Seismic vulnerability assessment of a hospital building with and without retrofitting using RC shear walls

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Abstract. Revisions to building regulations in Indonesia necessitate assessing building structures, especially hospital buildings. A structural assessment using the current building codes and vulnerability analysis is necessary to ensure the building's strength against the working loads. In this study, an assessment of the Third-Class Inpatient Building at the Sijunjung Regional General Hospital was carried out using the finite element method (ETABS V21). The structural assessment of the existing hospital building revealed that the inter-story drift values exceed the drift limit, and column and beam structural elements cannot withstand the working loads. The recommendation for retrofitting the building structure is to add RC shear walls to the existing building. The retrofitted building shows an increase in its structural capacity, and the inter-story drift and the strength of the structural elements have met the requirements based on the current Indonesian building codes. Furthermore, structural fragility curves of the hospital building were developed with and without retrofitting against earthquake loads. The vulnerability analysis results indicated that retrofitting the hospital building with shear walls reduces the probability of building damage due to earthquake loads by 52.69% at the level of extensive damage at a PGA of 0.60 g.

1 Introduction

Health development aims to enhance awareness, willingness, and the ability to live healthily for everyone, thereby improving public health and serving as an investment in developing socially and economically productive human resources. Hospitals are essential infrastructure needed to meet human health needs [1]. Sijunjung General Hospital, hereafter referred to as RSUD Sijunjung, is one of the hospitals in Sijunjung Regency that frequently undertakes development and improvements to enhance the quality and services of the hospital, including the construction of a Third-Class Inpatient Building at RSUD Sijunjung.

The building must be strong, rigid, and stable to withstand the loads imposed on its structure. Based on current building codes, routine inspections of building reliability, especially following updates to building codes, are necessary, as seen in the Assessment and Analysis of Office Building Retrofits in Riau Province, Indonesia [2]. Moreover, standards for building assessments continually evolve and improve over time. For example, earthquake resistance design procedures for buildings are regulated in SNI 1726:2012 [3], which was updated to SNI 1726:2019 [4]. Similarly, SNI 1727:2013, which specifies minimum loads for building and structural design [5], was revised to SNI 1727:2020 [6], and the requirements for structural concrete in buildings specified by the National Standardization Agency were updated from SNI 2847:2013 [7] to SNI 2847:2019 [8]. Visual observations revealed structural issues in columns, beams, and walls, leading to concrete quality testing to determine the building's suitability. Concrete quality was assessed using a hammer test, a non-destructive method outlined in SNI 4430:1997 [9]. This testing method involves applying an impact load to the concrete surface, with results obtained relatively quickly [10]. However, most tests indicated concrete quality above the planned 25 MPa.

Considering that hospital buildings are critical infrastructure that must remain safe during earthquakes and that numerous instances of structural element damage have been observed, coupled with the existing building's location in a seismically active area, it is essential to conduct a structural assessment. This assessment involves a structural response analysis to the loads applied, including seismic loads, using the ETABS V21 structural calculation software, following the current Indonesian National Standards (SNI) regulations [11-13].

2 Evaluation of the existing building

2.1 Existing building data

The existing building uses a reinforced concrete structure, a composite material with steel retrofitting embedded within the concrete. This configuration is designed to withstand tensile forces in the structure, resulting in

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reinforced concrete having significant strength against both compressive and tensile forces [14].

Data related to structural analysis were obtained from existing as-built drawings and building design documents [15], as presented in Tables 1-3 and Figs. 1 and 2.

Table 1. Existing building data

Name	Data
Building name	Third-Class Inpatient Building at Sijunjung Regional General Hospital
Function	Hospital
Structure type	Dual system
Amount floor	4 floors
Building height	12 m
Floor slab thickness	13 cm
Building area	± 5,035.82 m^2
Column sections	K1(55x55), K2(40x50), and K3(40x40)
Beam sections	B1(35x60), B2(30x60), B3(30x50), B4(25x40), B1cor(30x50), B2cor(30x40), and B3cor(20x40)
Concrete quality	25 MPa
Steel reinforcing bar quality	BJTS U-28 BJTP U-42

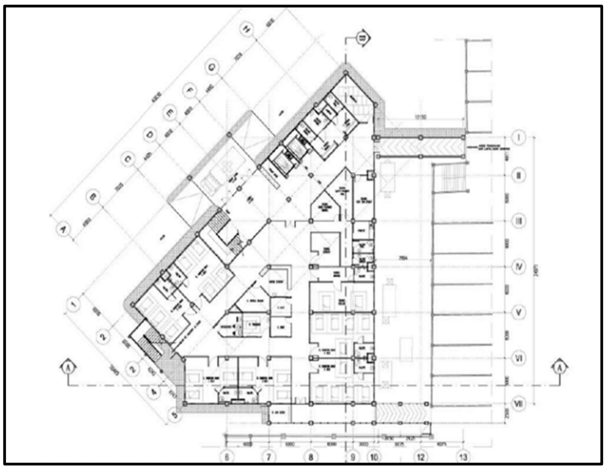

Fig. 1. The plan view of the third-class inpatient building at the Sijunjung regional general hospital

