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Inelastic Deformation Demands of Non-Ductile Reinforced Concrete Frames Strengthened with Buckling-Restrained Braces

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ABSTRACT: This study focuses on estimating inelastic deformation demands for non-ductile RC frames strengthened with BRBs or similar metallic devices. The hysteretic behavior of a combined RC-BRB system depends on the relative strength and stiffness of the RC frame and the BRBs. The behavior could be dominated by the pinched hysteretic behavior of the non-ductile RC frame or the elastic–plastic strain hardening hysteretic behavior of the BRBs depending on the relative strength of the frame and the BRBs. Results from a parametric study involving dynamic analyses of RC-BRB single-degree-of-freedom systems were used to obtain the C_2 factor in the Displacement Coefficient Method as a function of the relative strength between the frame and the BRBs. A 5-story frame was selected as an example. The target displacement of the frame was computed using the Displacement Coefficient Method with the coefficients modified by the results of this study. Nonlinear dynamic analyses were performed to verify the deformation demands of the frame.

1 INTRODUCTION

In recent years, the use of buckling restrained braces (BRBs) has gained popularity as an attractive way to retrofit a non-ductile RC structure (Ishii et al. 2004, Di Sarno and Manfredi 2010, Oviedo et al. 2010). This is due to the stable hysteretic behavior of the BRBs which can significantly enhance the energy dissipation of the system. The hysteretic behavior of an RC-BRB system is 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. For a frame with relatively small BRB strengths, the behavior is 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. A number of trial design and analysis cycles are generally needed in order to ensure that the performance of the retrofitted structure meets the target.

Recently, the authors presented a direct strengthening design approach (Khampanit et al. 2014) 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 approach utilized the results from a parametric study which considered the dynamic response of RC-BRB system with varying BRB strengths. The 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-BRB system. This paper presents an example of how the target displacement of an RC-BRB system can be computed using the Displacement Coefficient Method with the coefficients modified by the results of the parametric study. The parametric study mentioned above is first reviewed. An example of a non-ductile RC frame strengthened with BRBs is then presented. The inelastic deformation demands of the frame were estimated using the Displacement Coefficient Method and nonlinear dynamic analyses were performed to verify the deformation demands of the frame.

2 DISPLACEMENT COEFFICIENT METHOD

The Displacement Coefficient Method (FEMA440) relies on 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, stiffness degradation, and strength deterioration, 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. The behavior could be dominated by the pinched hysteretic behavior of the non-ductile RC frame or the elastic–plastic strain hardening hysteretic behavior of the BRBs depending on the relative strength of the 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 hysteretic behavior as a function of RC and BRB relative strengths.

3 PARAMETRIC STUDY

A parametric study has been carried out as part of the development of a direct strengthening design method (Khampanit et al. 2014). A single-degree-of-freedom 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 Figure 1. The parametric study was carried out with r_s of 1, 2, 3 and 4, R of 2, 3 and 5, and the elastic period values of the combined system ranging from 0.1s to 3.0s with a 0.1s interval. The analysis was carried out for 20 ground motions representing large-magnitude-small-distance earthquakes with magnitude 6.6 to 6.9 and distances ranging from 15-30 km. More details of the parametric study can be found elsewhere (Khampanit et al. 2014).

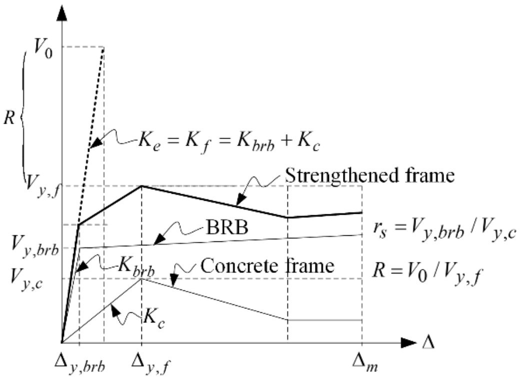


Figure 1. Idealized force–displacement relationships of the concrete frame and BRB (Khampanit et al. 2014).

