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Seismic Performance of Disjointed Horizontally Irregular Building by Remodeling the Column and Beam

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Abstract. Introduction to the seismic parameter for structural analysis has increased the awareness of better quality for a building to reach safety purpose limit. Considerably, the configuration and shape of the building must be restricted to the regular one. This paper will harness horizontally irregular building to be remodeled into several regular buildings. Furthermore, linear dynamic analysis by using response spectra is harnessed for gaining behaviour of the buildings and capacity of structural members. Beams are chosen to be discontinuous at several corners to create separation on the building; hereinafter, console beam system is implemented. Next, the double column is utilized to obtain the separation of the horizontally irregular building. Entirely, the discontinuity issue of applying dilatation leads to the behaviour of the building and capacity of the structural member inside. Further discontinuity distance which is shown in a double column system can be settled down by applying dilatation in the accurate building axis so that the failure will not be severe or simply deducting the gap between twin columns. In contrary, console beam satisfactorily behaves in order to decrease horizontal irregularity even turn it into the regular building. Moreover, the capacity of the building can be significantly enhanced as the shear wall is installed.

Keywords: Horizontal irregularity, double column, console beam, shear capacity, flexure capacity.

1 Background

Structural problems may arise due to several problems such as external load, properties of the structural member, the geometry of the structure, and so on. Particularly in reinforced concrete structure, many factors contributed to the deterioration of it which can be summarized as follows: (1) errors in design assumptions (or design processes), (2) specifications or use of inappropriate materials, (3) poor workmanship, (4) environmental effects, (5) overloading due to under-design or change of use, (6) accidental effects such as fire, and (7) inappropriate repairs [1]. Concerning on one of the environmental effects

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namely earthquake which occurrence cannot be easily predicted, whereas the design consideration has already been included for many structures in Indonesia since big earthquake experiences in the past years. The seismic risk of a structure is a measure of expected future damage caused by the earthquake which is expected to occur in the construction site [2].

1.1 General

Seismic design for most structures will be better considered starting from low to high rise building either using static or dynamic analysis. Seismic forces very rapidly with time. Therefore they impose a dynamic loading on buildings [3]. The rotational response of building structures during strong ground motions has been proved to be the main cause of partial or total collapse [4].

There are several aspects created good seismic behaviour which are proper seismic structural configuration, lateral stiffness, lateral strength, and ductility. In terms of structural configuration, building geometry provides a high contribution to how the failure will be; so that some prevention during the design process must be detail analyzed. For instance, structures with concave geometries are preferred to those with concave geometries, as the former demonstrates superior earthquake performance [5]. Except, some other categories of building geometry in horizontal and vertical direction will result in a different seismic response.

Introducing irregularity of the building structure will result in the critical behaviour of the structure under earthquake in terms of period, drift, displacement, base shear, and so forth. This will incur several steps to be chosen for design consideration. Torsion due to large drift, re-entrant corner, and diaphragm discontinuity are some criteria for being said as a horizontal irregularity. The otherwise soft story, mass irregularity, and discontinuity of lateral resisting element are categorized as a vertical irregularity. Certain seismic design category will not allow for several types of irregularity to exist in the building especially for E and F seismic design category [6].

Some solutions come up in order to advance the seismic behaviour of a structure such as installing earthquake resistant system and improving building geometry so that the concentration of the load can be disjointed into another part of the building. A shear wall, bracing, the outrigger is some of the systems which can be selected for strengthening the building capacity under lateral load e.g. earthquake. The behaviour of shear wall is identical with cantilever beam if it is installed for high rise building whereas flexural behaviour is predominant. Nevertheless, the shear behaviour will eminently act once the shear wall is attached to low rise building [7].

Modification on the building geometry through dilatation has been suggested to create disjoint which is usually placed in the building intersection floor plan. The double column is the simplest way to disjoint the building plan; furthermore, it will strictly separate the building plan into another block of the building. Besides, console beam (also known as corbel) can be another recommended solution for disjointing the building plan. The term "corbel" is generally restricted to cantilevers having shear-span depth ratios less than unity. Such a small ratio causes the strength of corbels to often be controlled by shear, which is similar to deep beams [8].