Fig. 2. The third-class inpatient building at Sijunjung regional general hospital

Table 2. Column reinforcement details

No	Type	Section		Flex. Reinf.	Shear Reinf,	
		Depth	Width		Support	Midspan
1.	K1	550	550	12D19	D13-150	D13-150
2.	K2	400	500	10D19	D10-150	D10-150
3.	K3	400	500	8D19	D10-150	D10-150

Table 3. Beam reinforcement details

No	Type	Section		Support Area		Midspan Area	
		Depth	Width	Tensile	Compr	Tensile	Compr.
1.	B1	350	600	D19	D16	D19	D16
2.	B2	300	600	D19	D13	D19	D13
3.	B3	300	500	D19	D13	D19	D13
4.	B4	250	400	D16	D10	D16	D10
5.	B1Cor	300	500	D16	D16	D16	D16
6.	B2Cor	300	400	D16	D16	D16	D16
7.	B3Cor	200	400	D13	D13	D13	D13

2.2 Modeling structure

Structural modeling was performed using various applications, including the ETABS software [16]. The structural model is shown in Fig. 3.

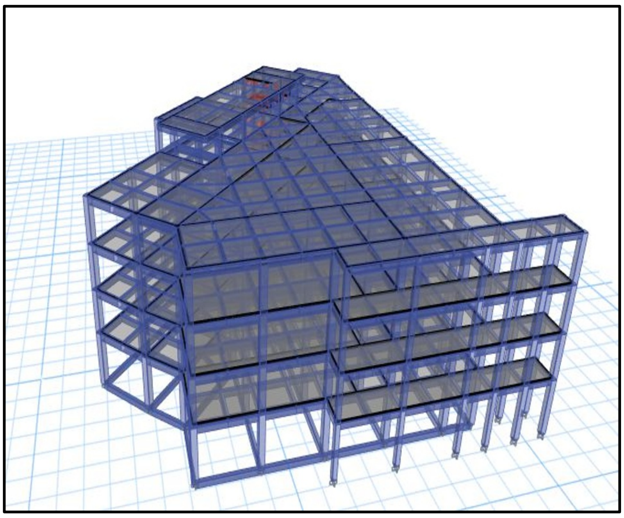

Fig. 3. 3D structural modeling of existing hospital building

2.3 Load analysis

2.3.1 Vertical load

The dead loads include the weight of the structural elements calculated using ETABS V21.2 and additional superimposed dead loads (SIDL) on the floor slabs, roof slabs, and beams. The superimposed dead loads on the floor slabs include finishing materials, ceramics, ceiling loads, and Mechanical, Electrical, and Plumbing (MEP) components, while the beams include the weight of walls on the structure.

According to SNI 1727:2020, live loads must represent the maximum expected load due to occupancy and use of the building. The live loads for the third-class inpatient ward at Sijunjung Regional General Hospital are listed in Table 4 [6].

Table 4. Live load based on room function

Function Room	Load (kN/m²)
Corridor	4.79
Corridor above the first floor	3.83
Operating room/ laboratory	2.87
Patient room	1.92

2.3.2 Horizontal load

The seismic loading is calculated based on SNI 1726:2019, which provides the guidelines for earthquake-resistant design of buildings and non-building structures [4]. According to these regulations and the building's utilization type, the structure is categorized under Risk Category IV with an importance factor (Ie) of 1.5. The structural type is a dual system of special reinforced concrete shear walls with a seismic load reduction factor (R) of 7, an overstrength factor (Ω) of 2.5, and a deflection amplification factor (Cd) of 5.5. Based on this structural type, a retrofitting parameter (Ct) of 0.0488 and a period parameter (x) of 0.75 are used. The acceleration parameters are derived from the earthquake data for Sijunjung Regency, with SDS and SD1 values of 0.658 g and 0.724 g, respectively. As shown in Fig. 4, these parameters are presented in a response spectrum graph.

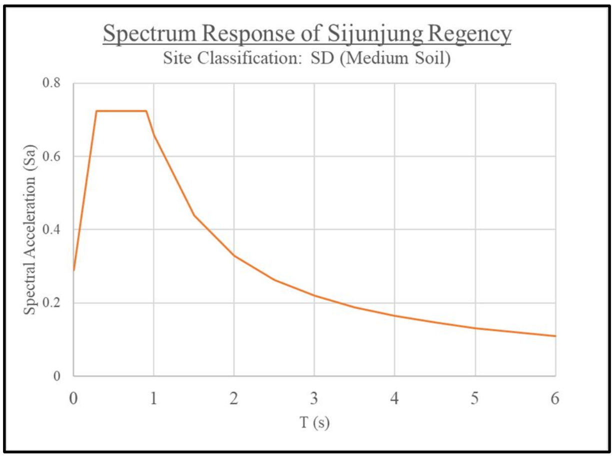

Fig. 4. Response spectrum design of Sijunjung regency, Indonesia

2.3.3 Load Combination

SNI 1726:2019 regulates the combinations of dead, live, and earthquake loads. Table 5 presents the load combinations of the structure model.

