmidt hammer tests. Visual observations revealed several defects in the columns and beams, including concrete bulging, segregation, and cracking. Furthermore, the hammer test results indicated that the compressive strength of most structural elements failed to meet the design specification of $f'c$ = 20.75 MPa, which also falls below the minimum requirements outlined in the Indonesian concrete code (SNI 2847:2019).

Various methods for the seismic retrofitting of existing school buildings have been investigated in previous studies. These include performance evaluation and loss estimation using detailed numerical models in Italy [2], the application of a retrofitting strategy based on the priority index method for a three-story reinforced concrete school building in Myanmar [3], and the assessment of seismic resilience using vulnerability curves to compare existing and retrofitted structures. However, few studies have focused on combining visual assessment with the structural strengthening of existing school buildings using shear walls.

In the present work, the SDN 08 Campago Ipuh elementary school building is evaluated based on current Indonesian building standards and retrofitted using shear walls with openings.

2. RESEARCH SIGNIFICANCE

Structural defects resulting from construction errors pose significant challenges when evaluating building strength, particularly for critical facilities that require high seismic safety, such as the school building investigated in this study. Consequently, accurately assessing structural capacity and proposing effective retrofitting techniques—specifically through the application of shear walls—have become critical areas of research. The outcomes of this study are expected to provide valuable insights for improving retrofitting practices in vulnerable building structures.

3. METHODOLOGY

3.1 Building Data

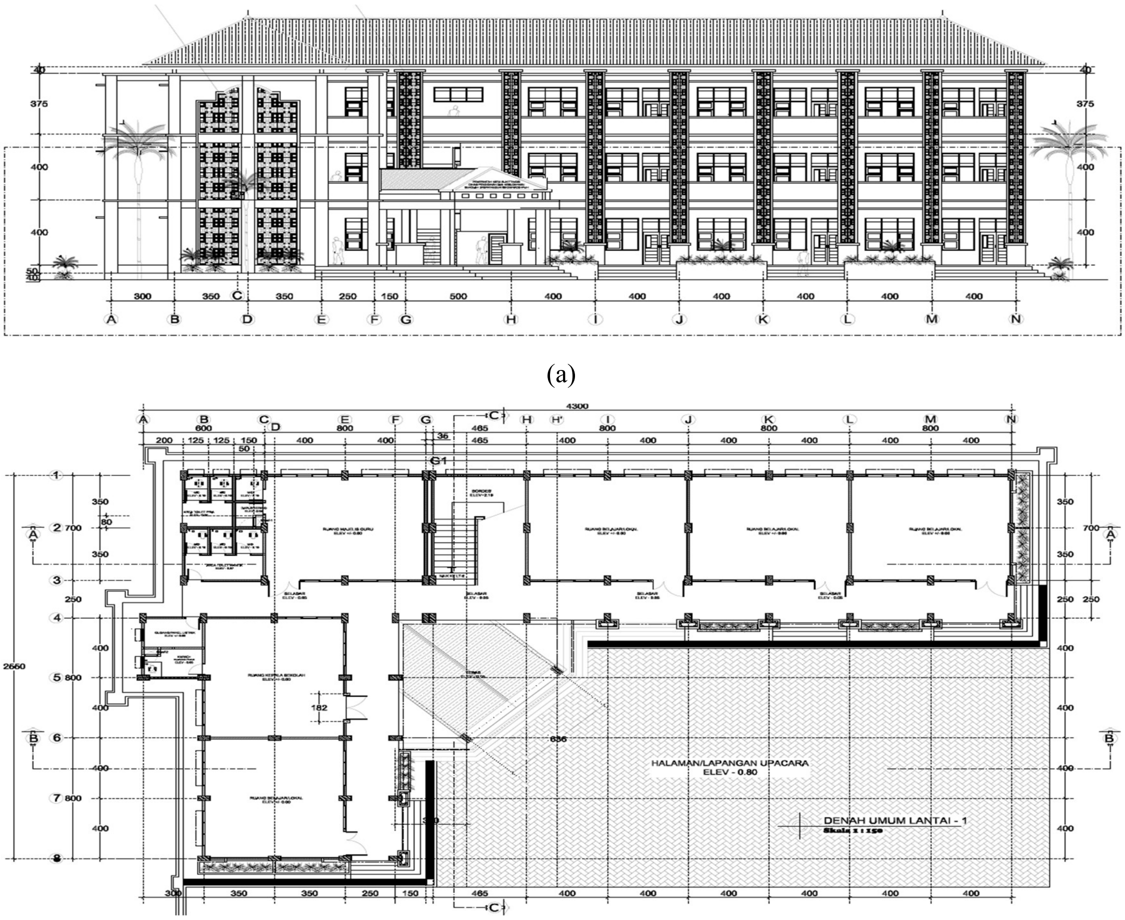
The structural data were obtained from field surveys, including as-built drawings and design documents of the SDN 08 Campago Ipuh building in Bukittinggi City. The building structure was modeled in three dimensions using ETABS software version 22.4.0. In the analysis, the structural system was subjected to dead, live, and seismic loads. Table 1 summarizes the existing structural properties of the building.