1.2 Modelization of structure

The geometry of U-shaped building from the existing building in East Jakarta called Heliconia Apartment Tower of Bassura City will be utilized by applying double column and console beam system for disjointing the building shape into more regular shape. This apartment consists of 25 floors with a typical floor plan. Originally, some floors are in the basement, lower ground, ground floor, and roof level having different height; but in this paper, we model the uniform 2.8 *m* height for each floor in order to make sure that vertical irregularity does not exist. Analogously with height, the properties of the structural members are synchronized to be the same properties and dimension from top to bottom floor.

Symmetric floor plan of this apartment has been identified of re-entrant corner horizontal irregularity in both *X* and *Y* direction which are 48% and 63% respectively. The placement of the shear walls is also symmetric as served in figure 1. Lateral-load-resisting systems consisting of identical and regularly spaced plane frames, with all bays having the same length and member cross-sections; will also have uniformly distributed seismic demands [9]. For further analysis, we also model the building without the shear wall for developing better discussions due to application dilatation proposed in this paper.

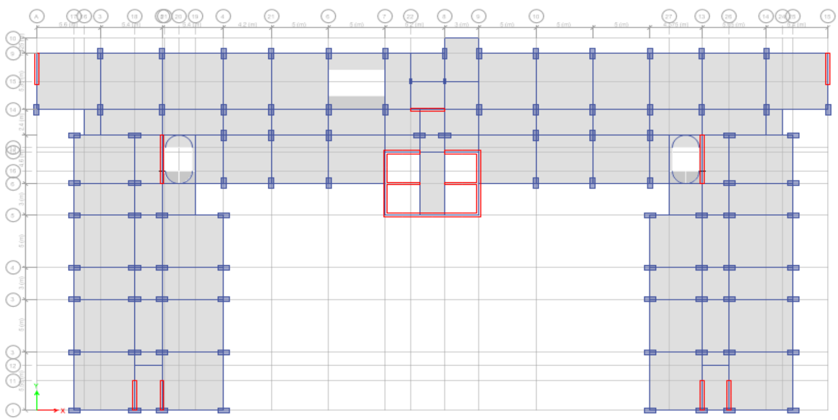

Fig. 1. Floor plan of Heliconia Apartment Tower

As mentioned before, double column and console beam are sorted for the dilatation adoption where four models (M1 to M4) are shown in figure 2. Model M1 and M3 are detected to have a re-entrant corner, whereas M2 and M4 are deployed into three regular buildings independently. Modelization and analysis will accommodate ETABS v.13 commercial software where some idealization and limitation rise during modeling.