Table 5. Load combinations

No	Load combination	Note
1.	U = 1.4 D	Dead load
2.	U = 1.2 D + 1.6 L	Dead and live loads
3.	U = 1.4 D + L ± 1.3 Ex ± 0.39 Ey	Dead, live, and earthquake loads
4.	U = 1.4 D + L ±0.39 Ex ±1.3 Ey	
5.	U = 0.7 D ±1.3 Ex ± 0.39 Ey	
6.	U = 0.7 D ± 0.39 Ex ± 1.3 Ey	

2.4 Inter-story drift

From the ETABS analysis results, the story forces are obtained, representing the inter-story drift values in millimeters. These values can then be calculated according to Table 6.

Table 6. Inter-story drift of the existing building

Story	Inelastic Drift (mm)		Drift Limit	Δ < Drift Limit
	ΔX	ΔY		
5	99.851	13.915	25.000	NOT OK
4	23.903	20.013	40.000	OK
3	50.538	22.132	40.000	NOT OK
2	63.906	20.324	40.000	NOT OK
1	68.281	15.077	50.000	NOT OK

The analysis results of inter-story drift in Table 6 indicate that the existing building does not comply with the Indonesian seismic codes as per SNI 1726:2019, chapter 7.8.6.

2.5 Structural capacity

2.5.1 Column capacity

The column is a vertical compression member in a structural frame that supports the loads from beams [17]. The cross-sectional capacity of a column to resist the combination of axial force and bending moment can be represented by an interaction curve between these two forces, known as the column P-M interaction diagram.

Analysis of the interaction diagram indicates that columns K1, K2, and K3 in the Third-Class Inpatient Building at Sijunjung Regional General Hospital are not capable of withstanding the working load in both the X and Y directions, as the P-M values (points) have crossed the P-M interaction diagram line, as shown in Figs. 5-7.

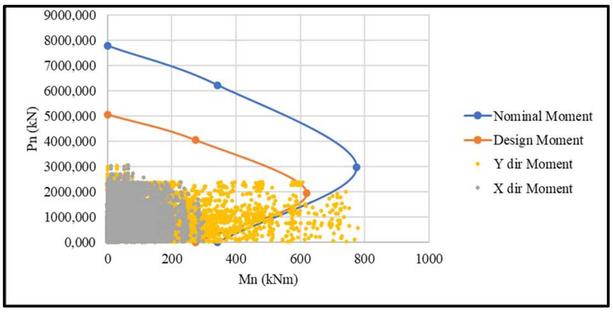

Fig. 5. P-M interaction diagram for column K1

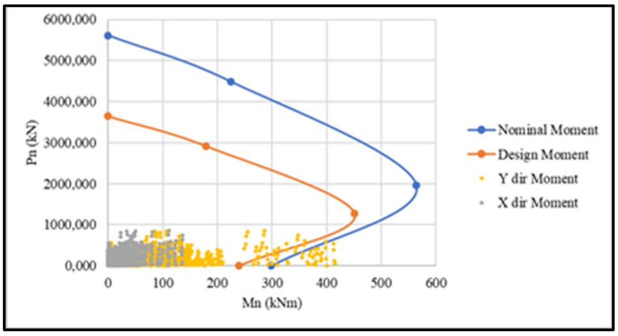

Fig. 6 P-M interaction diagram for column K2

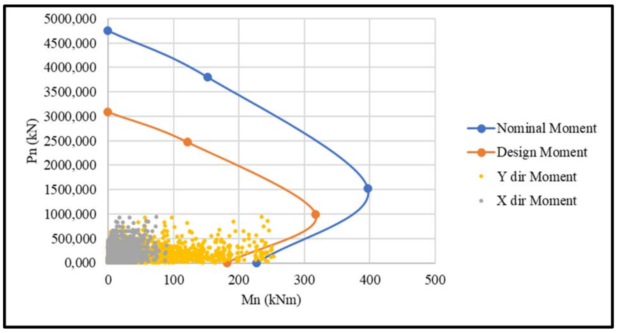

Fig 7. P-M interaction diagram for column K3

The results of the column's shear strength are shown in Table 7. The table compares the reduction factor nominal shear strength (ϕVn) and ultimate shear force (Vu).

Table 7. Shear capacity of columns

Fl.	Code	Width	Depth	ΦVn	Vu	ΦVn ≥ Vu
1	K1	550	550	473.490	252.824	OK
	K2	400	500	276.800	123.521	OK
	K3	400	400	218.800	87.404	OK
2	K1	550	550	473.490	302.292	OK
	K2	400	500	276.800	112.086	OK
	K3	400	400	218.800	122.086	OK
3	K1	550	550	473.490	226.292	OK
	K2	400	500	276.800	85.414	OK
	K3	400	400	218.800	91.814	OK
4	K1	550	550	473.490	141.254	OK
	K2	400	500	276.800	48.847	OK
	K3	400	400	218.800	57.283	OK
5	K1	550	550	473.490	189.066	OK

The table above shows that the columns of the Third-Class Inpatient Building at Sijunjung Regional Hospital can resist the shear forces acting on the structure.

