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REUSABILITY STUDY OF STEEL LEANING COLUMN STRUCTURE UTILIZING NONLINEAR STATIC ANALYSIS

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Abstract: Two major earthquakes hit twoplaces in Indonesia in 2018, Palu city with 7.7 SR earthquake, and Lombok island by 6.4 SR earthquake. Many building especially concrete structure building got heavily damaged and even collapsing. Most of the damaged parts are the building's beam-column joint, due to improper reinforcing. This damaged building is very difficult to repair due to disintegrated concrete. Thus, this building cannot be used anymore, and nothing can be done except removing the remains and build a new structure. Because of this reason, this paper is studying a concept of reusability in structure, with the purpose to minimize structural damage in certain part of the building using leaner column theory. Leaning columns are columns that are pinned at each connection and provide no bending restraint in system. Theoretically leaning column cannot support axial and lateral loads, but since it is designed to lean on other structure, it can still resist the forces. Hence, this column is not suffering from lateral moment due to earthquake load, and the section is not exposed to damage. This paper is studying behavior of leaning column on exterior part of the structure with numerical simulation. Three-story building is modeled, one is with leaning column system, and the other is without leaning column. Performance-based design analysis with pushover method is carried. Result indicating that by using leaning column, exterior structure is not suffering from high moment when being hit by earthquake, and in other word, the exterior structure is not damaged when the earthquake comes and still can be used again.

Keywords: earthquake, damage, leaning column, pushover, reusability

INTRODUCTION

Several major earthquakes recorded in Indonesia recently, Palu city with 7.7 SR earthquake, and Lombok island by 6.4 SR. many building collapsed during the earthquake and a lot of building suffer from light to heavy damage. Light damaged building can be easier to recover, however, heavily damaged building is very hard and expensive to be recovered, thus lead to be demolished. A properly designed building may react in four conditions depend on their performance level, which is operational, immediate occupancy, life safety, or collapse prevention (see table 1). In the operational state, no structural damage is measured, only architectural cracks in partition wall or ceiling. In the Immediate occupancy state, structure still remains its strength and stiffness. In life safety state, crack is starting to happen in the structural area, and in collapse prevention state, plastic hinge is already happening. When a building stays in operational and immediate occupancy state, there will be no need to repair the building. If the building suffers life safety state, it is still possible to recover the building by structural retrofitting, but it will be a different case if the building is already entering collapse prevention stages. It is really difficult to retrofit building that in collapse prevention.

To create a sustainable structure, building should be designed to meet IO performance, that after seismic event, building can be used immediately and suffer only minor damage, but it will cost higher than usual building. To overcome this problem, study of leaning column is carried.

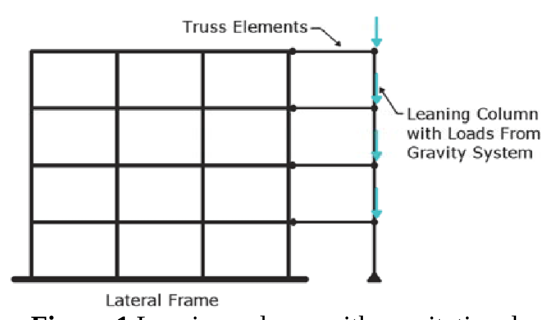


Figure 1. Leaning column with gravitational load

Table 1. Performance Criteria ASCE 41-17

Performance Level	Structural Frame
Operational	Minor or no damage to structural frame. Since repair is not required, operations are not interrupted.
Immediate Occupancy	Minor, repairable damage to structural frame. Does not interfere with immediate use, but may interfere with long-term use.
Life Safety	Structural frame is permanently damaged and may not be repairable.
Collapse Prevention	Structural frame is near collapse.

Leaning column is column that are pinned at each connection, and provide no bending restraint in a frame (see Figure 1 and 2). Because of the zero bending restrain, this structure is not suffering from lateral earthquake forces, and may not be damaged in case of earthquake. leaning column cannot stand on its own because of the pinned connection, and designed to “lean” on other structure, example on the core structure.

