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PERFORMANCE BASED SEISMIC EVALUATION AND RETROFITTING OF UNSYMMETRICAL MEDIUM RISE BUILDINGS- A CASE STUDY

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ABSTRACT:

Most of the low/medium rise residential buildings are often built with irregularities such as soft/weak storey, torsional irregularity, vertical and plan irregularity, unsymmetrical layout of in-fill walls etc. Post earthquake studies show that the most of the reinforced concrete buildings having such irregularities were severely damaged under strong seismic ground motion. This paper presents an overview and case studies of performance based seismic evaluation and retrofitting of such buildings with special emphasis on performance based approach, using full nonlinear-dynamic analysis. These buildings have un-symmetry in lateral load carrying capacity in both plan and elevation. Several retrofitting techniques such as addition masonry infill wall, column jacketing with reinforced concrete, and application of buckling restrained braces are studied in order to improve the overall seismic performance of such irregular buildings. Moreover, effects of each retrofitting techniques on the overall performance of buildings are presented.

KEYWORDS: Structural Irregularities, Performance Based Design, Buckling Restraint Braces, Nonlinear Dynamic Analysis, Gravity Load Designed

1. INTRODUCTION

Reinforced concrete (RC) buildings primarily designed to resist gravity load with little or no seismic resistance are often called “Gravity Load Designed (GLD) buildings”. In developing countries, due to lack of expertise in design concept and construction practices, many buildings are GLD buildings. The seismic performance of GLD buildings is very poor due to non-ductile reinforcement detailing and inappropriate proportioning of beams and columns which results in strong beam-weak column behavior. Furthermore, GLD buildings are not designed based on modern seismic building codes. Therefore, most of them have irregularities such as soft story, setback, unsymmetrical plan, etc which make it difficult to predict the behavior of the buildings when subjected to earthquake. Most of the time, instead of enhancing the seismic performance, these irregularities are indeed making the condition become worse. The condition becomes completely worst if the buildings are located in seismic prone areas with high seismic activity. If an earthquake with strong ground shaking happens, it will cause collapse of the buildings as well as loss of lives and materials as seen in many past earthquake disasters.

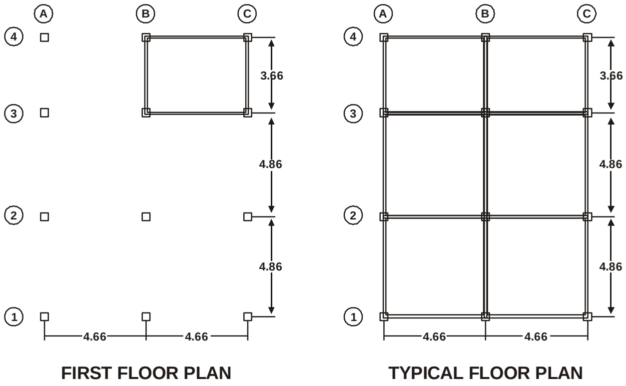
In order to prevent future disasters, these GLD building need to be retrofitted to enhance the performance under earthquake. One of the most important developments in earthquake engineering in recent years is the introduction of designing “damage controlled structures” (Huang et al., 2001). The basic idea of this concept is a global structure mainly consists of a primary structure and an auxiliary structure in which the primary structure will remain elastic even under strong earthquake while the auxiliary structure will take all of seismic forces. Damages will only occur in the auxiliary structure in which the damaged elements can be replaced after the earthquake and the structure remains operative even under strong earthquake. This “damage control” concept can be applied not only for designing new structures, but also for retrofitting existing structures. Furthermore, this concept fits well with the condition of GLD buildings in which the primary structures are not designed to resist earthquake loading.

This paper presents performance based evaluation and retrofitting of unsymmetrical/irregular buildings with several retrofitting methods, demonstrated by case study. Retrofitting techniques such as addition of masonry infill walls, column jacketing with reinforced concrete, and application of buckling restrained braces are presented in order to improve the overall seismic performance of such irregular building. The effectiveness of retrofitting techniques is in terms of enhancing the seismic performance of GLD buildings. Other factors such as cost, time, and aesthetics are not considered in this study.

2. BUILDING CONSIDERED

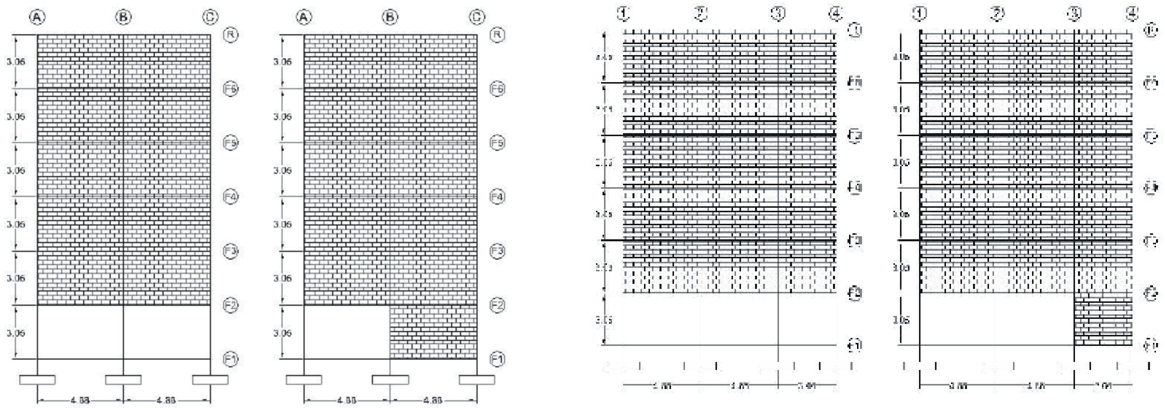
A typical six story residential building with a soft/weak first story taken from field survey data in Bangladesh is chosen to be investigated in this study. From statistical analysis, soft/weak first story is the most common type of irregularity found in GLD buildings in Bangladesh.

