Shear failure of building floor beams due to December 7, 2016 Pidie Jaya earthquake

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Abstract. The 6.5 SR magnitude earthquake experienced in Pidie Jaya Regency on December 7, 2016 caused the failure of several structures including the District Attorney's Building with almost all the beams on the first floor observed to have shear cracks. Besides that, some flexural cracks were also found, although only in a few places. This study aimed to determine the cause of the shear failure in the building and the amount of deformation observed in the structures due to the earthquake. Therefore, an assessment was conducted in the field to determine the quality of concrete and the adequacy of shear reinforcement installed. A time history analysis was also performed using the Pidie Jaya earthquake history recorded by the Meteorology, Climatology and Geophysics Agency (BMKG). The results showed the required shear strength of the floor beams due to earthquake load was lower than its shear capacity due to a low compressive strength of the concrete in the beam and installation of insufficient shear reinforcement. Furthermore, the flexural strength required in the beams in some places was also greater than the available flexural capacity while the lateral deformations due to the earthquake were also observed to be very large thereby causing the inter-story drift of the building structures to exceed the value allowed by earthquake-resistant building standards (SNI 1726:2012). This subsequently led to the failure of the building floor beams, however, since the strength of the column was greater than the required standard, no crack was observed in the column.

Introduction

The main causes of structural failure during earthquakes include building mass irregularities, low quality of construction materials, soft stories, inconsistent earthquake response, the collision of two buildings constructed side by side due to large lateral deformation, floating columns, unfavourable soil influence, and insufficient foundation [1]. These failures are usually in the form of beam shear failure, building floor collapse due to insufficient strength between the floors, weak column - strong beam, beam-column joint failure, and a very large inter-story drift [2-6]. Moreover, the level of deformation due to insufficient structural stiffness can cause cracking and, with subsequent loads, structural damage [7]. The errors in the choice of an adequate structural system at the design phase also have the ability to cause structural failure [4].

The Province of Aceh in Indonesia is located in a very active tectonic zone and apart from the three large plates known globally, there are other nine small ones combined to form the path of meeting complex [8-11]. The 6.5 SR magnitude earthquake experienced in Pidie Jaya Regency with the epicentre at coordinates 5.25 latitude north, 96.24 East longitude, and a depth of 15 Km at 05:03:36 am in West Indonesia Time on Wednesday, 7th December 2016 caused the structural failure of several buildings in Pidie Jaya, Bireuen, and Pidie Regencies. One of these was the

District Attorney Building located in the Pidie Jaya Regency Government Office Complex, Manyang Lancok Village, Meureudu District. Almost all the floor beams have shear cracks as shown in Fig. 1a as well as flexural cracks as indicated in Fig. 1b. The building was built in 2013 with reinforced concrete structures and has 3 floors with a building length of 38.00 m, width at 33.50 m, and a total height of 14.20 m. This means it was only 3 years old at the time of the earthquake.



Fig.1 Cracks of the floor beams: (a) shear cracks; (b) flexural cracks

The purpose of this study was to analyze the causes of the beam's failure by comparing the required structural strength due to earthquake forces and the capacity of the structures. Moreover, the history of deformation magnitude in buildings during earthquakes was analysed through the provision of the acceleration of ground motion history at the time of the earthquake. Based on the maximum deformation observed, the inter-story drift was also evaluated and compared with the value allowed by SNI (Indonesian National Standard) 1726:2012.

Research Method

Site Assessment. The research started with the collection and studying of the as built drawings with a focus on the building size, structural members, and details. Furthermore, field assessments were also conducted and the structural member dimension was measured by using a meter instrument, permanent structural deformation with a water pass as shown in Fig. 2(a), arrangement and diameter of the reinforcing steel using a profometer shown in Fig. 2(b), while the concrete compressive strength was tested using the non-destructive method with a Schmidt hammer type N/N as shown in Fig. 2(c) [12]. Moreover, the data on the tensile strength of the reinforcing steel was obtained from job specifications at the time of building construction and was found to be 320 MPa for longitudinal reinforcement and 240 MPa for stirrup.



