Capacity-Based Seismic Design of a Middle-Rise Residential Building in an Area of Moderately-high Seismicity

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Abstract. As Indonesia is located across three active tectonic plates, it is prone to a high potential earthquake threat. Strict regulations have been introduced to prevent damage to buildings caused by seismic activity. This study aims to examine the behavior of a middle-rise residential building in a moderately-high seismicity area (i.e. Semarang City) and the design of the Reinforced Concrete (RC) members under seismic load. The design was based on the capacity method and the strong column-weak beam concept was applied to the plastic hinge effect that occurred in the beam. Therefore, the analytical computation was performed, taking the structural seismic response into account. Also, the code-based design calculation of RC members was achieved. The measured structural response showed that the building fulfilled the requirements stated in the Indonesia Code of Earthquake-based Design. The first two modes of the building translated in the Y and X directions, which is the preferred response under the earthquake. The story-drifts that occurred were within the acceptable limits and the structural stiffness in the X and Y directions were found to be similar. Finally, the exact design of RC members was found to satisfy the code.

1. Introduction

Indonesia is vulnerable to high potential earthquake hazards because it is situated across three active tectonic plates [1–5]. Recent seismic activities in Indonesia have lead to excessive damage to structures and caused loss of life. In order to prevent this damage, strict regulations are contantly being reviewed and altered to meet the current conditions [6]. Large earthquakes have hit Indonesia many times in recent decades [7–9]. The seismic forces exerted on high buildings will have more complex effects than those seen in low-rise buildings, as many structural elements may have been damaged and weakened [10]. Consequently, the strength and capacity of the higher buildings under seismic loading need to be more carefully observed and calculated.

Many structures are designed on stiffness and strength criteria, with the stiffness being attributed to the serviceability limit state, which maintains the displacements under the loading impact and keeps them within the acceptable limit. However, strength is related to the ultimate limit state and assumes that the forces in the structure, due to loading, remain in the elastic range [11]. By using the capacity design method, the flexural capacity of critical member sections, based on hypothetical behavior under seismic load, can be achieved. This is expressed in the assumption that the static equivalent of seismic load increases slowly until the near-collapse state of the building is reached and the object still remains elastic. Also, the plastic hinges effects are expected to occur simultaneously at the predetermined locations (assumed to be located at the end of the beam), to process the strong column-weak beam mechanism. Finally, the ductile behavior mechanism can be formed and the structure can possess an acceptable seismic resistance.

Numerous researchers have studied the capacity-design method on buildings to obtain the resistant design of the structures [12–16]. However, studies on the more complex conditions of the structural model should be considered to enrich the understanding of the seismic loading effects on Reinforced Concrete (RC) buildings. Hence, this study addresses the structural behavior of middle-rise residential buildings located in moderately-high seismicity (i.e. Semarang City) and soft soil conditions. Also, the structural design of the RC members under earthquake loading can be calculated based on the capacity design method. Numerical simulation, using ETABS software, was performed to develop a model of the RC building. The code-based design calculation was also achieved and depends on the structural model, which takes the suitable structural behavior under seismic conditions into account.

2. Numerical simulation

The numerical model in this research is taken from a residential RC building with 17 stories and the special moment frame system. The total height of the building is 51 metres, with an area of 28 x 60 m in the X and Y direction, respectively. From the car parking spaces on the basement floor up to the third floor, the floor composition becomes half-floors to account for the movement of the cars into the parking spaces. The base of the actual building is not at the same level, some structures are lower than others. This may cause the center of mass to not be the same as the center of stiffness, which may result in rotation behavior. The soil condition is assumed to be soft, which is likely to create significant site amplification effects during the earthquake events [17] and can increase the inter-story drifts and lateral deflections in mid-rise buildings [18].

The analytical solution was carried out with the appropriate finite elements model created in the ETABS simulation program. The building was designed with the beam-slab option, which accounts for the RC columns, beams, slabs, and shear walls in the three-dimensional analysis. Linear models considering elastic behavior are used for structural development. The models are comprised of frame and shell elements to represent structural components. The lateral stability of the building can be achieved by the dual system, combining the special moment frame system and the RC shear walls. The concrete's compressive strength and the yield strength of the reinforcement are recorded as 25 MPa and 400 MPa, respectively. Thus, all ordinary RC beam members are modeled as frame elements, however, the shear walls are modeled as linear, thin shell elements. The seismic loads absorbed in the building were expected to be accommodated by the combined system.

