USE OF VERTICAL UNBONDED POST TENSIONED ON PRECAST CONCRETE WALL TO COUNTERACT VERTICAL EARTHQUAKE

by Dwi Dinariana

USE OF VERTICAL UNBONDED POST TENSIONED ON PRECAST CONCRETE WALL TO COUNTERACT VERTICAL EARTHQUAKE

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Abstract

On September 28, 2018, earthquake of magnitude M = 7.4 hit Palu and Donggala region, Central Sulawesi, Indonesia. The earthquake caused intensity of MMI IX in several areas and was followed by massive tsunami and liquefaction in several locations. Record of earthquake data shows that there is significant vertical earthquake that caused major damage on buildings though they had been designed according to design codes set by the Indonesian National Standard. One of buildings damaged by wave of vertical earthquake is the rental low-cost housing flats in Lere, Palu. This building was constructed in 2010-2011 using precast system of structure, designed according to design code of SNI 1726-2002 (equivalent to UBC 1997) and tested its performance against earthquake according to ACI 374.1-05. Detail examination reveals that there is a very large vertical earthquake causing failure mechanism not covered by mechanism of design capacity as assumed in the design code. In the future, it is recommended to employ structural system in the form of precast walls connected using unbonded post-tensioned connection installed vertically. The connection is expected to overcome strong vertical earthquake. This paper presents development process of seismic design code that can be used to design high performance building against vertical earthquake. The first stage is to redesign housing flats Lere, Palu employing performance-based design criteria according to ACI ITG-5.2-09 (2009). In the second stage, the building performance against earthquake is tested in laboratory according to ACI ITG-5.1M-07, followed by the verification of design method using time history analysis based on test data (2020). In the final stage, the development and implementation of design standard will be conducted (2021).

Keywords: vertical earthquake; precast wall system; unbonded post-tension; high performance; design code

1 Introduction

Rental Housing flat Lere in Palu, Central Sulawesi is one of rental housing flats built by Directorate General Cipta Karya, Ministry Public Works and Housing in cooperation with local government of Palu during fiscal year of 2010-2011. Currently this housing flat has been fully donated to local government of Palu. A series of earthquakes shook Palu and Donggala on Friday, September 28, 2018. Unfortunately, this rental housing flat is one of buildings affected by Palu earthquake. To assess the severity of building damage induced by earthquake, structural integrity for building safety and serviceability of building, structural engineering investigation were conducted by engineering experts. The result of the study will be used as an input for local government of Palu on how to handle the damaged building. According to the analysis from Meteorological, Climatological, and Geophysical Agency in Indonesia (BMKG)[1], the largest earthquake with magnitude of 7.4 took place with source located 26 km north of Donggala, Central Sulawesi and at the depth of 11 km. Considering the epicenter location and the depth of hypocenter, the earthquake was caused by activity at Palu Koro Fault and could be classified as shallow earthquake. From source mechanism analysis, the earthquake was generated by deformation with movement mechanism from horizontal fault structure (slide-slip). This study is carried out by assessing building condition using visual method and simple tools based on practical criteria and secondary earthquake data. It is then followed by modeling and analysis the building structure using software ETABS to be able to describe the damage mechanism occurred in the building.

2 Analysis and Discussion

2.1 Visual Investigation of Building

Post-earthquake assessment of building condition [2][3][4] of rental low-cost housing flat Lere in Palu was conducted on October 13th, 2018. Visual observation and analysis show that this housing flat suffered major damage in both structural and architectural components as can be seen in Figs 1.a and 1.b, respectively.

(a) (b)

Fig. 1 – Pictures of damaged rental low-cost housing flat Lere: (a) major architectural damage, (b) major structural damage concentrated on base columns undergone compression failure and combined shear and tensile failure