Table 1. Building Existing Data

Name	Data
Building name	SDN 08 Campago Ipuh Bukittinggi City
Function	Educational facilities
Width Building	± 25.5 m
Length Building	± 43.0 m
Heigh Building	±13.05 m
Slab thickness	12 cm
Column dimension	K1 (30x60 cm)
Beam dimension	B1 (30x50 cm), B2 (30x60 cm) B3 (25x50 cm), BTL (30x50 cm)
Concrete compressive strength	18.5 MPa (1st floor columns) 13 MPa (2nd floor columns)
Steel yield strength	320 MPa (deformed bar) 240 MPa (plain bar)

3.2 Modeling of Structures

The structural model was developed using ETABS software version 22.4.0. The building's elevation and layout plan are illustrated in Fig. 1, while the 3D numerical models are shown in Figs. 2 and 3.



(a)

(b)

Fig.1 Building layout: (a) front view and (b) floor plan

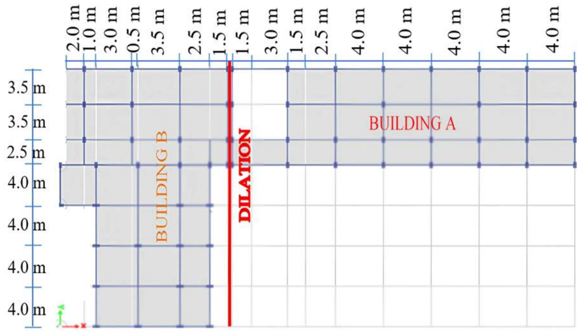
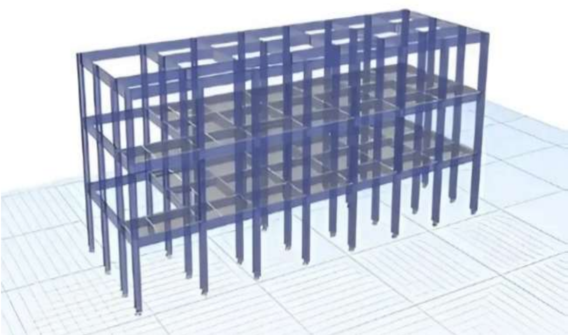


Fig.2 Expansion joint in the building structure



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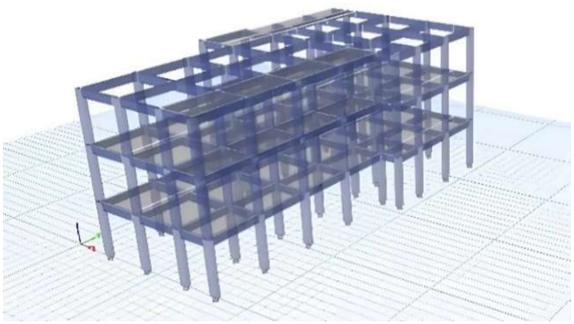


(b)

Fig.3 3D numerical models of the building structure in ETABS v22.4.0: (a) Building A and (b) Building B

3.3 Load Analysis

The evaluation of structural loads, including dead, live, and seismic loads, was conducted in accordance with Indonesian standards SNI 1727:2020 [4] and SNI 1726:2019 [5].