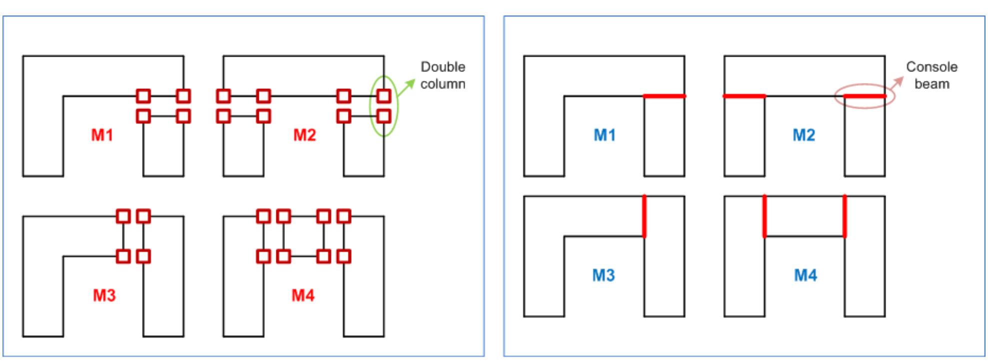

Fig. 2. Double column and console beam placement for each model

Application of twin identical column as the main column is placed in the distance of 3 *m* for M1 and M2, otherwise, M3 and M4 is 4 *m* between them. The analysis was conducted in one file for each model which resulted in one compact building analysis even though the floor plan has been separated due to the double column application. Henceforth, idealization of console beam is established by modifying one-end support restraint into the roller. Shear wall, non shear wall, double column, and console beam will be noted as SW, NSW, DC, and CB consecutively. Replacing the shear wall with columns is taken into consideration for modeling the non-shear wall model in ETABS. Besides the shear wall, the existing diaphragm wall in the basement is attached in the analysis for both SW and NSW system.

1.3 Structural parameter

Material properties, the dimension of a structural member used, load cases, and response spectra parameter needed for the analysis are described in this section. Table 1 informs the typical dimension for column, beam, slab, and wall for the whole member structure as well as the material properties of those members.

Table 1. Properties and dimension of the structural member

No.	Structural member	Dimension (*mm*)	Material properties (*MPa*)
1	Column	K1H-1H -- 450×1000	44.13
2	Beam	G34A-1 -- 300×450	34.23
3	Slab	130 200	34.23 34.23
4	Wall	W1H-1 – 350	44.13

Regarding seismic design, reference code of SNI 1726-2012 is used for design consideration of building under earthquake which mostly refers to FEMA, IBC, and ASCE code. The load cases are derived into18 combinations which are mainly seen in equation (1) through (6). Based on soil investigation, characteristic of the hard soil was identified so that the site class C can automatically be referred to seek the S_{DS} and S_{D1} values which are $0.516g$ and $0.301g$ respectively.

$$1.4\ DL \quad (1)$$
$$1.2\ DL + 1.6\ LL \quad (2)$$
$$1.2\ DL + 1.0\ LL \pm 0.3\ (\rho\ Q_{EX} + 0.2\ S_{DS}\ DL) \pm 1.0\ (\rho\ Q_{EY} + 0.2\ S_{DS}\ DL) \quad (3)$$
$$1.2\ DL + 1.0\ LL \pm 1.0\ (\rho\ Q_{EX} + 0.2\ S_{DS}\ DL) \pm 0.3\ (\rho\ Q_{EY} + 0.2\ S_{DS}\ DL) \quad (4)$$
$$0.9\ DL \pm 0.3\ (\rho\ Q_{EX} - 0.2\ S_{DS}\ DL) \pm 1.0\ (\rho\ Q_{EY} - 0.2\ S_{DS}\ DL) \quad (5)$$
$$0.9\ DL \pm 1.0\ (\rho\ Q_{EX} - 0.2\ S_{DS}\ DL) \pm 0.3\ (\rho\ Q_{EY} - 0.2\ S_{DS}\ DL) \quad (6)$$

Linear dynamic analysis for the seismic design is chosen by harnessing response spectra curve as expressed in figure 3. A response curve is a graph of maximum, or spectral, response of a range of single degree of freedom oscillators to a specified ground motion, plotted against the frequency or period of the oscillators [10]. Input of response spectra to the ETABS will be translated into lateral force in *X* and *Y* direction of the building plan with 5% damping.

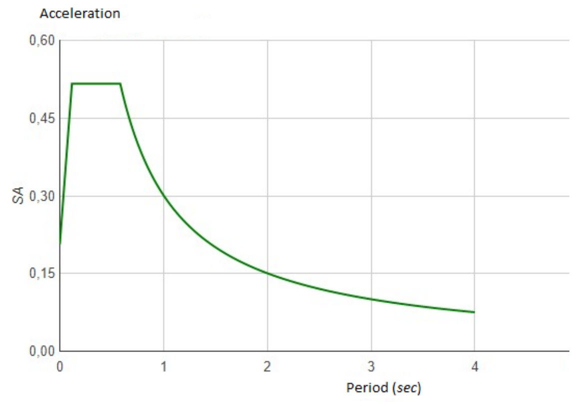

Fig. 3. Response spectra curve for site class C

2 Behaviour of structure

All buildings deform to some extent as they are shaken, and the deformation of the building substantially alters the force distribution. Small, massive buildings are relatively stiff, but as buildings become taller and lighter they tend to become more flexible [11]. Deformation is noticed to be one of the parameter indicating the behaviour of the structure under load. Limitation of displacement and drift must be fulfilled so that the building can be safely occupied later. Besides, some other parameters will be discussed in this chapter such as period, frequency, and base shear so that we can conclude which type of dilation is best applied.

