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Md Abul Hasan
Associate Professor,
Department of Disaster
Engineering & Management,
Chittagong University of
Engineering and Technology,
Chittagong-4349, Bangladesh

Md Nour Hossain
Lecturer, Department of
Disaster Engineering &
Management, Chittagong
University of Engineering and
Technology, Chittagong-4349,
Bangladesh

Mohammed Rias Uddin
Post Graduate student,
Department of Disaster
Engineering & Management,
Chittagong University of
Engineering and Technology,
Chittagong-4349, Bangladesh

Biplob Kanti Biswas
Assistant Professor,
Department of Architecture,
Chittagong University of
Engineering and Technology,
Chittagong-4349, Bangladesh

Corresponding Author:
Md Abul Hasan
Associate Professor,
Department of Disaster
Engineering & Management,
Chittagong University of
Engineering and Technology,
Chittagong-4349, Bangladesh

Seismic vulnerability assessment and retrofit of hospital building using base isolation devices

Md Abul Hasan, Md Nour Hossain, Mohammed Rias Uddin and Biplob Kanti Biswas

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Abstract

Numerous existing hospital buildings around the world have been found vulnerable to earthquake. In this paper, the vulnerability assessment of an existing hospital building is performed, and the implementation of base-isolation (BI) device as retrofitting strategy is done. In an illustrative example, the Ancillary Building (AB) of Chittagong Medical College Hospital (CMCH), which is very important for the people of the surrounding area located in earthquake-prone region, Chittagong, is considered in this study. For the vulnerability study, firstly, preliminary assessment has been done using FEMA-310 guidelines showing that there are several non-compliance (NC) elements, which reveals the presence of structural deficiency. After that, detailed vulnerability assessment as per FEMA-310 has conducted. For detail assessment, static and dynamic analysis was done. Static analysis was performed based on the Bangladesh National Building Code-1993 (BNBC-1993) and BNBC-2006 guidelines. In addition, for dynamic analysis, 36 ground motions have been used for structural response evaluation. The result of static analysis reveals that the existing hospital building is safe for designed ground motion suggested in BNBC-1993. However, AB is not safe according to BNBC-2006. The results of dynamic analysis (linear time history and response spectrum) provide enough evidence that the existing hospital building is safe up to ground motions having PGA 0.1825 g beyond this PGA value the AB is vulnerable. For this reason, BI devices have been used as a proposed retrofitting strategy and structural performance of retrofitted AB has been investigated. The results report that the proposed retrofitting method is effective in decreasing the seismic effect on the hospital building and keeping it safe for design earthquake of PGA 0.28 g suggested in BNBC-2006.

Keywords: Hospital building, vulnerability assessment, structural analysis, retrofitting, base isolation device

Introduction

Hospital is very crucial for human civilization and provides lifesaving medical care on a daily basis to the community people when they need it (Hasan and Bhuiyan, 2014, 2015 and 2018; Hasan, 2016) [8-11]. Community expects the hospital and its staff to save lives in an emergency and to care for community members if they are seriously injured or become seriously ill. All hospital facilities should be capable of continued operation during and after natural disasters. This means special design consideration is needed for the protection of hospital buildings from the effect of seismic action. Therefore, every building code in the world considers a higher importance factor for the seismic design of hospital buildings to be operational during and after an earthquake. The Bangladesh National Building Code (1993) [4] suggested for consideration of 25% higher importance than the standard occupancy building. Similarly, Euro Code-8 (2004) [6], Australian Building Code-11704 (1993) [4], and New Zealand Building Code-4203 (1992) [3] suggest to provide 75%, 20%, and 30% higher importance than normal buildings, respectively.

However, it is observed that numerous hospital buildings around the world are damaged in different earthquakes causing huge loss of life and economics even though special seismic design provisions have been taken. For example, damage to hospital building structures was observed in the 1971 San Francisco Earthquake, 1994 Northbridge Earthquake, and 2001 Bhuj Earthquake, etc. (Hasan and Bhuiyan, 2018) [8]. Moreover, Bangladesh is geographically located in the high seismic risk zone. Prior to 1993, there was not any guideline for designing earthquake-resistant structures in Bangladesh. In 1993, Bangladesh National Building Code (1993) [4] provided guidelines for building design considering earthquake load and suggested for seismic zoning coefficient, Z=0.15 g for Chittagong City.