2.5.2 Beam Capacity

The load-bearing capacity of beam analysis was carried out by reviewing all types of beams on each floor. Table 8 shows that the beam capacity is insufficient to withstand the forces acting on the structure, particularly for beams B1, B2, and the corridor beam.

3 Retrofitting the building with shear walls

3.1 Design of shear walls

Based on the structural evaluation, the appropriate retrofitting is using shear walls. Shear walls are structural walls made of reinforced concrete designed to resist shear and lateral forces caused by earthquakes. They must be designed to provide adequate stiffness to reduce inter-story drift caused by lateral loads such as earthquakes [18].

Table 8. Flexural and shear capacity of beams

Fl.	Code	ΦMn	Mu	ΦMn ≥ Mu	ΦVn	Vu	ΦVn ≥ Vu.
1	B1	350.54	529.23	NOT OK	465.87	468.71	NOT OK
	B2	292.74	425.73	NOT OK	310.50	381.50	NOT OK
	B3	286.81	115.71	OK	372.60	102.70	OK
	B4	109.91	105.01	OK	285.58	86.04	OK
	B1cor	171.15	228.32	NOT OK	258.75	185.37	OK
	B2cor	81.60	193.53	NOT OK	207.00	173.13	OK
	B3cor	37.15	68.80	NOT OK	134.48	77.63	OK
2	B1	350.54	380.39	NOT OK	465.87	351.90	OK
	B2	292.74	298.50	NOT OK	310.50	260.24	OK
	B3	286.81	187.10	OK	372.60	129.95	OK
	B4	109.91	98.06	OK	285.58	81.88	OK
	B1cor	171.15	216.47	NOT OK	258.75	176.92	OK
	B2cor	81.60	168.28	NOT OK	207.00	152.67	OK
	B3cor	37.15	59.43	NOT OK	134.48	68.11	OK
3	B1	350.54	339.47	OK	465.87	350.50	OK
	B2	292.74	300.71	NOT OK	310.50	253.16	OK
	B3	286.81	175.32	OK	372.60	127.28	OK
	B4	109.91	84.55	OK	285.58	70.99	OK
	B1cor	171.15	148.95	OK	258.75	124.13	OK
	B2cor	81.60	115.71	NOT OK	207.00	108.01	OK
	B3cor	37.15	42.67	NOT OK	134.48	51.59	OK
4	B1	350.54	118.38	OK	465.87	102.93	OK
	B2	292.74	162.66	OK	310.50	121.09	OK
	B3	286.81	86.81	OK	372.60	74.54	OK
	B4	109.91	49.74	OK	285.58	45.50	OK
	B1cor	171.15	75.72	OK	258.75	56.89	OK
	B2cor	81.60	61.98	OK	207.00	58.40	OK
	B3cor	37.15	39.44	NOT OK	134.48	48.82	OK
5	B2	292.74	114.76	OK	310.50	74.73	OK
	B3	286.81	198.42	OK	372.60	199.49	OK
	B5	72.87	52.90	OK	134.48	27.87	OK