The additional dead load and live load applied in the model is based on the Indonesian Standard Code for Loading in the Building, with the values for apartment buildings being 125 kg/m^2 and 250 kg/m^2, respectively. However, the input for the earthquake load analysis used the dynamic spectrum response method, applied to the moderately-high seismicity area in Semarang City with a damping value of 5%. To simulate the expected arbitrary earthquake loading, the seismic loading influence on the major effective direction of 100% is assumed to be occurring at the same time as the effect of only 30% effective loading, perpendicular to the main direction [19]. The plastic hinge effect, expected to occur at the end of the beam to account for the method of the strong column with the weak beam, and the structural components can display ductile behavior. Figure 1(a) to 1(c) depict the structural model for the mid-rise residential building, in terms of the structural plan layout, side view, and three-dimensional isometry, respectively.

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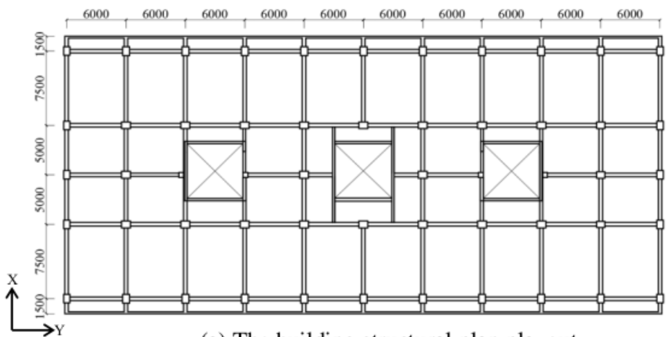
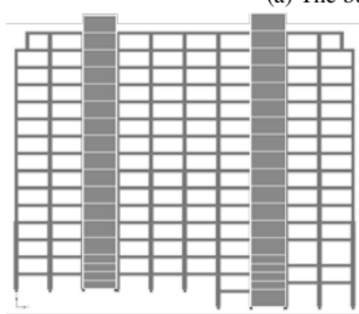
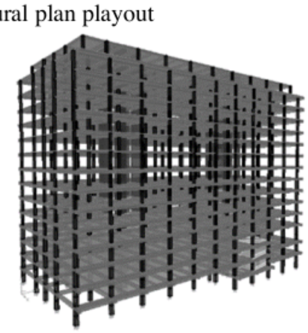


(a) The building structural plan playout



(b) The side view of the building



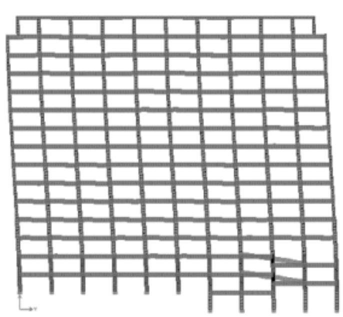
(c) The 3D isometry of the building

Figure 1. The structural model for the residential building.

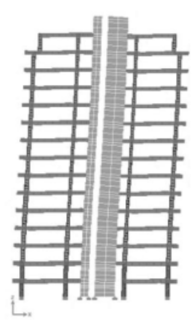
3. Overall response evaluation

3.1. Modal analysis

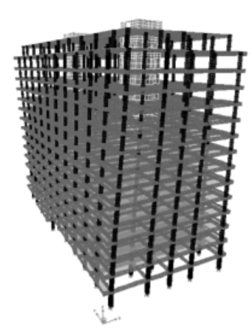
The mode shapes of the building are shown in Figure 2. Thus, the natural periods and modal participating mass ratios of the first ten modes are shown in Table 1.



(a) Translation in Y direction, with $T_{1(cracked)}$ = 1.225 s



(b) Translation in X direction, with $T_{2(cracked)}$ = 1.2 s



(c) Torsion, with $T_{3(cracked)}$ = 1.12 s

Figure 2. Mode shapes and natural period of the residential building.

