Seismic Risk Mitigation of RC Frame Building in North-East India Using Buckling Restrained Braces

Aakash Kumar and Needhi Kotoky

Abstract North-East (NE) India has experienced several devastating earthquakes in the past decades. The seismic susceptibility of reinforced concrete frame buildings has been exposed by these earthquakes. In this region, most of the existing buildings are non-ductile as they are built before the introduction of modern seismic design codes. Seismic safety and resilience of these non-ductile structures can be increased by the use of a reliable retrofitting scheme. Therefore, buckling-restrained braces (BRBs) are designed to withstand earthquake-induced cyclic lateral loadings as a passive control system. In this study, the influence of BRBs in reducing the seismic risk of non-seismically designed frame is discussed. A finite element model of a 3-story 3-bay low ductility moment-resisting RC frame is developed. Nonlinear time-history analyses are carried out using a suite of ground motions to incorporate record-to-record variability. For both as-built and BRB retrofitted frame seismic fragility curves are obtained. For seismic risk assessment, the site-specific seismic hazard curve of Guwahati city giving relationship between annual probability of exceedance and peak spectral acceleration at 1.0 s is obtained. The estimation of seismic risk reduction as a result of the application of the BRBs retrofit within the bare frame is done by convolution of the seismic fragility curves with the regional seismic hazards for the Guwahati region. The findings of this study present the significance of BRBs on the seismic performance of the building, as well as the efficacy of a BRB retrofit for the NE region.

Keywords Buckling-restrained braces · Seismic risk mitigation · Seismic retrofitting · Reinforced concrete frame · North-East India

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1 Introduction

North-East (NE) India has experienced several devastating earthquakes such as 1897 Shillong earthquake (M_w 8.1), 1934 Bihar Nepal earthquake (M_w 8.1), 1950 Assam earthquake (M_w 8.7), and 2011 Sikkim earthquake (M_w 6.9). The seismicity of NE India is the combined effect of the Burmese arc in the east and the Indian–Eurasian Plate boundary in the north [1]. This region is among the highly earthquake-prone regions of the world. In this region, most of the existing buildings are non-ductile as they are built before to the introduction of modern seismic design codes. Due to the limited ductility capacity, these buildings are significantly vulnerable to severe ground shaking. Demolishing these seismically deficient structures and replacing them with modern structures is not feasible. As a result, seismic retrofitting is seen as a reliable technique for reducing seismic risk. For seismic design and retrofit of structures, steel braces are widely used. However, these bracings are prone to collapse when experiencing high cyclic or dynamic loads such as earthquakes. Restraining devices are added outside or within the braces, modifying them to buckling-restrained braces (BRBs) to mitigate the buckling effect as passive control system [2]. Passive control systems have proven to be very efficient devices for newly constructed as well as seismically retrofitted existing structures [3, 4]. The addition of a bracing system to a low-ductility frame enhances the structure's collapse modalities as well as the probabilistic characteristics of its seismic response [5]. Along with additional stiffness and strength to seismic deficient buildings, BRBs provide good energy absorption efficiency as a seismic-resistant structural element. These braces contribute to the additional path for lateral loads caused by earthquakes, improving the seismic performance of the frame. Therefore, this retrofitting technique may lead to a reduction in seismic vulnerability and losses of RC frame buildings in case of future earthquakes.

Addressing the gap, this study evaluates the influence of BRBs in seismic risk reduction of older non-seismically designed RC frame buildings. The next section introduces a benchmark 3-story low ductility RC frame representative of typical design details before the introduction of modern seismic design codes is chosen and BRB retrofit design is carried out. Next, the finite element modeling strategy of the case-study frame is discussed followed by a discussion on the design of BRB retrofit. To obtain seismic fragility curves, non-linear time-history analyses (NLTHA) are performed on the detailed finite element model of the as-built and retrofitted frames. Finally, for seismic risk assessment, the site-specific seismic hazard curve of Guwahati city giving the relationship between the annual probability of exceedance and peak spectral acceleration at 1.0 s [6] is convolved with seismic fragility curves to obtain lifetime seismic risk. The findings of this study present the significance of BRBs on the seismic performance of the building, as well as the efficacy of a BRB retrofit for the NE region.

2 Case Study Building—Finite Element Modelling of Bare and BRB Retrofitted Frame

2.1 Description of Case Study Frame

A 3-story 3-bay low ductile moment-resisting RC frame has been considered for the present study. In this frame, the bay width is taken as 5.49 m and each story height within the frame is taken as 3.66 m. Concrete compressive cube strength of 24 MPa and Grade 40 steel reinforcing bars with a yield strength of 276 MPa have been used for the frame modeling. The beam size is 260×460 mm, and the column size is 300×300 mm. Before the introduction of modern seismic codes, buildings were mostly designed for gravity loads alone, without taking seismic design into account.