Fig. 2 Structural assessment: (a) measurement of structural deformation; (b) Measurement of reinforcing bar arrangement and diameter; (c) hammer test for concrete compressive strength

Structural Modelling. The building is modelled as a space frame using SAP 2000 software with the structural plan shown in Fig. 3. The height of the first, second, and third-floor columns is 4 m each while the size of the columns section is 500 mm x 500 mm with a longitudinal reinforcement of 16D19 mm for each of the floors. The size of the floor beams is 350 mm x 700 mm with the reinforcement in the positive and negative moment areas A_s = 10D19 mm and A'_s = 5D19 mm. The size of the ring beams is 200 mm x 300 mm with the reinforcement in the positive and negative moment areas A_s = 3D16 mm and A'_s = 2D16 mm. The thickness of the floor slab is 12 mm and modelled as a rigid diaphragm.

Structural Analysis. Time history analysis was used to calculate the effect of earthquake loads using the SAP 2000 software and this involved the application of the data on ground movement

acceleration recorded during the Pidie Jaya earthquake by the Meteorological, Climatological, and Geophysical Agency (BMKG) [6] as well as the dead and live loads on the structure. Moreover, the concrete and steel strength data were also inputted before analysis and the axial force, shear force and bending moment were obtained afterward. These forces were combined to determine the required strength using different combinations of loads as stated in SNI 1727:2013 standards [13]. Meanwhile, structural cross-section capacity was also calculated based on the SNI 2847:2013 standards [14].

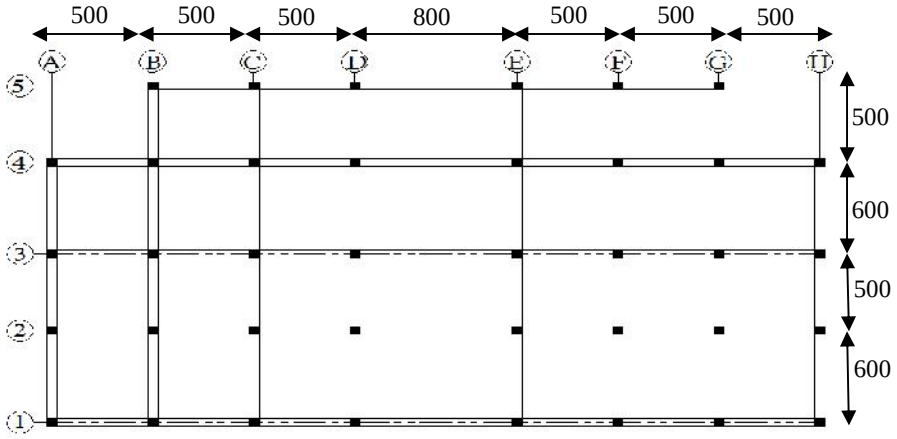


Fig. 3 Building structural plan

In the time history analysis, the soil on which the structure is built was assumed to be soft based on the results of previous studies conducted in the Pidie Jaya region using microtremor analysis which showed the soil to have a dominant period greater than 0.6 seconds [15]. Moreover, it was also supported by the value of V_s30 found to be between 42.51-178.73 m/s [16] as well as the classification of the SNI 1726:2012 [17].

Results and Discussion

Assessment Results. The tests conducted on the field showed the concrete compressive strength for the column was 21.24 MPa, the floor beam was 12.40 MPa, the ring beam was 20.21 MPa, and the floor slab was 20.38 MPa. Meanwhile, the minimum compressive strength for structural concrete according to SNI 2847: 2013 is 17.5 MPa [14]. Therefore, the requirements of SNI 2847:2013 standard were met except for the compressive strength of the floor beams. This means one of the causes of the cracks in the floor beam is the lack of concrete quality during construction.

The steel reinforcement analysis showed stirrups were installed with the same distance along the beam span, at 200 mm. Meanwhile, in the area near the column, the beam receives greater shear force and this requires more stirring. Therefore, the shear failure observed in almost all the beams was also caused by the lack of stirrups in the shear span area. The diameter of the stirrup used was 10 mm which is in accordance to SNI 2847:2013 for building structures to withstand earthquake loads [14]. The reinforcement diameter used on the floor slab was 10 mm and installed every 100 mm distance in accordance with the provisions of SNI 2847:2013 standard, therefore, no crack was found on the floor slab.