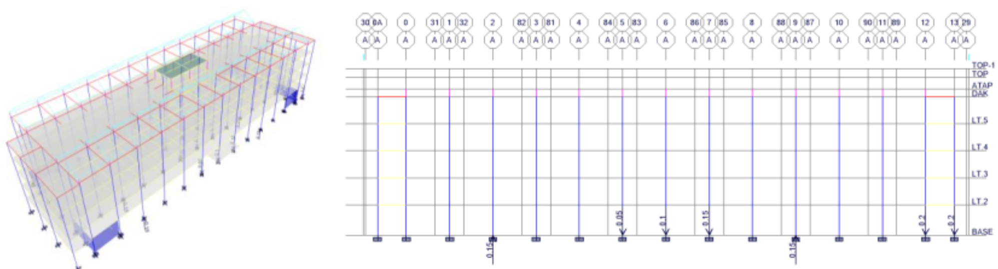
2.2 Failure Mechanism of Building

Failure mechanism of structure occurred at rental low-cost housing flat Lere was triggered by vertical earthquake load as dominant load in this earthquake. The wave of vertical load led to significant soil deformation and thus caused one point of structure deforming going down and the other point going up (forming wave-like vertical deformation along length of the building). This failure mechanism can be described using Fig. 2.

Fig. 2 – Soil deformation pattern due to vertical earthquake (pictures continuous along the length of building)

2.3 Damage Modeling and Analysis

To take into account the effect of vertical earthquake causing damage in building in the form of vertical deformation, structural model including the vertical deformation at the base (ground displacement) based on deformation observed on the field as shown Fig. 3, is developed. The structural model was prepared using structural analysis software ETABS (computer aided design).



(a) (b)

Fig. 3 – ETABS Structural model for rental low-cost housing flat Lere with input ground displacement according to measurements from the field: (a) 3D model building, (b) model section along the length of building

After running the structural analysis using software ETABS, the outputs of the analysis in terms of deformation and axial forces are obtained as shown in Fig. 4.

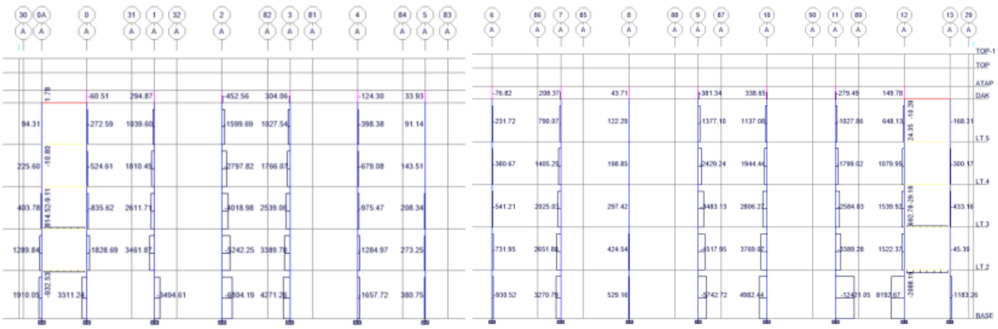


Fig. 4 – Output axial force due to ground displacement

From Fig. 4, it can be seen that vertical movement of ground surface can result in large axial forces in columns. These axial forces have different direction between two adjacent columns. For example, at column 2-A in which ground surface move upwards 15 cm, there is compression force of 6304.2 kN and at adjacent column (column 3-A) in which ground surface displace downwards 15 cm, the column has tensile force of 4271.3 kN. On another example, at column 12-A where the ground surface beneath it move downwards 20 cm, the column has axial compression force of 8192.7 kN and at column 11-A where the ground surface beneath it move upwards 20 cm, the column has axial tensile force of 12421.1 kN. Meanwhile, based on theoretical formula, the compressive and tensile capacity of reinforced concrete column can be evaluated as follows: compressive capacity = 0.85 fc' Ag= 0.85 x 29.05 (350x500) = 4,321,187 N = 4321.2 kN and tensile capacity = 0.5 $\sqrt{fc'}$ Ag = 0.50 x $\sqrt{29.05}$ (350x500) = 471,607.954 N = 471.607 kN.

From the above discussion, it is clear that the axial forces, both in tension or in compression, exceed their capacities. As can be seen in Fig. 5.a, column 2-A underwent compression failure. On the other hand, Fig. 5.b shows that column 3-A suffered a combination of tensile and shear failure. Since the tensile capacity of column is much lower than the actual axial tensile force in column, the column was separated into two parts and then displaced to the side due to lateral force as shown in Fig. 5.b. Thus, from data and computer model simulation, considering that the large vertical earthquake load coming earlier than the of horizontal earthquake load, it explains the damage mechanism took place on building under investigation.