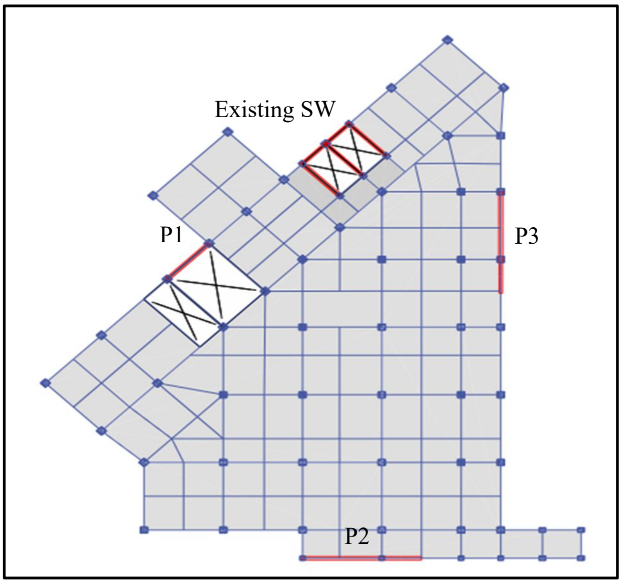

Fig. 8. Plan for shear wall placement

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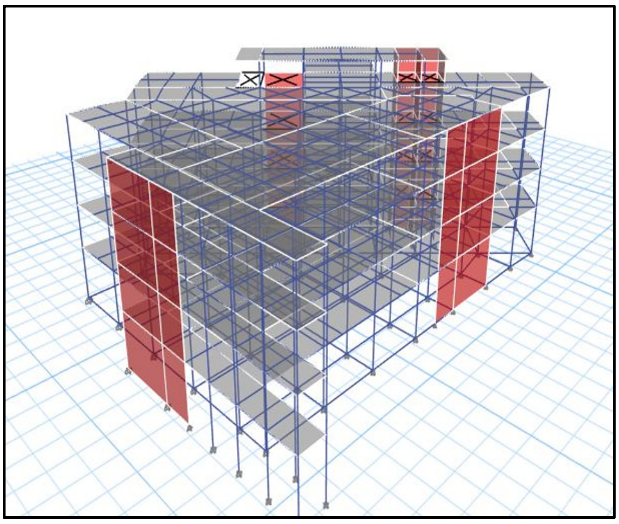

Fig. 9. 3D location of the shear wall

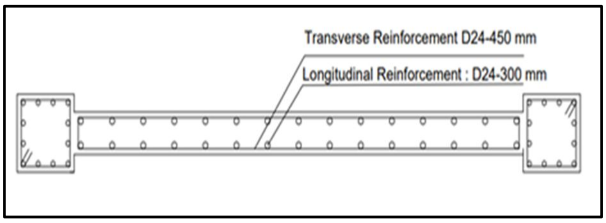

Fig. 10. Details of shear wall P1

The following are the recommended locations and details for the shear walls in the Third-Class inpatient ward at Sijunjung Regional General Hospital, as illustrated in Figs. 8-10.

The shear walls use transverse retrofitting of D24-300 and longitudinal retrofitting of D24-450 for the shear wall sections P1, P2, and P3. The shear walls, with a thickness of 300 mm, replace the existing building walls. Shear wall P1 has a length of 4.485 m, while shear walls P2 and P3 each measure 9 m [19].

3.2 Inter-story drift of the retrofitted building

Following the retrofitting with shear walls, the structural stiffness increases, leading to a reduction in inter-story drift values. The inter-story drift values post-retrofitting are presented in Table 9.

Table 9. Inter-story drift after retrofitting

Story	Inelastic Drift (mm)		Drift Limit	Δ after retrofitting < Drift Limit
	Δ max without	Δ max with		
5	99.851	20.141	25.000	OK
4	23.903	13.974	40.000	OK
3	50.538	13.790	40.000	OK
2	63.906	12.214	40.000	OK
1	68.281	8.246	50.000	OK

3.3 Structural capacity after retrofitting

3.3.1 Column capacity after retrofitting

The results of the structural capacity assessment after retrofitting with shear walls are presented in Figs. 11-13.

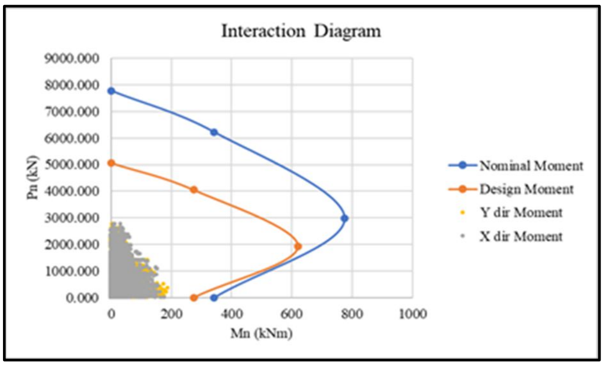

Fig. 11. P-M interaction diagram for column K1 after retrofitting

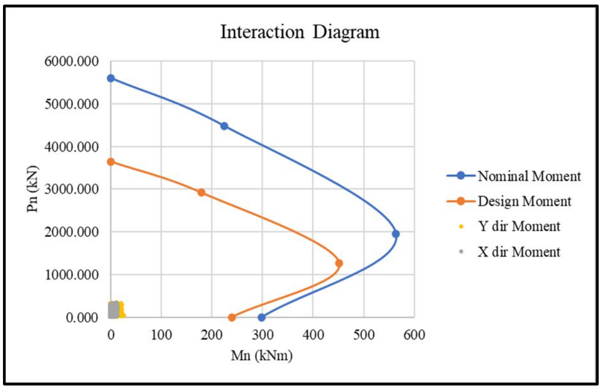

Fig. 12. P-M interaction diagram for column K2 after retrofitting

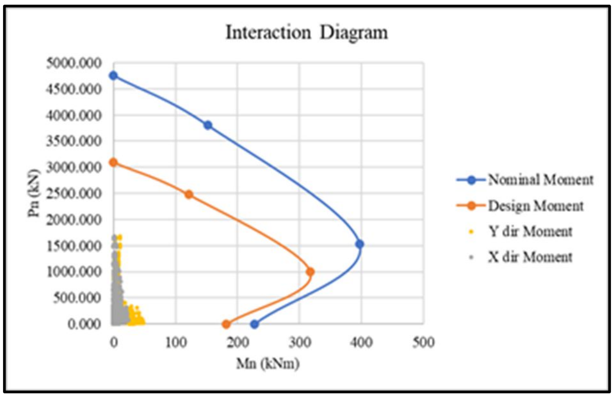

Fig. 13. P-M interaction diagram for column K3 after retrofitting

Analysis of the capacity checks in Figs. 11-13 indicate that columns K1, K2, and K3, which initially could not withstand the applied moments, exhibit enhanced strength and can support the structure following the retrofitting with shear walls.