Examples of the results from the parametric study in terms of the coefficient C_2 (the displacement of the system divided by the displacement of the equivalent elastic-perfectly plastic system, $C_2 = \Delta/\Delta_{EPP}$) are shown in Figure 2. The results are also compared with the C_2 coefficient given by FEMA440. 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. The values of C_2 suggested by FEMA440 are also generally higher than those of the combined systems except for cases with high R and low r_s values. For R of 2, the difference between C2 from FEMA440 and this study could be significant.

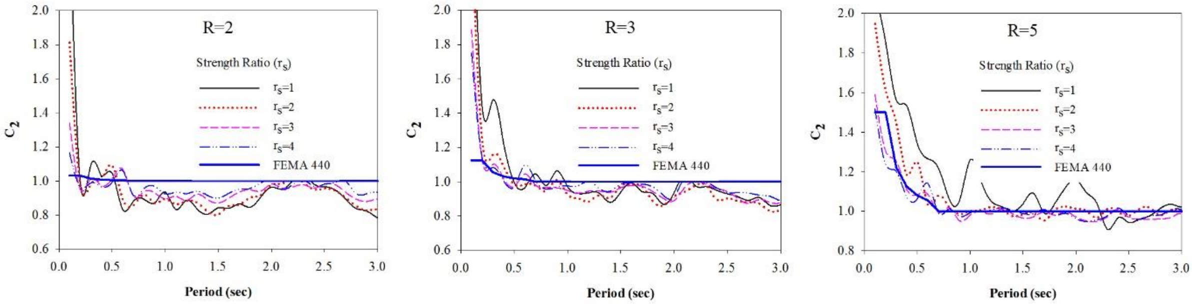


Figure 2. Values of C2 factor for different strength ratios compared with those from FEMA440.

4 EXAMPLE STRUCTURE

The Displacement Coefficient Method was applied to an example structure. The structure for this study was a 5-story non-ductile RC frame strengthened with BRBs. The plan and elevation views of building are shown in Figure 3. Only the response of structure in the N-S direction was considered. It was assumed that the structure had adequate seismic resistance in the E-W direction. The two perimeter frames were strengthened using BRBs. The details of the structure and the design of the BRBs are described in Khampanit et al. (2014). Each of strengthened frames was responsible for half of the total building mass with the seismic resistance assumed to be provided entirely by the strengthened frames.

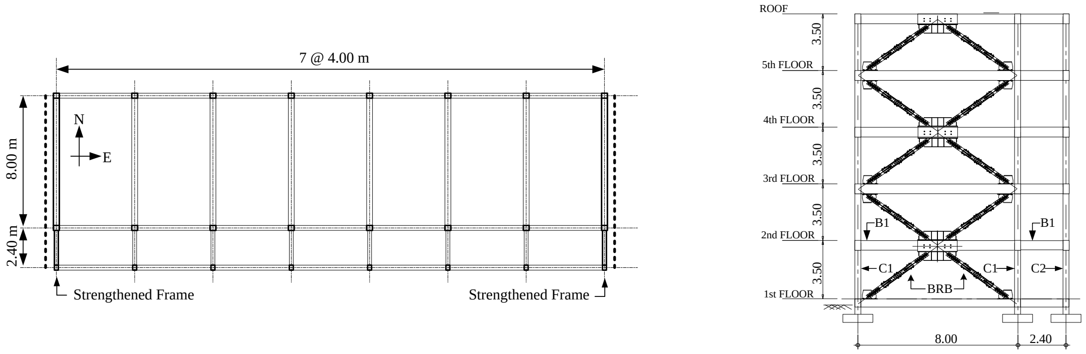


Figure 3. Example structure (Khampanit et al. 2014)

An analytical model of the structure was created using a computer software PERFORM 3D (CSI 2007). Pushover analysis was performed to determine the load-deflection response. The plot of base shear versus roof displacement is shown in Figure 4. With this plot, the Displacement Coefficient Method can be applied to compute an estimate of the inelastic deformation demands for a given hazard. In this example, the target displacement was computed using the median spectral acceleration value from the spectra of shown in Figure 5. These spectra were obtained from 20 ground motions scaled to match with the design response spectrum used to design the BRBs. The floor displacements extracted from the pushover analysis corresponding to the target displacement are shown in Figure 6.