(a) (b)

Fig. 5 – Structural damage: (a) compression failure in column, (b) tensile-shear failure in column

2.4 Investigation on Precast System

Structural components of rental low-cost housing flat Lere in Palu use precast system that has been tested at structural laboratory of the Research Institute of Human Settlement and Institute of Road Engineering Ministry of Public Works and Housing. Reduction factor *R* of 4.35 – 5.05 means that this system fall into structural category moderate moment resisting frame as shown in Fig. 6.

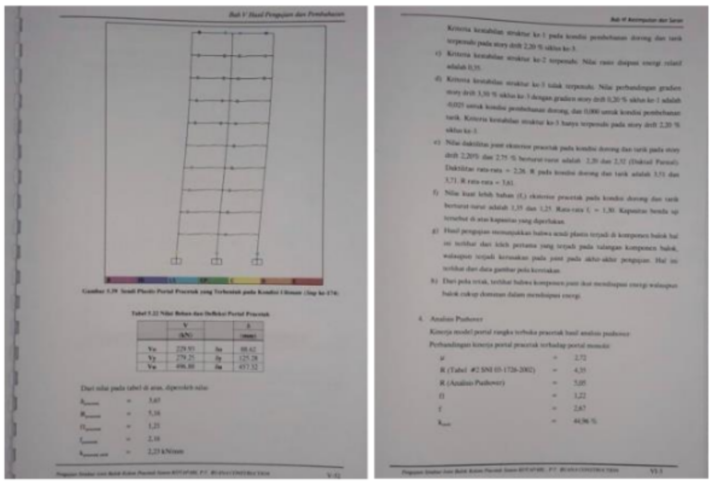


Fig. 6 – Lateral resistance system category of precast system which is used

According to Indonesian seismic design code (SNI 03-1726-2002) and concrete building code (SNI 03-2843-2002), moderate moment resisting frame structure can still be used for region medium earthquake risk (zone 3, 4, 5), without using shear wall. Shear wall in this building is only provided in the first floor to prevent soft story effect. Damage mode of sway mechanism that was employed based on the assumption of the earthquake would not occur in this building with the dominant vertical earthquake load. Random column failure in the first-floor results in random failure mode on structure above the first floor. There is no clear damage pattern on every component of the structure. However, if one compares damage evolution from several components with those crack pattern from testing shown in Fig. 7, one can see similarity in pattern. Cracks started from beam and then go into the joint as can be seen in Fig. 8. Stirrups in column and joint were properly installed, but dominant vertical earthquake load led to concrete crushing as shown in Fig. 9.

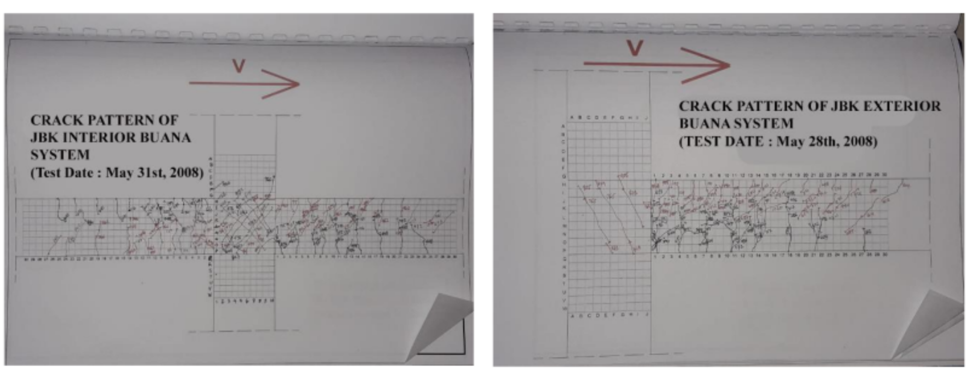


Fig. 7 – Crack pattern at interior and exterior beam-column joints during testing in Laboratory

Fig. 8 – Damage of beam-column joint due to earthquake

Fig. 9 – Stirrups installed properly in column, beam and joint, concrete crushing because of tension

3 Research and Development of Precast and Pre-stressed Concrete System in Indonesia

For overcoming the aforementioned earthquake, new pre-stressed precast concrete system is developed. The new structural system is expected to handle significant vertical earthquake load.

3.1 Description of Beam Dissipater Connection System

The object of the test is designed based on Waskita Beton Precast's Beam-Column Joint System Technology in building construction project using combination of beam-column joint system, as follows:

1. Precast and pre-stressed concrete system for exterior span and interior span with system classification as Special Moment Resisting Frame (SMRF) as shown in Figs 10-14.