Comparison of Required Strength and Capacity. The required shear strength (V_u) of all loading combinations in SNI 1727:2013 (Comb 1 - Comb 6) was compared with the beam shear capacity (ϕV_n) as shown in Fig. 4(a). It was discovered that the shear beam capacity is smaller than the required shear strength in the shear span area, therefore, the failure was due to the inability of the beam to withstand the shear forces caused by the earthquake. However, the small value of shear capacity was observed to be due to the low quality of the concrete and insufficient shear reinforcement (stirrups). Meanwhile, the value was greater than the required shear strength for all

load combinations in the middle of the beam span, therefore, no shear crack was recorded in the area.

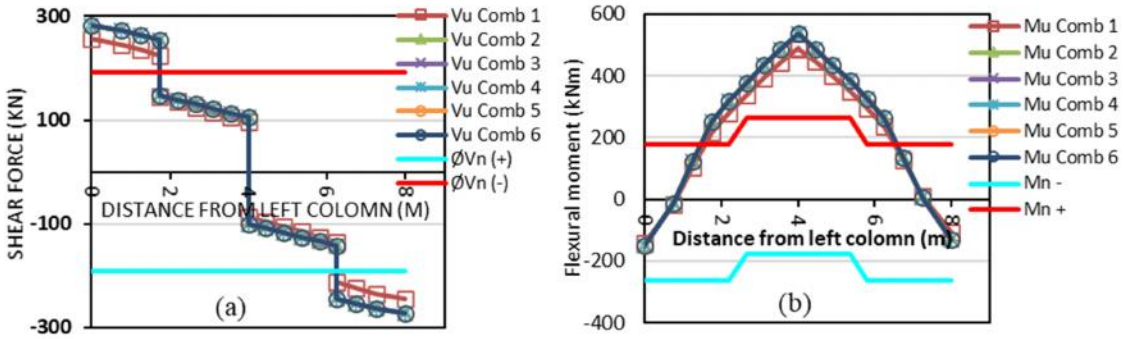


Fig. 4 Comparison of: (a) V_u and ϕV_n; (b) M_u and ϕM_n of beam

The required flexural strength (M_u) of all load combinations required in SNI 1727:2013 (Comb 1 - Comb 6) was also compared with beam flexural capacity (ϕM_n) as shown in Fig. 4(b). The results showed the beam flexural capacity is smaller than the required flexural strength in the positive moment area and this caused the flexural cracks observed in the middle of the beam span due to its inability to withstand the flexural moments experienced during the earthquake. Moreover, the small flexural capacity of the beam was observed to be due to the low quality of the concrete and inadequate longitudinal tensile reinforcement in the middle of the beam span. However, a contrasting result was obtained at the negative moment part with the beam flexural capacity found to be greater than the required flexural strength for all load combinations. Therefore, no flexural crack was recorded in this area.

The capacity of the column cross-section to withstand a combination of axial compressive load (ϕP_n) and bending moment (ϕM_n) is illustrated using an interaction diagram in Fig. 5. The combination of the required axial load (P_u) and the required bending moment (M_u) due to the earthquake for all loading combinations was also plotted on the diagram. The results showed the column cross-section capacity was much greater than the required strength to withstand earthquake loads. Therefore, during the Pidie Jaya earthquake, there was no failure in the column structures.

