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Structural Capacity and Seismic Responses Evaluation of Low-Rise Buildings by Implementing Building Information Modeling (BIM) Framework

Amanda Lumondang, Erik Wahyu Pradana*, Senot Sangadji

Department of Civil Engineering, Faculty of Engineering, Universitas Sebelas Maret, Surakarta, Indonesia

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ABSTRACT

Building Information Modeling (BIM) has been widely applied in structural design and construction management. However, BIM implementation in evaluating existing structures has not been widely adopted. Thus, BIM was implemented in this study to evaluate the structural capacity and seismic responses of low-rise buildings due to earthquake loads. The case study was conducted on the Pakubuwono X Mosque building, designed in 2017 based on SNI 2847:2013, SNI 1726:2012, and SNI 1727:2013. This research was carried out numerically by involving the interconnection of Autodesk Revit and Autodesk Robot SAP software, which worked within the BIM framework. The structural model of the Pakubuwono X Mosque building was developed using Autodesk Revit, which was connected to Autodesk Robot SAP for analysis and structural design processes. Furthermore, the design products of Autodesk Robot SAP are reconnected with Autodesk Revit to be integrated with architectural and MEP (mechanical, electrical, and plumbing) design products. In this study, the structural capacity evaluation was carried out on the floor slabs, beams, and columns. Furthermore, the seismic response in the form of modal participation mass ratio, fundamental period, base shear, and story drift are also reviewed in this study. In conclusion, all structural elements (floor slabs, beams, and columns) are adequate to support the design load, as indicated by the demand-capacity ratio (D/C Ratio), which is less than 1.0. Furthermore, all parameters of seismic response reviewed in this research comply with the requirements set out in SNI 1726:2012.

1. Introduction

Digital construction promotes the digital technologies utilization in construction work execution in order to increase productivity and provide higher-quality results [20]. In the last decade, the development of digital construction has been shown by the increasing Building Information Modeling (BIM) implementation. Currently, the implementation of BIM in the construction industry is also being carried out by many countries worldwide. One of the reasons is BIM promises work efficiency and various other benefits [1].

Many other countries have carried out studies related to BIM implementation. Those studies discuss BIM implementation in construction project conceptual design [18]; [5], cost estimation [14], and optimization for environmentally friendly projects [8]; [21]. Currently, BIM is also being studied by many academics in Indonesia. Several studies have evaluated the application of BIM in the AEC (architecture, engineering, and construction) industry in Indonesia and concluded that the application of BIM in Indonesia is still in the development phase [1]. Furthermore, most stakeholders involved in construction projects in Indonesia (project owners, planning consultants, supervisory consultants, and contractors) have also implemented BIM in their work [9]. It demonstrates the enormous growth potential for adopting and applying BIM in Indonesia's construction industry. So far, research on the adoption and implementation of BIM in Indonesia has been chiefly done on structural design work [15]; [16] and construction management, such as calculating the volume

*Corresponsding author.
E-mail: erikwpradana@staff.uns.ac.id

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of materials [7]; [17], project scheduling [6]; [11]; [19], and construction cost estimation [10]; [12]. However, there has not been much BIM implementation in evaluating existing structures. Thus, BIM was implemented in this study to evaluate the structural capacity and seismic responses of low-rise buildings due to earthquake loads. The case study was conducted on the Pakubuwono X Mosque building, designed in 2017 based on: (a) SNI 1726:2012 "Tata Cara Perencanaan Ketahanan Gempa untuk Struktur Bangunan Gedung dan Non Gedung [2], (b) SNI 1727:2013 "Beban Minimum untuk Perancangan Bangunan Gedung dan Struktur Lain" [3], and (c) SNI 2847:2013 "Persyaratan Beton Struktural untuk Bangunan Gedung" [4].

2. Method

This research was carried out numerically by involving the interconnection of Autodesk Revit and Autodesk Robot SAP software, which worked within the BIM framework. The structural model of the Pakubuwono X Mosque building was developed using Autodesk Revit with a design load as presented in Table 1. The material properties used in the structural model include: (i) the compressive strength of concrete is taken as 30 MPa, (ii) the yield stress of reinforcing steel with a diameter of less or equal to 12 mm and more than 12 mm is taken as 280 MPa and 420 MPa, respectively. Furthermore, the structural model developed using Autodesk Revit is connected to Autodesk Robot SAP for analysis and structural design processes. Lastly, the design products of Autodesk Robot SAP are reconnected with Autodesk Revit to be integrated with architectural and MEP (mechanical, electrical, and plumbing) design products.