2.1 Period of structure

The natural period of a building is the time taken by it to undergo one complete cycle of oscillation. The reciprocal of the natural period of a building is called natural frequency [5]. Comparison of several models built in this paper can be detail observed from figure 4. Simply discussed that the existing building results in the same period as the console beam model has proven the discontinuity created by implementing this type of dilatation will give a better result than a double column.

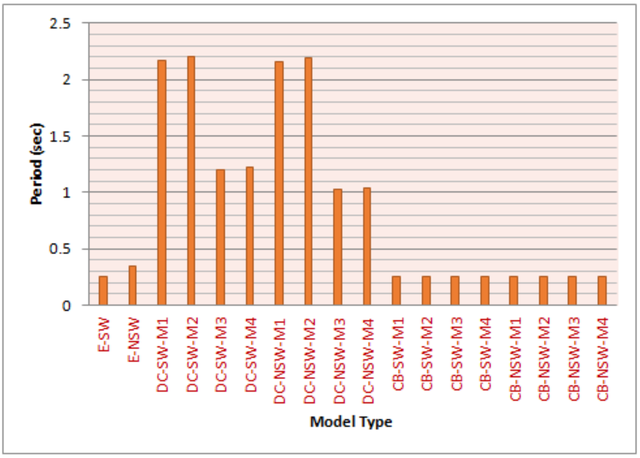

Fig. 4. Period of structure for all model types

Console beam does not give a significant difference of period for any model type even for SW and NSW. Application of SW results better 1% period than NSW since the discontinuity of the all structural system is convincible. Existing (E) building needs the same period with any kind of SW model to complete one cycle. In contrary, experiment for the NSW model will give the satisfying result as the console beam applied. It may improve the period almost 30% as we applied the console beam in any model type.

The gap between twin columns for double column system delivers higher period for any SW and NSW model type. Shear wall contributes less well in absorbing the energy from the earthquake so for SW-M1 and SW-M2 model type compares to SW-M3 and SW-M4. The irregularity of SW-M1 and SW-M2 model still exists noting that the period of these two models is reaching 9 times greater than the existing building. Basically, the same trend also happens on the NSW model, but the period resulted due to applying double column is smaller than E-NSW system about 6 times. Focusing on the output of period of structure, CB is stiffer than DC and the SW is more flexible than NSW.

2.2 Displacement versus base shear

Base shear can be generally determined by the multiplication of structural mass and seismic response coefficient [12]. This value will be equal to the seismic force that can be resisted by the building after being divided into other direction of the building (*X*, *Y*, and *Z* direction). On the other hand, displacement is the value of deformation compared to the base of the building. The main concern in this section will be top displacement which value will be related to the base shear of the building as shown in figure 5.