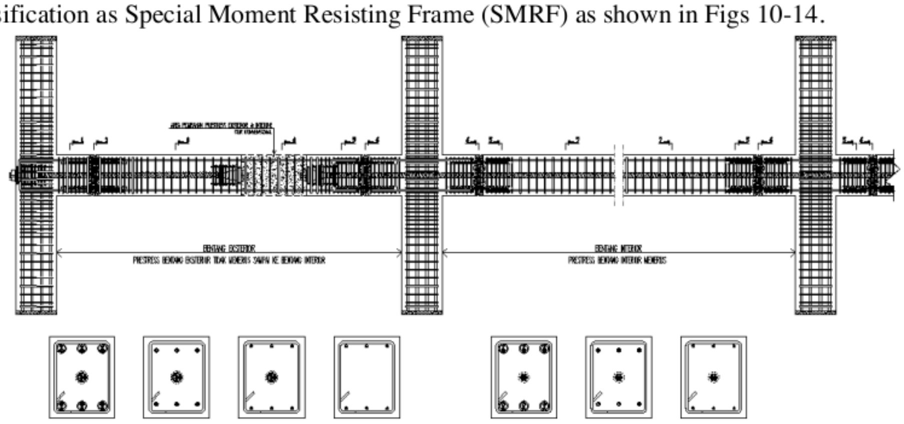


Fig. 10 – Beam Dissipater Connection Using Combination Type 1

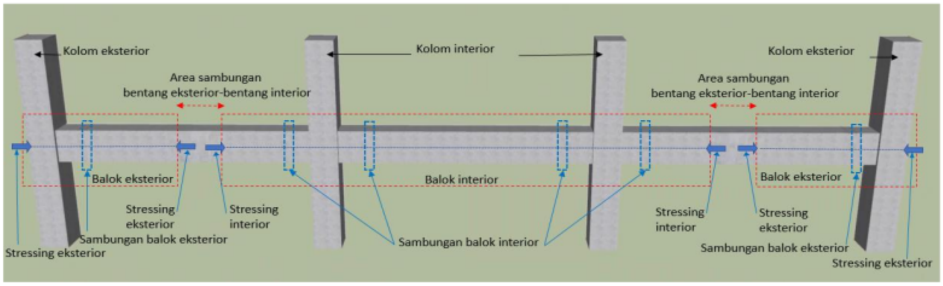


Fig. 11 – Joint Component of Combination Type 1

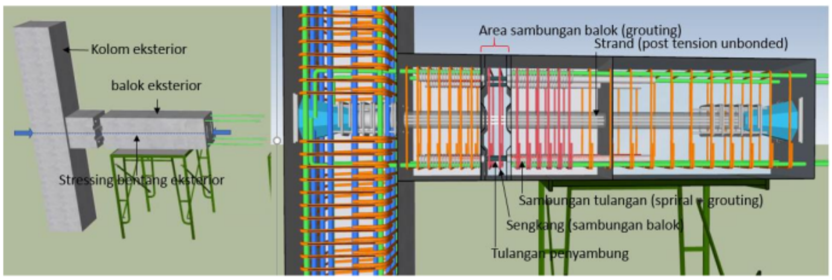


Fig. 12 – Exterior Joint Component of Combination Type 1

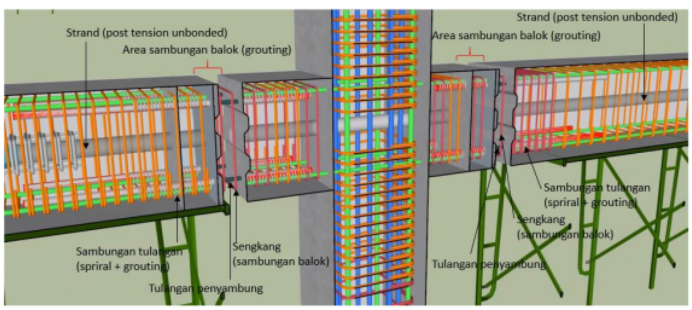


Fig. 13 – Interior Joint Component of Combination Type 1

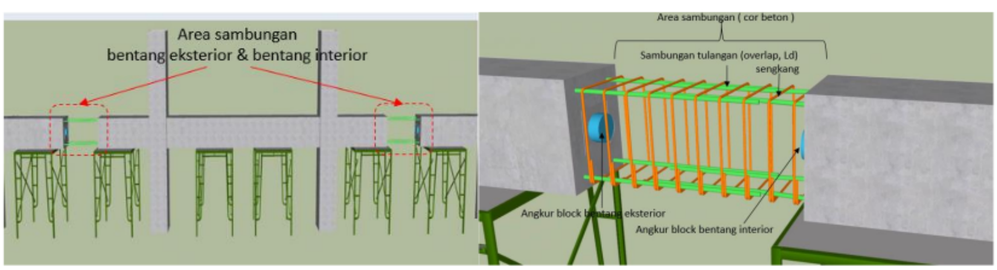


Fig. 14 – Component of Exterior – Interior Joint Connection Using Combination Type 1

2. Precast Reinforced Concrete System for interior span and exterior span with system classification as Special Moment Resisting Frame (SMRF) as shown in Figs 15-17.