Nevertheless, recent research (Al-Hussaini, Hossain, and Al-Noman, 2012) [1] has shown that considered earthquake load in BNBC (1993) [4] does not represent the realistic seismic scenario in Bangladesh. Therefore, BNBC (1993) [4] has been revised to consider the greater effect of the earthquake and recommended assuming seismic zoning coefficient, Z = 0.28 g for Chittagong city [6]. This indicates that existing hospital buildings constructed before 2006 may not survive an earthquake having a PGA of higher than 0.18 g. Therefore, vulnerability assessment of existing hospital buildings in Bangladesh should be done.

A seismic vulnerability assessment of structure is a comprehensive engineering study that is used to evaluate the susceptibility of the structural systems to potential damage from seismic shaking. The results from the seismic vulnerability assessment determine the need for retrofitting. The retrofitting of a vulnerable structure can be done by implementing base-isolation (BI) devices since it not only provides safety against collapse but also largely reduces damage, which is crucial for facilities that should remain operational after severe earthquakes like hospitals building. After retrofitting hospital buildings using BI devices, a seismic vulnerability assessment is performed to determine the effectiveness of BI devices.

Physical description and modelling of hospital building

Chittagong Medical College Hospital (CMCH) was established in 1957 and started functioning in the present location in 1960 with only 120 beds and few outpatient services. It is providing treatment to 2 million patients annually in which most of them are underprivileged. For this reason, it is the most demanding hospital for the people of this city.

Fig. 1 represents the Ancillary Building (AB) of CMCH. Two types of columns (rectangular and circular) were used in this building. The rectangular columns having six different sizes are used here with a maximum size of 750 mm x 625 mm. Three types of circular columns were used with a maximum diameter of 625 mm.

From structural drawings, it is found that the compressive strength, modulus of elasticity, and poisson’s ratio of concrete are 25 MPa, 23670 MPa, and 0.2, respectively. The tensile strength and modulus of elasticity of steel are 415 MPa and 200000 MPa, respectively. For modeling purposes, the compressive strength and poisson's ratio of clay brick are considered 13.7 MP and 0.19, respectively. For detailed analysis, the hospital building needs to make an analytical model which represents the actual condition of the building. For this purpose, structural analysis software SAP 2000 has been used for modeling the hospital building. Beam and column elements are modelled as frame element while the floor, roof, mat foundation, and shear walls are modelled as shell elements. The existence of masonry infill is modelled as equivalent strut model by Stafford-Smith and Carter (1969) [16]. Fig. 2 represents the analytical model of the considered AB.

Fig 1: 3-D of Ancillary Building (AB)

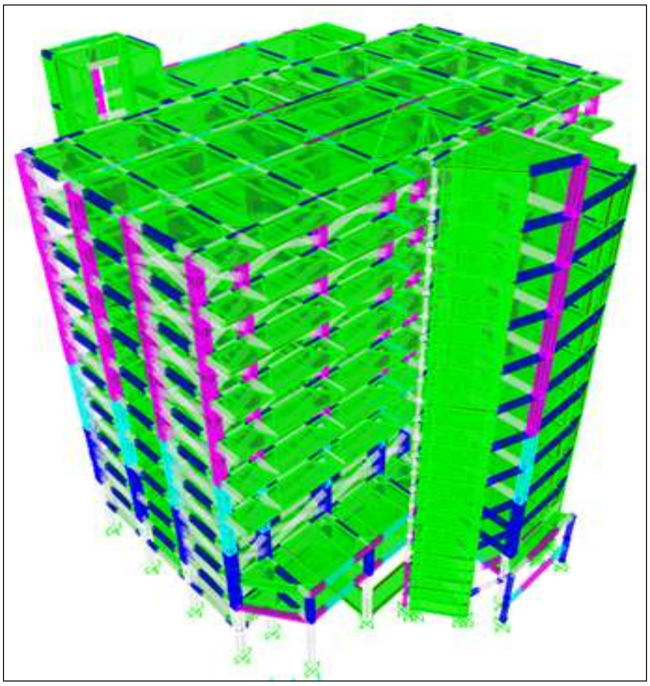


Fig 2: Analytical model of AB

Preliminary vulnerability assessment

After collecting all data and drawings, the hospital building was visited for some physical measurements to verify the accuracy of data and drawings. Then preliminary vulnerability assessment is done as per FEMA-310 (1998), which consists of 3 sets of checklists that allow a rapid evaluation of the structural, non-structural, and foundation/geologic hazard elements of the building and site conditions. The result of the preliminary vulnerability assessment is illustrated in Table 1, Table 2, and Table 3 which indicates that there are several Non-compliance (NC) elements. The NC elements include short column, short captive column, and stirrup and tie hooks. The presence of NC elements indicates that the structure has some deficiency. For this reason, a detailed vulnerability assessment is needed to make a more reliable conclusion.