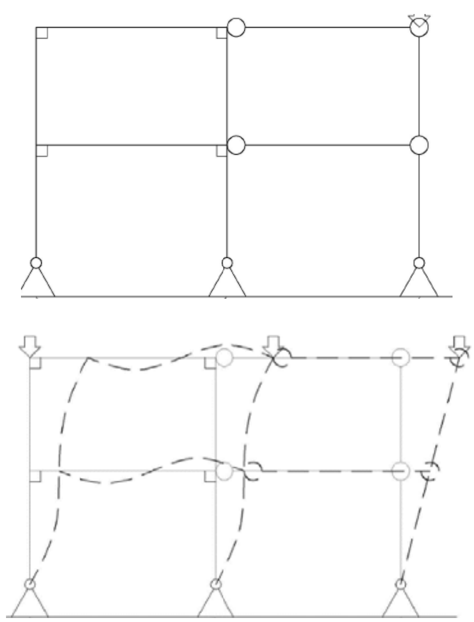


Figure 2. Leaning column with lateral load

By applying leaning column in exterior structure, leaning column portal does not receive any extensive moment when earthquake happens, instead the moment frame/core is the one who takes the forces. This structure concept can reduce the damage on exterior structure, by transferring the forces into the core structure (moment frame/core wall structure). In this paper, a performance-based design of 3D leaning column structure is modeled. Pushover analysis of the structure is carried.

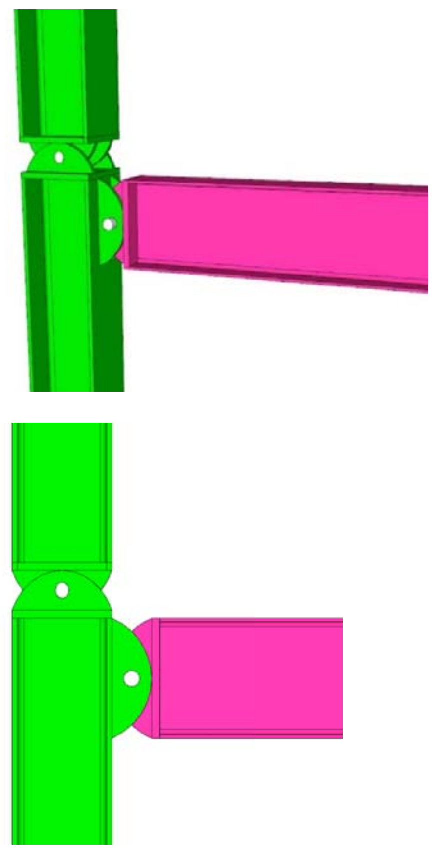


Figure 3. Leaning column connection

PERFORMANCE-BASED DESIGN

To observe the behavior of leaning column, performance-based design is carried. Most of the structures are designed by using design codes, such as SNI in Indonesia. Codes are made to ensure safety in the building design, especially in the event of earthquakes, but building codes cannot tell directly the performance of the designed building. Performance-based design instead can give information about the building's performance.

Building performance level

As mentioned in FEMA 356 , building performance is the combined performance of both structural and non-structural components of the building. Different performance levels are used to describe the building performance using the pushover analyses, which are described below.

1. Operational level (OL):
   This performance level building are expected to sustain no permanent damages. The structure retains original strength and stiffness.
2. Immediate occupancy level (IO):
   Buildings meeting this performance level are expected to sustain no drift and structure retains original strength and stiffness. Minor cracking in partition walls and structural elements is observed. Elevators can be restarted. Fire protection is operable.
3. Life Safety Level (LS):
   This level is indicated when some residual strength and stiffness is left available in the structure. Gravity load-bearing elements function, no out of plane failure of walls and tripping of parapet is seen. Some drift can be observed with some failure to the partition walls and the building is beyond economical repair. Among the non-structural elements failing hazard mitigates but many architectural and mechanical and mechanical systems get damaged.
4. Collapse Prevention Level (CP):
   Buildings meeting this performance level are expected to have little residual strength and stiffness, but the load-bearing structural elements function such as load-bearing walls and columns. Building is expected to sustain large permanent drifts, failure of partitions infill and parapets and extensive damage to non-structural elements. At this level the building remains in collapse level.

To model a performance based design, two methods can be used, which is nonlinear static analysis and nonlinear dynamic time history analysis. In this paper, nonlinear static pushover analysis is selected.