Modal analysis was performed to determine the vibration modes of a building. A combination of mass, from 100% of dead load and superimposed dead load plus 30% of the live load, is considered in modal analysis. The first two modes of the building translated in the Y and X directions, respectively, gave the preferred response under earthquake loading. Furthermore, the rotation behavior appears in the third mode, as presented from the tiny value of the participating mass with no dominant value for the X and Y direction. Approximately 66.91% of the total mass was determined to be participating in the first translation modes, showing that the higher modes were significant in the seismic response. Sufficient numbers of modes are considered so that more than 90% of the mass is participating in a total participating mass ratio in each orthogonal direction.

Table 1. Mass participation ratio for the structural building model.

Mode	Period (s)	Modal mass participation ratio			
		Y (%)	X (%)	Cumulative Y (%)	Cumulative X (%)
1	1.225	0.017	0.669	0.017	0.669
2	1.200	0.648	0.024	0.665	0.693
3	1.120	0.058	0.006	0.724	0.699
4	0.352	0.136	0.002	0.860	0.701
5	0.339	0.013	0.018	0.873	0.720
6	0.330	0.000	0.140	0.873	0.861
7	0.178	0.040	0.000	0.914	0.861
8	0.175	0.007	0.000	0.921	0.862
9	0.157	0.001	0.056	0.922	0.918
10	0.116	0.002	0.001	0.924	0.919

3.2. Base shear

The elastic seismic base shear above ground level, resulting from static lateral force procedure, and response spectrum analysis, with an R-value as the modification coefficient, are summarized in Table 2. It was mentioned in the Indonesian Standard Code of Earthquake-resistant Design [20] that the comparison value between the dynamic and static procedures for base shear force is over 85%.

Table 2. The ratio of base shear force above ground level.

Base shear	Equivalent static (V)	Dynamic response (V_t)	Ratio (V_t/V)
F_x (kN)	18351.55	19116.11	1.04
F_y (kN)	18720.55	19500.48	1.04

The calculated results show that the value of the comparison between the static and dynamic base shear meets the requirements in the code, which was found to have been exceeded by 85%. This means that the magnification of earthquake forces is not required. It can also be seen from Table 2 that the distribution of base shear in a residential building shows results that are not much different for the X and Y direction. This means that the seismic effects on the building are almost the same in both directions, regarding the base shear force.

3.3. Story drifts

Story drifts, due to earthquake loading along the height, are plotted in Figure 3 and it was checked whether the drifts were within the acceptable limits or not. The requirements stated in the Indonesian Code [20] can be stated as equation (1). The symbol of ρ stands for the redundancy factor which should be obtained from several preconditions mentioned in the standard code and the value of ρ in this work can be taken as 1.3. Thus, the height of the floor below the corresponding story was signified by the h_{sx} notation.

$$\Delta_i < \left(0.02h_{sx}\right)/\rho \tag{1}$$

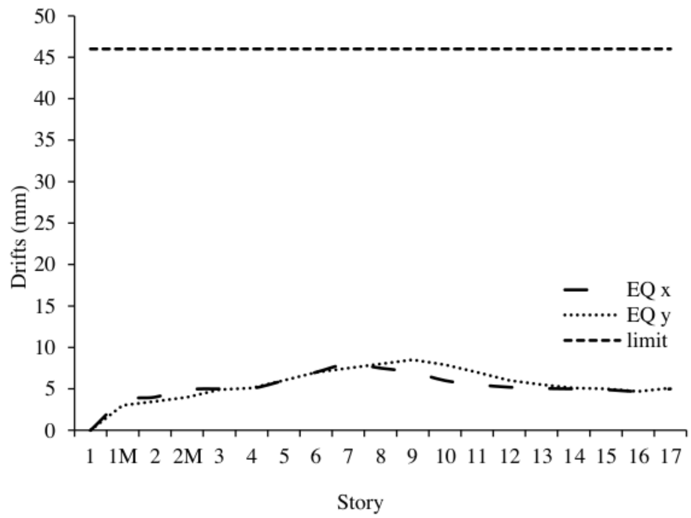


Figure 3. The story drifts in the X and Y direction due to seismic loading.

Figure 3 shows that the story drifts are within the acceptable limit, which is 2% under seismic loading. The maximum calculated story drifts in the X and Y directions are 8.34 mm and 8.67 mm, respectively. This is still below the acceptable limit of 46.15 mm, as calculated with equation (1).