3.3.2 Beam capacity of the retrofitted building

Table 10. Beam capacity of beams the retrofitted building

Fl	Code	ΦMn	Mu	ΦMn ≥ Mu	ΦVn	Vu	ΦVn ≥ Vu.
1	B1	350.54	222.07	OK	465.87	210.59	OK
	B2	292.74	168.07	OK	310.50	157.00	OK
	B3	286.81	123.46	OK	372.60	94.47	OK
	B4	109.91	58.01	OK	285.58	59.52	OK
	B1cor	171.15	83.59	OK	258.75	74.86	OK
	B2cor	81.60	33.71	OK	207.00	38.28	OK
	B3cor	37.15	21.10	OK	134.48	27.49	OK
2	B1	350.54	234.68	OK	465.87	253.18	OK
	B2	292.74	108.79	OK	310.50	163.67	OK
	B3	286.81	93.24	OK	372.60	106.70	OK
	B4	109.91	60.27	OK	285.58	59.67	OK
	B1cor	171.15	99.45	OK	258.75	105.59	OK
	B2cor	81.60	42.44	OK	207.00	45.72	OK
	B3cor	37.15	21.81	OK	134.48	30.89	OK
3	B1	350.54	245.34	OK	465.87	259.12	OK
	B2	292.74	196.34	OK	310.50	175.75	OK
	B3	286.81	136.11	OK	372.60	116.23	OK
	B4	109.91	61.21	OK	285.58	60.56	OK
	B1cor	171.15	116.69	OK	258.75	121.06	OK
	B2cor	81.60	45.24	OK	207.00	48.17	OK
	B3cor	37.15	24.14	OK	134.48	32.04	OK
4	B1	350.54	211.62	OK	465.87	258.14	OK
	B2	292.74	130.67	OK	310.50	115.59	OK
	B3	286.81	114.22	OK	372.60	95.56	OK
	B4	109.91	61.21	OK	285.58	45.36	OK
	B1cor	171.15	92.56	OK	258.75	86.15	OK
	B2cor	81.60	34.56	OK	207.00	35.92	OK
	B3cor	37.15	21.62	OK	134.48	23.51	OK
5	B2	292.74	108.86	OK	310.50	70.47	OK
	B3	286.81	43.02	OK	372.60	32.52	OK
	B5	72.87	35.14	OK	134.48	27.75	OK

Table 10 shows that the beams in the third-class inpatient building at Sijunjung Regional Hospital can resist the flexural and shear forces acting on the structure.

4 Development of fragility curve

Fragility curves enable engineers and decision-makers to comprehend the likelihood of different damage scenarios, which is crucial for risk assessment, emergency planning, and mitigation strategies. By identifying the most vulnerable aspects of a building, fragility curve analysis informs the implementation of retrofitting measures and enhances overall seismic resilience. This method provides a probabilistic approach to seismic risk assessment, offering a more nuanced perspective than deterministic methods, and is instrumental in improving the safety and preparedness of communities in earthquake-prone areas. The seismic vulnerability assessment can be illustrated in Fig. 14.

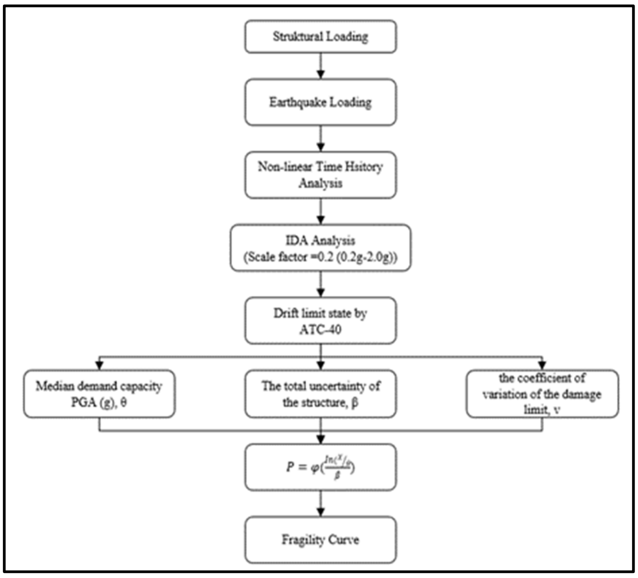

Fig. 14. Seismic vulnerability assessment flowchart

4.1 Non-linear time history analysis

In this study, non-linear time history analysis was performed using four types of earthquake data (Sijunjung Regency, Chi-Chi, Kobe, and Superstition Hills) with a scaling range of 0.2 to 2.0 and an interval of 0.2. Non-linear time history analysis is utilized as a parameter (EDP) to generate fragility curves with maximum drift values.