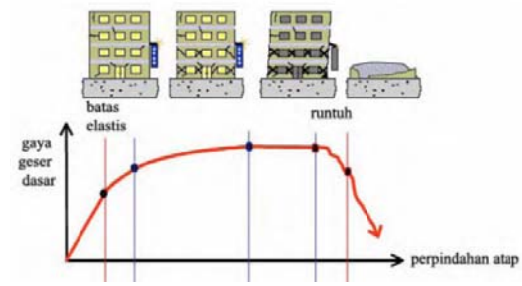


Figure 4. Performance Criteria FEMA 356

Nonlinear static pushover analysis

Pushover is a static-nonlinear analysis method where a structure is subjected to gravity loading and a monotonic displacement-controlled lateral load pattern which continuously increases through elastic and inelastic behavior until an ultimate condition is reached (CSI, 2017).

In nonlinear static pushover analysis, two method can be used, which is Displacement Coefficient Method (DCM), documented in FEMA-356 and Capacity Spectrum Method (CSM) documented in ATC-40. Both methods depend on lateral load-deformation variation obtained by non-linear static analysis under the gravity loading and idealized lateral loading due to the seismic action.

Displacement Coefficient Method (DCM) is a non-linear static analysis procedure which provides a numerical process for estimating the displacement demand on the structure, by using a bilinear representation of the capacity curve and a series of modification factors or coefficients to calculate a target displacement. The point on the capacity curve at the target displacement is the equivalent of the performance point in the capacity spectrum method.

Capacity Spectrum Method (CSM) is a non-linear static analysis procedure which provides a graphical representation of the expected seismic performance of the structure by intersecting the structure's capacity spectrum with the response spectrum (demand spectrum) of the earthquake. The intersection point is called as the performance point, and the displacement coordinate dp of the performance point is the estimated displacement demand on the structure for the specified level of seismic hazard.

METHODOLOGY

To observe the behaviour of leaning column, two analysis model is carried, the first model is a simple 3 story steel structure, that has been designed to be safe according to SNI 1726-2012 and SNI 1729-2015 (Tata Cara Perencanaan Struktur Baja untuk Bangunan Gedung). The second model is the same structure but equipped with leaner column system on the exterior frame structure, leaving only the interior as the stiff structure. In the normal frame structure, lateral forces due to earthquake will be carried by all the frame system, but in leaner structure, only the interior or core of the building carry the lateral loads.**.**