2.2 Finite Element Modeling of Bare Non-Ductile Frame

The case study building frame is modeled in the finite element package OpenSees [7]. The *beamWithHinges* element, which consists of 2 plastic hinge regions at the element end and a central elastic element defined by fiber sections, is used to model the nonlinear flexural hysteretic response of beams and columns [9]. The plastic hinge lengths for columns and beams are obtained as per Panagiotakos and Fardis [10]. A moment–curvature analysis of the section is used to estimate the elastic component of effective flexural stiffness while taking into account the axial force level introduced by dead loads. *FiberSection* is used to define the ends of column and beam cross-sections with rectangular concrete patches and reinforcement layers. *uniaxialMaterial Hysteretic* model is used to model the longitudinal reinforcements whose controlling parameters like degraded unloading stiffness, pinching, and damage are calibrated using experimental results. The nonlinear degrading *Concrete02* material model is being used to model confined and unconfined concrete within fiber sections. The contribution of the slab is modeled in the beams using T-sections with effective width 4 times the beam width. A *zerolength* shear spring placed at the column top is used to model the shear response of columns in older non-ductile buildings. The *uniaxialmaterial limit-state* created by Elwood [11] is used to designate the characteristic attributes of this shear spring [11]. Building joints (interior and exterior) are modeled using a multilinear response envelope and a trilinear unloaded path is implemented using *Pinching4* material [12]. High axial stiffness is assigned to the beam for the modeling of diaphragm of rigid floor. Gravity loads are distributed across the beams, whereas the masses are concentrated in the lumped form at the beam-column joints.

2.3 BRB Design for Case-Study Frame

In this study, a case study frame has been taken and retrofitted with BRBs at each story, BRBs are introduced in the central bay. The elastic brace exhibiting sufficient over-strength is attached in series with an elastoplastic dissipative device to form the dissipative braces. This configuration gives, autonomous calibration of the strength ($F_c{}^i$) and stiffness ($K_c{}^i$) of the dissipative diagonal braces. At each story, $K_c{}^i$ is designed to maintain the first mode shape of the as-built frame after retrofitting in order to prevent significant changes to the internal force distribution in the frame within the elastic behaviour. Moreover, the $F_c{}^i$ distribution is intended to achieve yielding of the devices across all stories at the same time. As a result, the overall ductility of the bracing system is equivalent to the ductility of the individual braces. For different strengths proportion coefficient (α) values, the bracing system can be designed. It is defined as the ratio of seismic base shears associated with BRB frame and bare frame. For the current study, α is taken as 1. One more significant parameter that affects the design is the dissipative brace ductility (μ_{BRB}) which has been considered as 15. Table 1 shows the properties of dissipative braces $K_c{}^i$ and $F_c{}^i$ at each story together with the material's yield strength ($f_{y,BRB}$), the area (A_{BRB}), and length (L_{BRB}) of the BRB device. The device behavior is modeled using *SteelBRB* material model in OpenSees.

3 Influence of BRB Retrofitting on Seismic Risk

This section presents the influence of BRBs in seismic risk mitigation of RC frame. First, seismic fragility curves of as-built and retrofitted frames are developed for different damage states (DS) using *NLTHA* considering a suite of ground motions. Next, seismic risk reduction has been evaluated as a result of the implementation of the BRBs retrofit within the bare frame due to the convolution of the seismic fragility curves with the regional seismic hazards for the Guwahati region.

Table 1 Design properties of the BRBs distributed across the floors of the retrofitted frame

Floor no	$F_c{}^i$ (kN)	$K_c{}^i$ (kN/m)	$f_{y,BRB}$ (MPa)	A_{BRB} (mm^2)	L_{BRB} (mm)
1	207.9	45,967.4	250.0	831.6	2799.3
2	178.9	30,940.0	250.0	715.7	3579.2
3	103.0	28,242.4	250.0	412.0	2257.4