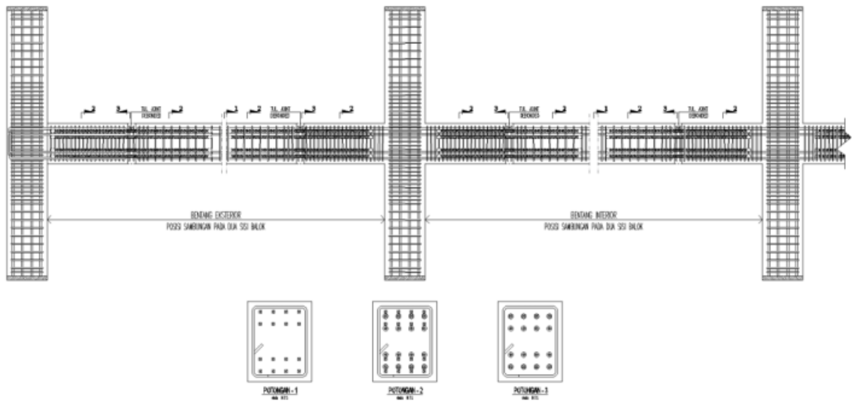


Fig. 15 – Beam Dissipater Connection Using Combination Type 3

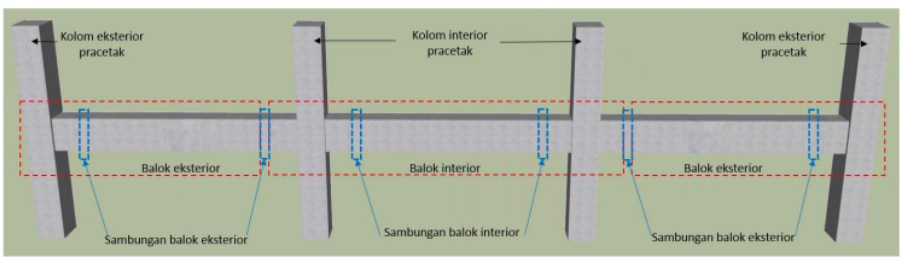


Fig. 16 – Joint Component of Combination Type 3

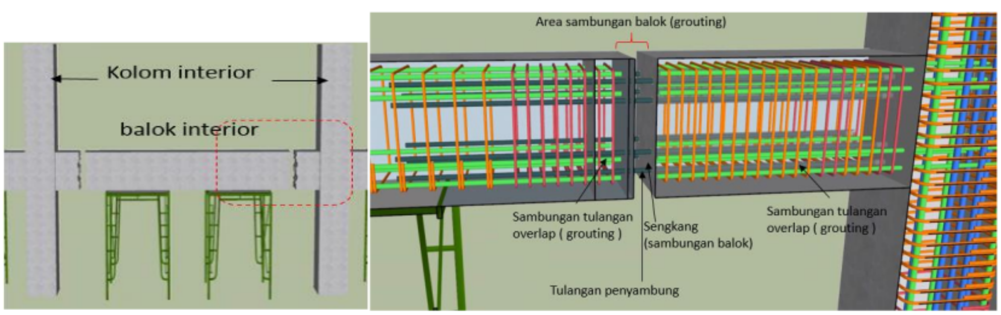
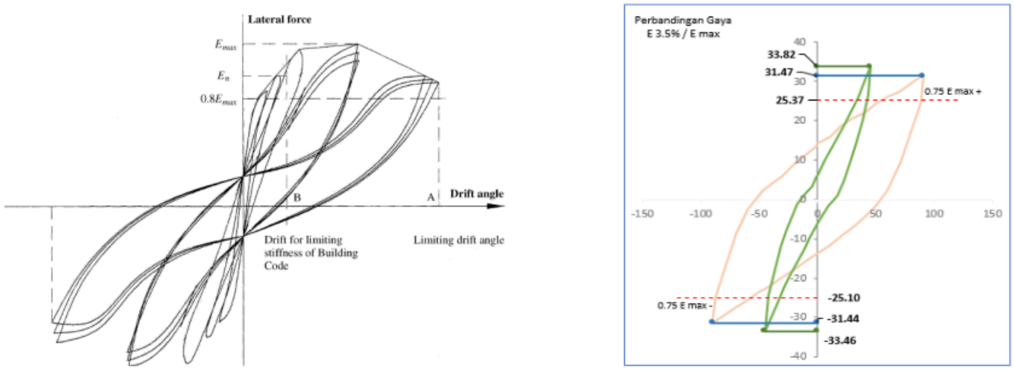


Fig. 17 – Component of Exterior and Interior Beam Joint Using Combination Type 3

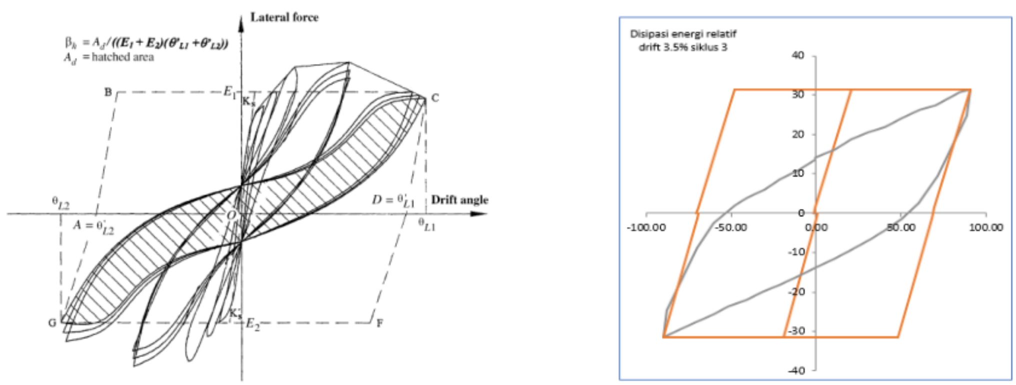
3.2 Beam Column Joint Testing (Figs 19 and 20)