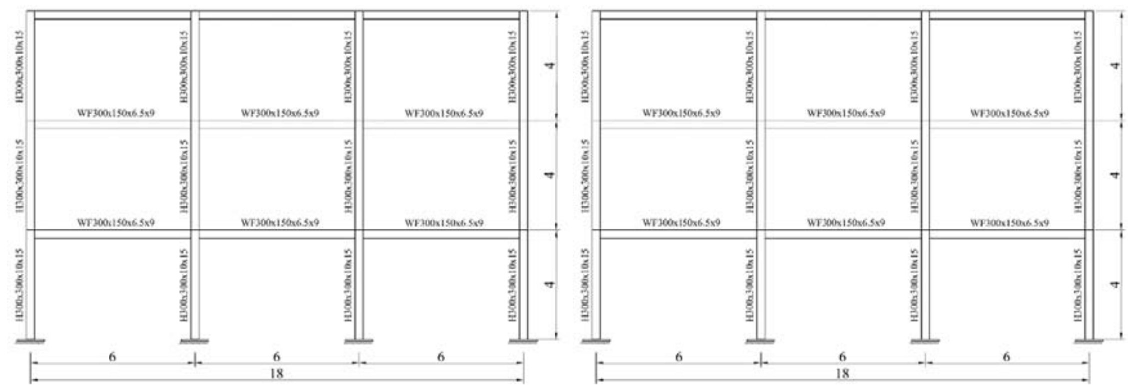


Figure 5. Steel Structure model, portal in X and Y direction

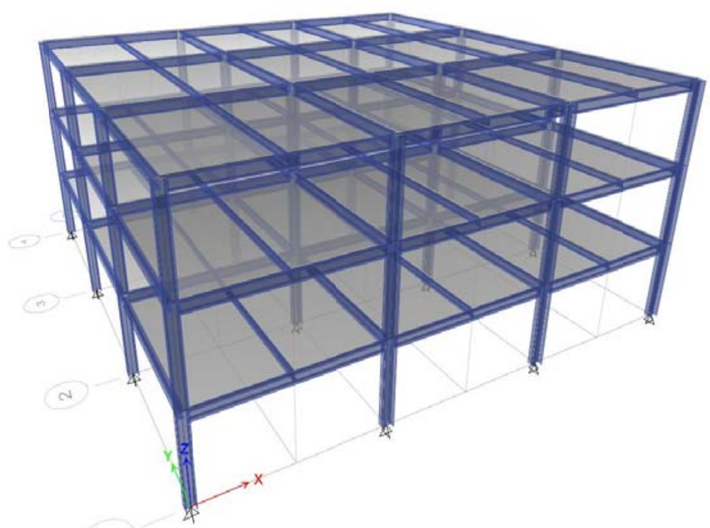


Figure 6. 3D view steel structure model

Structure designed is 3 story steel structure, with deck as floor system. WF300x150x6x9 is used as beam section properties with span of 6 meter for x and y direction. H300x300x10x15 is used for column section, with story height of 4 meter. A secondary beam WF200x100x5.5x8 is placed in the centre of each beam span in x direction. Structure's foundation is modelled as pinned restrain, as potrayed footing foundation. Material used is steel, with young modulus of E =200.000 MPa, yield strength of 240 MPa, and ultimate strength of 370 MPa. Nonlinear behaviour data is shown below in figure 7. Hysteresis type is set to kinematic to accommodate high ductility of steel structure.

Plastic hinge is the location of inelastic action of the structural member. The maximum moments caused by the earthquake occur near the ends of the beams and columns, the plastic hinges are likely to form there and most ductility requirements apply to section near the junction. In this case plastic hinge is assigned on relative distance of 0.1 and 0.9 of the member.

The P-M2-M3 hinge is best suited for nonlinear static pushover. Plastic hinges are placed in beams and column in 0.1 and 0.9 of relative length of the section, and set to be deformation controlled (ductile) of major moment. Hinge properties described in Figure 3.