3.1 Seismic Fragility Comparison of Bare and Retrofitted Frame

Seismic fragility curves representing vulnerability under seismic shaking constitute critical precursors to seismic risk assessment of building structures. The seismic fragility curves for as-built and BRB retrofitted frames are developed using a two-step approach. In the first step, probabilistic seismic demand models (PSDMs) for critical are developed. Seismic fragility curves are developed in the second step using the demand model (obtained in first step) and limit state capacity model. PSDMs that relates the median peak engineering demand parameter (*EDP*) of the RC frame with the intensity measure (*IM*) of the ground motion is developed by conducting NLTHA of the RC frame using a suite of ground motion representative. The NLTHAs employ a synthetic suite of 150 unscaled strong ground motions so that the structure experiences behavior ranging from the linear to the non-linear domain, hence encompassing the various DS defined. Following *NLTHA*, *PSDMs* are developed for as-built and retrofitted BRB frames to estimate median seismic demand using the relation given:

$$\ln(EDP) = \ln a + b \ln(IM) \quad (1)$$

where, *EDP* is the engineering demand parameter, ln *a* and *b* are the linear regression coefficients, and *IM* is ground motion intensity measure. This study considers maximum inter-story drift ratio ($IDR_{\max}$) as *EDP* to estimate structural damage due to earthquakes. The bare and retrofitted frame has distinct fundamental time periods (1.2 s for the bare frame and 0.6 s for the BRB retrofitted frame), therefore, to allow comparison of PSDMs and fragility curves spectral acceleration at 1.0 s [S_a(1.0 s)] is considered as *IM*. Figure 1a shows the comparison of PSDMs of as-built bare frame and BRB retrofitted frame. The figure shows the data points (S_a(1.0 s)− $IDR_{\max}$ pairs) obtained from *NLTHA* simulations, and regression lines represent the median estimate of seismic demand for bare and retrofitted frame. Comparison of *PSDMs* results indicates a reduction in median seismic demand for BRB retrofitted frame as compared to as-built frame.

Following the development of *PSDMs* for bare and retrofitted frame, limit state capacity of different *DS* –slight (S), moderate (M), extensive (E), and complete (C) in terms of $IDR_{\max}$ are obtained using nonlinear static pushover analysis. Figure 1b shows the pushover curve of bare and retrofitted frames and markers corresponding to the attainment of different DS. These markers are obtained by measuring local *EDPs* such as material strains of steel and concrete in beams and columns and accounting for shear failure of columns. A detailed description of various *DS* is given in Table 2.

Finally, *PSDMs* and limit state capacity of different *DS* are utilized to develop seismic fragility curves. The seismic fragility for a particular *DS* follows lognormal distribution and is estimated as:

$$P[DS|S_a(1.0s)] = \Phi\left(\frac{\ln(S_a(1.0s)) - ln(med)}{\zeta}\right) \quad (2)$$

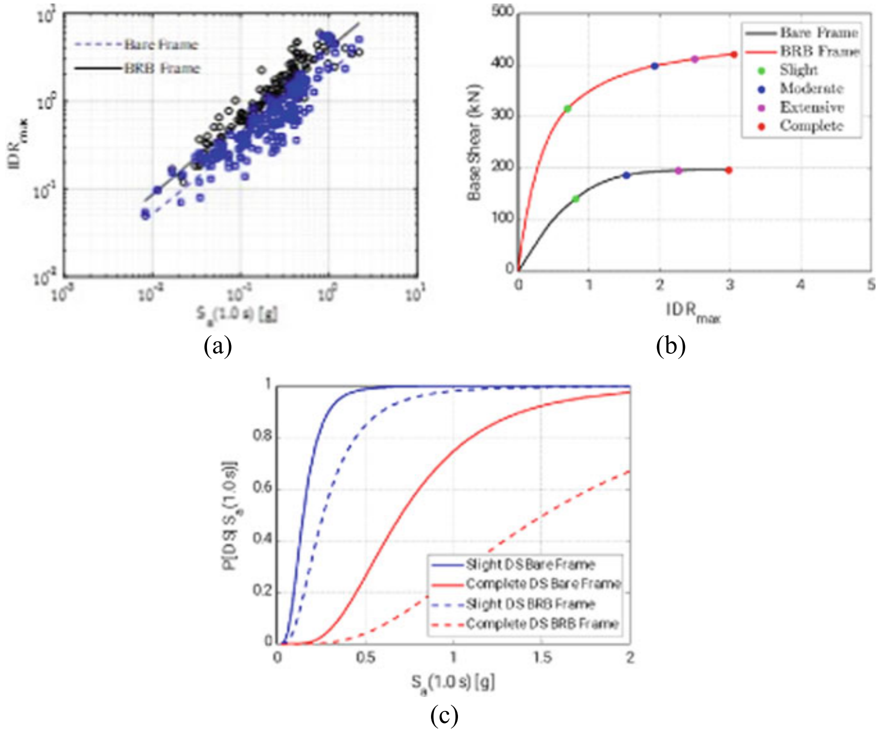


Fig. 1 **a** Nonlinear time history response and fitted PSDMs for as-built bare frame and BRB retrofitted frame, **b** Pushover curves of bare and BRB retrofitted frames showing markers corresponding thresholds of different DS, **c** Seismic fragility curves of as-built and retrofitted frames for slight and complete DS.