In this study, the structural capacity evaluation was carried out on the floor slabs, beams, and columns. Furthermore, the seismic response in the form of modal participation mass ratio, fundamental period, base shear, and story drift are also reviewed in this study. Suppose the structure is adequate to resist the loads or internal forces with a demand-capacity ratio (D/C ratio) of less than or equal to one. In that case, the capacity evaluation results can be deemed safe [13]. The demand-capacity ratio (D/C ratio) shows the relationship between the internal forces resulting from the ultimate load combination and the structural element capacity. Furthermore, the seismic response in the form of modal participation mass ratio, fundamental period, base shear, and story drift are also reviewed in this study based on the SNI 1726:2012 [2].

3. Results

3.1 Interconnection of Autodesk Revit with Autodesk Robot SAP

The structural model was developed by implementing the interconnection of Autodesk Revit and Autodesk Robot SAP software. The structural model developed by using Autodesk Revit can be seen in Figure 1. Furthermore, the structural model that was connected to Autodesk Robot SAP can be seen in Figure 2.

3.2 Seismic Response Evaluation

Modal Participation Mass Ratio

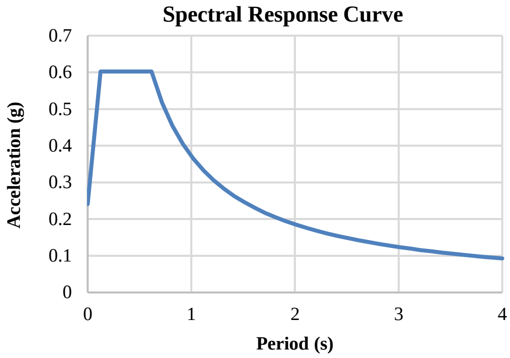
Modal participation mass ratio was obtained from the analysis of vibration modes by using Autodesk Robot SAP involving seven vibration modes. It can be concluded that the modal participation mass ratio in the X and Y directions for seven vibration modes is 90.9762% and 90.8286%, respectively. It has complied with the minimum requirements set out in SNI 1726:2012, which is not less than 90% (as shown in Table 2).

Fundamental Period

Based on the vibration modes obtained from Autodesk Robot SAP, the fundamental period of the structural model (T_c) is 0.4976 seconds for the X direction and 0.4934 seconds for the Y direction. The value of T_c is then compared with the values of T_a and $C_u.T_a$ according to the provisions stipulated in SNI 1726:2012. The value of T_a is 0.9785 seconds and $C_u.T_a$ is 1.3699 seconds. Since the value of T_c, both in the X direction and in the Y direction, is less than the value of T_a, it can be concluded that the fundamental period of the structure (T) used is equal to T_a, which is 0.9785 seconds.

Table 1. Design Load

1. Gravity Load		**2. Earthquake Load (Spectral Response)**
1.1 Self-weight		S_{DS} = 0.602 s S_{D1} = 0.372 s
Automatically calculated by Autodesk Robot SAP		
1.2 Superimposed Dead Load on Floor Slab		
Sand	= 0.80 kN/m^2	
Mortar	= 0.66 kN/m^2	
Ceramics	= 0.24 kN/m^2	
Ceiling and hangers	= 0.20 kN/m^2	
MEP installation	= 0.25 kN/m^2	
Total Superimposed Dead Load on Floor Slab	= 2.15 kN/m^2	
1.3 Superimposed Dead Load on Beam		
Wall	= 7.50 kN/m	
1.3 Live Load		
Public Area	= 4.79 kN/m^2	