Detailed vulnerability assessment

Detailed vulnerability assessment includes static and dynamic analysis of the structure.

Table 1: Basic structural check.

Building System	
Evaluation Statement	Notification
Load Path	C
Adjacent Building	C
Mezzanine	NA
Weak Story	C
Soft Story	NC
Geometry	C
Vertical Discontinuities	C
Mass	C
Torsion	C
Deterioration	C
Post Tensioning Anchors	NA
Lateral Force Resisting System	
Evaluation Statement	Notification
Redundancy	C
Interfering walls	C
Shear stress check	C
Axial stress check	C
Concrete column	C

Note: C = compliance; NC = non-compliance; NA = not applicable.

Table 2: Supplemental structural check.

Lateral Force Resisting System	
Evaluation Statement	**Notification**
Flat slab frames	C
Pre-stressed frame elements	NA
Short captive columns	NC
Beam bars	C
Column-bar splices	C
Beam-bar splices	C
Column-tie spacing	C
Stirrup spacing	C
Joint reinforcing	C
Joint eccentricity	C
Stirrup and tie hooks	NC
Deflection compatibility	C
Flat slabs	NA
Diaphragm continuity	C
Plan irregularities	C
Lateral load at pile caps	NA

Table 3: Geological site hazard and foundation check.

Geological Data	
Evaluation Statement	**Notification**
Liquefaction	C
Slope failure	C
Surface fault rupture	C
Foundation performance	C
Deterioration	C
Pole foundations	NA
Overturning	C
Ties between foundation elements	C
Deep foundations	NA
Sloping sites	C

Static analysis as per BNBC and dynamic analysis which includes linear time history and response spectrum have been conducted. The results of the various structural analysis provide the idea regarding the behavior of the building during an earthquake and the possibility of failure of structure globally or locally. For this reason, after each analysis, the response of the hospital building is required to evaluate from global and local failure points of view. In this research, the global responses of the structure are compared with the allowable limit provided by BNBC. In the next step, local failure probability is also examined since during the earthquake, the structure may be safe globally but may fail locally.

Static analysis

The hospital building is analysed for earthquake loading using the equivalent static force method considering seismic zoning coefficient of Z = 0.15 g and Z = 0.28 g. The reason behind to use of two seismic zoning coefficients is the AB was designed for earthquake load recommended in BNBC (1993) [4], however, BNBC (1993) [4] has been revised to consider the greater effect of the earthquake and the seismic zoning coefficient for Chittagong is 0.28g according to BNBC (2006) [5]. The response modification factor is used here to consider the effect of the yielding of structure. The response modification coefficient is considered 5. The self-weight of all structural and non-structural members is calculated using the size and unit weight of the material. The live load is also applied according to the guideline of BNBC. Superimposed dead load from a floor finish, permanent equipment, etc. are also taken into consideration. Moreover, load from partition wall and random wall are also calculated and applied to the corresponding supporting members. After that for considering the earthquake load, the structural importance factor (I) and soil site coefficient (S), and necessary data are assumed as per code. Then, the hospital building is analysed, and the responses are computed. Fig. 3 represents the floor displacement with story level for seismic zoning coefficient of Z = 0.15 g and Z = 0.28 g. As shown in this figure, it is confirmed that the maximum floor displacements are within the limit provided in BNBC (1993) [4] for both seismic zoning coefficients.

Fig. 4 demonstrates the number of columns that fail due to considered seismic loads. The local strength of the structural members is checked and hence it is found that all column remains safe due to seismic load for zoning coefficient of Z = 0.15 g but eight-column fails due to earthquake load for zoning coefficient of Z = 0.28 g. Notably, the failure of the columns is defined based on their reinforcement demand and capacity ratio.

