Assessment and Retrofitting Augmentation Methods of Seismic Performance on Existing RC Buildings Across India

Ankeeta Karmakar

1 Introduction

The super-continent Gondwana had broken into African, Antarctica, Australian, and Indian tectonic plates about 140 million years ago [3]. The Himalayan mountain belt is the seismically active part of this entire Indian tectonic plate. The plate has experienced major earthquakes over the last few decades—Shillong (1897), Kangra (1905), Bihar–Nepal (1934), Assam (1950), Gujarat (2001), Kashmir (2005) [4], Sikkim (2006) and (2011), Imphal (2016).

Gujarat earthquake (2001) was one of its kinds with a magnitude of 7.7 and duration of 22 s, which caused devastating effects in 21 districts, 7904 villages, and 182 administrative subdivisions of the district. The fatalities associated counted to 20,005, whereas 20,717 were seriously injured [5]. In the densely populated city, Ahmedabad, about 50 reinforced concrete buildings collapsed and a damage of $7.5 billion was estimated in the entire state [6]. An important facet of the ground motion was that it caused the collapse of RC building located at 250–300 km away from the epicenter [7].

Sikkim, a state that lies on the Himalayan foothills, has encountered two devastating forms of earthquakes—(a) February 2006 of 5.7 magnitude and (b) September 2011 of 6.9 magnitude. The earthquake of 2006 caused primary damages to RC buildings due to poor construction practices and design methodology. The second major earthquake that lasted for 40 s caused casualties of about 148. A damage of about $14 billion was estimated. The capital city—Gangtok experienced the complete collapse of two under construction five-storied buildings [8]. The region encountered aftershocks of 5.0, 4.5, and 4.2 magnitudes due to the severe earthquake [9].

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(a) (b)

Fig. 1 Columns (fourth level) of Royal Group of Institution in Guwahati that faced damages due to the Imphal earthquake 2016

The Sumatra tsunami (2004) of magnitude 9.1 hits the Andaman and Nicobar Island of India causing fatalities of about 1500 and affecting more than 14 countries. The earthquake caused huge destruction on RC infrastructures, whereas the buildings whose major structural members were timber and masonry withstood the severe ground motions [10].

The land of Manipur was shaken by an earthquake of 6.7 magnitude in January 2016, which hits the capital city of Imphal, destroying more than 2000 three-story and four-story offices and residential buildings [11]. Due to the sparse population in the region, the reported fatalities were very minimal [12]. Newly built RC structures were damaged, a majority of publicly funded, and government buildings were affected badly due to failure to complying with the Indian standard code of Practice for seismic design, IS 1893 [13]. The earthquake was felt in few cities of Assam, which caused few damages to the RC buildings in the region of Silchar (260 km away) and Guwahati (490 km away). Figure 1 shows columns of the five-story Royal Group of Institution building located in the region of Guwahati, which experienced damage due to the severe ground motions of the Imphal earthquake.

2 Seismic Performance of Existing Buildings by Zones

According to BIS, India is divided into various seismic zones based on past seismic activity. According to the IS 1893 (Part 1): 2016, the country is divided into four seismic zones, II through V with increasing magnitude of intensity. The majority of India's northeastern and northwestern geographical area lies under seismic zones IV and V. The fifth revision of seismic zonation map of India resulted after the 1993 Latur earthquake, which shook the region of Maharashtra at an intensity of IX (magnitude 6.3) causing huge destructions [14]. In the previous edition, Latur laid in seismic zone I, but later after the revision of 2002, it lies between seismic zones II and III. The probability of exceedance of all the seismic zones of India is 10% in 50 years with Peak Ground Acceleration (PGA) of 0.1 g to 0.4 g.

Table 1 shows the four major earthquakes that the country experienced with their respective seismic zones along with the varied observed PGA. During these four major earthquakes, maximum reinforced concrete-framed structures did not perform well. The observed deformations were gravity load failure, open story failure, and component deformation modes being flexural, flexural shear, lap splice, sliding shear. The loss of gravity load capacity has been observed in all the major earthquakes in India. The deformation is witnessed when the structural element fails to bear its gravity load-carrying capacity, which often occurs due to shear failure in the member. In RC columns, a loss of axial load carrying capacity can give rise to a gravity failure, which can further extend to the total collapse of the structure.