3.3.1 Dead load

Dead load, as defined in SNI 1727:2020 Article 3.1.1, comprises the weight of all permanent building construction materials, including walls, floors, roofs, ceilings, stairs, fixed partitions, finishes, cladding, and other architectural and structural components, as well as fixed service installations. The dead load applied to the SDN 08 Campago Ipuh building model includes the structural self-weight, which is computed automatically by the ETABS v22.4.0 software.

The supplementary dead load applied to the floor slab is 1.11 kN/m², while the roof contributes 0.87 kN/m². Additionally, the wall loads acting as distributed loads on the beams are 10 kN/m for the first and second stories, and 9.375 kN/m for the third story.

3.3.2 Live load

The live loads considered in the structural design follow the provisions of SNI 1727:2020. According to the code, the design live load should represent the maximum load anticipated from occupancy and building use, and it must not be lower than the prescribed minimum values [5]. Therefore, the live loads applied are adjusted based on the functional use of each room within the school building, namely:

- Classrooms: 1.92 kN/m^2.
- Corridor above the 1st floor: 3.83 kN/m^2.
- Offices: 2.4 kN/m^2.
- Balconies and decks: 4.79 kN/m^2.

3.3.3 Earthquake load

Seismic load refers to the ground motion generated by an earthquake that impacts a structural system. The structural analysis of the SDN 08 Campago Ipuh building in Bukittinggi City employed a dynamic response spectrum analysis approach. This earthquake load analysis was carried out in accordance with SNI 1726:2019.

The response spectrum data for the earthquake analysis were sourced from the RSA application provided by Puskim PUPR, as illustrated in Fig. 4.

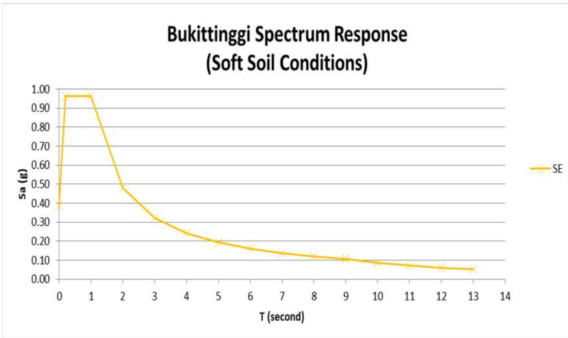


Fig.4 Design response spectrum curve of Bukittinggi City

3.3.4 Load combination

When dead, live, and earthquake loads act simultaneously, it is necessary to ensure structural safety. Therefore, these loads are combined to allow the structure to withstand them. The load combinations applied to the structure are regulated in accordance with SNI 2847:2019 [6], as shown in Table 2.

Table 2. Load combination

Load combination	Main load
U = 1.4 D	D
U = 1.2D+1.6L+0.5 (Lr or R)	L
U = 1.2D+1.6(Lr or R)+(1.0L or 0.5W)	Lr or R
U = 1.2 D+1.0W+1.0L+0.5(Lr or R)	W
U = 1.2D+1.0E+1.0L	E
U = 0.9D+1.0W	W
U = 0.9D+1.0E	E

4. RESULTS AND DISCUSSION

4.1 Analysis of the Existing Structure

The existing structure was evaluated to assess its capacity to sustain applied loads. This stage involved calculating the cross-sectional strength of structural members in accordance with the Indonesian concrete code, SNI 2847:2019.

4.1.1 Inter-story drift

According to Article 7.8.6 of SNI 1726:2019, inter-story displacement (Δ) is determined by calculating the difference in lateral deflections at the centers of mass above and below the story being evaluated. In cases where the centers of mass are not vertically aligned, the drift may be measured at the base of the story using the vertical projection of the center of mass from the story above. When a design considering tensile clearance is applied, the displacement must be evaluated using the full design seismic force without any reduction factors [5].