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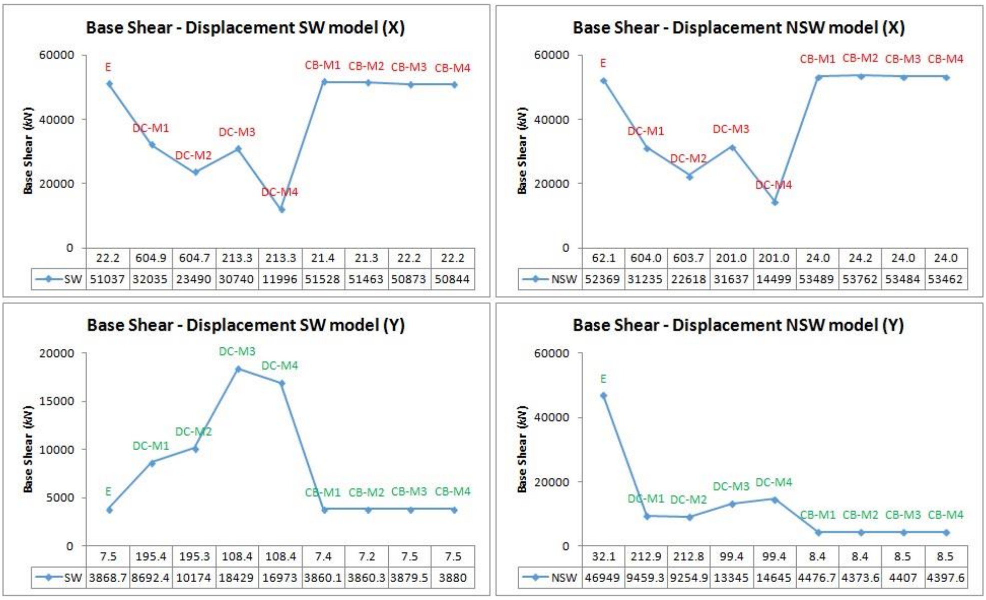

Fig. 5. Base shear versus displacement in *X* and *Y* direction

The highest displacement value is reached in *X* direction particularly for DC-M1-SW, DC-M2-SW, DC-M1-NSW, and DC-M2-NSW model. They reach 604 *mm* displacement value measured from the base floor, which bases shear value about 32,000 *kN*. DC model shows better displacement value once the base shear is small, next it informs the dilatation direction is better given in *Y* direction. Smaller base shear in *X* direction will also give smaller displacement. Discontinuity in *Y* direction will not create a bad effect on the displacement value than *X* direction as the strong axis of the building, as the maximum displacement value in *Y* direction only one third from the *X* direction. In contrary, higher base shear in *Y* direction resulted in smaller displacement. We may conclude that giving dilatation in strong axis will not be suggested. Furthermore, the contribution of shear wall is not much in preventing high deformation.

Fascinatingly, the CB model does not give a different result with E-SW and E-NSW model. The displacement and base value are slightly constant for any applied direction of dilatation. It is suggested to modify the dilatation on the strong axis of the building since the displacement provides better behaviour. The role of shear wall is successfully gained in controlling displacement up to 10% from NSW model.

The former discussion indicates that CB model provides better displacement value than DC. Consideration of putting dilatation direction is better in the strong axis direction of the building since applying in weak axis will only result in less bad displacement value for both directions. In order to increase the deformation behavior, we can simply take advantage of a lateral resisting system such as a shear wall.

2.3 Drift

Besides displacement, detail deformation behaviour of each story based on drift value can be obtained. Drift is defined as the lateral displacement of one floor relative to the floor below. Drift control is necessary to limit the damage to the interior partitions, elevator and stair enclosures, glass, and cladding systems [13]. As the building has no irregularity in the vertical direction, we can make sure that the stiffness for each floor is appropriate to resist lateral load so that the drift in each floor can be well controlled as provided in E-SW model.

Figure 6 presents drift value in the strong axis direction of the building where the DC system contrast varies to the CB system.