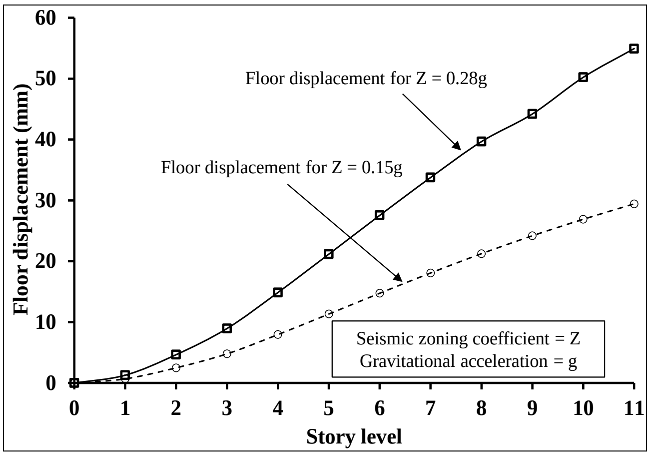


Fig 3: Floor displacement for two seismic zoning coefficients.

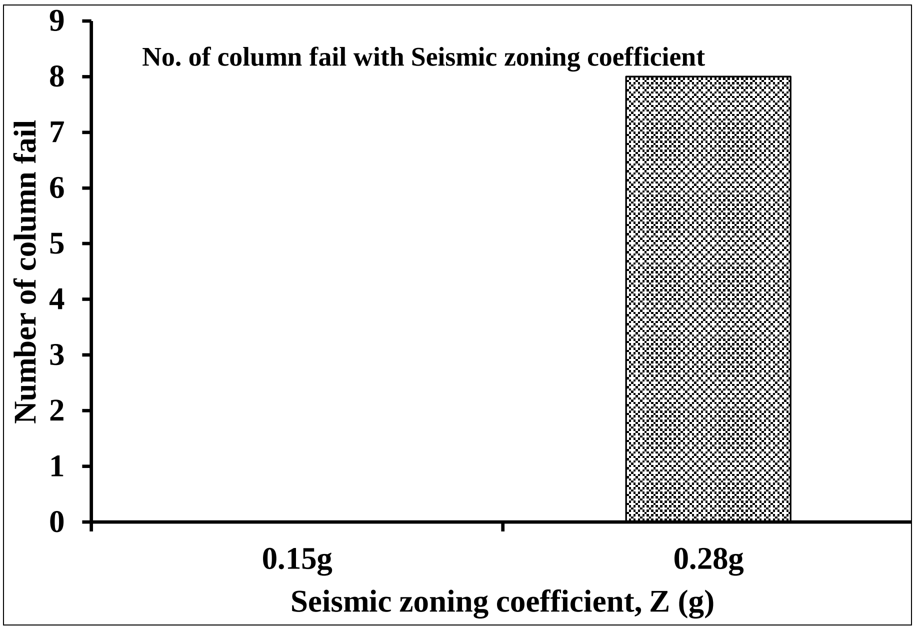


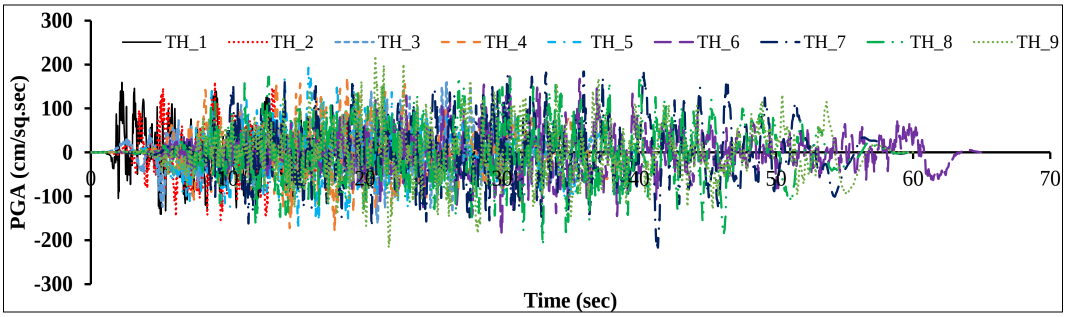
Fig 4: Number of columns fail for two seismic zoning coefficients.