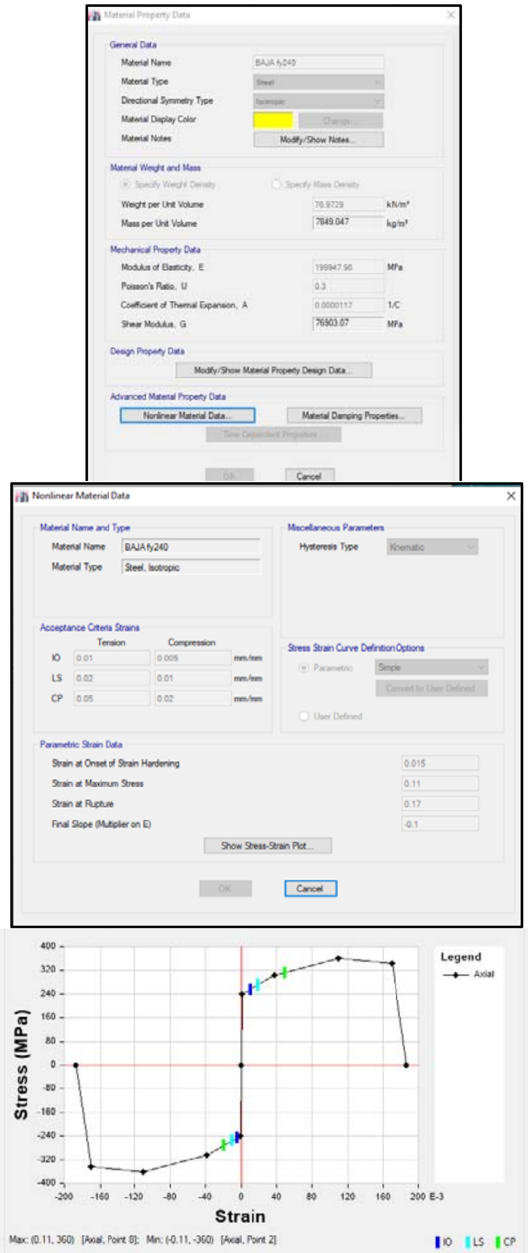


Figure 7. Nonlinear material properties - steel

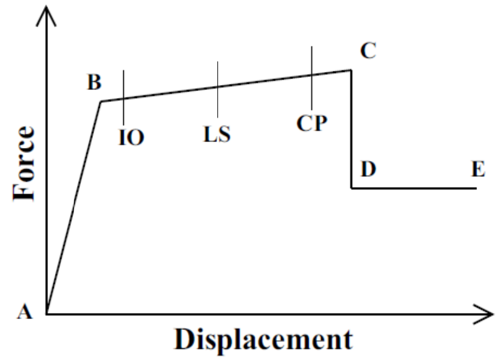
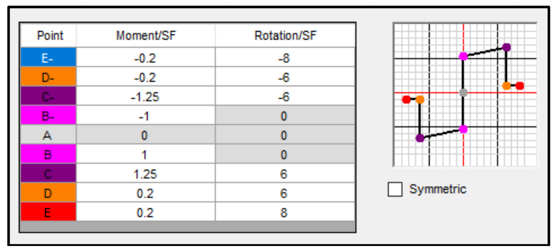


Figure 8. Nonlinear material properties – steel



Point	Moment/SF	Rotation/SF
E-	-0.2	-8
D-	-0.2	-6
C-	-1.25	-6
B-	-1	0
A	0	0
B	1	0
C	1.25	6
D	0.2	6
E	0.2	8

Figure 9. Hinge properties assigned

Structure loading is set to have deadload, liveload, and pushover loading. Loading described as in Table 2 below.

Table 2. Loading and analysis data

Loading	Self weight	Steel 7850 kg/m^3
	Additional Dead Load	1 kN/m^2
	Live Load	2.5 kN/m^2
	Wall Load	3.12 kN/m^2
Analysis	P-delta effect	Not considered
	Mass Source	1D + 1ADL + 0.25L
	Pushover control	Displacement control 500mm

In Pushover analysis, displacement control is selected to provide better analysis of ductile structure. Control point is located on joint 1 on the top story, as illustrated on Figure 10 below.

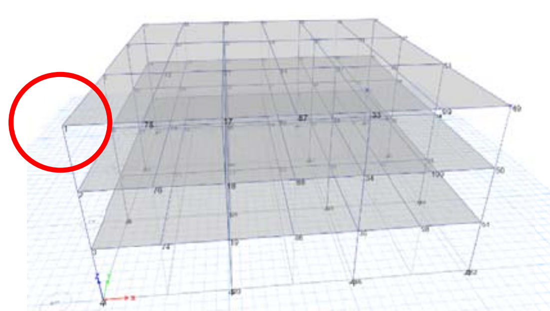


Figure 10. Displacement control location

Structure is checked due to gravitational loads, and pushover load. The two model of normal frame structure and leaning column frame structure is tested, and being observed. Behaviour of the two frame will be compared when gravitational and lateral forces is applied.

RESULT AND DISCUSSION

Behaviour of leaning column will be observed from gravity load to lateral load, figure 11 displaying portal 2 in the model when liveload is applied. In leaning column, exterior frame can rotate one to another because of the pinned connection, imitating the behaviour of truss structure, therefore no negative moment is occur. In other hand, positive moment occured have high differences.

In normal frame system, maximum beam moment occurred due to liveload is 38.3 kNm (+) , but in leaning frame system, maximum moment is recorded 72.5 kNm (+). Moment occurred in leaner frame is 89% larger than the normal frame system, thus the exterior leaning frame does need higher section capacity compared to normal frame.