The flexural failure in concrete members occurs in two modes as brittle and ductile. When the ultimate capacity of the compression zone is reached, the member deforms in ductile flexural failure. On the other hand, when the concrete member crushes before yielding the reinforcement, brittle flexural failure gets generated. When the member deforms due to the availability of no shear resistance provided by transverse reinforcement, shear failure occurs. Flexure shear is one of the major types of failure observed in RC-framed structure experiencing severe ground motions. The flexural-shear failure rises by the formation of cracks due to flexural tensile stress, which propagates diagonally in the member, giving rise to increased tensile stress from concrete tensile strength and leading to entire member crushing in shear. Few deformations in the RC buildings were observed due to splicing of reinforcement at critical locations, which gave rise to failure at beam–column junction.

According to IS 1893 (Part 1):2016, the westernmost state of India, Gujarat lies on three seismic zones—III, IV, and V. The epicenter of the Gujarat earthquake (2001) was in Bhuj, which lies on zone V. The reason for collapse of maximum of buildings during the Bhuj earthquake (Gujarat) was due to substandard construction practices and failure to comply with IS code of practices. Severe structural damage in RC-framed buildings was seen 300 km away from epicenter in the city of Ahmedabad [18]. The majority of the failures occurred in the buildings having no infill wall in the first story, which was adopted to provide facilities for parking. In Sikhara region of Ahmedabad, a newly constructed "H"-shaped 10-story building saw the collapse

Table 1 Description of few major earthquakes across India

Region	Date	Time	Seismic Zone	Magnitude	PGA (g)
Imphal	4 January 2016	4:35	V	6.7	0.11—0.34 [13]
Sikkim	18 September 2011	18:10	IV	6.9	0.2—0.45 [15]
Andaman and Nicobar Island	26 December 2004	7:28	V	8.7	0.1 [16]
Gujarat	26 January 2001	8:46	V	7.7	0.38 [17]

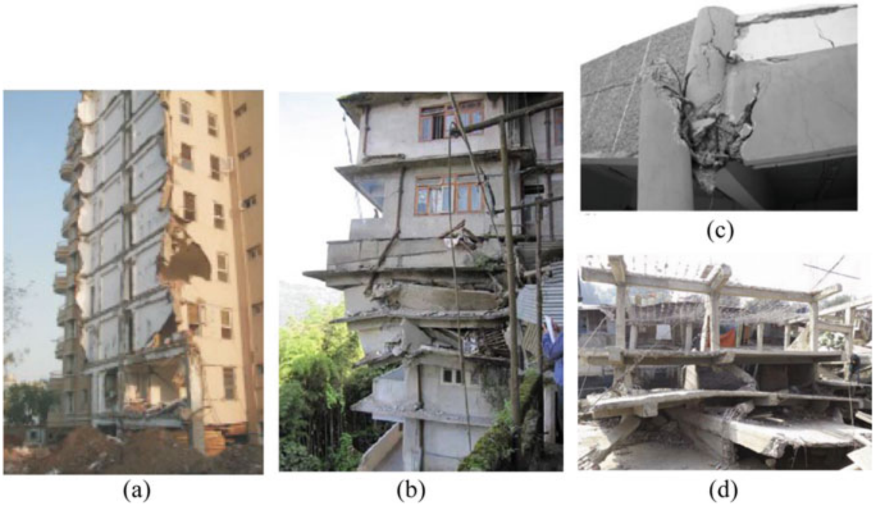


Fig. 2 **a** Collapse of an H-shaped 10-story newly constructed apartment building in the region of Sikhara, Ahmedabad [18], **b** Collapse of middle stories due to the 6.9 magnitude Sikkim earthquake (2011) in the region of Balwakhani, Gangtok [9], **c** Failure due to short column mechanism in few columns of New Passenger Terminal, Port Blair [19], **d** Complete collapse of a four-story building in the region of Dewlahland, Imphal [13]

of an entire wing of one of the open arms, which caused the lives of 89 persons, as shown in Fig. 2a. The open first story with no infill wall created a soft story mechanism where the lateral load resistance was significantly lesser than the upper stories. The presence of infill wall on the above-ground stories made the levels stiffer and resulted in attracting a huge amount of earthquake forces compared with the open ground story that caused large-scale destruction in the entire city of Ahmedabad.