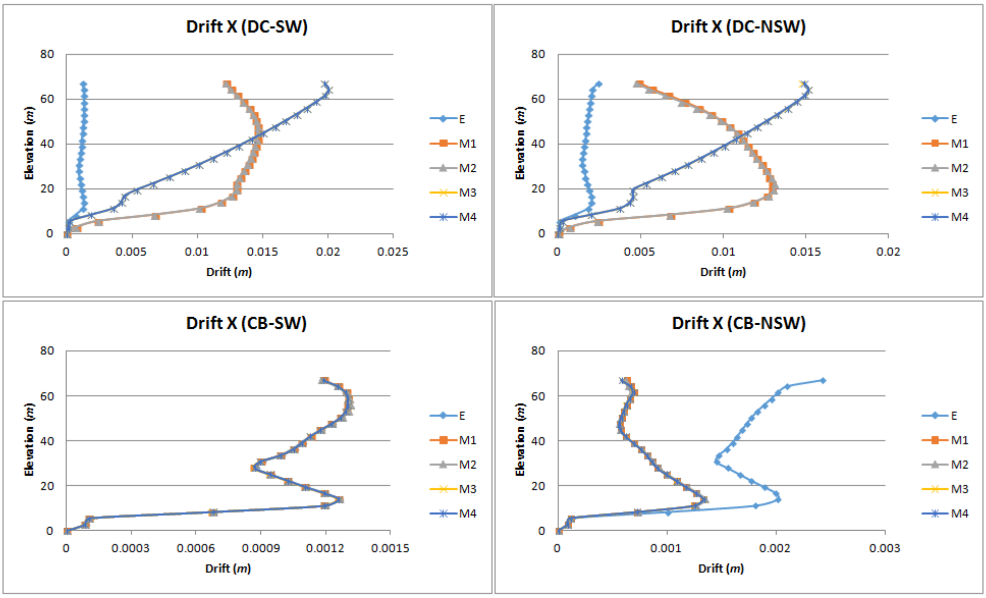

Fig. 6. Drift *X* for DC and CB system

Existing building with the shear wall has higher rigidity so that the drift value is smaller than the E-NSW model. As the dilatation attached, DC-SW and DC-NSW behave more flexible than the existing model. DC-SW-M1 and DC-SW-M2 produce the highest drift at 17F (44.8 *m* high), otherwise DC-NSW-M1and DC-NSW-M2 results the greatest drift at 7F (22.4 *m* high). Story rigidity results better for NSW where the dilatation applied in the strong axis, which presents lower ductility behavior than the SW system. Worse condition occurred when the weak axis dilatation set (DC-M3 and DC-M4), the flexible story continues more as the building height advances. Nonetheless, top displacement on DC-M1 and DC-M2 is about 3 times higher than DC-M3 and DC-M4.

Next, both CB system performs alike the existing building, especially CB-SW system. None of the direction of dilatation creates differences for the whole model. At the height of 58.8 *m*, the drift reaches maximum value among all floors for all model types. Uniquely the maximum drift value also resulted for CB-NSW model; however, the location is still on the floor height of 14 *m*. As we concern the non shear wall model, the drift of the existing model seems to be more ductile due to higher drift. Clearly, modifying the beam into console beam will produce smaller drift so that the seismic behaviour can be upgraded.

Noting that *Y* direction is the weak axis of the building, the drift also results in smaller values than the strong axis. Different maximum drift location from strong axis direction, DC-SW, and DC-NSW for M1 and M2 occurs below the 7F of the building. Other facts of drift behaviour are just the same as strong axis direction as detail seen in figure 7.