The building has two identical spans with 4.88 m length in X-direction whereas in Y-direction it has two long spans with 4.88 m length and one short span with 3.66 m length. The story height is same in all floors which is 3.05 m. Furthermore, the GLD building investigated has soft story in the first floor due to absence of infill walls. In the first floor, the infill walls are only in the corner part of the building plan while in other floors the infill walls are distributed well in the building plan. This arrangement of infill walls in the first floor is probably due to the function of the first floor as a car park area. The details of building plan and elevation view as well as infill walls configuration can be seen in following figures.



FIRST FLOOR PLAN TYPICAL FLOOR PLAN

Figure 1: Building Floor Plan



ELEVATION VIEW 1 AND 2
ELEVATION VIEW 3 AND 4
ELEVATION VIEW A
ELEVATION VIEW B AND C

Figure 2: Building Elevation

Note that in Figure 1, the dotted lines refer to infill walls with openings (for doors, windows, etc). The infill walls with openings are assumed to have less stiffness as compared to solid infill walls (23% reduction in the wall stiffness).

The columns and beam details are presented in table 1 and building properties in table 2.

Table 1: Columns and Beam Sizes

Section	**Size (b x d) (mm)**	**Longitudinal Reinforcement**	**Transverse Reinforcement**
Column	356 x356	12D16	3D12@152
Beam	254 x457	4D16(top); 3D16(bottom)	3D12@152

Table 2: Summary of Building's Data

Concrete strength	17 MPa	Infill wall thickness	127 mm (5 inch)
Rebar strength	454 MPa	Superimposed dead load	75 kg/m^2
Masonry prisms strength	9 MPa	Design live load	200 kg/m^2
Slab thickness	152 mm (6 inch)	Effective live load	20 kg/m^2

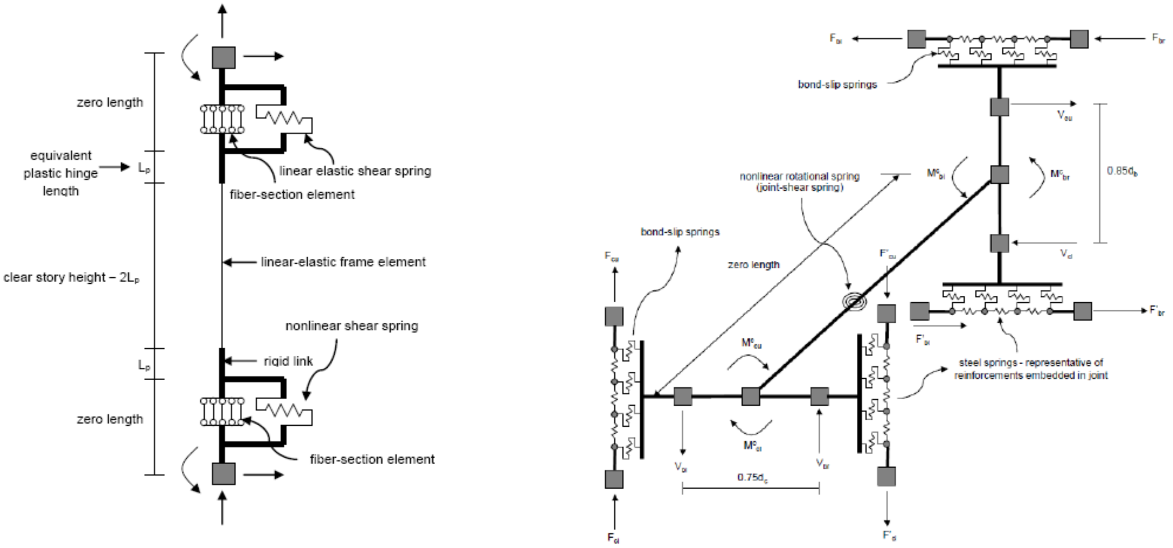
3. MODELING OF RC STRUCTURE

In this study, OpenSees is used as a computational platforms used. OpenSees is being used widely nowadays to perform numerical simulation in the field of earthquake engineering. It provides many benefits for its users and serves as a powerful tool for numerical simulation of nonlinear systems.

The RC column and beam model are adapted from Suthasit (2007) which is able to simulate flexural failure, bond failure in lap-splice region (lap-splice failure), and shear failure. The architecture of the model can be seen in Figure 3. This model has been verified by Chandra (2009) and Rayamajhi (2009) with some experimental results and the comparisons between them show that this model can simulate quite well many possible failure mechanisms including the brittle ones.

A RC beam-column joint model developed by Suthasit (2008) that can simulate some deformation modes such as bond slip rotation and joint shear rotation is used in this study. The model architecture can be seen in Figure 3. The verifications of the model can be seen further in Chandra (2009) and Rayamajhi (2009).