The epicenter of the Andaman and Nicobar earthquake (2004) was in Sumatra, an Indonesian Island, which lies on seismic zone V. A study conducted showed that the majority of RC building collapsed due to improper reinforcement detailing, workmanship, and quality control during the construction of the infrastructure [19]. Old unreinforced building withstood the ground motions, but RC buildings whose ground story was an open story encountered severe damages and total collapse. Due to the presence of infill masonry wall on upper stories, little or no damage was observed. A study has shown that during the ground motion, the infilled frames acted as shear wall till the infill materials reached the brittle failure [20]. This might have also occurred during the earthquake, leading to short column mechanism. Few columns of the entire New Passenger terminal deformed due to the short column mechanism as shown in Fig. 2b. Due to the inappropriate detailing of ductile reinforcement, the columns failed in shear and flexural resistance on the beam–column joints.

Sikkim is in the northeastern part of India whose majority of the land is on hilly terrain and lies on seismic zone IV. Huge construction practices are carried out in the capital city Gangtok to accommodate the increasing population on sloping grounds.

This type of construction practice has given rise to irregular and unsymmetrical plans both vertically and horizontally [21]. Figure 2c shows the gravity load failure of a nine-story building in the region of Balwakhani, Gangtok during the Sikkim earthquake (2011). Various failures occurred due to lapping of longitudinal reinforcement at inappropriate locations, no adequate confining reinforcement, extensive extension of upper story over cantilever beam, inferior material quality, and poor workmanship.

One of the northeastern states, Manipur, lies on the seismic zone V. During the earthquake of 2016, huge destructions were seen. The three-story RC building of Sports Authority of India experienced severe damages, which led to its demolition at a few months of its life. Figure 2d shows a four-story building that collapsed completely during the earthquake. The Asia's largest all women's market "New Market building" (Ima Keithel) experienced major damages [13]. In the building, PVC pipes of 150 mm were concealed inside the circular columns, which jeopardized the confinement of exterior columns causing the reduction in strength and spalling of concrete. Failures in RC buildings were seen majorly due to no ductile detailing, inadequate spacing of transverse reinforcement, unequal clear cover, lack of confining reinforcement, inferior material quality, and failure to complying with IS code of practices. On the other hand, the old traditional wooden buildings showed better performance as compared with the RC buildings.

The observed drawbacks in the construction practices that led to the failure of RC buildings were poor construction materials, failure to comply with IS codes, no ductile detailing, inadequate longitudinal and transverse reinforcement, and widely spaced stirrups and ties, to name a few. Many schools and government buildings which were erected with strict supervision ended up being damaged during the earthquake. Newly constructed buildings like the H-shaped RC building in Gujarat and Passenger Terminal in Andaman and Nicobar Islands have also shown unexpected failures. All the failure mechanisms and deformations observed are similar across the various regions of the country. The difference in earthquake magnitudes and reported PGA did not have any significant impact on the failure mechanism shown by these RC buildings.

3 Analysis and Retrofitting Techniques

Various seismic retrofit techniques for strengthening a damaged-reinforced concrete member have been studied and adopted in practical applications across the country. Diverse methods include few conventional techniques like braces, jacketing, and infills and modern techniques like the use of advanced materials like Fiber-reinforced Polymers (FRP) and Shape Memory Alloys (SMA) [22]. Even though the greatest disadvantages of using retrofit techniques are cost, feasibility, and material availability [22], these techniques have proven to potentially increase the degraded strength. FRP is a system that constitutes fibers embedded in a polymeric matrix, which is used to increase the strength and ductility of the damaged member and provides effective confinement to the member [23]. Concrete jacketing is another