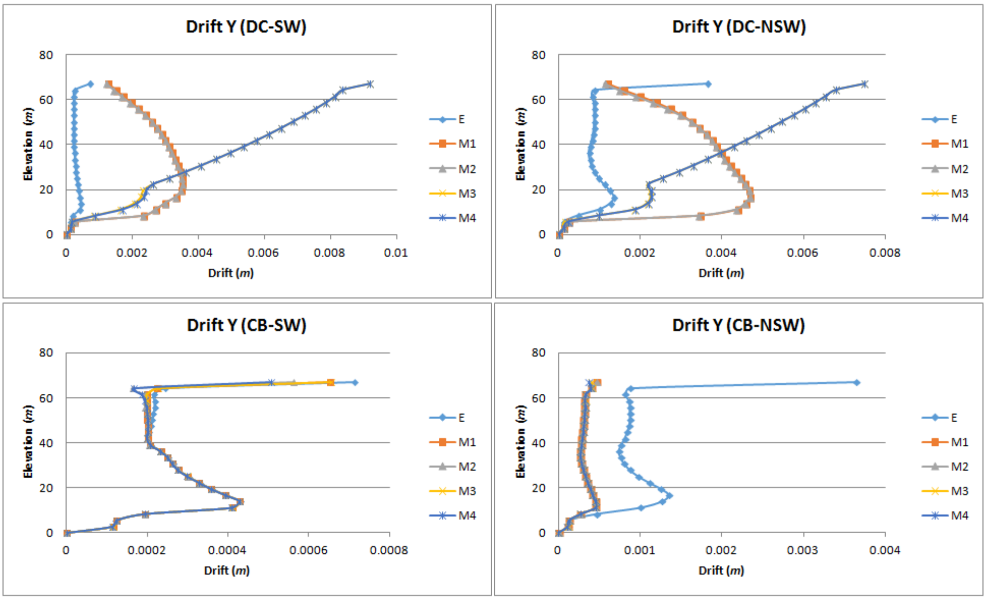

Fig. 7. Drift *Y* for DC and CB system

Wholly, CB proves better behaviour in terms of drift for any placement of the console beam to the existing building. Maximum drift in both axes of building describes flexibility in NSW model; henceforth the installation will increase the stiffness of the building due to the absence of vertical irregularity. Discontinuity of the dilatation results in an inappropriate response of the whole building system as discussed above.

3 The capacity of the structure member

Principally, there are two prominent member structures discussed in this chapter including beam and column. The location of each structural member can be referred in figure 8. Some judgments did during remodeling the building may appear deviation so that we will deal with them in order to conclude best.

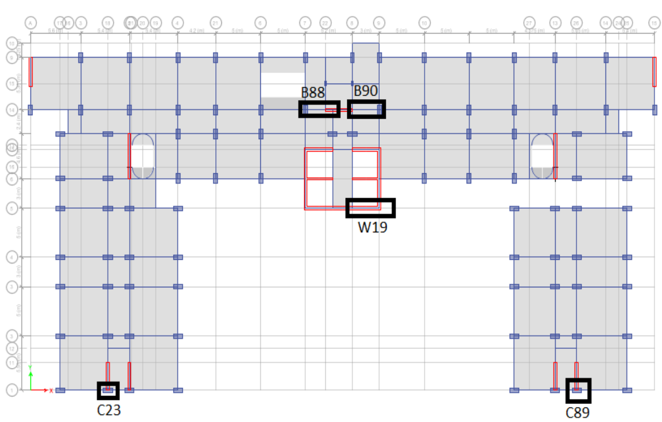

Fig. 8. Selected member structures (beam and column)

3.1 Beam

Shear and flexure capacity of the beam will focus on B88 and B90 as noted in figure 8. We limit some values to be presented in the table, but the rest is slightly different from the existing building. Basically, lower results of shear capacity and flexure capacity are shown for both DC-SW and DC-NSW model compare to existing. In contrary, random values are served for CB-SW and CB-NSW, where most of the values are for CB-SW almost the same value with the existing. Meanwhile, CB-NSW shows smaller value than existing.

Table 2. Beam capacity at 15F

Model	B88		B90	
	Shear Capacity (*kN*)	Flexure capacity (*kN.m*)	Shear Capacity (*kN*)	Flexure capacity (*kN*)
E-SW	269.75	152.02	118.20	157.41
E-NSW	169.15	137.14	81.09	61.21
DC-SW-M1	268.34	151.65	117.44	156.17
DC-SW-M2	267.97	151.54	117.05	155.58
CB-SW-M1	270.33	152.30	118.58	157.89
CB-SW-M2	270.34	152.30	118.58	157.89
DC-NSW-M3	167.14	136.48	78.97	58.49
DC-NSW-M4	167.20	136.32	78.73	58.42
CB-NSW-M3	167.00	135.67	75.51	54.26
CB-NSW-M4	166.43	135.45	75.63	54.37

Associated with those statements, the capacity of the beam is better for CB system rather than DC. As shear wall functioned as resisting lateral load, some amount of the load can be taken over resulting higher shear and flexure capacity resisted. The installation of the shear wall may reach two times of non shear wall system beam capacity.