Beam-Column Joint designed and tested according to ACI 374.1-05[5].

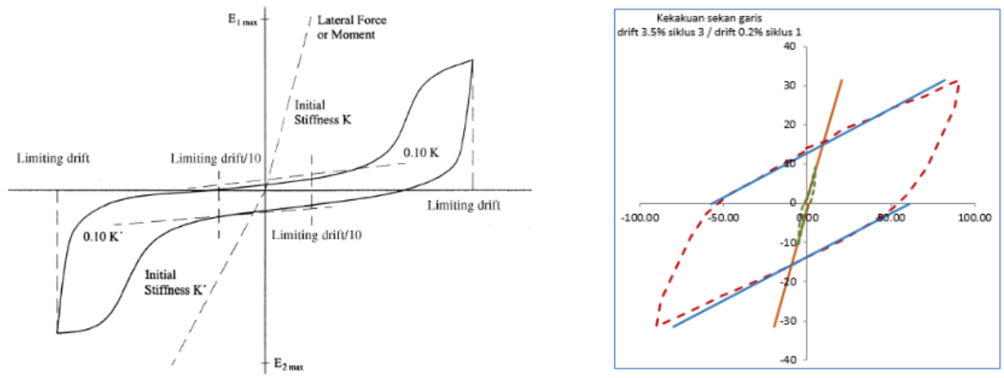
Fig. 19 – Beam column joint test



(a) Strength criteria



(a) Energy dissipation criteria



(c) Stiffness criteria

Fig. 20 – Beam column joint test criteria check

3.3 Bearing Wall Testing (Figs 21 and 22)

Bearing Wall designed and tested according to ACI ITG-5.1M-07[6] and ACI ITG-5.2-09[7]