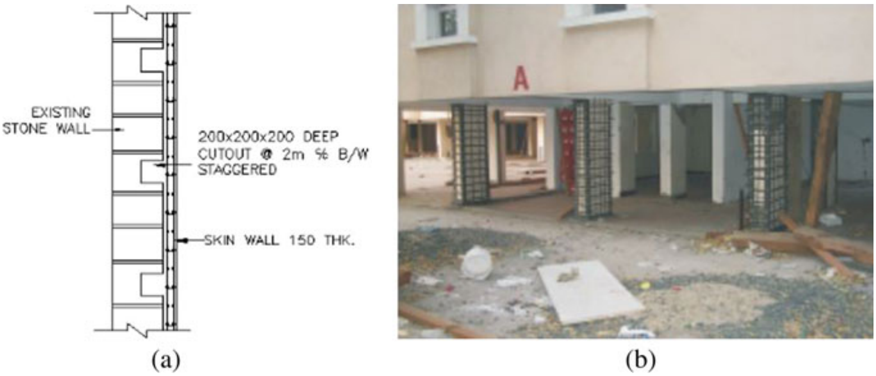


Fig. 3 Different retrofitting measures adopted to strengthen—**a** Mani Mandir, Morbi [23], **b** H-shaped 10-story apartment building, Sikhara [18]

form of retrofitting method, which is used widely in the construction field due to the cost efficiency, ease of implementation, and availability of materials [24]. When a new layer of reinforced concrete is applied to the deformed member, the capacity of the member increases in terms of stiffness, ductility, axial, and shear strength in uniform and distributed manner [23, 25].

During the Bhuj earthquake (Gujarat) 2001, the Mani Mandir complex located at Morbi at 125 km away from the epicenter experienced severe damages. The building was constructed during 1930s. Dynamic analysis was carried out to observe the seismic performance, and retrofitting technique was implemented. The building was constructed using yellow sandstone, but after carrying out the dynamic analysis, few members like wall, bastion were retrofitted using reinforced concrete skin walls of 150 mm thickness, as shown in Fig. 3a [26]. As mentioned in Sect. 2, an entire wing of a 10-storied H-shaped building in Sikhara collapsed. The columns at the open ground story of the other wing of the building have been strengthened using concrete jacketing as shown in Fig. 3b.

During the Sikkim earthquake 2011, the Moonlight School of Chungthang region, constructed in the year 1985, encountered collapse of the second story, which propagated to the upper story, as shown in Fig. 4a. During the non-linear static pushover analysis, two forms of design analysis were applied—Design Basis Earthquake (DBE) bearing PGA of 0.18 g and Maximum Considered Earthquake (MCE) bearing PGA of 0.36 g. Using the guidelines of ATC-40, the performance point was found out and was compared with FEMA-365 guidelines. The analysis resulted in hinges at the region of immediate occupancy and life safety for the maximum considered earthquake at 22 columns of the corridor of the school building. Glass Fiber-Reinforced Polymer (GFRP) was used to strengthen the columns of the structure, which generated hinges during the non-linear static pushover analysis [25].

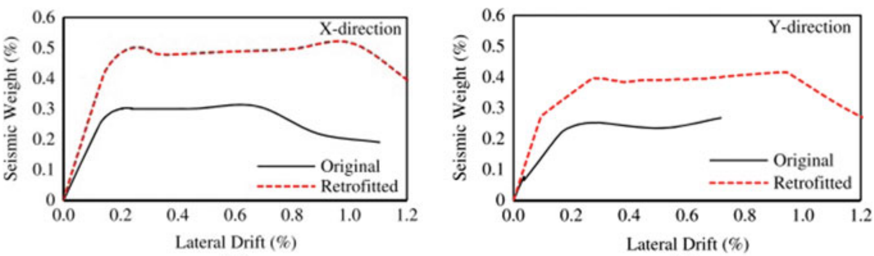
During the Imphal earthquake 2016, the New Market building (Keithel 3) constructed in the year 2006 encountered severe damages in various structural components due to poor workmanship, substandard quality of material, and failure

(a) (b)