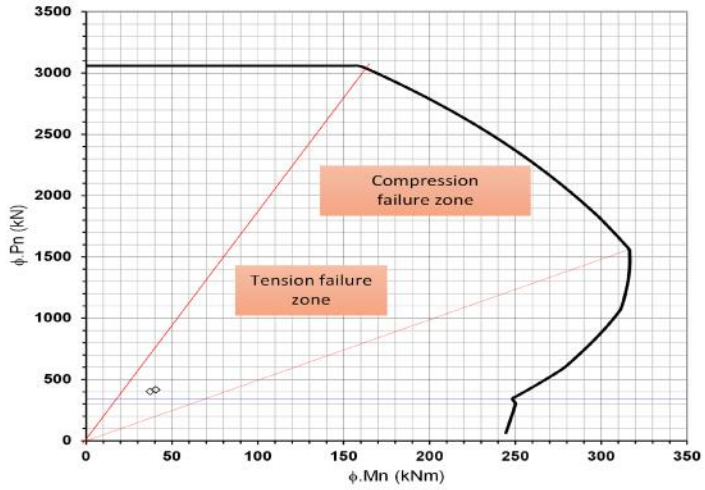


Fig.5 $\phi P_n - \phi M_n$ interaction diagram of the column

Lateral Displacements. The lateral displacements in the X and Y directions at the top of the building structure during the earthquake are shown in Figure 6. The results showed the lateral displacement in the Y direction was much greater than the X direction. The maximum value at the X direction was observed in the 21st second to be 9.88 mm while it was 25th second in the Y

direction at 147.50 mm. This shows the stiffness of the building structure in the X direction is much greater than in the Y direction.

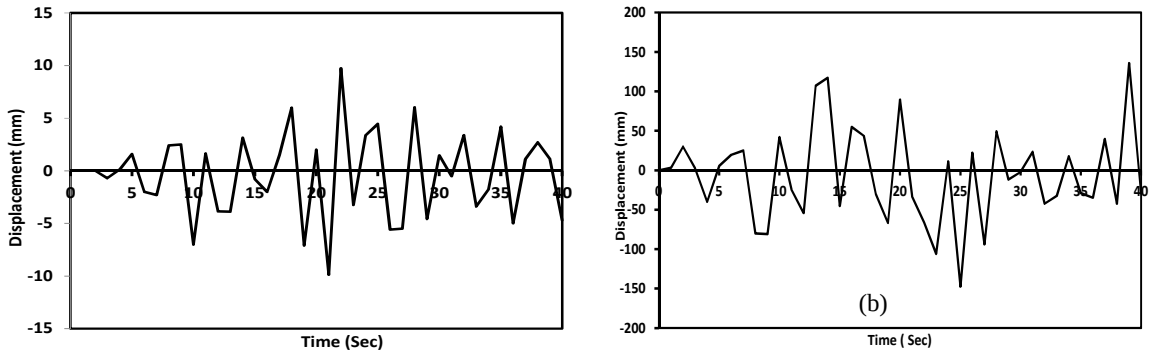


Fig.6 Lateral displacements: (a) in the X direction; (b) in the Y direction

Inter-Story Drifts. The inter-story drifts at 1st, 2nd and 3rd stories in the X and Y directions for all loading combinations, 1 – 6 together with limit value permitted by SNI 1726: 2012, are shown in Table 1. This shows the building has a large deformation and not safe for use if no structural strengthening is conducted.

Table 1 Inter-story drifts

Story	Inter-story drift (%)		
	X direction	Y direction	SNI 1726:2012 limit
1	7.41	21.78	2
2	2.80	20.00	2
3	0.95	9.86	2

Conclusions

A time history analysis was conducted to study the shear failure of beams and deformation of building structures due to December 7, 2016 Pidie Jaya earthquake and the results produced the following conclusions:

1. The shear failure of the floor beams due to the earthquake from the Pidie Jaya District Attorney's Building was due to the very small shear capacity of the beam compared to the shear forces due to the earthquake. However, the small value was due to the low quality of the concrete and lack of shear reinforcement in the shear span of the beam.
2. Flexural cracks were also discovered in the beam due to the smaller value of the beam's flexural capacity compared to the flexural strength required during the earthquake in the positive moment area. The small value was observed due to the low quality of the concrete and lack of longitudinal tensile reinforcement in the middle of the beam span.
3. The capacity of the column cross-section due to a combination of axial compressive force and bending moment is much greater than the load on it due to the earthquake, therefore, there was no column failure.
4. Inter-story drift of this building structure exceeded the limit permitted by SNI 1726: 2012, therefore, it is not safe for use and requires structural strengthening.

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