Table 3. Inter-story drift values in the X and Y directions for Building A

Story	Inelastic Drift (mm)		Drift Limit	Δ < Drift Limit
	Δ_X	Δ_Y		
3	23.995	15.330	37.500	OK
2	89.844	41.375	40.000	NOT OK
1	88.187	33.528	40.000	NOT OK

Table 4. Inter-story drift values in the X and Y directions for building B

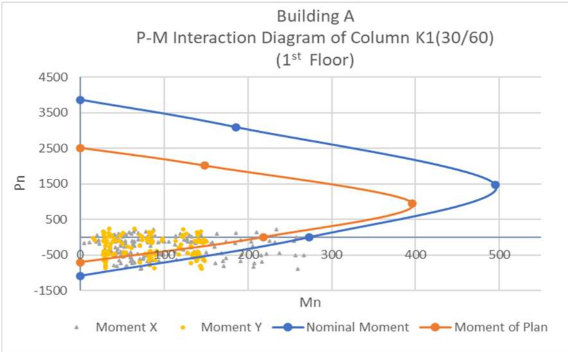
Story	Inelastic Drift (mm)		Drift Limit	Δ < Drift Limit
	Δ_X	Δ_Y		
3	19.818	23.657	37.500	OK
2	74.525	62.011	40.000	NOT OK
1	64.519	53.233	40.000	NOT OK

In accordance with Article 7.12.1 of SNI 1726:2019, the inter-story drift induced by the design lateral forces must not exceed the prescribed drift limit. The calculated inter-story drifts in the X and Y directions are presented in Tables 3 and 4. As shown in the tables, the inter-story drifts for Buildings A and B in both directions exceed the allowable limits.

4.1.2 Column capacity

The relationship between axial force (P) and bending moment (M) is represented by the P–M interaction diagram [7]. This diagram is used to evaluate a column's ability to resist applied loads. When the load point falls within the nominal axial and moment capacity curve, the column is considered adequate. Conversely, if it lies outside the curve, the column is deemed insufficient to carry the loads.

Figs. 5 and 6 show the interaction diagrams of columns in Buildings A and B. It can be seen that the columns of Buildings A and B on the 1st and 2nd floors lack sufficient strength to sustain the applied loads, as the combination of axial force and bending moment exceeds the nominal capacity limits.



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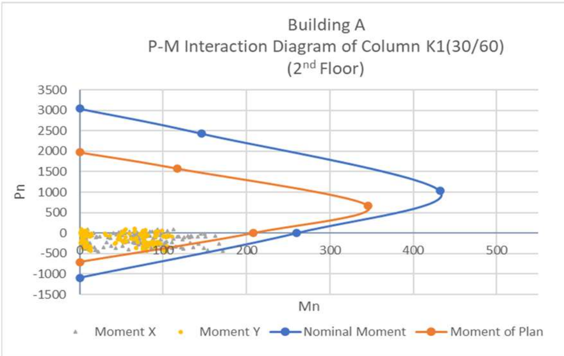

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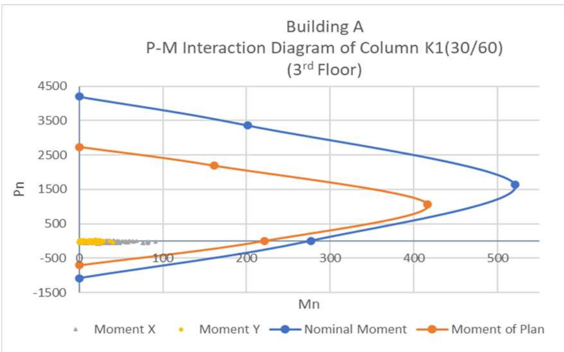

