Seismic Strengthening of Soft-Story RC Moment Frames

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Abstract

This study was conducted to compare seismic strengthening techniques for soft-story RC buildings and to retrofit actual buildings as a pilot case. Two methods were selected, a strengthening technique using Buckling Restrained Braces (BRBs) and a conventional method using concrete column jacketing. Two soft-story RC buildings located in northern Thailand having the same structural framing and details were strengthened using the two different approaches. Background works that formed the basis for the strengthening design concepts of these buildings are briefly presented. Nonlinear analyses are used to assess the performance of the two buildings and to compare their response with that of the un-retrofitted structure. The effectiveness of using passive energy dissipating devices such as BRBs in controlling the excessive soft story drift is discussed in comparison with that of using the concrete jacketing method. The differences and limitations of the two strengthening techniques are also discussed.

Keywords: Seismic Retrofitting, Buckling Restrained Braces, Concrete Jacketing, School Buildings, Seismic Evaluation

1. Introduction

When a magnitude 6.3 earthquake occurred in Mae Lao, Chiang Rai Province, on May 5th 2014, several soft-story RC buildings were damaged. The earthquake strongly demonstrated the vulnerability of these buildings in seismically active areas in Thailand. Seismic strengthening of these buildings has become a crucial safety issue. For this reason, two RC buildings were selected for retrofitting in a pilot project to evaluate suitable technology for Thailand. A number of retrofitting schemes for RC frames developed in the past were evaluated. Two methods, in particular, were selected, a modern strengthening technique using Buckling Restrained Braces (BRBs) and a conventional method using concrete column jacketing.

This paper focuses on summarizing the observed performance of these buildings and comparing the effectiveness of two selecting strengthening methods. Background works that formed the basis for the strengthening design concepts of these buildings are presented. Nonlinear analyses are used to assess the performance of the retrofitted buildings and to compare their response with that of the un-retrofitted structure. The effectiveness of using passive energy dissipating devices such as BRBs in controlling the excessive first story drift is discussed in comparison with that of using the concrete jacketing method.

2. Details of Prototype Frames

Two school buildings with soft-story characteristics located in Chiang Rai were selected for retrofitting in a pilot project to evaluate suitable retrofitting technology. Although a number weaknesses exist within the structure, the soft-story was the most important aspect to eliminate. A number of retrofitting schemes for RC frames developed in the past were evaluated. Two methods, in particular, were selected, a modern strengthening technique using Buckling Restrained Braces (BRBs) and a conventional method using concrete column jacketing. Two different seismic strengthening techniques were used so as to provide options for the school owners. The two selected buildings share the same framing and member details. The overview of one of the buildings and the key plans are shown in Fig. 1.

3. Retrofitting Design

3.1 Strengthening with Buckling Restrained Braces

In recent years, the use of BRBs has gained popularity as an attractive way to retrofit a non-ductile RC structure [1-4]. The stable hysteretic behavior of the BRBs can significantly enhance the energy dissipation of the system. However, the hysteretic behavior of an RC-BRB system is also quite complex especially for the case involving a non-ductile RC frame. The hysteretic behavior of a combined RC-BRB system depends on the relative strength and stiffness of the RC frame and the BRBs [4]. For a frame with relatively small BRB strength, the behavior is still dominated by the pinched hysteretic behavior of the non-ductile RC frame. On the other hand, for a frame with relatively large BRB strength, the behavior is governed by the elastic–plastic strain hardening hysteretic behavior of the BRBs. One of the main challenges of using the BRBs to strengthen a structure is how the sizes of the BRBs can be selected and how the inelastic deformation demands of the system can be estimated.