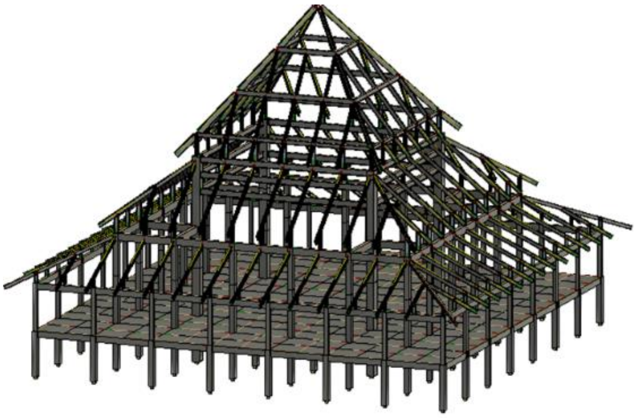


Figure 1. 3D Structural Model on Autodesk Revit

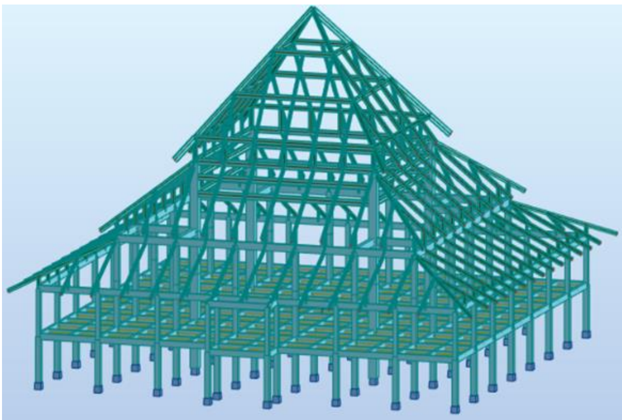


Figure 2. 3D Structural Model on Autodesk Robot SAP

Table 2. Modal Participation Mass Ratio

Mode	Frequency (Hz)	Period (s)	*UX* (%)	*UY* (%)	*UZ* (%)
1	2.0095	0.4976	37.5811	17.9982	0.0001
2	2.0268	0.4934	56.2652	56.1630	0.0001
3	2.1101	0.4739	56.9521	56.1657	0.0001
4	3.1084	0.3217	56.9523	56.1662	0.0001
5	3.4208	0.2923	57.0973	56.1669	0.0001
6	3.4750	0.2878	72.8740	70.7337	0.0058
7	3.6025	0.2776	90.9762	90.8286	0.0060

Base Shear

Based on the structural analysis conducted by Autodesk Robot SAP, the base shear of the structure due to earthquake load (spectral response) for the X and Y axis was obtained at 2520.28 kN and 2511.42 kN, respectively. Furthermore, the base shear of the structure due to earthquake load (equivalent lateral forces) for both the X and Y axis obtained at 2390.76 kN. So it is concluded that the scale factor does not need to be enlarged.

Story Drift

Story drift is the lateral displacement of a floor with respect to the floor below, and story drift ratio is story height divided by story drift. Story drift was evaluated in accordance with Clause 7.8.6 SNI 1726:2012. It can be concluded that the story drifts in the X and Y axis comply with the requirements set out in SNI 1726:2012, where the story drift on both axes is less than the allowable story drift (see Figure 3 and Table 3).

3.3 Structure Capacity Evaluation

Evaluation of Floor Slabs Structural Capacity

The floor slab is designed using reinforced concrete material with a thickness of 150 mm. The main reinforcement design uses P12-150 with P12-200 shrinkage reinforcement. The structural capacity evaluation results of the floor slab structure indicate that the slabs are adequate to support the design load. It is stated by the demand-capacity ratio (D/C Ratio), which is less than 1.0 (see Table 4).

Evaluation of Main Beams Structural Capacity

The column-to-column connecting beam is known as the main beam. Structural capacity evaluation of the main beam structure is carried out at B1-300x600 and B5-400x700. Furthermore, the details of longitudinal and transverse reinforcement for each type of the main beam are presented in Figure 4.

The structural capacity evaluation results of the main beam structure show that B1-300x600 and B5-400x700 are adequate to support the design load. It is stated by the demand-capacity ratio (D/C Ratio), which is less than 1.0 (see Table 5 and Table 6).

Evaluation of Secondary Beams Structural Capacity

Structural capacity evaluation of the secondary beams structure is carried out at B2-300x500 and B3-250x400. Furthermore, the details of the longitudinal and transverse reinforcement for each type of secondary beam are presented in Figure 4. In conclusion, the structural capacity evaluation results of the secondary beam structure show that B2-300x500 and B3-250x400 are adequate to support the design load. It is stated by the demand-capacity ratio (D/C Ratio), which is less than 1.0 (see Table 7 and Table 8).