Linear time history analysis

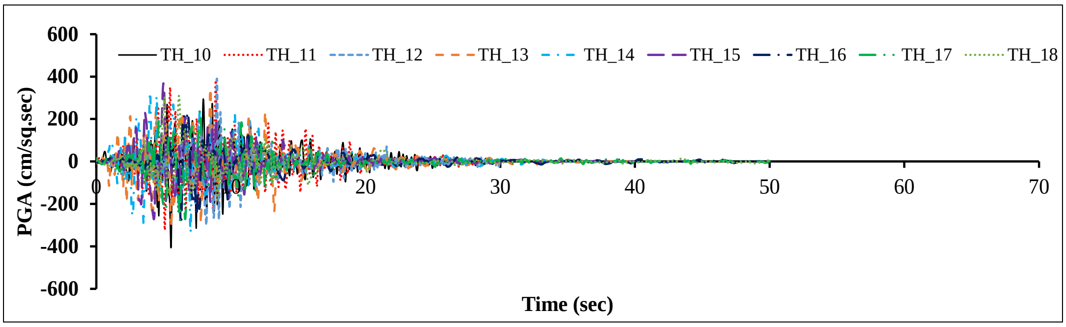
The mathematical model of the hospital building is analysed for 36 ground motions illustrated in Fig. 5 (a), (b), (c) & (d), those PGA varies from 0.1625 g to 0.795 g. Notably, each ground motions are identical. The uncertainty properties of the earthquake ground motion regarding the ground type, intensity, and frequency contents have a great effect on the time history responses of the structural members (Bhuiyan *et al*., 2009). These are considered in selecting the ground motions.

The responses of linear time history analysis are presented in Fig. 6 which is compared with the allowable displacement as per BNBC (1993) [4]. The allowable maximum floor displacement for the AB is 64.08 mm. The AB is safe for low to medium earthquakes; however, it exceeds the code limit for a strong earthquake. From Fig. 6, it is clear that the hospital building is unsafe for the ground motion of TH_14, TH_15, TH_24 to TH_29, and TH_31 to TH_36. The displacement of AB depends on the period of earthquake. The maximum displacement is found 132.5 mm for TH_33 having a PGA of 0.7506 g.

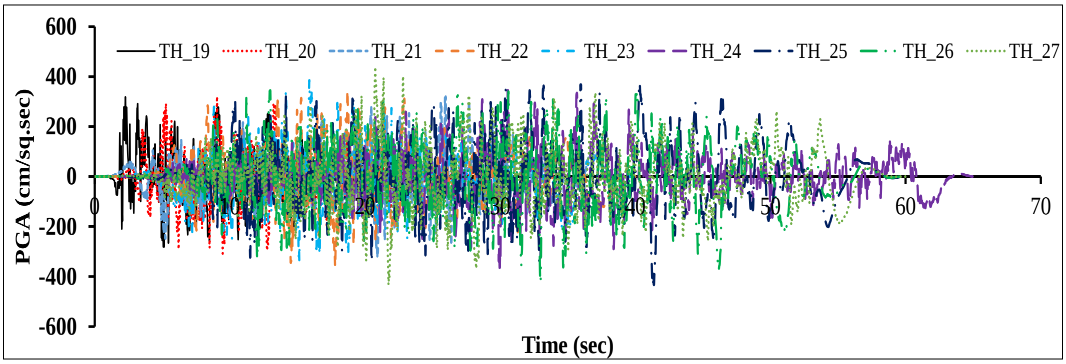
The DCR (demand capacity ratio) of structural members is computed to check the adequacy of the local member strength when these ground motions are applied to the hospital building structure. DCR represents the ratio of longitudinal reinforcement's demand to its capacity for each time history load. Fig. 7 illustrates the number of column failures for corresponding ground motion. It is observed from Fig. 7, that the structure is fully safe for the first six earthquakes (TH_1 to TH_6). Nevertheless, when the PGA is increased, the structural members are observed to fail, and the number of failed columns gradually increased with the increase of PGA value. The maximum number of columns failed for the time history (TH) loading of TH_32.