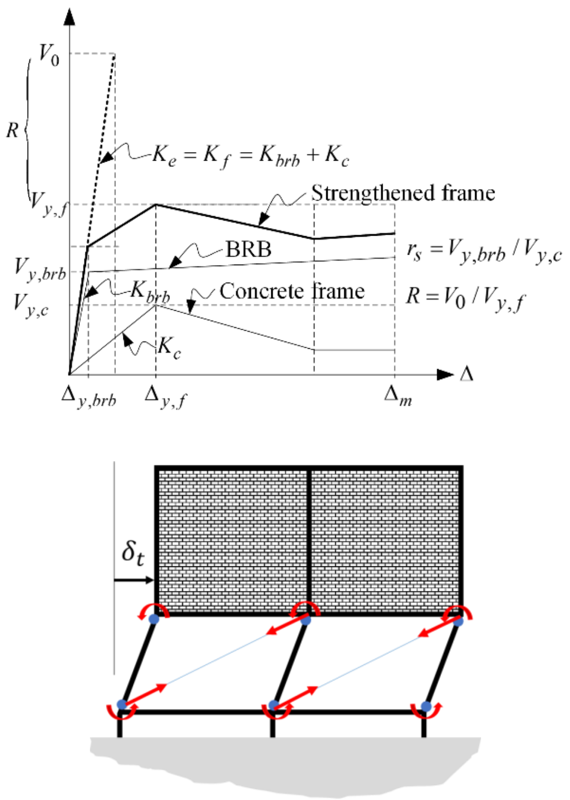
Fig. 1 The overview of the study building.

Khampanit et al. (2014) [4] presented a strengthening design approach that takes into account the complex hysteretic behavior of the combined RC-BRB system. The approach is based on the energy balance concept and plastic design. The design method utilized the results from a parametric study which considered the dynamic response of RC-BRB system with varying BRB strengths. This same parametric study results can also be applied in the well-known Displacement Coefficient Method (FEMA440) to estimate the inelastic deformation demands of the RC frames strengthened with BRBs [5]. The Displacement Coefficient Method utilizes different coefficients to modify the elastic deformation demand of an equivalent single-degree-of-freedom system to give an estimate of the inelastic deformation demand. The displacement at the roof (called the target displacement, δ_t) of a given system is computed by

$$\delta_t = C_0 C_1 C_2 C_3 S_a \frac{T_e^2}{4\pi^2} g \qquad (1)$$

where C_0 is the coefficient to convert SDOF displacement to MDOF roof displacement, C_1 is the coefficient that gives the ratio of the expected maximum inelastic displacement of an elastic-perfectly-plastic system to that of the elastic displacement, C_2 is the coefficient that modifies the displacement due to effects of hysteretic behavior (the displacement of the system divided by the displacement of the equivalent elastic-perfectly plastic system, $C_2 = \Delta/\Delta_{EPP}$), C_3 is the coefficient that takes into account the P-Delta effects, T_e is the effective period, S_a is the spectral acceleration, and g is the acceleration due to gravity.

As mentioned, the hysteretic behavior of a combined RC-BRB system depends on the relative strength and stiffness of the RC frame and the BRBs. To apply the Displacement Coefficient Method to a combined RC-BRB system, it is important to take into account the variation in the hysteretic behavior. This can be done through the coefficient C_2 which considers the effects of the combined hysteretic behavior as a function of RC and BRB relative strengths. For this purpose, a parametric study was carried out as part of the development of a direct strengthening design method [4]. A SDOF analytical model that represents a non-ductile RC frame strengthened with BRBs was used. The SDOF model consists of 2 parallel springs with the first string (K_f) representing the non-ductile concrete frame and the second spring (K_{brb}) representing the BRBs. The hysteretic response of the RC part was assumed to be trilinear with strength degradation and Takeda hysteretic model. The hysteretic response of the BRBs was assumed to be bi-linear with strain hardening. The combined response is defined by a parameter called the strength ratio (the strength of BRBs divided by that of the concrete frame, r_s) and the reduction factor (the ratio of the strength required for the system to remain elastic to the strength of the combined response, R). The load-deformation plot of the combined system is shown in Fig. 2. In all, a total number of 24000 time history analysis runs were used to conduct the parametric study. More details of the parametric study can be found elsewhere [4].



$$V_{y,f} = \sum \frac{M_{pc}}{h_c} + \sum P_y \cos(\theta)$$

$$r_s = \sum P_y \cos(\theta) / \sum \frac{M_{pc}}{h_c}$$

Fig. 2 Idealized force–displacement relationships [4].

Examples of the results from the parametric study in terms of the coefficient C_2 are shown in Fig. 3. The results were based on the assumption that the yield drift of the RC frame and that of the BRBs are in the ratio of 4:1. This ratio was based on the configuration of a typical Thai school building. Overall, the strength ratio significantly influences the factor C_2, especially in the short period range. In this range, as the strength of the BRBs increases, the value of C_2 becomes closer to a value of 1.0 meaning that the behavior becomes similar to that of an EPP system. For periods within the practical ranges, the factor C_2 is less than 1.0 which indicates that the deformation is lower than that of an EPP system. This is most likely due to the positive post-yield stiffness provided by the BRBs.