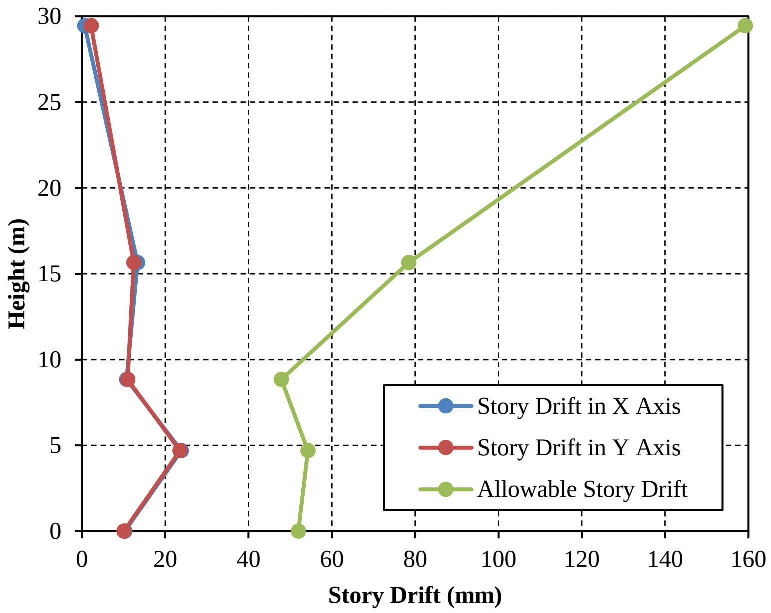


Figure 3. Story Drift in X and Y Axis Compared to Allowable Story Drift

Table 3. Story Drift Evaluation Results

Story	*X*-Axis Deviation	*Y*-Axis Deviation	*X*-Axis Story Drift	*Y*-Axis Story Drift	Allowable Story Drift	Check: *X*-Axis	Check: *Y*-Axis
Hall	0.00	0.00	0.00	0.00	0.00	OK	OK
Ground Floor	2.79	2.75	10.25	10.08	51.92	OK	OK
Emper Roof	9.30	9.17	23.87	23.54	54.23	OK	OK
Pananggap Roof	12.23	12.17	10.74	11.01	47.88	OK	OK
Brunjung Roof	15.88	15.57	13.38	12.47	78.46	OK	OK
Roof Top	16.06	16.17	0.68	2.20	159.23	OK	OK

Table 4. Moment Capacity Calculation of Floor Slabs

Position	Ultimate Moment (M_u) (kNm)	Moment Capacity (ϕMn) (kNm)	D/C Ratio
X-Direction (Mid Span Reinforcement)	14.93	20.49	0.73
X-Direction (Near Support Reinforcement)	7.63	20.49	0.37
Y-Direction (Mid Span Reinforcement)	16.45	18.21	0.90
Y-Direction (Near Support Reinforcement)	8.57	18.21	0.47

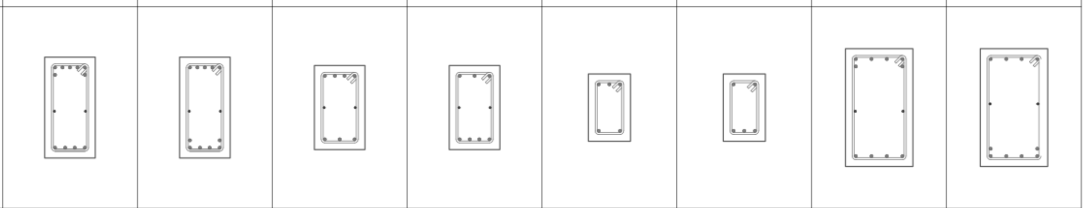
CODE	B1		B2		B3		B5	
POSITION	NEAR SUPPORT	MID SPAN	NEAR SUPPORT	MID SPAN	NEAR SUPPORT	MID SPAN	NEAR SUPPORT	MID SPAN
SECTION								
DIMENSION	300x600	300x600	300x500	300x500	250x400	250x400	400x700	400x700
UPPER REINFORCEMENT	7D19	5D19	4D19	3D19	3D19	2D19	6D19	4D19
BOTTOM REINFORCEMENT	4D19	6D19	3D19	4D19	2D19	3D19	4D19	6D19
MIDDLE REINFORCEMENT	2P12	2P12	2P12	2P12	-	-	2P12	2P12
TRANVERSAL REINFORCEMENT (MM)	2P12-100 0.25L	2P12-150 Rest	2P12-100 0.25L	2P12-150 Rest	2P12-100 0.25L	2P12-150 Rest	2P12-100 0.25L	2P12-150 Rest