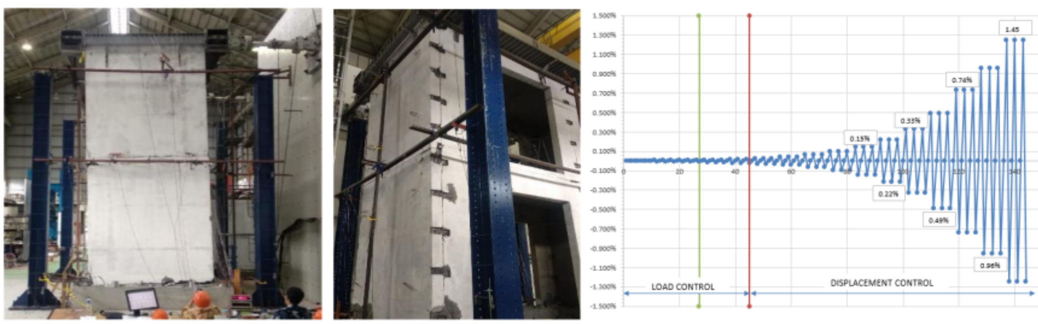
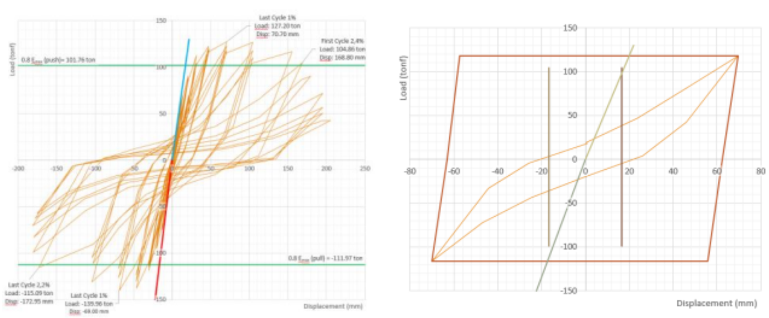


Fig. 21 – Bearing wall test



Cycle area= 4.561,79

Paralelogram area= 29.488,17

Ratio area = 15,5% > 12.5% **OK**

K_{Push} = 1,03 > 0,59 **OK**

K_{Pull} = 0,91 > 0,67 **OK**

Angle K_{Push} = 45,74° > 8,04° **OK**

Angle K_{Pull} = 42,16° > 8,15° **OK**

Fig. 22 – Test result of bearing wall structure

4 Performance Based Design

Pushover analysis is used to evaluate the performance of the building structure in the event of an earthquake by being represented using the level of performance according to the rules, so this plan is commonly referred to as performance-based earthquake resistant planning. Plastic hinge behavior of the beam in joint and at the base of the wall, acquired from test result. The performance Level will inform the behavior of building collapse in the event of an earthquake in accordance with the existing conditions. Analysis carried with the same ETABS model and resulting the Performance Level close to Immediate Occupancy (IO).

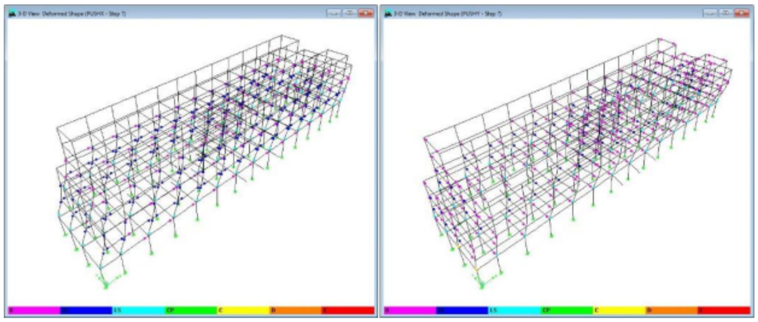


Fig. 23 – Deformed Shape Pushover (PUSH-X and PUSH-Y)