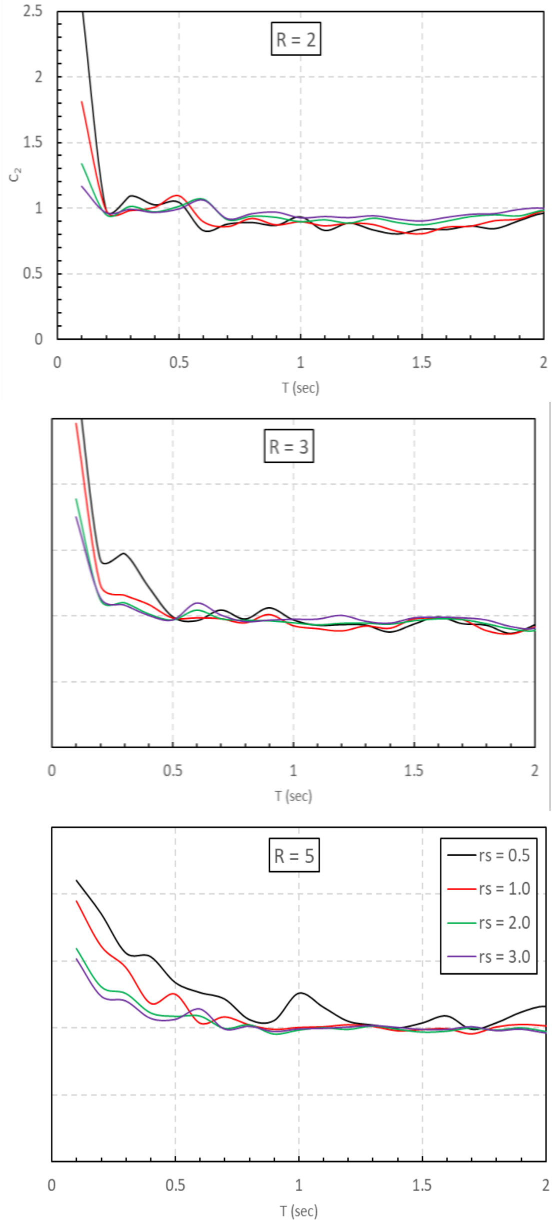


Fig. 3 Values of C2 factor for different strength ratios compared with those from FEMA440 (Khampanit and Leelatviwat 2015).

For the design of the study building, the selection of the BRB capacity can be determined such that the story strength of the first story after retrofitting is slightly smaller than the strength of the upper story considering the infill wall. This would ensure that the BRBs would be activated. The story drift of the frame under a given ground motion intensity can then be estimated using the displacement coefficient described above. Based on this concept, a total of eight BRBs were used, four BRBs with the capacity of 160 kN in the longitudinal direction of the frame and four BRBs with the capacity of 275 kN in the transverse direction of the frame. The configuration of the BRBs are shown in Fig. 4.

The columns in the braced bays from pile cap to the ground floor are also strengthened using concrete jacketing to cope with the increased demand.

Fig. 4 BRB configuration of the prototype building.

3.2 Strengthening with Concrete Jacketing

In Concrete Jacketing method, concrete columns are enlarged by casting new concrete around existing columns. It is well known that the bond interface between new and existing concrete are crucial in creating a compatible response between new and existing concrete. In addition, the design is governed by minimum practical requirements for the thickness of the jacket as well as the minimum amount of longitudinal reinforcement in the new concrete. The story drift of the frame under a given ground motion intensity can also be estimated using the displacement coefficient described above (with C_2 equal to one assuming ductile detailing in the new jacketed column). Based on this concept, a total of 24 columns were strengthened. The typical details are shown in Fig. 5.