Figure 4. Main Beam and Secondary Beam Reinforcement Design

Table 5. Moment Capacity Calculation of Main Beams

Beam	Position	Ultimate Moment (*Mu*) (kNm)	Moment Capacity (ϕMn) (kNm)	D/C Ratio
Beam B1	Upper Near Support	301.05	353.69	0.85
	Lower Near Support	108.11	212.12	0.51
	Upper Mid Span	133.09	260.98	0.51
	Lower Mid Span	216.54	308.17	0.70
Beam B5	Upper Near Support	260.22	388.06	0.67
	Lower Near Support	211.14	263.71	0.80
	Upper Mid Span	122.98	263.71	0.47
	Lower Mid Span	130.86	388.06	0.34

Table 6. Shear Capacity Calculation of Main Beams

Beam	Position	Ultimate Shear Force (V_u) (kN)	Concrete Shear Resistance (V_c) (kN)	Steel Shear Resistance (V_s) (kN)	Shear Capacity (ϕV_n) (kN)	Check: Shear Capacity	D/C Ratio
Beam B1	Near Support	304.19	146.91	333.10	360.01	OK	0.84
	Mid Span	180.09	146.91	222.06	276.73	OK	0.65
Beam B5	Near Support	193.31	0	404.39	303.29	OK	0.64
	Mid Span	91.97	237.81	269.59	380.55	OK	0.24

Table 7. Moment Capacity Calculation of Secondary Beams

Beam	Position	Ultimate Moment (*Mu*) (kNm)	Moment Capacity (ϕ*Mn*) (kNm)	D/C Ratio
Beam B2	Upper Near Support	99.36	174.64	0.57
	Lower Near Support	53.71	133.48	0.40
	Upper Mid Span	16.45	133.48	0.12
	Lower Mid Span	79.50	174.64	0.46
Beam B3	Upper Near Support	63.06	99.83	0.63
	Lower Near Support	42.16	68.55	0.62
	Upper Mid Span	14.52	68.55	0.21
	Lower Mid Span	42.16	99.83	0.42

Table 8. Shear Capacity Calculation of Secondary Beams

Beam	Position	Ultimate Shear Force (V_u) (kN)	Concrete Shear Resistance (V_c) (kN)	Steel Shear Resistance (V_s) (kN)	Shear Capacity (ϕV_n) (kN)	Shear Capacity Check	D/C Ratio
Beam B2	Near Support	103.03	122.49	277.72	300.16	OK	0.34
	Mid Span	79.56	122.49	185.15	230.73	OK	0.34
Beam B3	Near Support	71.03	78.80	214.39	219.89	OK	0.32
	Mid Span	55.78	78.80	142.93	166.29	OK	0.34

Evaluation of Column Structure Capacity

Capacity evaluation of the column structure is carried out at K1-800x800, K2-500x500, and K3-400x400. Furthermore, details of longitudinal and transverse reinforcement for each column type are presented in Figure 5. The evaluation of the column structure capacity results shows that K1-800x800, K2-500x500, and K3-400x400 can support the design load. It is evidenced by the fact that all combinations of axial force and ultimate moment are within the column axial-moment interaction curve and that the shear capacity is not less than the ultimate shear force that must be supported (see Figure 6 and Table 10). Furthermore, the K1-800x800, K2-500x500, and K3-400x400 column designs have also met the strong column weak beam requirements (see Table 9).