Fig. 4 **a** Total collapse at the second story leading to extensive damage at the third story of Moonlight School building at Chungthang, Sikkim [25], **b** Damages in the columns due to short column effect in the New Market building, Imphal [24]

to compliance with Indian Standard guidelines as shown in Fig. 4b. For the non-linear analysis with PGA of 0.36 g, the non-linear flexural hinges were assigned to the beams and columns using the definition generated by Paulay and Priestley [27]. The shear hinges were assigned to the model using the shear force—shear deformation (V-Δ) models explained in IS 456. As the region of Imphal is located at the remotely hilly terrain, to have an easy, convenient, and quicker solution with implementation of local resources, concrete jacketing was adopted to strengthen the column that failed in flexure and shear. The pushover curves generated before and after retrofitting showed that the stiffness and lateral strength increased remarkably as shown in Fig. 5. The load and moment curve for the most critical column (C6-GR) showed an increasing capacity by three times as shown in Fig. 6. The capacity of all the columns increased sufficiently and the demand pairs were laid inside the interaction curve [24].

The northeastern part of India, Assam, lies on a seismic belt of zone V with its capital city, Guwahati, being the most densely populated region in the entire state.



(a) (b)

Fig. 5 Pushover curve obtained for the original and retrofitted building after the analysis in the direction of **a** X axis, **b** Y axis [24]

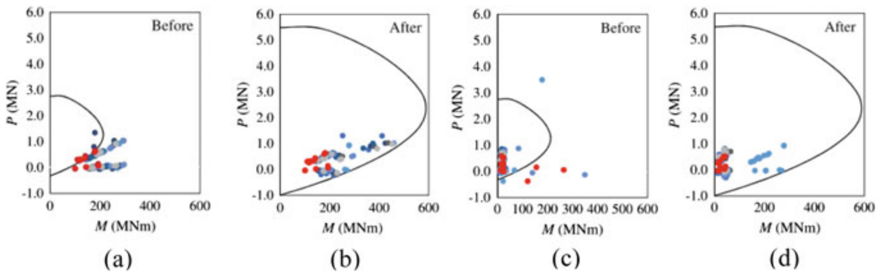


Fig. 6 P–M interaction curves for all the columns of New Market building in comparison to C6-GR in the direction **a** X-axis (before strengthening), **b** X-axis (after strengthening), **c** Y-axis (before strengthening), and **d** Y-axis (after strengthening) [24]

A study shows that the city has encountered a construction boom in terms of multi-storied mid-rise building apartments with open ground story and no lateral load resisting systems [28]. Minor tremors of earthquake are felt almost every month in the region with the very recent being an earthquake of 4.4 magnitude at a 32 km depth in a region of Nongstoin, Meghalaya, which is at 150 km.

An evaluation was made to reduce the seismic vulnerability by introducing infill masonry walls to the reinforced concrete frame at certain locations of the ground story [28]. Two buildings were chosen for the analysis—(a) Sample building of five stories and (b) an irregular existing building. For each of the buildings, three different scenarios of modeling were considered—(i) Bare frame, (ii) Open ground story, and (iii) Masonry retrofitted building. For the retrofitting technique, 5 inches and 10 inches infill masonry walls were considered in the study. Plastic hinges were assigned as per the guidelines of FEMA 356 (inbuilt in SAP2000), and a pushover analysis was carried out. The pushover curve for the sample building as shown in Fig. 7a resulted that a considerable increase in horizontal base shear is observed when infill masonry walls of 5 inches and 10 inches are considered as a structural element. On the other hand, Fig. 7b shows that for the existing building, the horizontal shear for bare frame increased considerably as compared with the sample building but the horizontal shear for open ground story increased. The masonry infill wall at strategic

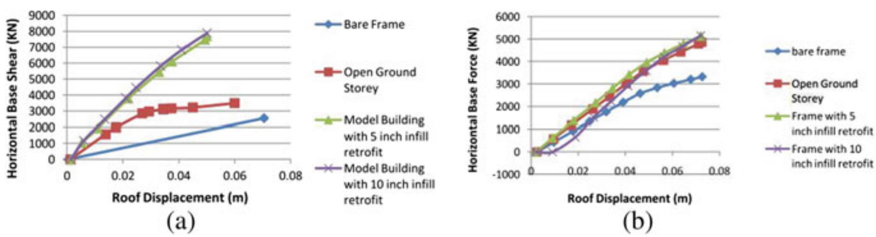


Fig. 7 The static pushover curve for all the three considerations of—**a** sample building, **b** existing building [28]

locations further increased the horizontal base shear, but a significant difference was observed for 5 inches and 10 inches of thickness infill wall [28].

