Drift Response Evaluation of Buckling-Restrained Braced Frames (BRBFs) under Sequential Seismic Disturbances

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Abstract. Buckling Restrained Braced Frames (BRBFs) are reliable lateral load resisting systems featured with Buckling Restrained Braces (BRBs) to safeguard building frames against earthquake-induced damages. BRBs are axial yielding type metallic dampers characterised with stable and balanced hysteretic behavior along with excellent low-cycle fatigue capacity. However, BRBFs are susceptible to relatively large drift responses mainly due to low axial stiffness of BRBs resulted from the higher seismic response modification factor, $R$. In the event of sequential seismic actions immediately after mainshock may induce additional drift demands which may adversely affect the reusability and retrofitting or in the worst case, it may lead to premature collapse of the BRBFs. The present study encompasses on drift response demand evaluation of BRBFs under the combined action of the main shock and sequential secondary ground shocks. For the study, a medium-rise BRBF used in the past investigation is selected and re-designed as per the recommended prevailing seismic provisions. Nonlinear time history analysis of BRBFs under the action of a suit of sequential ground disturbances is carried out and the results are analysed in terms of drift responses.

1. Introduction

Structural systems located in seismic regions are vulnerable to sequential tremors followed by Mainshocks. The Secondaryshocks or Aftershocks soon after Mainshocks may cause extended damages to the already yielded (under Mainshocks) structural components [1]. Normally the seismic analysis and design provisions account for the effect due to Mainshocks or Primaryshocks only. Investigations showed that the Secondaryshocks vary in terms of magnitude, space, frequency content, and duration compared to Primaryshocks. Many times the variation of these parameters under Aftershocks is more detrimental compared to the Mainshocks[2].This, in turn, poses serious concern over the adequacy of post Mainshock-Aftershock performance of the Structures. The effect of combined Primaryshock-Secondaryshock action on Buckling Restrained Braced Framed structural systems also not different from the above-discussed threat.
Buckling-Restrained Braced Frames (BRBFs) are ductile and stable lateral load resisting system which can be used to shield the structures against seismic induced hazards. BRBFs are characterised by axial yielding of Buckling Restrained Braces (BRBs). BRBs include a metallic core plate placed inside a mortar filled steel encasement, a de-bonding agent, that is embedded at the inter-face of metallic core plate and the surrounding mortar filled steel casings. The de-bonding agent will ensure the free axial movement of BRBs under inelastic reversed cyclic loading conditions and the surrounding mortar filled steel/metallic casing can act as a lower mode buckling-restrainer and to guide the metallic centrally placed metallic (mostly steel) core plate to yield in compression as well [3]. This makes the BRBs to be capable of yielding in both compression and tension and providing a balanced and stable hysteretic response under the inelastic cyclic loading conditions [4]. Figure 1 shows the schematic longitudinal as well as cross-sectional details of BRBs. The BRB metallic core plate has relatively longer restrained (using mortar filled steel encasing) yielding zone at the middle portion, followed by restrained transition zones and un-restrained connection zones towards either end successively.

Figure 1. Schematic representation of BRB along with longitudinal and cross-sectional directions respectively.

However, past studies on Mainshock response evaluation showed that BRBFs are vulnerable to large lateral deformations and resulting drift responses under moderate to high seismic disturbances [5-7]. The relatively large response modification factor value, the capability of BRBs to yield in both tension and compression, and the resulting lower axial stiffness (elastic and post yield) may cause this unintended drift response of BRBFs [7-9]. In the event of sequential ground disturbances, this effect may become even worst and may adversely affect the reliability of the structure in the post-earthquake regime, so that the reusability and retrofitting of BRBFs may become unattainable. Further, the previous investigation reports on seismic response of BRBF under the sequential ground shakings are very limited and hence it warrants further investigations [10, 11]. In the present analytical study, the effect of sequential seismic disturbances, which is Mainshock or Primaryshock followed by Aftershock or Secondaryshock on a six-storey BRBF designed as per current seismic provisions is focussed. For the analysis a suite of ground motion records which comes under Maximum Considered Earthquake (MCE) hazard level is selected and a set of non-linear time-history analysis is performed. Successively, the seismic response evaluation of BRBF is carried out based on the residual (permanent) drift ratio and maximum inter-story drift ratio of the six-story BRB frame.