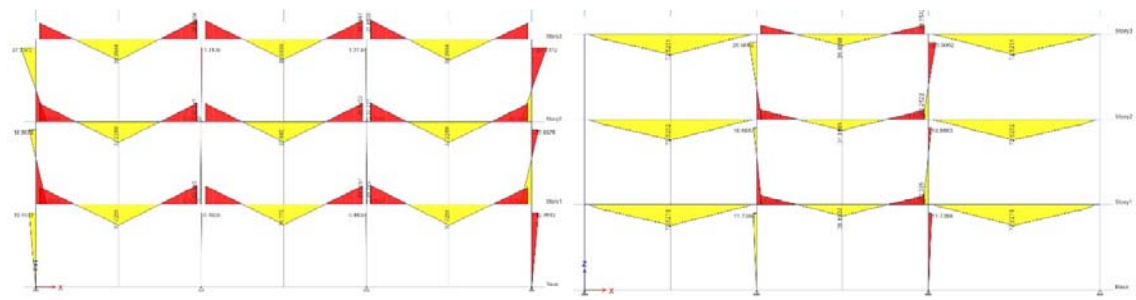
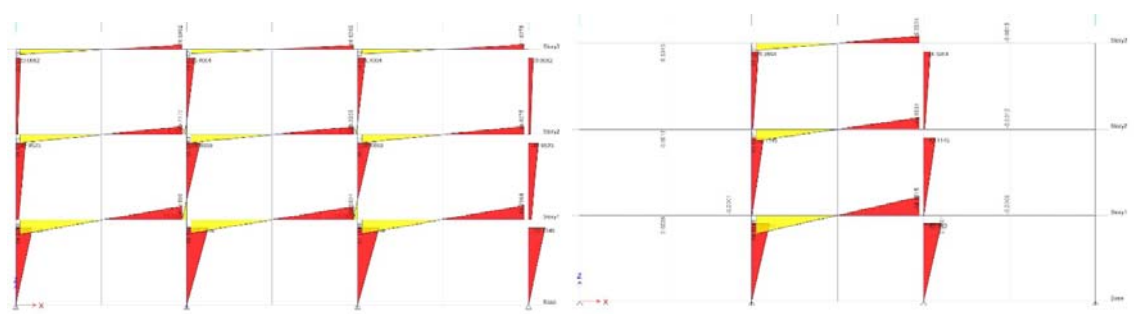
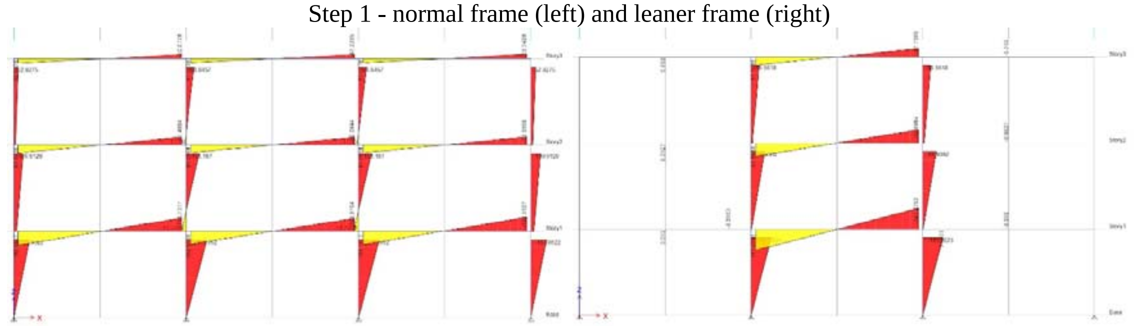


Figure 11. Liveload moment on normal frame (left) and leaning frame (right)

A different perspective is found during the moment result of the pushover load. Step 1 to 3 of the pushover is displayed on figure 12 below. Result indicating that in normal frame, moment is distibuted equally to every frame, but in leaning frame system, only the interior frame of the structure is experiencing moment. This is proving that the exterior frame is not resisting moment from lateral loads.



Step 1 - normal frame (left) and leaner frame (right)



Step 3 - normal frame (left) and leaner frame (right)

Figure 12. Pushover moment of normal frame (left) and leaner frame (right)

The behaviour of the exterior frame that did not resist any moment can also be seen in plastic hinges location as displayed on Figure 13 and 14. In normal frame structure, hinge failure happen in all location, mainly beam hinges. In the inputted displacement, some of the hinges also already in LS state, indicating that there are already plastic hinge happen. In other place, the leaning frame only have plastic hinges at interior structure, therefore the exterior structure is remain intact from the lateral loads. This is will make exterior structure safe from any kind of seismic activity, and the section is not damaged and can be used again. In other hand, the interior structure of the leaning frame did receive more forces, but this can be overcome by making a core wall system to resist lateral forces.