Table 1 – Pushover Capacity/Demand Comparison PUSH-X and PUSH-Y

PUSHOVER CAPACITY/DEMAND COMPARISON

Step	Teff	Beff	Sd (C)	Sa (C)	Sd (D)	Sa (D)	ALPHA	PF*Ø
0	0.410	0.050	0.000	0.000	0.076	1.825	1.000	1.000
1	0.410	0.050	8.654E-03	0.207	0.076	1.825	0.679	1.307
2	0.427	0.070	0.016	0.349	0.074	1.622	0.682	1.299
3	0.482	0.141	0.023	0.404	0.070	1.215	0.688	1.261
4	0.554	0.210	0.032	0.426	0.075	0.981	0.688	1.230
5	0.586	0.230	0.037	0.430	0.079	0.928	0.689	1.218
6	0.696	0.267	0.053	0.439	0.101	0.841	0.687	1.188
7	0.716	0.271	0.056	0.441	0.106	0.833	0.686	1.184

PUSHOVER CAPACITY/DEMAND COMPARISON

Step	Teff	Beff	Sd (C)	Sa (C)	Sd (D)	Sa (D)	ALPHA	PF*Ø
0	0.358	0.050	0.000	0.000	0.058	1.825	1.000	1.000
1	0.358	0.050	6.920E-03	0.217	0.058	1.825	0.664	1.486
2	0.386	0.083	0.014	0.388	0.056	1.526	0.665	1.463
3	0.423	0.126	0.022	0.485	0.057	1.282	0.657	1.481
4	0.469	0.175	0.029	0.528	0.059	1.089	0.656	1.469
5	0.553	0.234	0.043	0.564	0.070	0.919	0.649	1.494
6	0.560	0.236	0.044	0.566	0.071	0.912	0.648	1.498

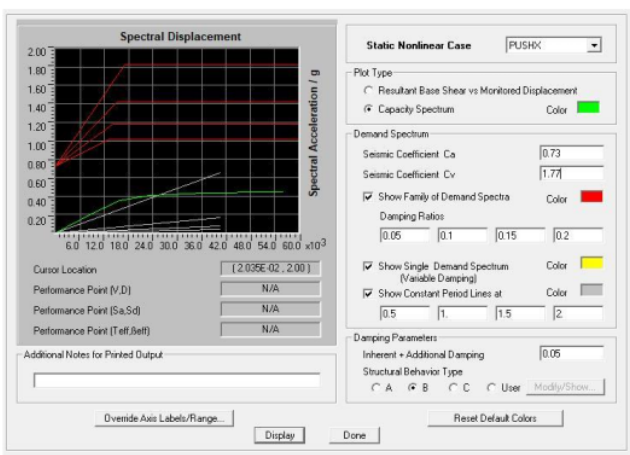


Fig. 25 – Result of Pushover Curve PUSH-X

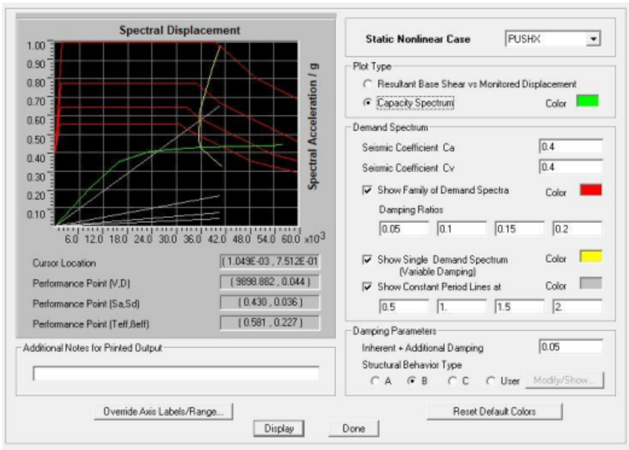


Fig. 24 – Result of Pushover Curve PUSH-Y

5 Conclusion

The building under investigation is severely damaged both in structural and architectural parts as well as its foundation. The damage of building was mainly caused by column failures at first floor due to high vertical earthquake load that occurred earlier than horizontal earthquake load. The phenomenon was able to be verified numerically using structural analysis software ETABS. In addition, the behavior of damage modes occurred in precast system beam-column have been confirmed during testing at the Research Institute of Human Settlement and Institute of Road Engineering Ministry of Public Works and Housing.

A new pre-stressed precast concrete system is under development and is expected to perform better against earthquake vertical load. The new structural system is expected to make building more rigid against vertically movement. Both preliminary test result and performance based design analysis shows improvement in building Performance Level from Collapse Prevention (CP) to Immediate Occupancy (IO).

6 Acknowledgments

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