In this study, a general approach for modeling of infill wall recommended by FEMA 356 (2000) is adopted. In this approach, the infill wall is modeled as a single equivalent diagonal compression strut with the same thickness and modulus of elasticity as the infill wall. BRB is modeled as a truss element with pin connection at both ends. The RC slab is modeled as rigid floor diaphragm and foundation modeling was done with fixed support.



(a) Modeling of Columns/beams (b) Modeling of beam column joint

Figure 3: Modeling of Building Components

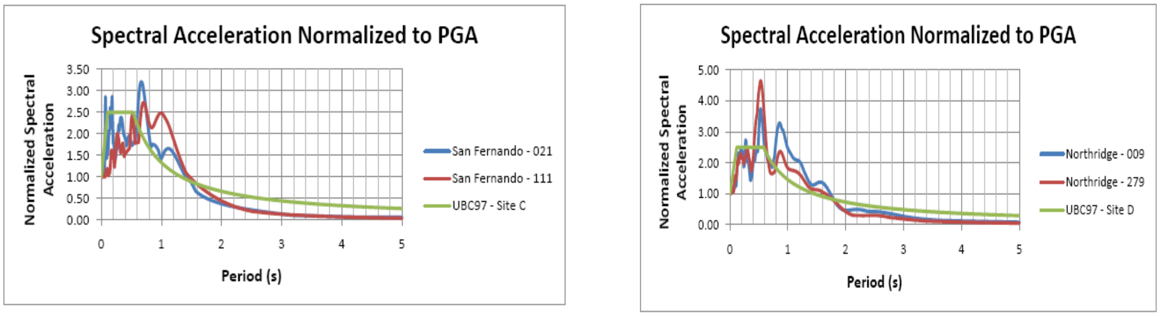
4. ANALYSIS METHOD

In this study, the seismic performance evaluation of the buildings is carried out by 3D nonlinear dynamic time history analysis. Two sets of ground motions taken from PEER Strong Motion Database NGA Project are used in this study. They are San Fernando (1971) earthquake and Northridge (1994) earthquake

Table 3: Characteristics of Ground Motion Records

Earthquake Name	Year	Earthquake Magnitude	EpiD (km)	Soil Class	PGA (g)	PGV (cm/sec)	PGD (cm)
San Fernando	1971	6.6	26	C	0.12	15.12	2.33
Northridge	1994	6.6	13	D	0.46	54	12.06

The original of these ground motion records as well as the spectral accelerations with 5 % damping normalized to peak ground acceleration (PGA) in both directions (x and y) with UBC 97 spectrum in respective site class.



(a) (b)

Figure 4: Scaled Response Spectra of Ground Motions with UBC 97 Spectrum

These ground motions later are scaled to simulate moderate, strong, and severe earthquakes. The summary of scale factors used and the respective PGA of each ground motion in both directions are presented in Table 4.

Table 4: Summary of Scale Factors Used and the Respective PGA of Each Ground Motion

Earthquake	San Fernando (SF) (1971)			Northridge (NR) (1994)		
Intensity	Scale factor	PGA-X (g)	PGA-Y (g)	Scale factor	PGA-X (g)	PGA-Y (g)
Moderate	1.6969	0.1872	0.2452	0.4354	0.1810	0.2249
Strong	2.5454	0.2808	0.3678	0.6531	0.2715	0.3374
Severe	3.3938	0.3744	0.4904	0.8708	0.3620	0.4498

5. RETROFIT SCHEMES

The performance objectives of the retrofit schemes are to improve the seismic performance of the GLD building by preventing soft story mechanism, to reduce building's global displacements, interstory drifts, and building's damages. Furthermore, the retrofit schemes selected should not have major effects to the building's occupancy or function. They should be applied in such a way that modification or disturbance to the building's occupancy or function is kept as minimum as possible. The seismic performance of the GLD building is poor due to soft story that exists in the first floor. This attracts deformation demand to be concentrated on the first floor and leads to soft story mechanism. Therefore, the retrofit strategy should aim for strengthening and stiffening the first floor so that the soft story mechanism will not occur and the deformation demand can be well distributed throughout the building. However, when strengthening and stiffening the first floor, it should be estimated properly so that the first floor will not be so strong or stiff that the damage will shift to other floors. This may need iterative process to find the optimum solution.

In this study, two methods of retrofitting have been carried out. First method is the combination of two traditional ways of retrofitting i.e. concrete jacketing and adding infill walls. Second method is using BRB.