4.2 Incremental Dynamic Analysis (IDA)

Incremental Dynamic Analysis (IDA) is used to obtain displacements resulting from seismic loads with a scaling factor of 0.2. The structural response from the incremental dynamic analysis, in terms of displacements, can be observed for the X and Y earthquake directions, as shown in Table 11.

Table 11. Maximum displacement earthquake X and Y directions

Sf	Eq.	X dir (mm)	Y dir (mm)	Eq.	X dir (mm)	Y dir (mm)	Eq.	X dir (mm)	Y dir (mm)
0.2	Chichi	5.12	6.72	Kobe	4.27	6.66	SH	5.06	6.61
0.4	Chichi	10.24	13.43	Kobe	8.55	13.32	SH	10.13	13.22
0.6	Chichi	15.36	20.15	Kobe	12.82	19.98	SH	15.19	19.83
0.8	Chichi	20.49	26.86	Kobe	17.10	26.64	SH	20.25	26.44
1.0	Chichi	25.60	33.58	Kobe	21.37	33.30	SH	25.32	33.05
1.2	Chichi	30.72	40.29	Kobe	25.64	39.96	SH	30.38	39.66
1.4	Chichi	35.85	47.01	Kobe	29.91	46.62	SH	35.44	46.27
1.6	Chichi	40.97	53.72	Kobe	34.19	53.28	SH	40.51	52.88
1.8	Chichi	46.09	60.44	Kobe	38.46	59.94	SH	45.57	59.49
2.0	Chichi	51.21	67.15	Kobe	42.73	66.61	SH	50.63	66.10

Based on the structural analysis results using the IDA method, IDA curves are obtained with various variations according to the number of earthquake records used as seismic loads. In this study, the maximum displacement values listed in Table 11 can be used to determine the drift

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ratio (%) and intensity measure (PGA (g)) as variables for the IDA curves. Damage limits are analyzed based on ATC-40, as shown in Table 12. The IDA curves for the hospital building are illustrated in Fig. 15, and those after retrofitting are depicted in Fig. 16.

Table 12. The limit state by ATC-40

Damages States	Drift Ratio (%)
Slight	0 - 0.01
Moderate	0.01 – 0.02
Extensive	0.02 – 0.115
Complete	0.115 – 0.33

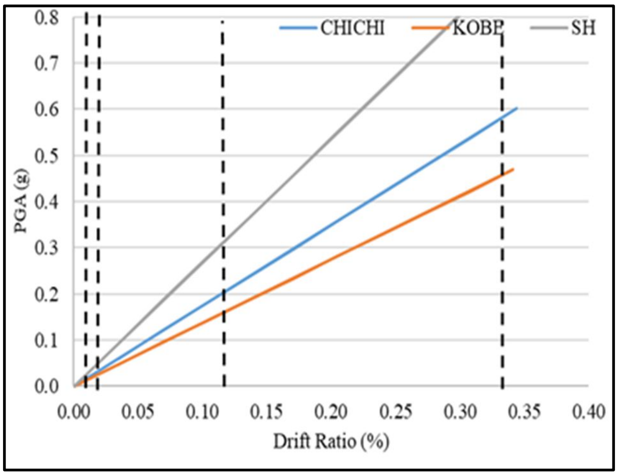

Fig. 15. Structural damage limit of the existing hospital building

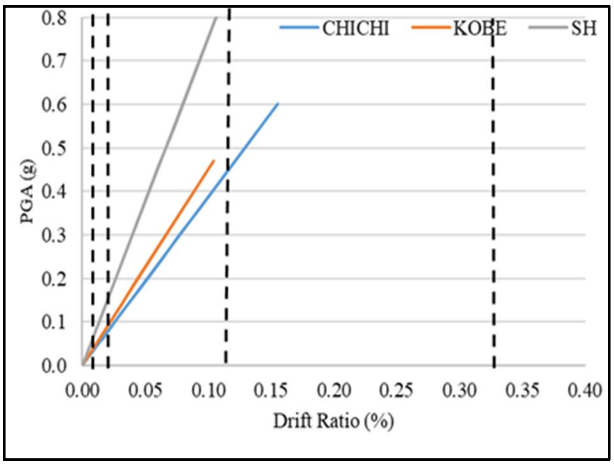

Fig. 16. Structural damage limit of the retrofitted hospital building

4.3 Seismic fragility curve

With the development of fragility curves for each building, a disaster risk map for a region is hoped to be created, providing an overview of the building fragility levels in that area.

Following the structural analysis results using the Incremental Dynamic Analysis (IDA) method, fragility curve parameters for various damage levels are obtained after retrofitting with shear walls, as shown in Tables 13 and 14. Subsequently, structural damage probabilities are determined to create seismic fragility curves, as illustrated in Figs. 17 and 18. The fragility curves show the probability of damage in percentage relative to PGA values.