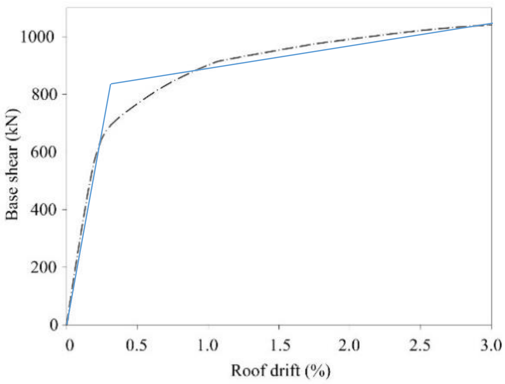


Figure 4. Base shear vs roof drift plot.

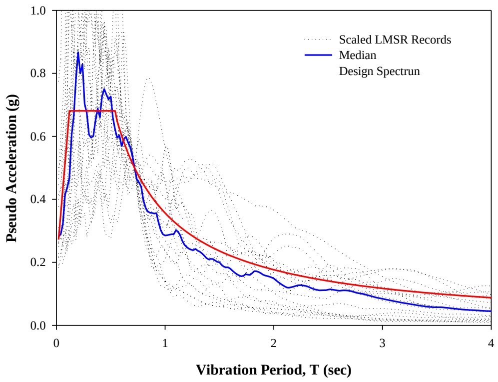
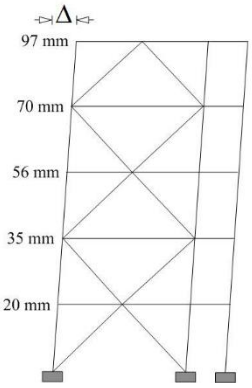


Figure 5. Spectra of ground motions

To verify the accuracy of the Displacement Coefficient Method, the structure was analyzed using nonlinear time history analyses. The analysis results in terms of peak inter-story drifts under the 20 ground motions used are shown in Figures 7. The figure also shows the story drift demands computed from the floor displacements given in Figure 6. Compared to the results from nonlinear time history analyses, the demand estimates using the modification coefficients were well within the acceptable range considering the simplicity of the approach. The difference was due largely to the tendency of the frame to develop a soft-story mechanism especially in the first story. Without the soft story response, the estimates appeared to closely follow the results from the dynamic analysis. In practice, the strengthening design should be revised to reduce the concentration of story deformation. It is well known that an approximate method such as the Displacement Coefficient Method can only provide an estimate of the overall response but may not be able to capture local failure or local concentration of deformation.



Parameter	Value
T_e	0.87 sec.
Sa	0.38g
R=Sa/(Vy/W)	1.95
C_o	1.4
$C_1 = 1 + (R-1)/aT^2$	1.02
r_s	4.2 (Use 4.0)
C_2	0.95 (From Fig 2)
C_3	1.0
$\delta_t = C_0 C_1 C_2 C_3 S_a \frac{T_e^2}{4\pi^2} g$	0.097m

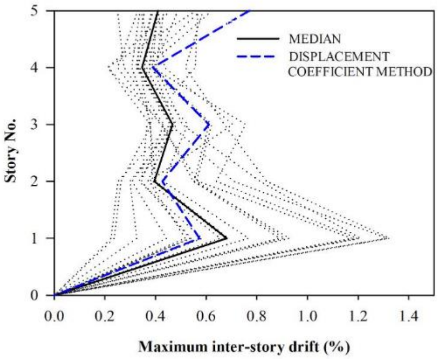


Figure 6. Floor displacement demands.

Figure 7. Maximum inter-story drift demands.

5 CONCLUSIONS

In this paper, the Displacement Coefficient Method was used to estimate the inelastic deformation demands of non-ductile RC frame strengthened with BRBs. The values of the modified C_2 factor from the results of a parametric study were provided. The coefficient takes into account the complex hysteretic behavior of an RC-BRB system depending on the relative strength and stiffness of the RC frame and the BRBs. It was found that the relative strength between the RC frame and BRBs can significantly influence the factor C_2 especially in the short period range. Based on the example frame, the demand estimates using the modification coefficients followed closely with the results from the nonlinear dynamic analyses. However, as the Displacement Coefficient Method is an approximate procedure, it is important to use it only as a tool for a preliminary design. The Displacement Coefficient Method should always be used in conjunction with a more accurate analysis approach in the final design check.

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