5.1 Concrete Jacketing and Adding Infill Walls

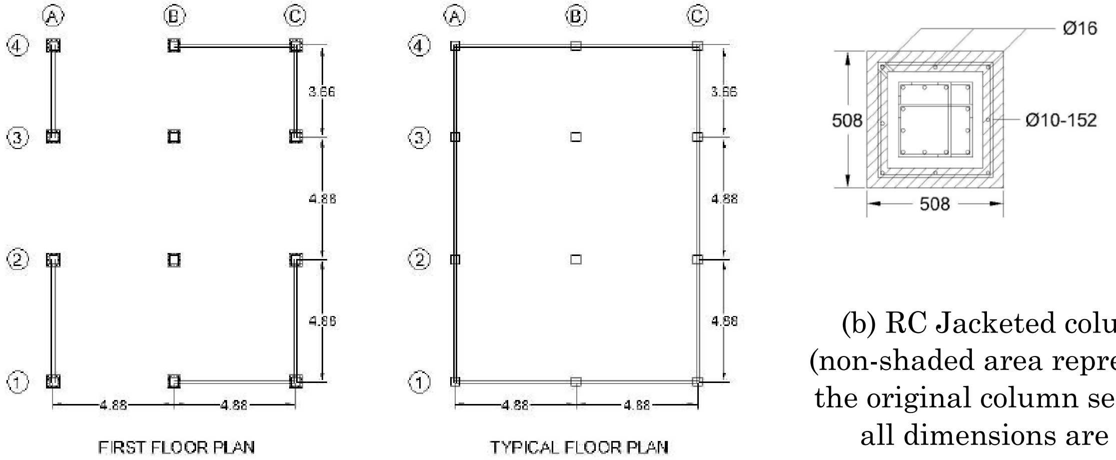
Both concrete jacketing and adding infill walls are simple traditional way of retrofitting. In this study, concrete jacketing is applied on all columns in the first floor to increase the story strength and stiffness as it is the weakest part of the building. Furthermore, several trial cases have been made to find the optimum solution for the retrofit scheme. However, from the preliminary analysis, it is found that concrete jacketing alone cannot give the desired performance objectives.

The addition of masonry infill walls can increase story strength as well as story stiffness. Nevertheless, in this case, it may need many additional infill walls in the first floor in order to provide enough additional lateral strength and stiffness so that the soft/weak story behavior can be avoided. Since the first floor is functioned as a car park area, thus addition of many infill walls which will cause major disturbance to the building's function is not allowed. Therefore, it can be concluded that this technique cannot satisfy one of the basic design considerations.

In this study, a combination of these two techniques is proposed. This combination is expected to yield a better solution which can satisfy the basic design considerations. This retrofit scheme from now on is referred as CJW scheme. In this scheme, all RC columns in the first floor are jacketed as shown in Figure 11. The jacketed section uses the same material properties as the original one. Furthermore, additional infill walls in the first floor are designed in such a way that they will provide enough additional lateral strength and stiffness to the first floor while keeping minimum modification or disturbance to the building's occupancy or function. This additional infill walls configuration is arranged symmetrically to avoid any torsional irregularity which may cause deformation demand to be concentrated only on some particular frames. Moreover, all interior masonry infill walls in the second to sixth floor are removed and changed with light partitions in order to reduce the story strength and stiffness of other floors. Thus, it is expected that soft/weak story behavior can be avoided and the performance objectives of the retrofit scheme can be achieved. The scheme and size of retrofitted column is shown in figure 5.

5.2 Buckling Restrained Braces (BRBs)

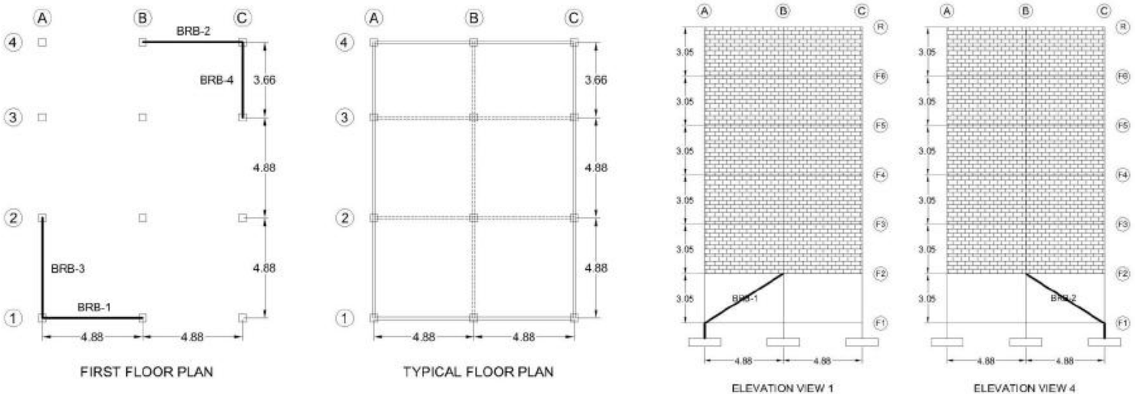
Study about the use of BRBs as a retrofit technique for GLD buildings has been conducted by Mazzolani et al. (2006). The results show that BRBs provide adequate improvement in structural strength, stiffness, and ductility as compared to other retrofit techniques. In this study, diagonal bracing configuration has been selected since it is the most suitable bracing configuration to be applied for retrofitting the GLD building. Firstly, all masonry infill walls in the first floor are removed and changed with light partitions which will not contribute much to the story strength and stiffness. This is done to remove any torsional irregularity that exists in the first floor. Later on, four BRBs are attached in the first floor as can be seen in Figure 6. These BRBs are placed and designed in such a way that they will not cause any torsional irregularity which may attract deformation demand to be concentrated on some particular frames.