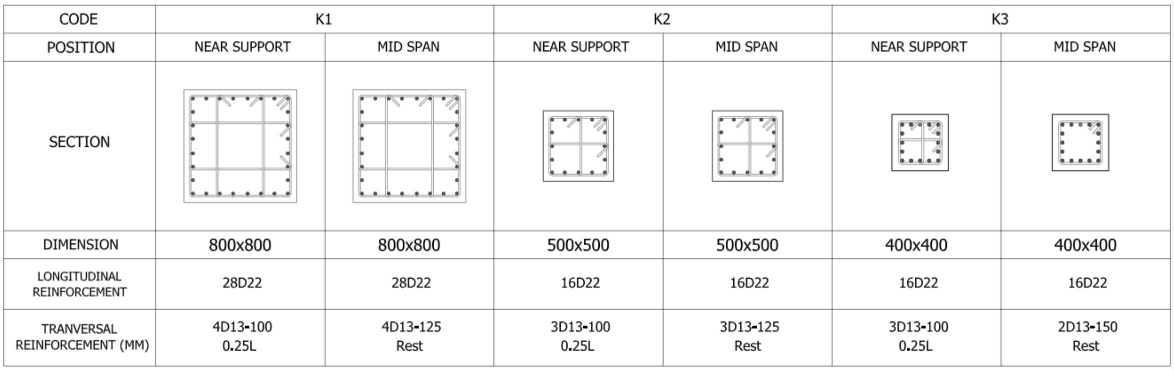
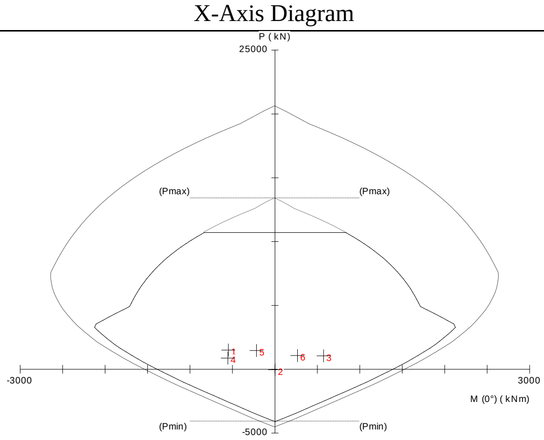
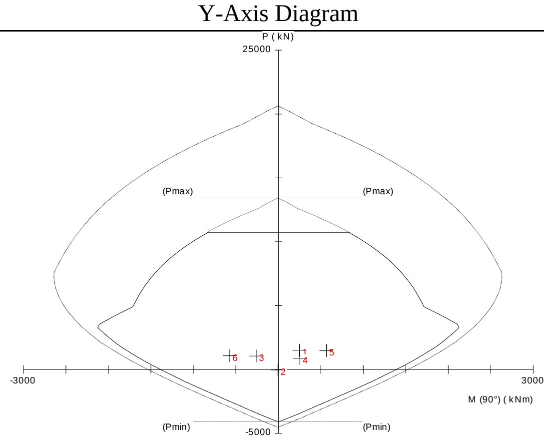