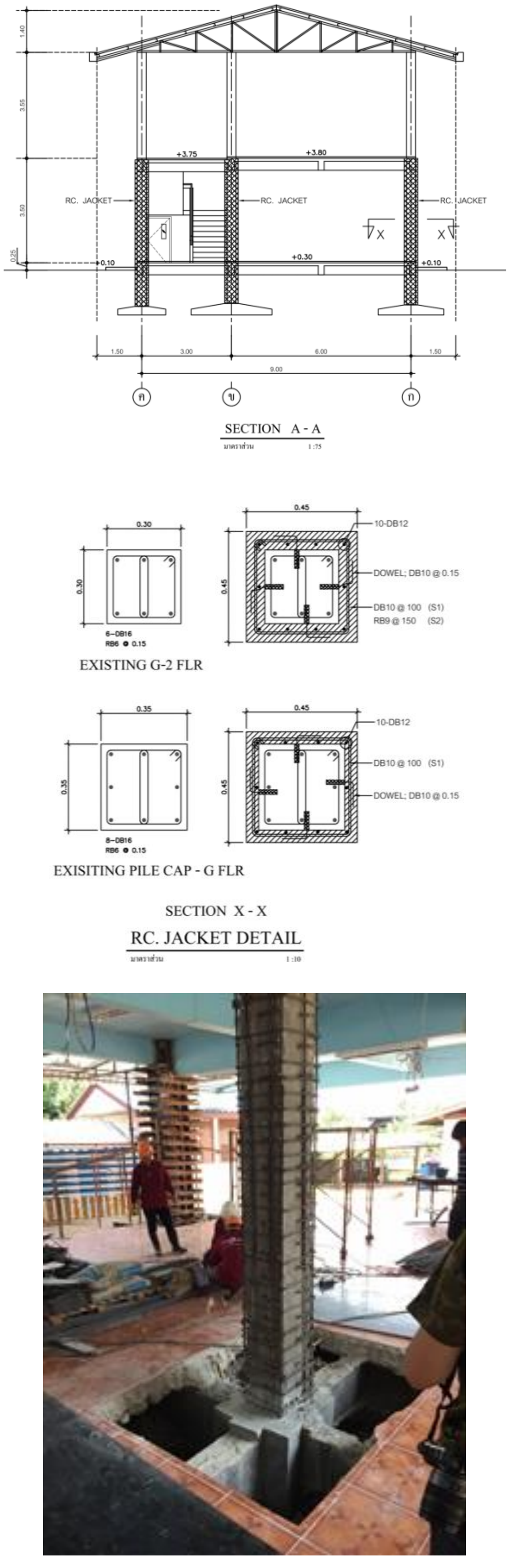


Fig. 5 Concrete jacketing details.

4. Response Analysis

Analytical models of the structures were created using a computer software PERFORM 3D [6]. A combination of fiber and lump plasticity elements were used. Fiber elements were used in the columns where significant inelastic activities took place. The infilled walls were modeled using equivalent diagonal strut elements. The performance assessment was carried out using inelastic static (pushover) and nonlinear dynamic analysis. The pushover analysis was used to determine the overall response, the sequence of yielding leading to collapse, and the failure mechanism. The nonlinear dynamic analysis was used to examine the behavior of the structure at the selected level ground motion intensity. A total of 6 ground motions were used. They were scaled such that the average spectrum matches with the target spectrum at 0.2s (the approximate period of the strengthened frames). The spectra are shown in Fig. 6 along with the target spectrum.

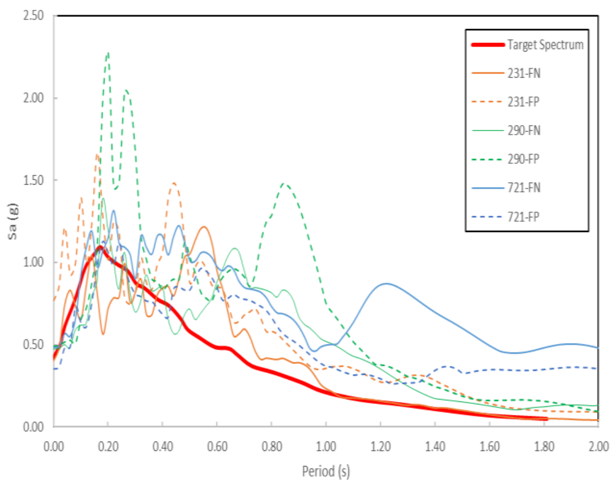


Fig. 6 Response spectra of ground motions used in this study.