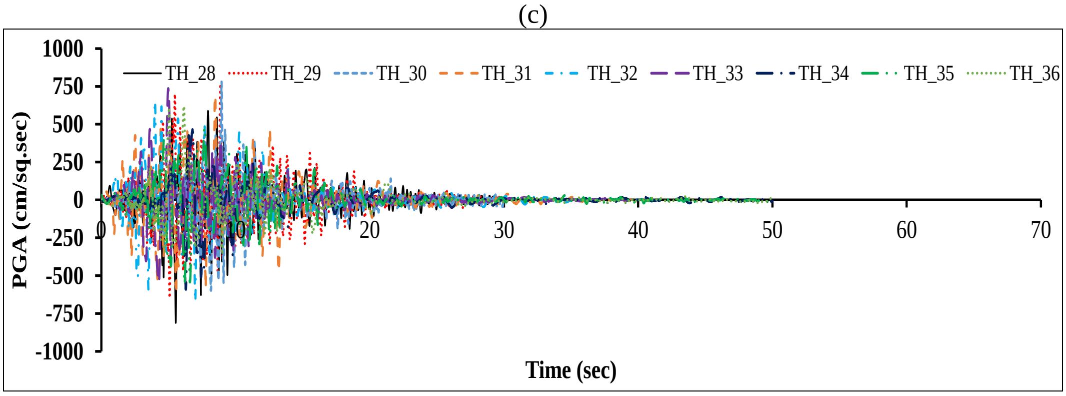
(a)



(b)



(c)



(d)

Fig 5: Time history (TH) data: (a) TH_1 to TH_9; (b) TH_10 to TH_18; (c) TH_19 to TH_27; (d) TH_28 to TH_36.

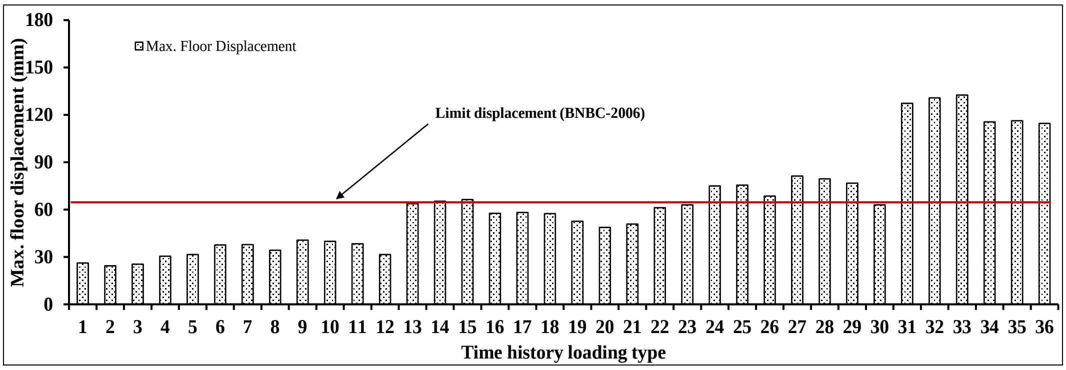


Fig 6: Variation in maximum floor displacement with time history loading type.

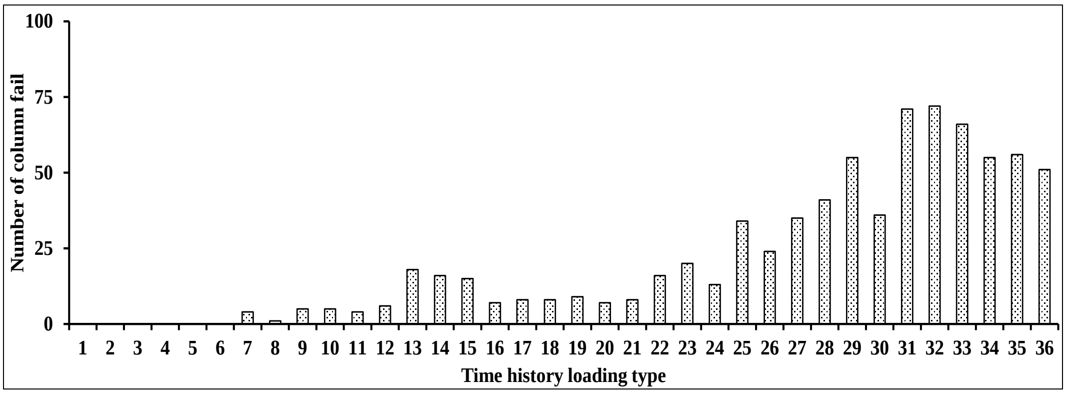


Fig 7: Number of columns fail with time history loading type.