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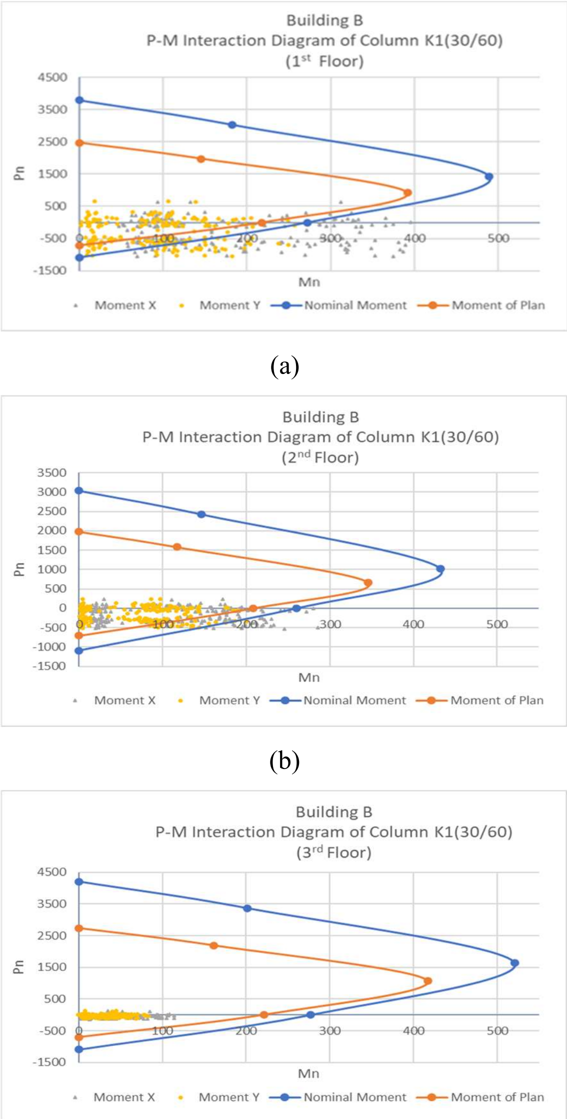
Fig.5 P-M interaction diagrams of columns in Building A: (a) 1st floor, (b) 2nd floor, (c) 3rd floor



(a)

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(c)

Fig.6 P-M interaction diagrams of columns in Building B; a) 1st floor, b) 2nd floor, c) 3rd Floor

4.1.3 Column shear capacity

The shear capacity of the columns was determined from the contributions of both the concrete and the shear reinforcement in accordance with SNI 2847:2019. The computed shear strengths for Buildings A and B are presented in Table 5. The results indicate that the columns in both structures adequately resist the applied shear forces.

Table 5. Column shear capacity of buildings

Floor	Code	Vr (kN)	Vu Building A (kN)	Vu Building B (kN)	Note
1	K1	195.924	113.437	195.447	OK
2	K1	181.316	57.018	156.284	OK
3	K1	201.259	47.381	55.876	OK

4.1.4 Beam moment capacity

The moment capacity of the beams must be calculated to ensure structural integrity and prevent failure, in accordance with the provisions of SNI 2847:2019. Table 6 presents the calculated moment capacities for the beams. The results indicate that the beams in Building A have sufficient strength to resist the applied bending moments; however, some beams in Building B, particularly B1 and B3, are insufficient to support the imposed loads.

Table 6. Beam moment capacity of buildings

Floor	Code	ØMn (kN.m)	Mu Building A (kN.m)	Note	Mu Building B (kN.m)	Note
1	B1	243.582	139.713	Ok	250.195	NOT OK
	B2	300.742	206.877	Ok	271.328	OK
	B3	173.255	137.303	Ok	186.776	NOT OK
	BTL	243.582	136.333	Ok	195.190	OK
2	B1	243.582	95.644	Ok	173.347	OK
	B2	300.742	170.246	Ok	215.058	OK
	B3	173.256	108.424	Ok	132.638	OK
	BTL	243.583	86.133	Ok	129.694	OK
3	B1	243.583	90.878	Ok	87.178	OK
	B2	300.742	57.856	Ok	75.179	OK
	B3	173.256	26.551	Ok	47.459	OK
	BTL	243.583	34.274	Ok	51.098	OK

4.1.5 Beam shear capacity

Shear force is a critical load that must be considered when designing reinforced concrete beams by providing shear reinforcement along the span. The fundamental concept of shear design states that the nominal shear capacity of the beam must exceed the applied shear force. Table 7 summarizes the calculated shear capacities of the beams. The results reveal that the beams in Building A are adequate to resist the applied shear forces, whereas certain members in Building B, specifically beams B1, B2, and BTL on the first floor, as well as beams B1 and BTL on the second floor, lack sufficient shear capacity to sustain the loads.