The plot of base shear versus roof displacement from pushover analysis is shown in Fig. 7. For this paper, only the results for the transverse direction are given. The results show similar trend in the longitudinal direction. The plot shows that because of the BRBs and concrete jackets, the stiffness and lateral strength of the retrofitted frames are much higher than those of the existing RC frame. The analysis results in terms of the peak inter-story drifts from non-linear dynamic analysis are shown in Fig. 8. The inter-story drift values of the existing structure were very high, particularly for the first story, indicating a soft story mechanism with drifts exceeding 3% for several cases. The existing RC frame had high probability of collapse under the design level ground motions. For the strengthened frame, the maximum story drifts were significantly reduced. Both strengthening techniques seemed to be equally effective in controlling the excessive story drifts with the concrete jacketing method having the smaller story drifts.

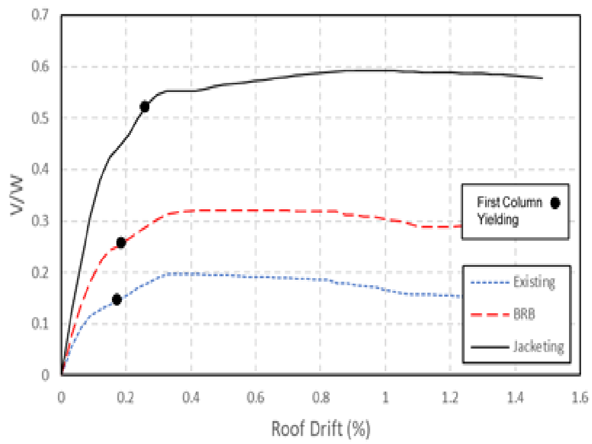


Fig. 7 Pushover curves.

Fig. 8 also provides the displacement estimated using Eq. 1 for the BRB case. The roof displacement was calculated from the single-degree of freedom behavior as in Fig. 2 assuming fixed bases at the ground floor. For the BRB frame, the strengthening ratio (r_s) was approximately 0.56 with R of 2.4. The C_2 factor was found from interpolation to be 1.17. Other factors were computed based on FEMA440 [7] (C_0=1, C_1=1.4, C_3=1). The estimated story drifts were found to be effective in predicting the drift values from dynamic analysis. This could be useful in the design phase to assess different strengthening solutions. It is important to note that, for a low-rise building with a short period, the C_2 for the BRB case could be much larger than one. This may indicate a drawback for using BRBs to strengthen low-rise buildings as opposed to concrete jacketing method. Nevertheless, because of the significant reduction in the story drift, As a result, the plastic hinge rotation demands in the column were also reduced. The plastic rotations are shown in Fig. 9. It can be seen that the rotations were within the life safety limits for the strengthened frames.