4. Structural design

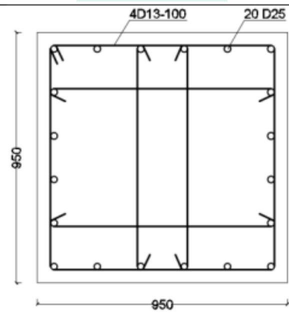
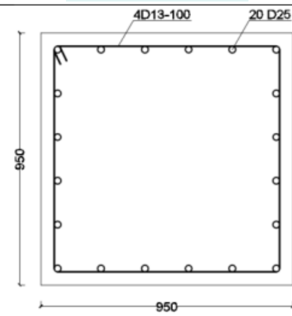
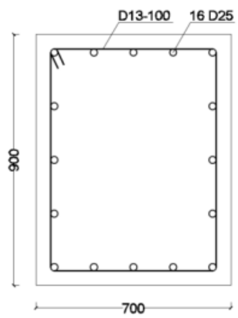
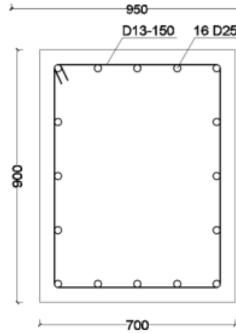
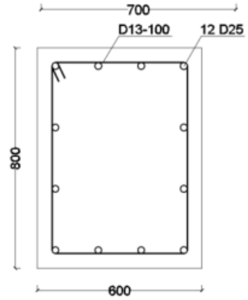
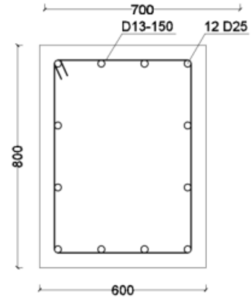
4.1. RC columns

Theoretically, the minimum value of the axial force acting on the columns should be more than 10% of the column's sectional area multiplied by the compressive strength of the concrete. The columns will transfer the combination of the axial force from the gravity load and the seismic force and also the flexural force from the beams to the foundations. The total area of longitudinal reinforcement obtained in the column is limited to between 1% and 4% by comparing the area of the column itself. The shear reinforcement calculation is based on equation (2), along with the total shear force, the moment acting on the top and bottom of the column, the clear span, the strength reduction factor, and the shear force contributed by the steel and the concrete are symbolized by V_u, M, l_n, $Ø$, V_s, and V_c, respectively.

$$V_u = \frac{M_{top} + M_{bot}}{l_n} \text{ and } V_s = \frac{V_u}{\phi} - V_c \tag{2}$$

Furthermore, in order to model the behavior of the columns, some control calculations need to be conducted, including the slenderness ratio, the bi-axial flexural check and a comparison between the flexural strength of the column and the beams. The calculation of the axial-flexural interaction diagram can then be evaluated and checked against their force demands. Table 3 outlines the reinforcements detail of the columns used in the RC building; three types of columns were considered in the design.

Table 3. The cross-section and reinforcement details of the RC columns (unit: mm).

Beam type	On the end side	On the middle side
C1 950x950		
C2 700x900		
C3 600x800		

4.2. RC beams

The reinforcement embedded in the RC beams is needed to resist stresses under the combination of gravity loading and earthquake forces. As the assumed placement of the plastic hinges is at the end of the beams, the beam ends should counter the positive and negative moments. Consequently, the use of the double reinforced section on the top and bottom of the beam is considered.

The calculation of the flexural reinforcement needed is based on the stress-strain diagram shown in Figure 4. The method adopted requires the steel in compression to be calculated, along with the compression zone of the concrete and the tensile reinforcement, see equation (3) and (4). The letter code symbolized the concrete's compressive strength, the yield strength of the reinforcement, the elastic modulus of the concrete, the area of compressive steel and the tensile steel, and the steel strain for $f_c^{'}$, f_y, E, $A_s^{'}$, A_s, and ε_s respectively. The acquired area of the reinforcements should be checked to the minimum and maximum boundary area of the steel for the section. Furthermore, the control of strength and strain (and also the moment capacity) is needed to prove whether the reinforcement is in accordance with the assumptions or not.