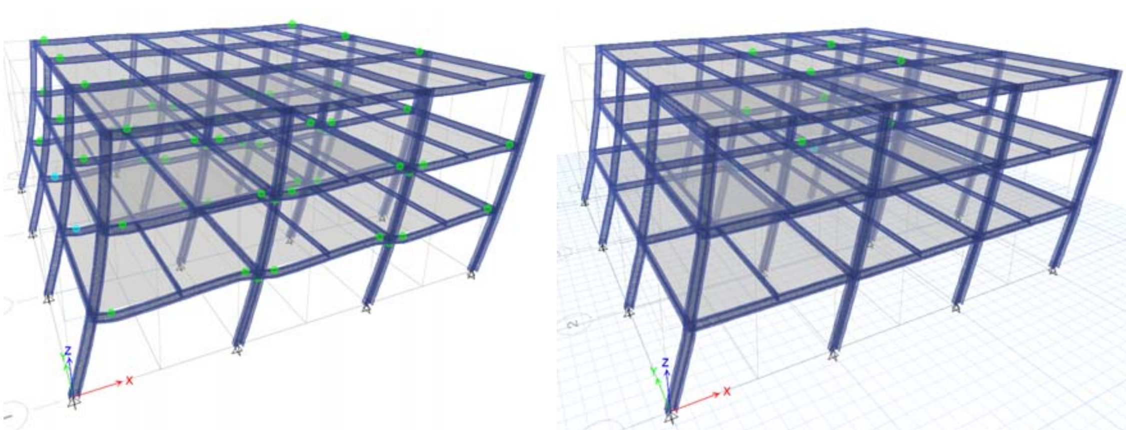


Figure 13. Plastic hinges location of normal frame (left) and leaner frame (right)

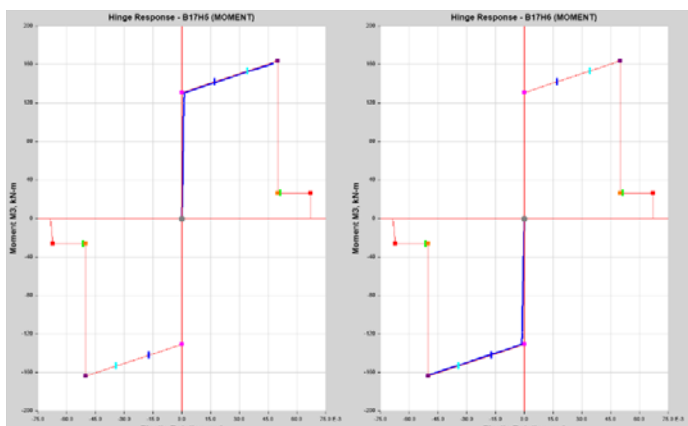


Figure 14. Interior frame plastic hinges of normal frame (left) and leaner frame (right)

Performance point is the point where the capacity spectrumintersects the appropriate demand spectrum. From figure 13 below, the performance point is shown between the normal frame and leaning frame. Green line indicating capacity curve and red line indicating single demand curve. In normal frame spectral displacement is observed 211mm and spectral acceleration of 0.3g, however the leaning frame system did not met the performance point criteria thus the building need to reinforced more.

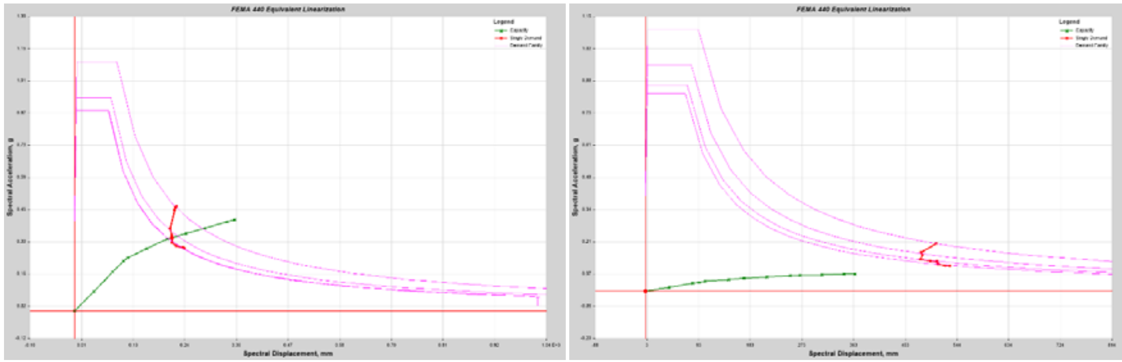


Figure 15. Performance point of normal frame (left) and leaner frame (right)

CONCLUSION

Reuseability is capability of a structure to be able to used again after being damaged, example from earthquake. From the nonlinear static pushover analysis, leaning column are proven to be not damaged in an event of earthquake which indicated by no moment occurred in exterior frame. This make leaning column are a reuseable section when an event of earthquake come.

However, the interior frame is subjected to much higher lateral forces, but this can be overcome by adding core shear wall on the centre of building.

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