2. Study building frame and modeling
To carry out the present analytical investigation, a six-story building frame located in Los Angeles-USA is selected [7-9, 12] and the building is assumed to be situated in soil site class D. The building has an equal bay length of 9.14 m each along with both horizontal directions in the plan. The bottom storey-height of the building is 5.49 m and all other top floors have a storey height of 3.96 m each. Along any horizontal direction, the building has 5 bays and six symmetrically placed BRBF along its periphery as shown in figure 2.Two storey-X configurations are adopted for all the BRBs along with the height. The selected BRBF (marked in figure 2) is designed as per current seismic provisions by taking a response modification factor, $R$ of value 8 [13]. Accordingly, the building frame is identified as 6XBRBF88. The seismic design weight of the building is obtained as 61080 kN. The design spectral acceleration corresponding to a long-period (1.0 s) and short period (0.2 s) is found to be 0.77g and 1.39g respectively, where g is the acceleration due to gravity. The seismic design response co-efficient and the approximate time period of the designed building frame are found to be 0.17 and 0.82 s respectively. To analyse, design, and model the beams and columns of study frame, nominal material yield strength $f_y$ of 345 MPa, the corresponding material overstrength (corresponding to yielding) factor $R_y$ is taken as 1.1. Similarly,
for BRBs these \((f_y \text{ and } R_y)\) values are taken as 248 MPa and 1.3 respectively [9]. The entire storey shear due to lateral loads are assumed to be resisted by respective BRBs and the corresponding BRB axial forces are obtained from the critical load combinations as per the recommended provisions. The strength adjustment factors corresponding to compression \((\beta)\) and tension \((\omega)\) are adopted as 1.1 and 1.4 respectively based on past reports [14]. All the BRBs are assumed with pinned end connections and all the column-beam joints are taken as moment free type for the study frame. For the first three floors, beams and columns are \(W14\times120\) and \(W14\times211\) and for the remaining top floors, the beams and columns are \(W14\times82\) and \(W14\times145\) respectively. Figure 2 gives the BRB cross-sectional details on respective floors obtained from the design.

The building frame is modelled in CSI SAP 2000 platform with applicable provisions [15]. The columns and beams are incorporated as all beam-column elements (from the in-built library) by applying axial load-moment \((P-M)\) and bending moment-rotation \((M-\theta)\) interaction hinges at a critical location of beams and columns [16]. End length off-sets for all the beams and columns are taken as 10% each at both ends. Similarly, for BRBs, a yielding zone length of 70% is assigned and applied with a tri-linear plastic hinge at mid-location of respective BRBs to include inelastic response shown in figure 2. The post-yield/elastic stiffness of BRBs is taken as 2% of its un-yielded (elastic) stiffness [7, 8] and the combined hardening model is considered for catching the hysteretic response of BRBs. In order to account for the \(P\)-Delta effect of loads, a continuous leaning column at a distance of one bay width from the study frame is modelled and these are connected with rigid elastic beams at respective floor heights. For all the non-linear time-history analysis a 2% Rayleigh damping is considered.

For the non-linear time-history analysis, a suite of 7 ground-motion records which comes under 2% exceeding probability in 50 years (MCE level) is considered [17]. All the selected ground motions have a time duration of 60s. The PGA of the selected ground motion records vary between 0.5g to 1.33g and the magnitude varies from 6.7 to 7.1 respectively. Figure 3 shows the response spectra \((g)\) of adopted ground motion records along with details such as Peak ground shaking Acceleration, PGA. For one set of Mainshock-Secondaryshock analysis, the same ground motion record is selected for both cases referring to past investigations [18, 19].
3. Analysis Results and Discussions

From the analysis, the first mode time period of the study frame is obtained as 1.05 s. The nonlinear time-history analysis of 6XBRBF8 under the selected set of Mainshock-Secondaryshock is carried out. The analysis results are presented in terms of the Residual Drift Ratio (RDR) and Inter-Storey Drift Ratio (ISDR) of the frame. The ratio of a maximum of the relative storey-displacement (lateral) to the corresponding storey height at any time during the seismic action is the maximum ISDR and the permanent drift left with the storey after the completion of seismic action is termed as the RDR. Both ISDR and RDR can be taken as an index to the extent of damage experienced to the frame system.