(a) Retrofitting scheme

(b) RC Jacketed column (non-shaded area represents the original column section, all dimensions are in millimeter)

Figure 5: (a) Retrofitting Scheme (Plan View) CJW Building b) RC Jacketed Column



(a) Plan view

(b) Elevation at 1 and 4 grid

Figure 6: (a) Plan View; (b) Elevation View of BRB Retrofitting Building

Table 5: Properties of BRB Used

BRB No.	Yield Strength (MPa)	Modulus of Elasticity (MPa)	Cross Section Dimension (mm)	Area (mm2)
BRB-1	320	200000	30 x 110	3300
BRB-2	320	200000	30 x 110	3300
BRB-3	320	200000	30 x 123	3690
BRB-4	320	200000	30 x 112.5	3375

6. ANALYSIS RESULTS

Overall, as compared to the original GLD building, the seismic performance of CJW and BRB buildings under moderate earthquake is much better. In the case of original GLD building, the seismic performance is very poor due to soft story that exists in the first floor which attracts deformation demand to be concentrated on the first floor. Thus, the columns and infill walls in the first floor are heavily damaged and it leads to soft story mechanism.

It is likely that the original GLD building cannot survive if it is subjected to strong or severe earthquake. Therefore, the seismic performance evaluation of the original GLD building is done only for moderate earthquake. On the other hand, in the case of CJW and BRB buildings, it can be seen that deformation demand can be well distributed throughout the buildings. The maximum story drift can be reduced significantly and kept below 1% for all cases which is within acceptable limit for moderate intensity earthquake. Moreover, from damage state, the retrofitted GLD buildings (CJW and BRB buildings) suffer minor damages when subjected to moderate earthquake. There are only some minor damages in columns and some damages in infill walls. Therefore, it can be concluded that the retrofit schemes proposed can significantly improve the seismic performance of the GLD building

Under strong earthquake, it can be seen from the analysis results that BRB building performs better than CJW building. In the case of BRB building, maximum story drift are less as compared to those of CJW building. Furthermore, from damage state, BRB building still suffers minor to moderate damages when subjected to strong earthquake whereas CJW building suffers moderate to extensive damages. Yet, no sign of failure or collapse is detected during the analysis. Moreover, for both buildings, the maximum story drift can be kept below 2% when subjected to strong earthquake.

Under severe earthquake, from the analysis results, it can be seen that both buildings are severely damaged. The comparison of storey drift and damages shows that CJW building deforms more than BRB building in all earthquakes.

7. CONCLUSION

Overall, it can be concluded that the retrofit schemes proposed can significantly improve the seismic performance of the GLD building. For CJW building, the risk of collapse is very high due to severe damages in beam-column joints. As compared to traditional retrofit techniques such as concrete jacketing and adding masonry infill walls, it seems that recent retrofit technique using BRBs gives a better solution in terms of the seismic performance.

Since the BRBs are designed to have lower strength as compared to other elements, thus it is expected that the BRBs will yield first before other elements reach their peak strength. In this case, due to their yielding and stable hysteretic behavior, BRBs can behave like effective fuses which limit the seismic forces acting on RC frames and thus it results in less building's damage as compared to CJW scheme. Moreover, in terms of effect to the building's occupancy, it seems that BRB scheme has less effect to the building's occupancy as compared to CJW scheme. In BRB scheme, the modifications made are only attachment of BRBs in the first floor and strengthening two base columns whereas in CJW scheme, the modifications made are strengthening all first floor columns, adding some infill walls in the first floor, and removing all interior infill walls in the upper floors.

Another advantage of BRB scheme over CJW scheme is post-earthquake repairing or rehabilitation. As can be seen in the damage state for moderate and strong earthquakes, the damages occurred in BRB building are mainly concentrated on the BRBs. This is a typical damage pattern of damage controlled structure which the damages are supposed to occur in the auxiliary structure while keeping the primary structure less damaged. Hence, after moderate and strong earthquakes, it is very easy to restore the building's capacity or strength by replacing the damaged BRBs with the new ones. On the other hand, in the case of CJW building, the damages are distributed in columns, beam-column joints, and infill walls and thus it needs a lot of effort to repair or rehabilitate the building in order to restore its capacity or strength. Indeed, this is a major advantage of damage controlled structure over traditional structure. Therefore, due to these advantages, it can be concluded that BRBs can serve as a good and effective retrofit technique for GLD buildings with a soft/weak first story.