Table 7. Beam moment capacity of buildings

Floor	Code	Vn (kN)	Vu Building A (kN)	Note	Vu Building B (kN)	Note
1	B1	165.320	139.430	Ok	323.121	NOT OK
	B2	201.260	142.206	Ok	228.251	NOT OK
	B3	152.224	93.629	Ok	145.370	OK
	BTL	165.320	143.702	Ok	278.712	NOT OK
2	B1	165.320	104.167	Ok	206.969	NOT OK
	B2	201.260	128.298	Ok	191.760	OK
	B3	152.224	81.372	Ok	123.693	OK
	BTL	165.320	93.977	Ok	166.431	NOT OK
3	B1	165.320	92.994	Ok	95.116	OK
	B2	201.260	34.214	Ok	44.106	OK
	B3	152.224	17.231	Ok	29.610	OK
	BTL	165.320	37.904	Ok	69.821	OK

4.2 Structural Retrofitting Analysis

The assessment of the existing structural elements provides information on which components are adequate and which are deficient. For the elements identified as weak, a retrofitting approach was proposed. Subsequently, the upgraded members were reanalyzed to ensure they achieved the minimum required strength of the building.

4.2.1 Retrofitting of a building using shear walls

The retrofitting method using shear walls aims to resist design earthquake loads and reallocate the lateral load-bearing function from the existing beam-column frame to the shear walls, allowing the frame to primarily support gravity loads (dead and live loads). Furthermore, the incorporation of shear walls significantly enhances structural capacity and minimizes lateral displacements during seismic events [8-11]. In some cases, shear walls must be designed with openings for windows or doors, resulting in a configuration known as a shear wall with openings.

Buildings with properly designed and detailed shear walls have demonstrated excellent performance when subjected to earthquake-induced ground motions. While shear walls in high-seismicity regions require specialized detailing, it has been observed that many existing buildings with shear walls, even those not explicitly designed for high seismic demands, remain standing and show no signs of imminent collapse [12].

When shear walls are utilized, seismic forces acting on the structure are primarily absorbed and resisted by these walls. The frame system, which would otherwise need to be designed as a Special Moment Resisting Frame (SRPMK) in compliance with SNI 1726:2019 and SNI 2847:2019, is now relieved of this requirement. Furthermore, the concrete portal frame system only resists gravity loads, while earthquake loads are resisted entirely by the shear walls.

Determining the geometry and placement of shear walls, along with anticipating potential failure modes, are critical factors in seismic design [13]. For these retrofitting recommendations, the shear wall locations were determined based on the number of panels, ensuring structural symmetry relative to the building's center of mass. The properties of the shear wall are as follows:

- Shear wall thickness : 15 cm
- Shear wall location : 1st floor
- Design compressive strength of concrete (*f'c*): 20.75 MPa

The location of shear walls in the retrofitted buildings A and B is shown in Figs. 7 and 8, respectively.

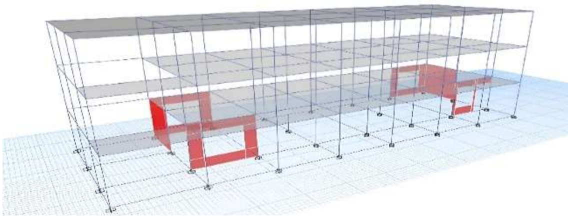


Fig.7 Location of shear walls in the retrofitted Building A

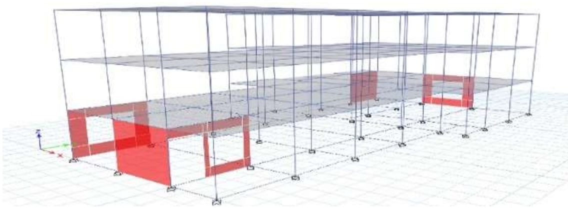


Fig.8 Location of shear walls in the retrofitted Building B

4.2.2 Analysis result for the retrofitted buildings

The analysis of the retrofitted structures with shear walls demonstrates that the inter-story drifts for both Buildings A and B, in both the X and Y directions, remain within the allowable limits, as presented in Tables 8 and 9. Furthermore, the columns in the strengthened buildings possess sufficient capacity to sustain the applied loads; axial and moment demands remain within nominal limits (Figs. 9-10), and the columns are also capable of resisting the acting shear forces (Table 10).