Response spectrum analysis

This method assumes a single degree of freedom system to be excited by a ground motion to obtain the response spectrum curves for peak displacement, peak velocity, or peak acceleration. 36 response spectrums load shown in Fig. 8 (a), (b), (c) & (d) are generated corresponding to 36 ground motions. The AB is analysed for each response spectra and the response of the global structure is computed. Fig. 9 reveals the maximum floor displacement of the existing hospital building for various response spectrum loading. It is observed from Fig. 9, the maximum floor displacement exceeds the allowable limit for response spectrum loading of RS_13 to RS_15 and RS_22 to RS_36. The maximum displacement of AB is observed for RS_31.

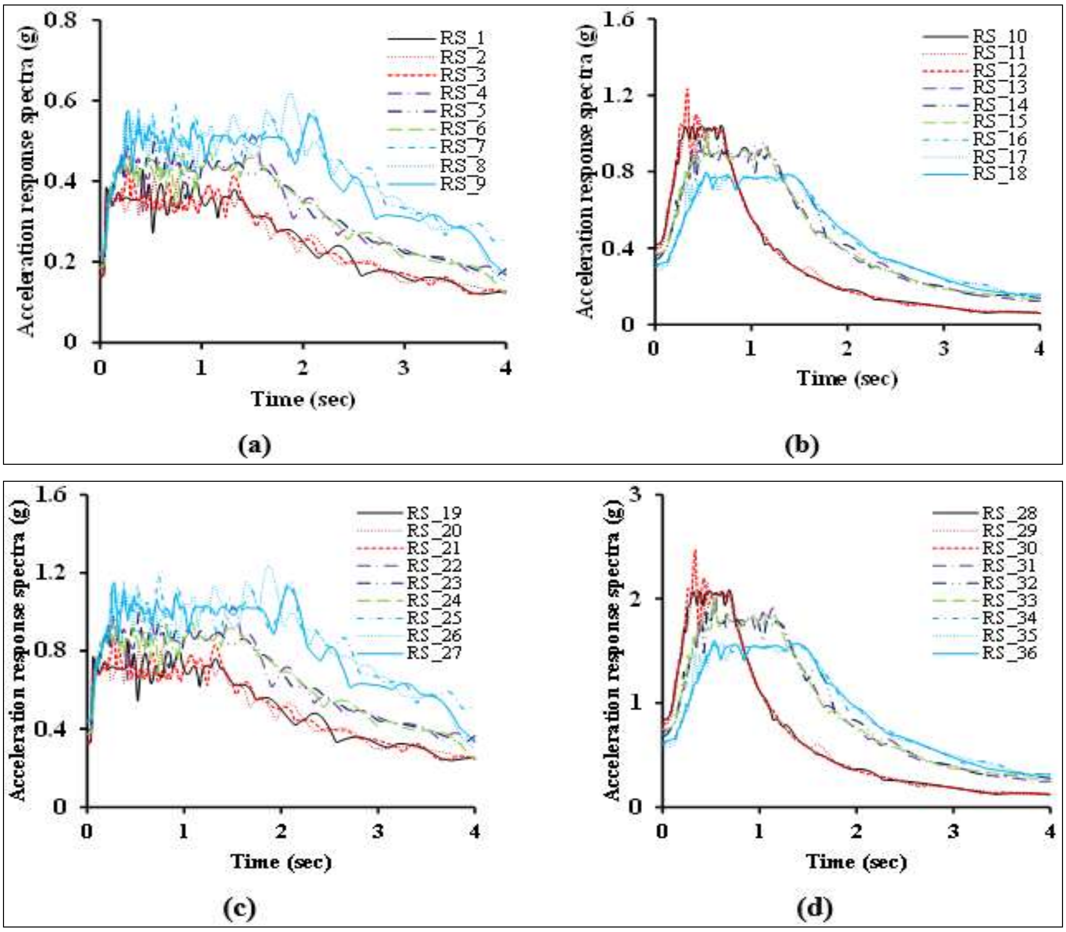


Fig 8: Response spectrum (RS) data: (a) RS_1 to RS_9; (b) RS_10 to RS_18; (c) RS_19 to RS_27; (d) RS_28 to RS_36.