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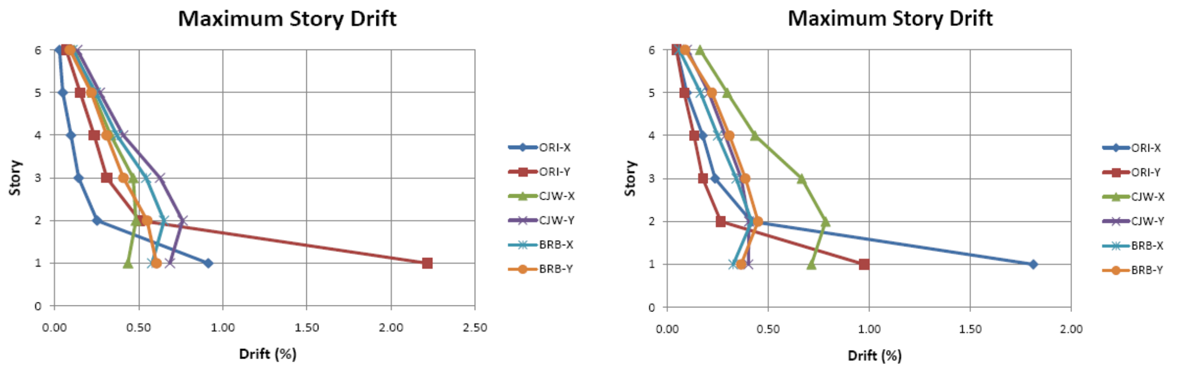
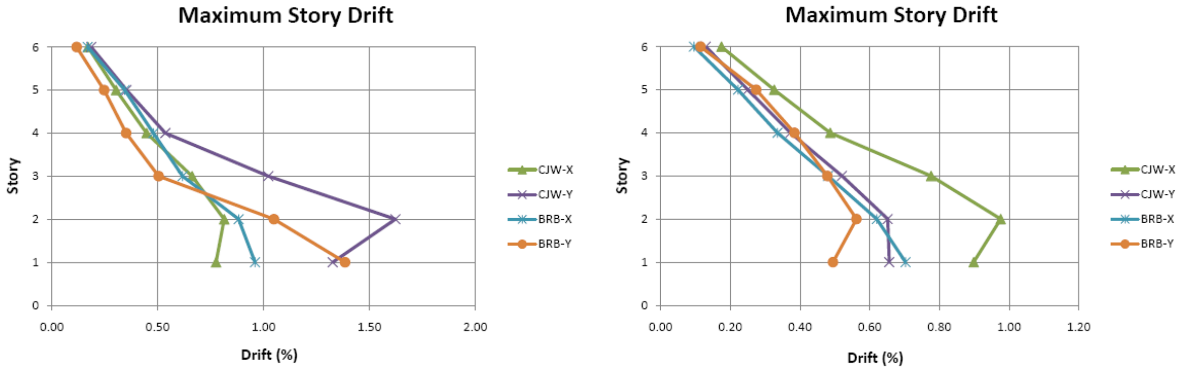
APPENDIX



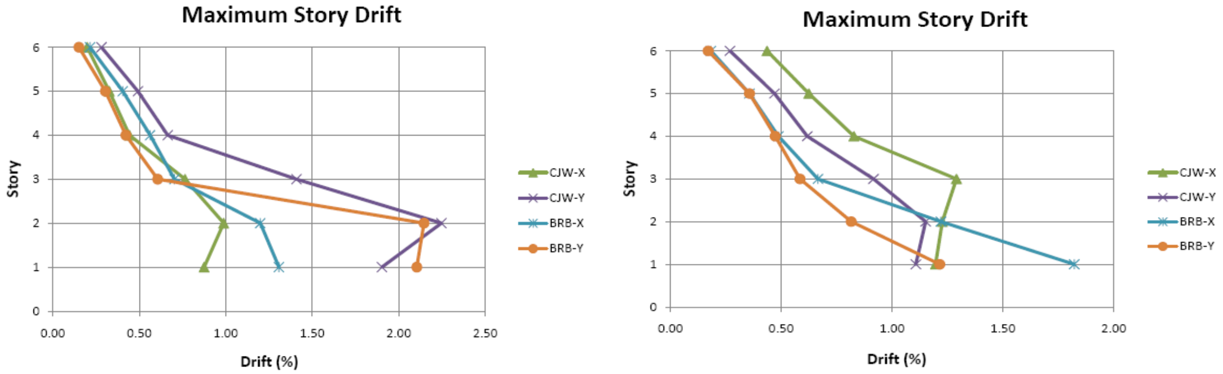
(a) San Fernando (SF) Earthquake (b) Northridge Earthquake(NR)

Figure 7: Comparison of Maximum Story Drifts in X and Y Direction of Three Buildings Subjected To Moderate SF and NR Earthquakes



(a) San Fernando (SF) Earthquake (b) Northridge Earthquake(NR)

Figure 8: Comparison of Maximum Story Drifts in x and y Direction of CJW and BRB Buildings Subjected To Strong SF and NR Earthquakes



(a) San Fernando (SF) Earthquake (b) Northridge Earthquake(NR)

Figure 9: Comparison of Maximum Story Drifts in x and y Direction of CJW and BRB Buildings Subjected To Severe NR Earthquake