Table 8. Inter-story drift values in the X and Y directions for retrofitted Building A

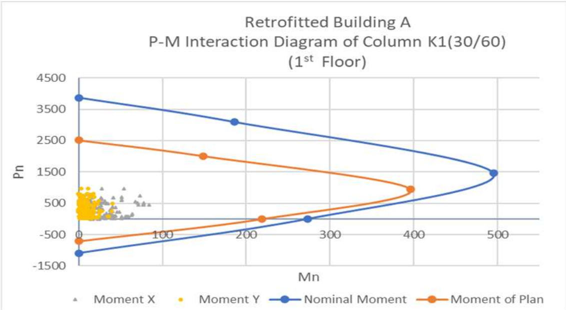
Story	Inelastic Drift (mm)		Drift Limit	Δ < Drift Limit
	Δ_X	Δ_Y		
3	18.355	11.279	56.250	OK
2	41.961	17.054	60.000	OK
1	6.248	8.382	60.000	OK

Table 9. Inter-story drift values in the X and Y directions for retrofitted Building B

Story	Inelastic Drift (mm)		Drift Limit	Δ < Drift Limit
	Δ_X	Δ_Y		
3	13.072	16.504	56.250	OK
2	29.220	27.229	60.000	OK
1	7.055	6.596	60.000	OK

Table 10. Column shear capacity of retrofitted Buildings A and B

Floor	Code	Vr	Vu		Note
			Building A	Building B	
		(kN)	(kN)		
1	K1	195.924	131.921	155.175	OK
2	K1	201.260	81.652	100.846	OK
3	K1	201.260	29.224	35.674	OK



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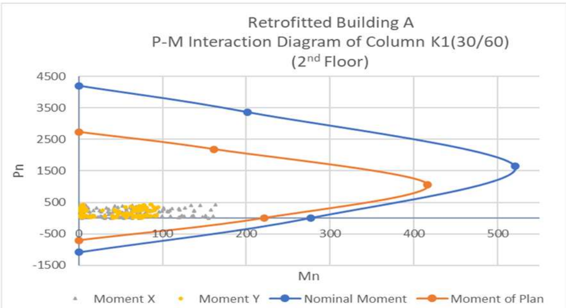

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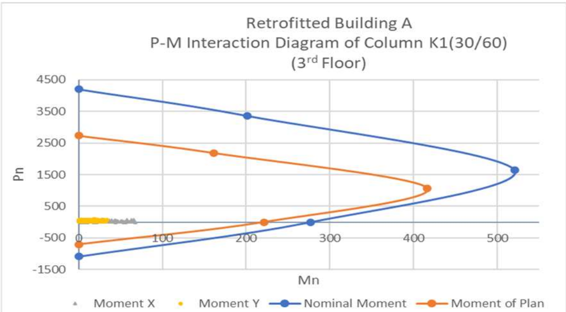

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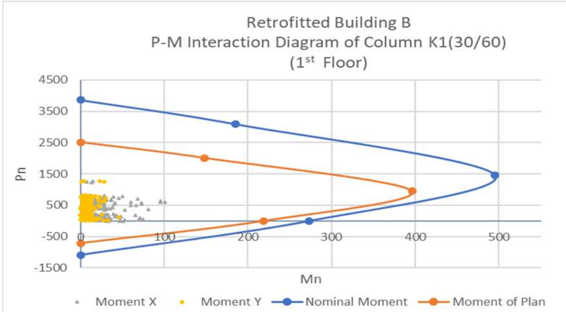
Fig.9 The P-M interaction diagrams of columns in retrofitted building A. a) first, b) second, c) third floor