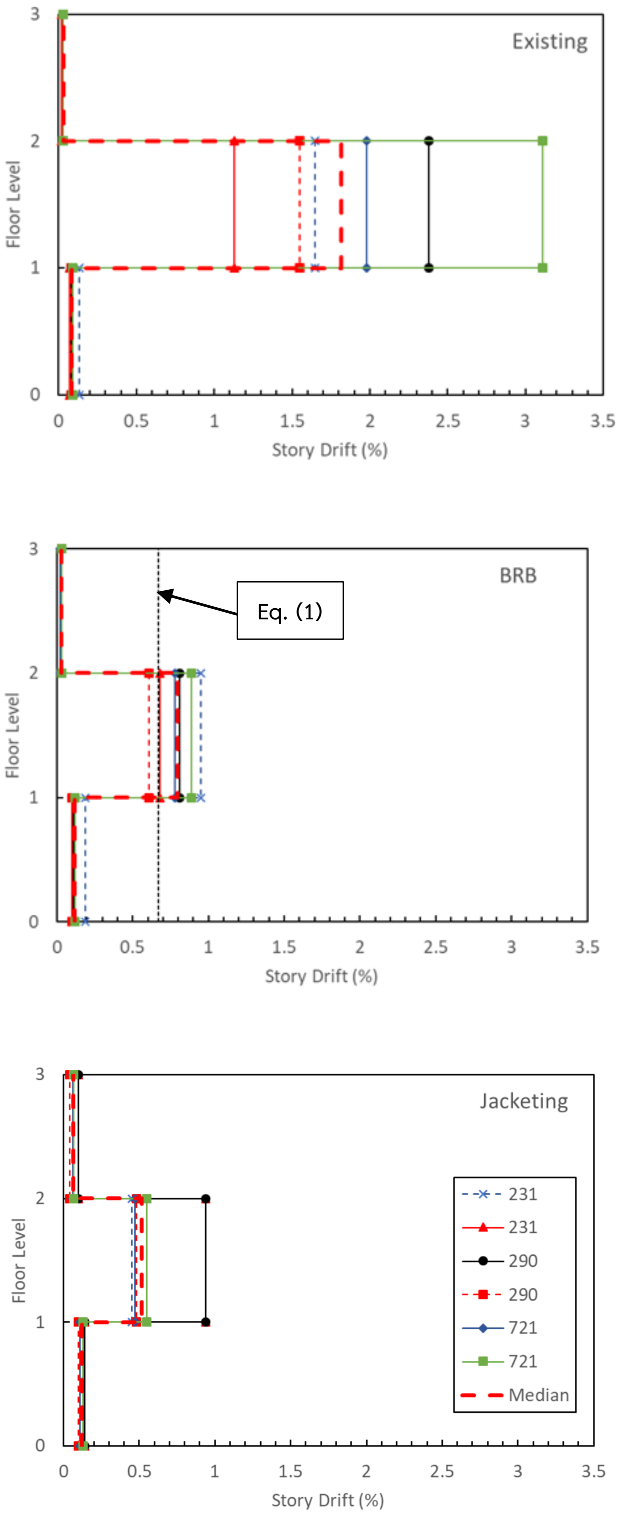
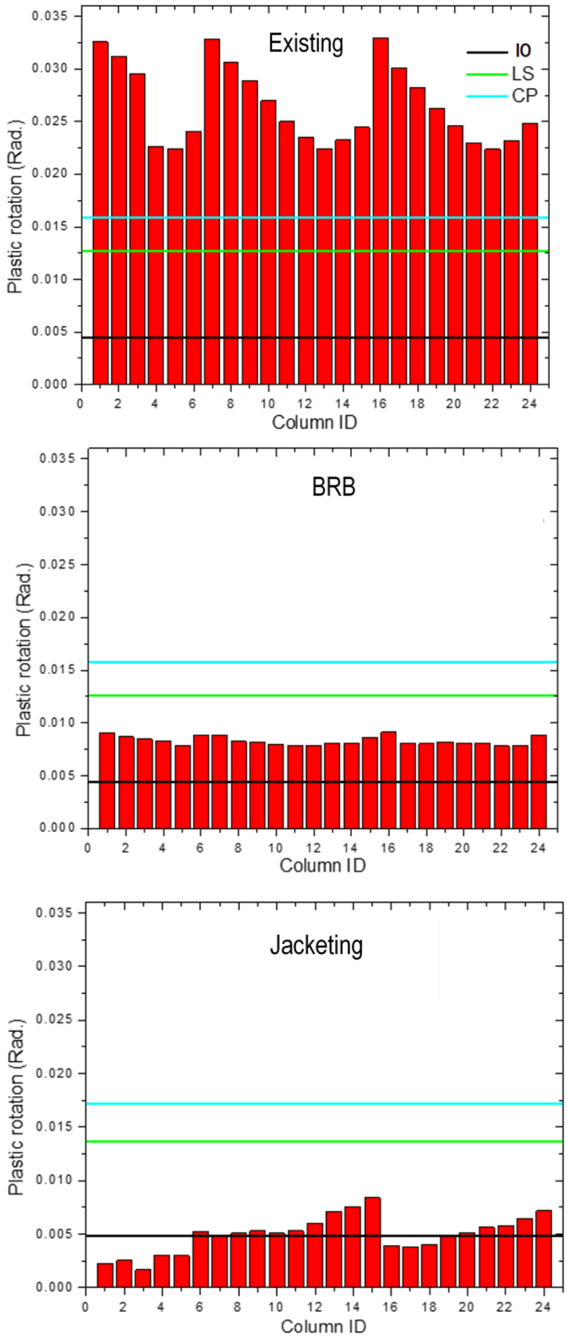


Fig. 8 Maximum and median story drift values.



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