![Response Spectra](image1)

**Figure 3.** Response spectra, magnitude and PGA of selected ground motions along with design spectra of study frame.

![ISDR-MS](image2)

![RDR-MS](image3)

![ISDR-SS](image4)

![RDR-SS](image5)

**Figure 4.** Variation of Inter-Storey Drift Ratio and Residual Drift Ratio under the selected set of Mainshock (MS) and Secondaryshock (SS).

Figure 4 shows the variation of RDR and ISDR of 6XBRBF8 under the action of selected Mainshock-Secondaryshock seismic simulations. The maximum ISDR of 4.40% (under Mainshock) is experienced due to LA40 on the second floor of the study frame. Similarly, the average maximum ISDR under Mainshock (ISDR$_{avg-MS}$) is found to be 3.00% at the second floor itself with a standard deviation (SD$_{ISDR-MS}$) of 0.95%. A similar trend is obtained for RDR response as well. Due to the action of
Mainshock the frame experienced a maximum RDR of 1.77% on the second floor of the frame. The corresponding average maximum RDR (RDR_{avg-MS}) and standard deviation (SD_{RDR-MS}) are 0.67% and 0.52% respectively. Secondary shock action effect on the frame also showed a comparable trend observed in the Mainshock results. Both the maximum ISDR and average maximum ISDR (ISDR_{avg-SS}) and the standard deviation corresponding to ISDR_{avg-SS} (SD_{ISDR-SS}) are obtained as 5.20%, 3.20%, and 1.26%, respectively. Whereas the maximum RDR, average maximum RDR (RDR_{avg-SS}), and the standard deviation corresponding to RDR_{avg-SS} (SD_{RDR-SS}) under Secondaryshocks are obtained as 2.42%, 0.84%, and 0.84%, respectively. The results showed the increase of ISDR and RDR is in the range of 5-10% and 20-25%, respectively.

Based on the non-linear time-history analysis, fragility curves are developed to understand the approximate seismic hazard levels of the frame considered. ISDR and RDR under Mainshock and Secondaryshock are considered as the Engineering Demand Parameter (EDP) for the analysis and fragility curves as per Gaussian distribution are plotted \[20\]. Provided, the EDP related mean as \(\mu\) and standard deviation as \(SD\), the cumulative normal distribution function is given as

\[
p[E D P > x] = 1 - \phi \left( \frac{x - \mu}{SD} \right)
\]

Figure 5 shows the fragility analysis curves (based on the normal distribution) of the study frame under Mainshock-Secondaryshock considering ISDR and RDR are Engineering Demand Parameters. The exceeding probability of ISDR over 4% is found to be 19% and 33%, respectively under Mainshock and Secondaryshock seismic disturbance level. Whereas the exceeding probability of RDR by 1% is obtained as 31% and 48%, respectively under the selected Mainshock and Secondaryshock ground disturbance levels.

![Fragility curves of 6XBRBFR8 considering ISDR and RDR.](image)

4. Conclusions
The nonlinear time-history analysis under the selected suit of Mainshock-Secondaryshock seismic records is carried out on a six-storey Buckling Restrained Braced Frame. The investigation results are presented in terms of Maximum Residual Drift Ratio (RDR) and Inter-Storey Drift Ratio (ISDR). Subsequently, fragility curves based on normal distribution are plotted taking Engineering Demand Parameters as ISDR and RDR. The Drift response evaluation showed that the increase of ISDR from Mainshock to Secondaryshock disturbances is in the range of 5-10%, whereas the increase of RDR is in the range of 20-25%. The resulting fragility curve showed that the exceeding probability of ISDR over 4% (from Mainshock to Secondaryshock hazard level) is in the range of 19-33% whereas the exceeding probability of RDR over 1% in the range of 31-48%. That is RDR response of 6XBRBFR8 showed higher variation in magnitude compared to ISDR.

5. References
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