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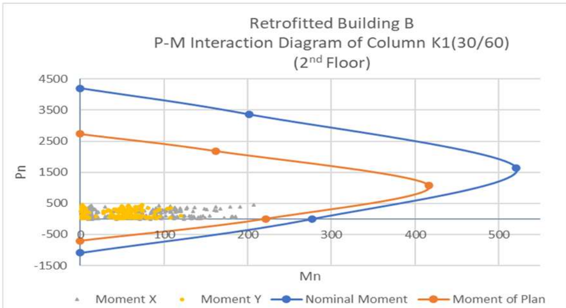

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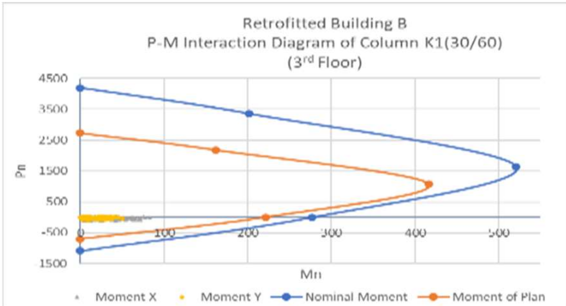

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Fig.10 The P-M interaction diagrams of columns in retrofitted building B. a) first, b) second, c) third floor

In addition, the flexural and shear strengths of the beams in the retrofitted buildings are sufficient to resist the applied loads, as detailed in Tables 11 and 12. These findings confirm that the use of shear walls with openings as a retrofitting strategy substantially enhances the load-bearing capacity of the structural components, thereby enabling the buildings to adequately withstand the imposed loads.

Table 11. Beam moment capacity of retrofitted Buildings A and B

Floor	Code	ØMn (kN.m)	Mu Building A (kN.m)	Note	Mu Building B (kN.m)	Note
1	B1	243.582	76.360	OK	89.786	OK
	B2	300.742	141.512	OK	153.044	OK
	B3	173.256	92.922	OK	87.254	OK
	BTL	243.583	54.245	OK	47.666	OK
2	B1	243.583	99.072	OK	112.791	OK
	B2	300.742	159.281	OK	177.484	OK
	B3	173.256	104.774	OK	100.860	OK
	BTL	243.583	72.433	OK	64.737	OK
3	B1	243.583	34.719	OK	47.193	OK
	B2	300.742	51.547	OK	59.222	OK
	B3	173.256	26.989	OK	30.231	OK
	BTL	243.583	29.278	OK	31.706	OK

Table 12. Beam shear capacity of retrofitted Buildings A and B

Floor	Code	Vn (kN)	Vu Building A (kN)	Note	Vu Building B (kN)	Note
1	B1	165.320	95.340	OK	105.238	OK
	B2	201.260	131.184	OK	135.757	OK
	B3	152.224	82.683	OK	87.249	OK
	BTL	165.320	58.606	OK	77.051	OK
2	B1	165.320	108.256	OK	123.291	OK
	B2	201.260	140.814	OK	146.215	OK
	B3	152.224	90.371	OK	94.885	OK
	BTL	165.320	89.500	OK	102.425	OK
3	B1	165.320	39.231	OK	54.540	OK
	B2	201.260	31.765	OK	34.751	OK
	B3	152.224	17.234	OK	18.461	OK
	BTL	165.320	33.385	OK	42.665	OK

5. CONCLUSIONS

Based on the outcomes of the field survey and the structural assessment of the SDN 08 Campago Ipuh building in Bukittinggi City, the following conclusions are drawn:

1. The existing capacity of the school building is insufficient to withstand design loads. The inter-story drift exceeds the limits permitted by SNI 1726:2019, and several columns in Buildings A and B, as well as beams in Building B, lack the necessary flexural and shear capacities to resist the applied loads.
2. The retrofitting strategy involved the incorporation of 15-cm-thick shear walls with a concrete compressive strength (*f'c*) of 20.75 MPa, all installed on the first floor.
3. Installing shear walls with openings significantly improved overall structural performance, enabling the building to sustain design loads while complying with the minimum strength and serviceability requirements stipulated by Indonesian building codes.

6. ACKNOWLEDGMENT

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