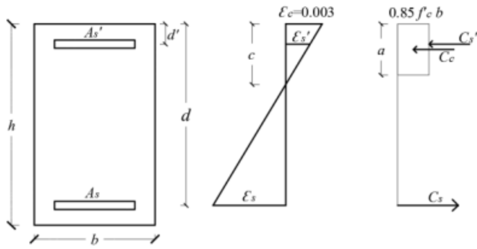


Figure 4. Stress-strain diagram for doubly reinforced beam section.

$$C_s^{'} + C_c = C_s \tag{3}$$

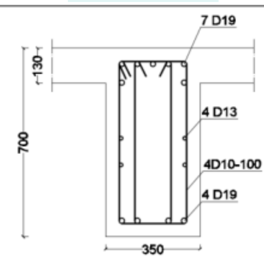
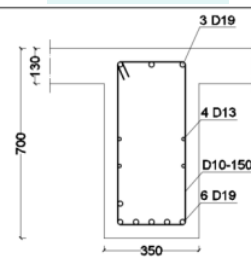
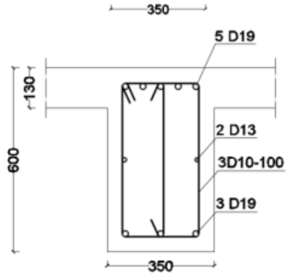
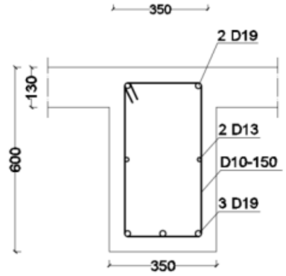
$$A_s^{'} \varepsilon_s^{'} E + 0.85 f_c^{'} ab = A_s f_y \tag{4}$$

Shear reinforcement is also needed, to prevent failure in shear and increase the ductility of the beams. The shear force of the beams can be calculated by using equation (5), where M_{pr} represents the probable moment caused by the combination of the 120% of dead load and the 100% of live load, l_n denotes the clear span of the beam, V_u for the ultimate shear force of the system, V_c stands for the concrete's shear force, and Ø denotes the strength reduction factor.

$$V_{sway} = \frac{M_{pr1} + M_{pr2}}{l_n} \pm \frac{V_u + l_n}{s} \text{ and } V_s = \frac{V_{sway}}{\phi} - V_c \tag{5}$$

Several types of primary and secondary beams were taken into account in this research. Following the design methods mentioned above, the results are summarized in Table 4, including the dimensions, flexural reinforcement and shear reinforcement of the RC beams in the building. The end-side length of the reinforcement was calculated from 25% of the clear span, located on each side of the beams.

Table 4. The cross-section and reinforcement details of the RC beams (unit: mm).

Beam type	On the end side	On the middle side
B1 350x700		
B2 350x600		

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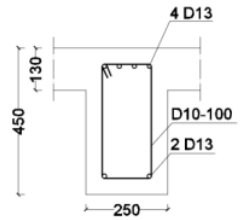
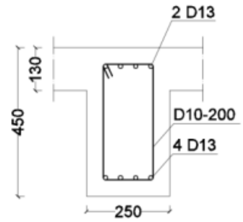
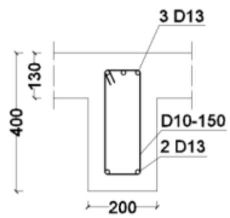
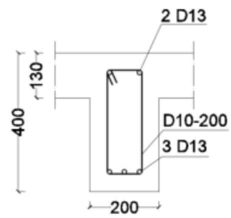
Beam type	On the end side	On the middle side
B3 250x450		
B4 200x400		

5. Conclusions

This paper focused on the structural behavior and design of RC members of a middle-rise residential building situated in a moderately-high seismicity area. The building was designed using the capacity-design method and by considering the placement of the plastic hinges at the end of the beams. The dual system combined the special frame system and the shear walls placement to withstand the earthquake loading impact in the building. Therefore, the numerical simulation, using ETABS software, was performed considering the seismic response and the soft soil condition. The structural design was calculated based on the new standard code for earthquake and RC design in Indonesia. The simulation results indicated that the RC building performed well under the designed earthquake load. The structural behavior was found to fulfill the requirements written in the code and performed within the acceptable limits. The structural design of the RC beams and columns was also found to satisfy the code.

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