Table 2 Description of damage states and IDR limits

Damage states	Description of failure	As-built bare frame–IDR_{max}	BRB retrofitted frame–IDR_{max}
Slight (S)	Yielding of 50% of columns at one story	0.81	0.72
Moderate (M)	Crushing/Spalling of concrete in 50% of columns at one story	1.53	1.81
Extensive (E)	Average of M and C *DSs*	2.27	2.40
Complete (C)	Initiation of shear failure in 50% of columns at one story	2.98	2.99

where P[DS| S_a(1.0 s)] is the probability of damage state exceedance given a S_a(1.0 s) intensity, *med* is the median of lognormal distribution for fragility and ζ is the dispersion of fragility. Figure 1c shows the comparison of seismic fragility curves of as-built and retrofitted frame for S and C DSs. Results show that the failure probability of the BRB retrofitted frame is significantly lower than that of the as-built frame. The median S_a (spectral acceleration corresponding to 50% probability of failure) for S, M, E, and C damage states of bare frame is 0.14, 0.32, 0.51, and 0.70 g. On the other hand, the median S_a for BRB retrofitted frame is 0.26, 0.82, 1.15, and 1.51 g, respectively. Clearly, across all DS implementation of BRB results in a significant reduction in vulnerability. The next section utilizes the developed seismic fragility curves for seismic risk assessment.

4 Seismic Risk Reduction of Retrofitted Frame

For seismic risk assessment, the site-specific seismic hazard curve of Guwahati city giving relationship between annual probability of exceedance and peak spectral acceleration at 1.0 s is obtained from past literature [6] and shown in Fig. 2a. Using the seismic fragility curves for the as-built or BRB retrofitted frame, as well as site-specific seismic hazard information for Guwahati region, the lifetime (T = 50 years) probability of DS exceedance, P_{Tf}, can be calculated as follows.

$$P_{Tf} = 1 - (1 - P_{Af})^T \tag{3}$$

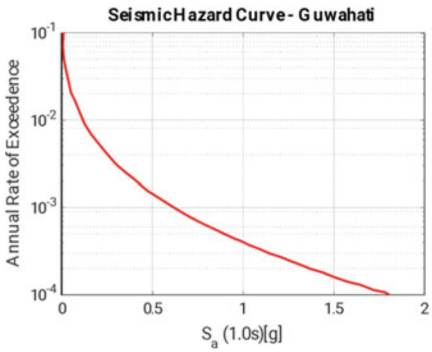
Hence, using the convolution of seismic fragility and site-specific hazard [$H(IM = im)$], the annual probability of DS exceedance, P_{Af} can be obtained as follows:

$$P_{Af} = \int_{im} [Fragility|IM = im] \left| \frac{dH(im)}{d(im)} \right| d(im) \tag{4}$$

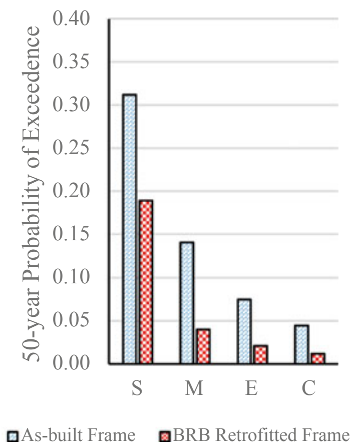
Figure 2b shows the $T = 50$ years probability of exceedance comparison for as-built and retrofitted frames. The results show that the failure probability of the BRB retrofitted frame is significantly lower than that of the as-built frame. The BRB retrofit leads to 39, 71, 72, and 73% reduction in seismic risk estimates of S, M, E, and C damage states.

5 Conclusions

In the present study, the influence of BRBs in reducing seismic risk of non-seismically designed frame in NE India is discussed. The proposed methodology's capability and effectiveness are evaluated by considering a realistic benchmark RC frame with



(a)



(b)

Fig. 2 **a** Seismic hazard curve of Guwahati region obtained from Nath and Thingbaijam [6] **b** Comparisons of seismic risk for the as-built and BRB retrofitted frames for S, M, E, and C damage states

limited ductility capacity retrofitted with BRBs. The retrofitted frame using BRBs significantly reduces seismic fragility, as indicated by the seismic fragility curves for the as-built and retrofitted frames. The estimation of seismic risk reduction as a result of the application of the BRBs retrofit within the as-built frame is due to the convolution of the seismic fragility curves with the regional seismic hazards for the Guwahati region. Results reveal 73% reduction in seismic risk estimates of complete damage state highlighting the influence of BRBs retrofit for non-seismically designed RC building in the NE region. As a future scope of the study, the work can be extended to different retrofit levels, and also variations in the case study frame can be introduced.

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