Table 13. Parameter of fragility curve for an existing building

Type of Earthquake	Slight PGA (g)	Moderate PGA (g)	Extensive PGA (g)	Complete PGA (g)
CHICHI	0.030	0.058	0.351	1,006
KOBE	0.020	0.038	0.233	0.668
SH	0.029	0.055	0.334	0.959
Total	0.08	0.15	0.92	2.63
N	3	3	3	3
σ	0.006	0.011	0.064	0.183
µ	0.027	0.051	0.306	0.878
v	0.208	0.208	0.208	0.208
ϴ	0.026	0.049	0.299	0.859
b	0.206	0.206	0.206	0.206

Table 14. Parameter of fragility curve for a retrofitted building

Type of Earthquake	Slight PGA (g)	Moderate PGA (g)	Extensive PGA (g)	Complete PGA (g)
CHICHI	0.053	0.100	0.607	1,741
KOBE	0.045	0.086	0.518	1,487
SH	0.075	0.143	0.866	2,486
Total	0.17	0.33	1.99	5.71
N	3	3	3	3
σ	0.016	0.030	0.181	0.520
µ	0.058	0.110	0.664	1,904
v	0.273	0.273	0.273	0.273
ϴ	0.056	0.106	0.640	1,837
b	0.268	0.268	0.268	0.268

The seismic fragility curves illustrate the relationship between Peak Ground Acceleration (PGA) and the probability of different damage levels to the building. Derived from the building's exposure scale estimation, the fragility curves are depicted as continuous line curves, with line colors representing the damage levels due to earthquakes. The red line indicates the PGA values at the building location.

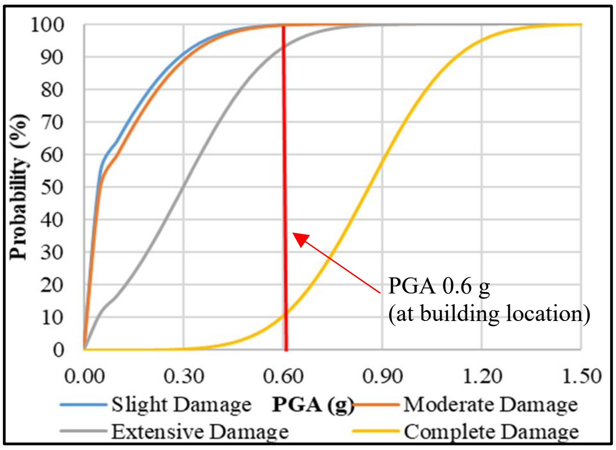

Fig. 17. Seismic fragility curves of the existing hospital building

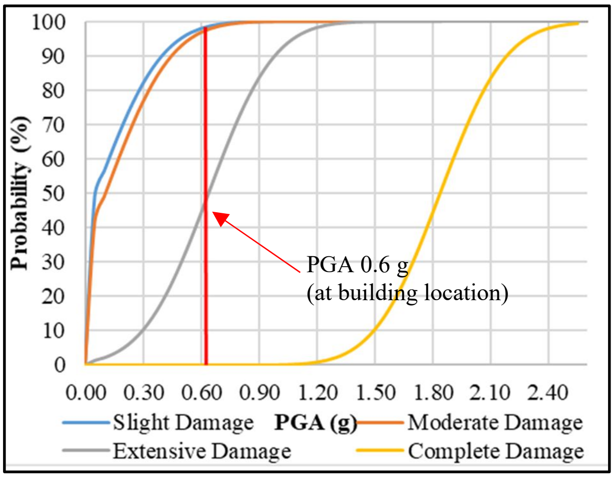

Fig. 18. Seismic fragility curves of the retrofitted hospital building

Fig. 17 shows that the building has a 100% probability of slight damage, a 100% probability of moderate damage, a 93% probability of extensive damage, and a 10% probability of collapse at a PGA of 0.60 g. After retrofitting, the probabilities of damage are reduced to 98% for slight damage, 97% for moderate damage, 44% for extensive damage, and 0% for the probability of collapse, as illustrated in Fig. 18.

5 Conclusion

Seismic vulnerability assessment of a hospital building with and without retrofitting using Reinforced Concrete (RC) shear walls indicates that the inter-story drift values of the structure exceed the drift limit. Furthermore, it was found that the column and beam elements are unable to support the loads applied to the structure based on seismic regulations (SNI 1726:2019), reinforced concrete structure regulations (SNI 2847:2019), and minimum load regulations (SNI 1727:2020). Therefore, the structure requires retrofitting with shear walls, using longitudinal retrofitting D24-300 mm and transverse retrofitting D24-450 mm, to withstand the forces acting on the structure.

The retrofitted building shows an increase in its structural capacity. The inter-story drift and the strength of the structural elements have met the requirements based on the current building codes, so this building is safe for hospital operations. The vulnerability analysis results indicated that retrofitting the hospital building with shear walls reduces the probability of building damage due to earthquake loads by 52.69% at the level of extensive damage at a PGA of 0.60 g (based on the Indonesian Seismic Map).

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