Figure 5. Column Reinforcement Design

Column	X-Axis Diagram	Y-Axis Diagram
Column K1		

Column K2

Column K3

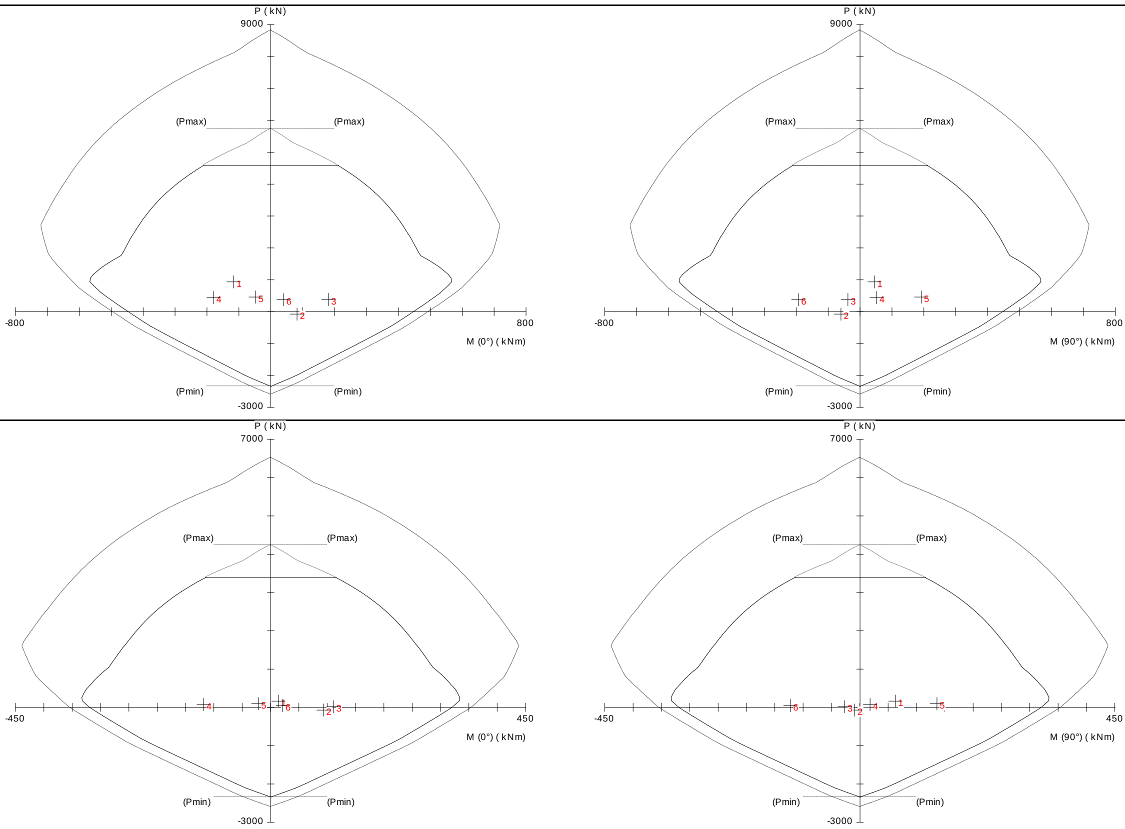


Figure 6. Column Axial-Moment Interaction Diagram

Table 9. Strong Column Weak Beam Evaluation

Column	Mnc_1 (kNm)	Mnc_2 (kNm)	Mn^- (kNm)	Mn^+ (kNm)	SCWB Requirements Check
K1	1541.14	1541.14	431.18	431.18	OK
K2	496.60	496.60	392.99	235.69	OK
K3	354.96	496.60	392.99	235.69	OK

Table 10. Shear Capacity Calculation of Columns

Column	Position	Shear Reinforcement Spacing (mm)	Check: Maximum Spacing	Ash/s	Check: Required Ash/s	Av/s	Check: Required Av/s
Column K1	Strong Axis Near Support	100	OK	5.31	OK	5.31	OK
	Weak Axis Near Support	100	OK	5.31	OK	5.31	OK
	Strong Axis Mid Span	125	OK	-	-	4.25	OK
	Weak Axis Mid Span	125	OK	-	-	4.25	OK
Column K2	Strong Axis Near Support	100	OK	3.98	OK	3.98	OK
	Weak Axis Near Support	100	OK	3.98	OK	3.98	OK
	Strong Axis Mid Span	125	OK	-	-	3.19	OK
	Weak Axis Mid Span	125	OK	-	-	3.19	OK
Column K3	Strong Axis Near Support	100	OK	3.98	OK	3.98	OK
	Weak Axis Near Support	100	OK	3.98	OK	3.98	OK
	Strong Axis Mid Span	150	OK	-	-	2.12	OK
	Weak Axis Mid Span	150	OK	-	-	2.12	OK

4. Conclusion

Capacity evaluation and structural responses of the Pakubuwono X Mosque building due to earthquake loads were carried out by implementing Building Information Modeling (BIM). This research was carried out numerically by involving the interconnection of Autodesk Revit and Autodesk Robot SAP software that worked within the BIM framework.

This study evaluated the structural capacity of the structural elements of floor slabs, beams, and columns. Furthermore, structural responses due to earthquake loads in the form of modal participation mass ratio, fundamental period, base shear, and story drift are also reviewed in this study.

In conclusion, from this study, all structural elements of floor slabs, beams, and columns can support the design load as indicated by the demand-capacity ratio (D/C Ratio), which is less than 1.0. Furthermore, all seismic response parameters under review (modal participation mass ratio, fundamental period, base shear, and story drift) have complied with the requirements in SNI 1726:2012.

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