A study was conducted to compare the strength of the column size using the guidelines of IS 456:2000. The strength was evaluated using concrete jacketing and FRP wrapping using IS 15988:2013 guidelines [23]. The strength for concrete jacketing, one layer and two layers of FRP wrapping, was evaluated based on minimum and maximum conditions provided in the guidelines. It was found out that increase in strength of the column section with concrete jacketing was 1.78 times more than one layer of FRP wrapping and 1.40 times more than two layer of FRP wrapping. Another study was conducted to test the performance of a column in flexure after concrete jacketing using slant shear and compression test and lamellar analysis. The test showed that the moment capacities of the retrofitted specimen increased substantially. The retrofitted beam–column joint sub-assemblage showed an increase in lateral capacity, ductility, and energy dissipation. During the lamellar analysis, good behavior of stress versus strain and moment versus curvature was observed [30]. A similar study was conducted to study the performance of a beam in flexure using slant shear test and lamellar approach after strengthening the beam implementing concrete jacketing. A reference specimen and two retrofitted specimens were tested under monotonic load and half cyclic loads. The reference specimen showed failure in the region of soffit of the beam, whereas the retrofitted specimen under monotonic loading showed no buckling or spalling. The specimen under cyclic loading performed better than all the specimens in terms of strength and ductility. The lateral capacity of the retrofitted specimen under monotonic and cyclic loading than the reference specimen was 1.46 and 1.23 times, respectively. The strength and ductility of the retrofitted sub-assemblage increased significantly. Good performance was observed at the moment versus rotation behavior of the retrofitted specimen during the layered analysis (lamellar approach) [31].

A few of the existing retrofitting techniques have been found to be useful for the deformed RC components across India. For adopting a retrofitting scheme, a vital step is to assess the availability of materials that are required to implement during the entire process. As discussed in Sect. 1, the Himalayan mountain belt is the seismically active part of the entire Indian tectonic plate and majority of its land is on hilly terrain. In a developing country where reinforced concrete structures are in remote and hilly locations, and the locations are zoned seismically active by the Indian Standard guidelines, it is important to note the ease of implementation. The strengthening process of concrete jacketing can be executed economically, quickly, with the use of locally available materials and manual labors. Local retrofitting through concrete jacketing increases the shear strength, thereby increasing the confinement of concrete with less amount of required work.

4 Conclusions

This paper reviews some of the works completed across different earthquake zones of India based on the performance of the existing reinforced concrete buildings during the major earthquakes. It was observed that despite being on different seismic zones as defined by the IS 1893 (Part 1): 2016, the sixth edition, with different observed earthquake magnitudes and peak ground accelerations, the reinforced concrete buildings across the regions showed a similar form of deformations. The various governing failures of reinforced concrete buildings during the earthquakes have been discussed in the study. Due to the presence of open ground story, the reinforced buildings witnessed partial to complete collapse with common component deformations of flexural, flexural shear, lap splice, and sliding shear. According to the Indian Standard Code of Practice, about 60% of India's geographical land lies under zones III, IV, and V. The northeastern region of the country lies on the Himalayan Belt and, therefore, is one of the most active regions.

To prevent the existing RC structures from witnessing severe damages in life and property, strengthening the existing deformed reinforced concrete components is vital. Local retrofitting of the concrete members can be implemented using concrete jacketing to increase the strength and ductility of the member. The process of concrete jacketing is found out to be economically feasible and can be implemented locally available materials and operated with minimal manual labors. Local retrofitting of RC members through concrete jacketing increases the confinement of concrete, thereby increasing the shear strength of the member. Several reinforced concrete buildings deformed during the major earthquakes have been strengthened using concrete jacketing. Future works can be exploring the various retrofitting methods across the globe and comparing their feasibility in India. However, as pointed earlier, most of them might end up being futile because of the lack of proper resources.

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