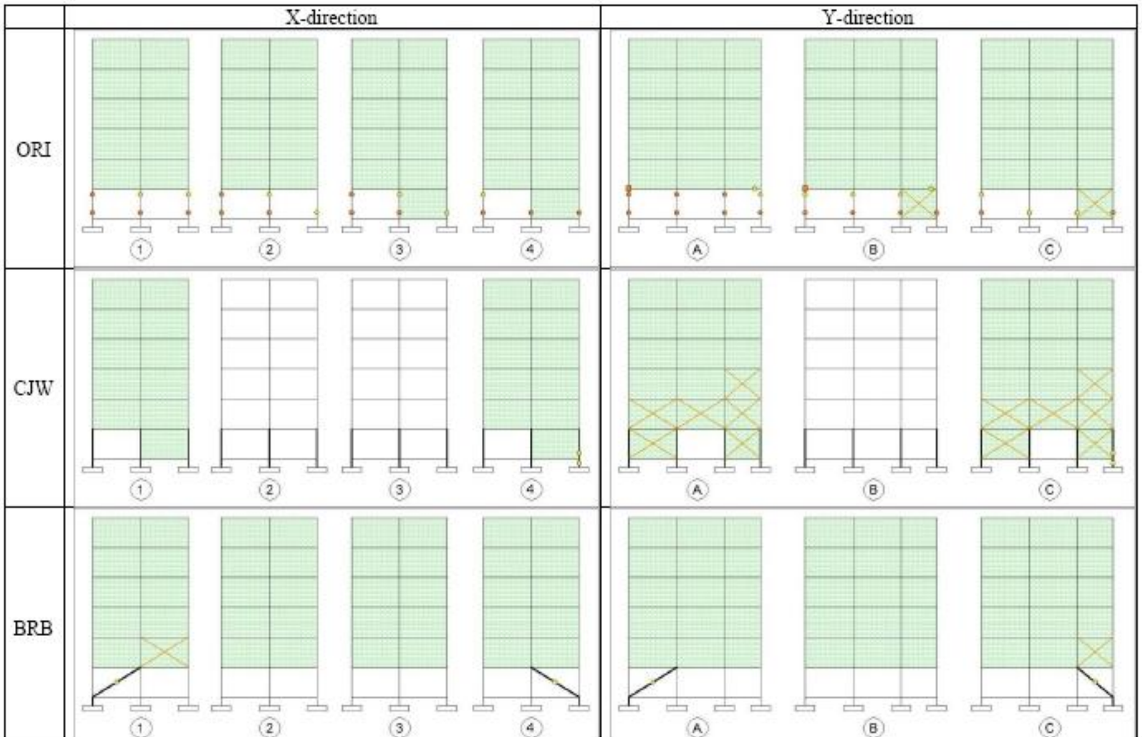


Figure 10: Comparison of Damage State of Three Buildings subjected to Moderate SF Earthquake

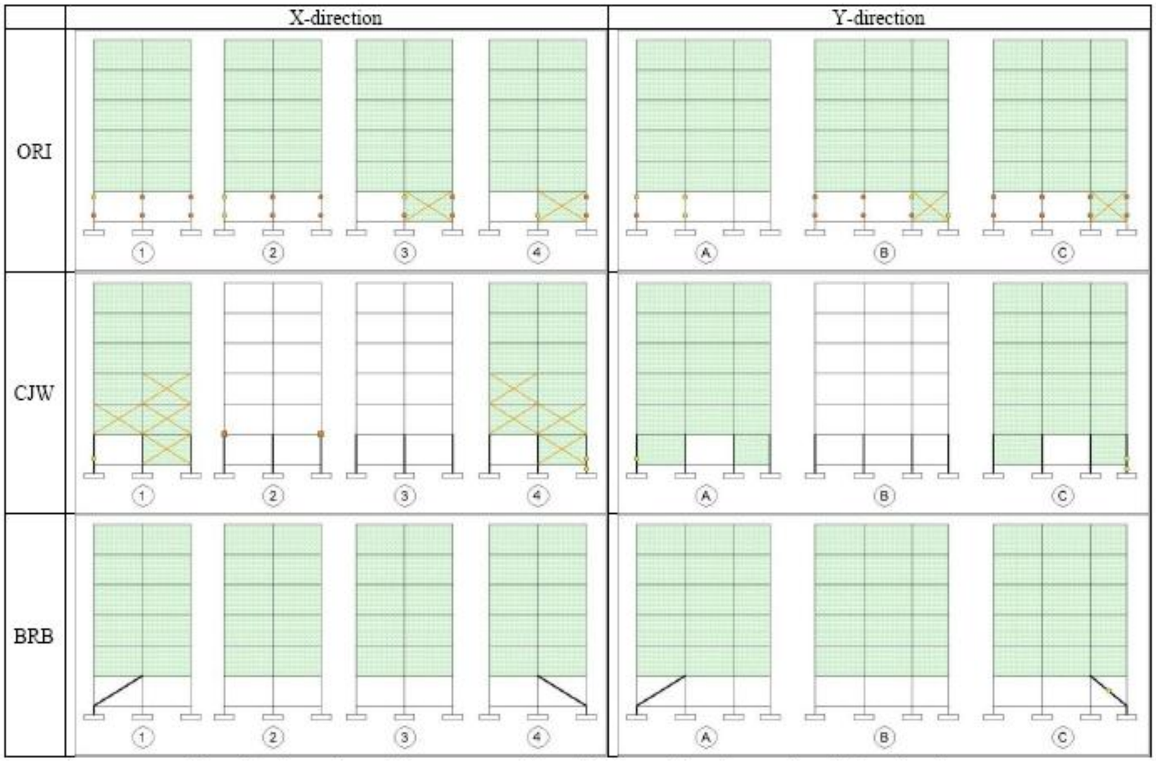


Figure 11: Comparison of Damage State of Three Buildings subjected to Moderate NR Earthquake