3.2 Column

Measuring the capacity of the column can benefit the interaction diagram between axial and moment of the given section property. In this paper, we did not modify the column section as the corbel existed to disjoint the horizontal irregularity of this building so that the column capacity will be based on the same given property as the existing. The modification of the corbel on the column should be concerned especially when transferring the load to the ground floor. One solution can be the addition of new columns or arrangement of the shear wall [14]. However, adjusting the end restraint of the beam precisely at the outer column surface has already been useful to see the different behaviour among existing and double column system.

Referring to figure 9, the column capacity of DC and CB system are well established so that the failure of C23 and C89 which is located at the basement floor can be identified. Generally, the failure of the column is due to axial, however, some of the DC-NSW columns are failed due to both axial and flexure. Pointing out to that failure, the section property of a K1H-1 column is still able to resist the load so that massive failure does not occur.

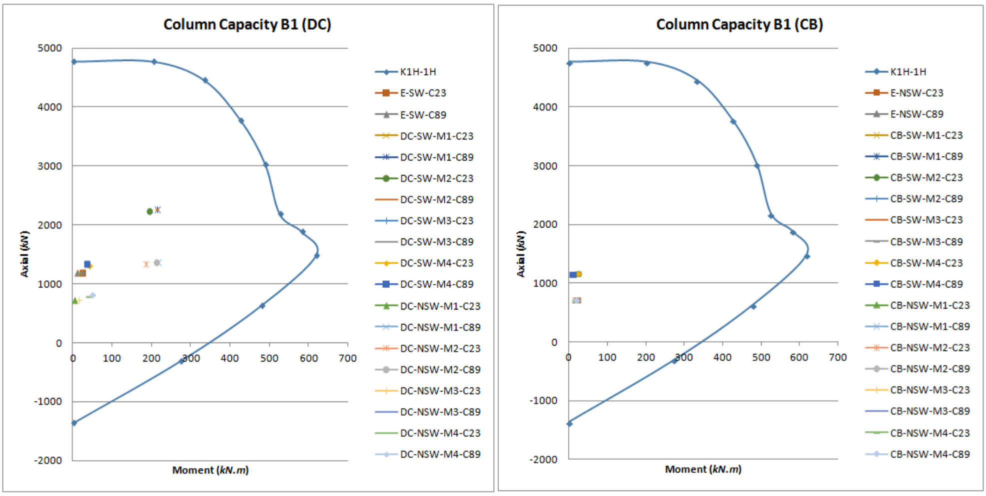

Fig. 9. Column interaction diagram of K1H-1H

Dissimilar performance of column for CB-SW and CB-NSW system indicates axial failure only. Load transmission of the CB system is relatively uniform so that the beam and column act well as a unit in resisting the load. Most flexure can be strongly guaranteed by the beam instead. Frankly, CB also grants better column capacity than DC due to the very small discontinuity.

4 Conclusions

Restricting some considerations for this building into horizontally irregular only has led some interesting summaries related to the choice of dilatation by harnessing double column and console beam system for this U-shaped building so that it can reach better behaviour. The previous study regarding the existing building (with vertical irregularity) will enrich the following conclusions:

(a). Remodeling the column into twin columns (DC) must adjust the distance gap between so that the discontinuity can be significantly lessened. Reviewing the distance by checking the allowable maximum displacement can be one way to set the most considerable distance. Assignment of the best dilatation direction will increase the performance of the building.

(b). Console beam is proven to be successful to disjoint the building plan either since the discontinuity yielded by this system is relatively small. Further analysis of the console failure should be taken into consideration in order to reach the better ductile structure. The direction of dilatation does not affect the behaviour and capacity much.

(c). Comparing to an existing building (with vertical irregularity exist), this model has a higher mass so that DC performs slightly better. However, CB is a highly recommended alternative.

(d). It is tremendously suggested to have better modelization in the future particularly to the column section close to the real shape of the console so that the column capacity will be able to accurately discuss.

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