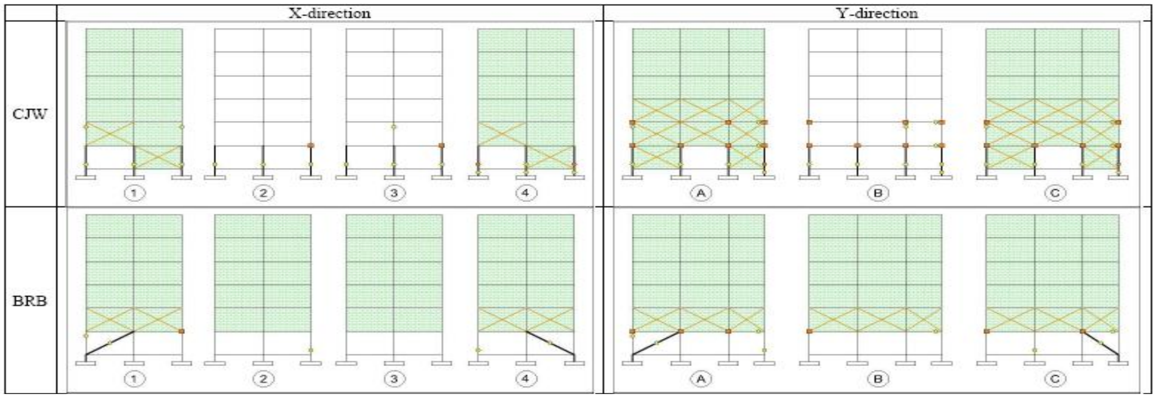


Figure 12: Comparison of Damage State of Three Buildings subjected to Strong SF Earthquake

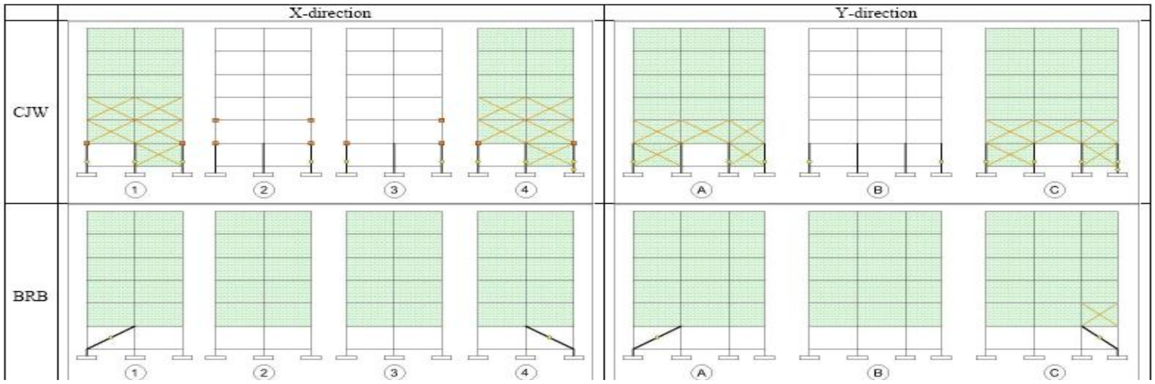


Figure 13: Comparison of Damage State of Three Buildings subjected to Strong NR Earthquake

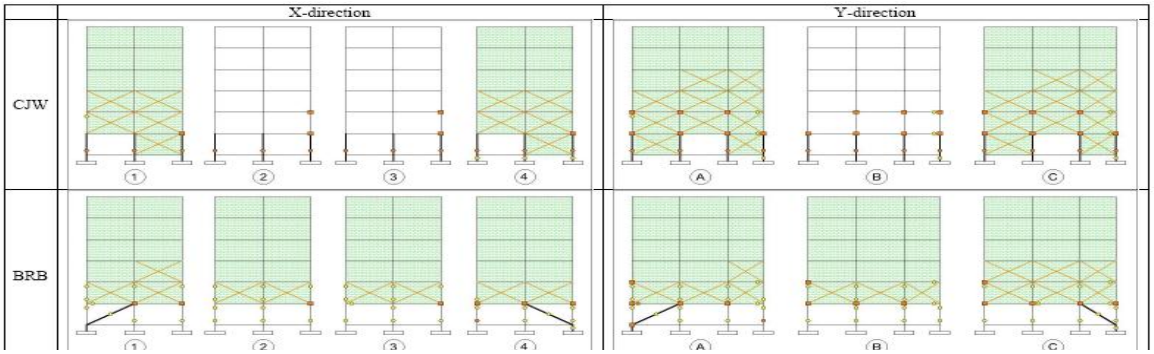


Figure 14: Comparison of Damage State of Three Buildings subjected to Severe SF Earthquake

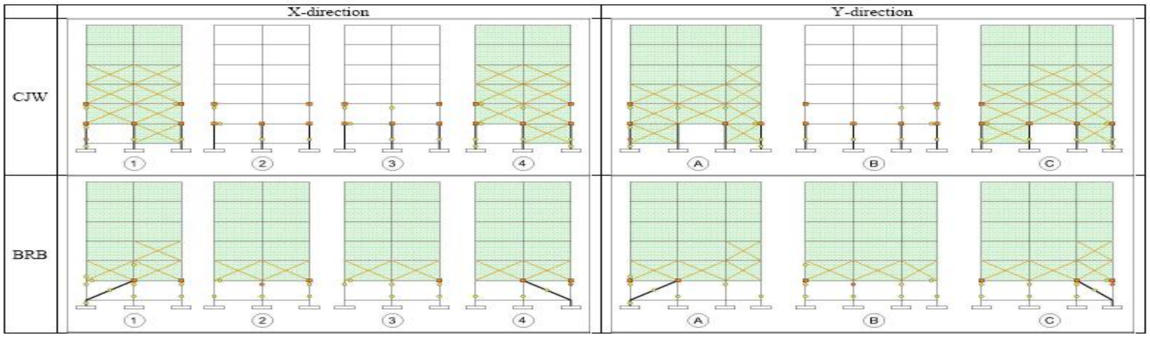


Figure 15: Comparison of Damage State of Three Buildings subjected to Severe NR Earthquake