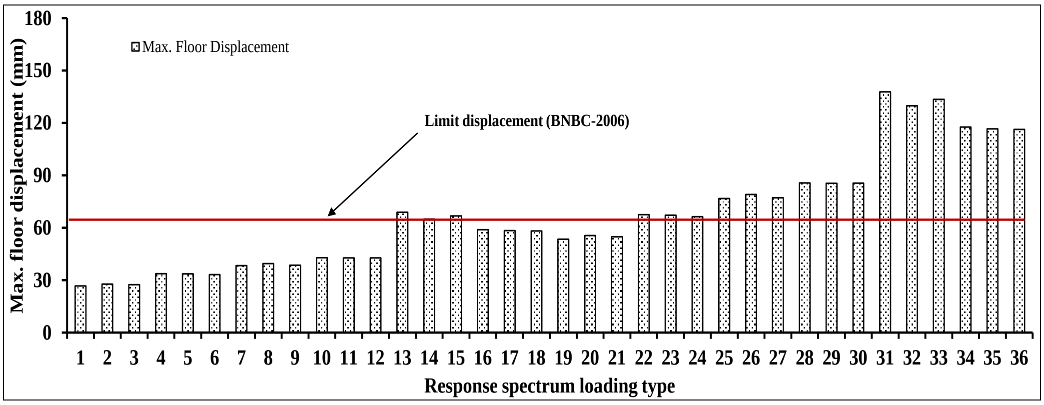


Fig 9: Variation in maximum floor displacement with response spectrum loading type.

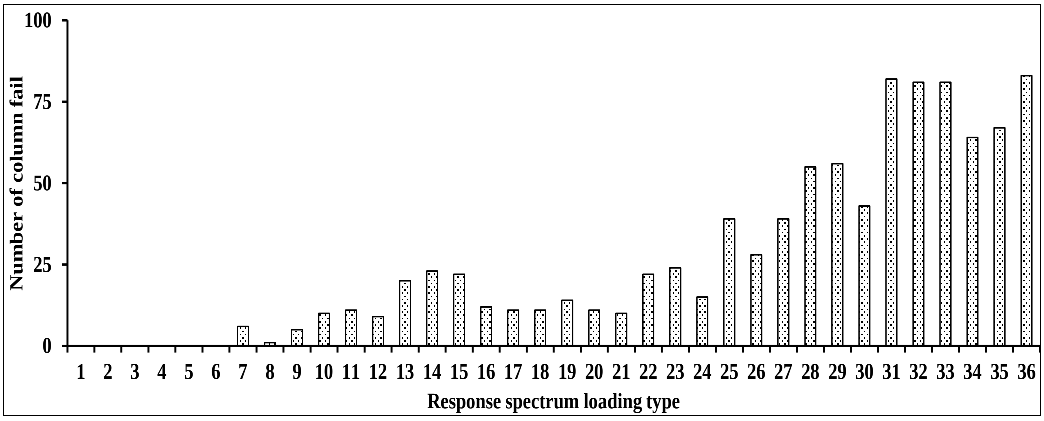


Fig 10: Number of columns fail with response spectrum loading type.

Moreover, the DCR values for the columns and beam are also computed to investigate the local failure scenario. For the beam elements, the DCR values remain within the limiting value for all given response spectrum loading. On the other hand, all columns remain safe for response loading of RS_1 to RS_6. Nevertheless, several columns start to fail for the remaining RS loading, and the maximum number is found for RS_36, which is shown in Fig. 10.

Retrofitting of hospital building using base isolation devices

The structural analysis results show that the hospital building is sufficiently earthquake-resistant to prevent the global failure of the structure. However, the designed column reinforcement is insufficient to resist the considered time history and response spectrum loadings as explained in Sections 4.1 and 4.2. Therefore, it can be concluded that the existing hospital building is vulnerable to medium to strong earthquakes and a necessary retrofitting strategy must be adopted to mitigate the earthquake disaster. Among the various available retrofitting method, BI devices are suitable for building retrofitting because it not only provides safety against collapse, but also largely reduces damage, which is crucial for facilities that should remain operational after severe earthquakes such as emergency response centers, hospitals, and fire stations. Among the various type of BI devices, the lead rubber bearing (LRB) is effectively used for building retrofitting.

The LRB consists of two steel plates at the top and bottom of the device, with several alternating steel shims and a central lead core. Fig. 11 demonstrates the components of LRB devices with the force-displacement relationship. For designing BI devices, a guideline provided by Japan Road Association (2000) is followed. Shear strength of rubber is assumed to be 6 MPa and maximum design displacement lies between 100 to 400 mm. The standard value of the shear strain of rubber is considered 100% in the USA and 200% in Japan. In this paper, shear strain is considered 175%. Equations (1) to (5) have been used for computing properties of LRB.

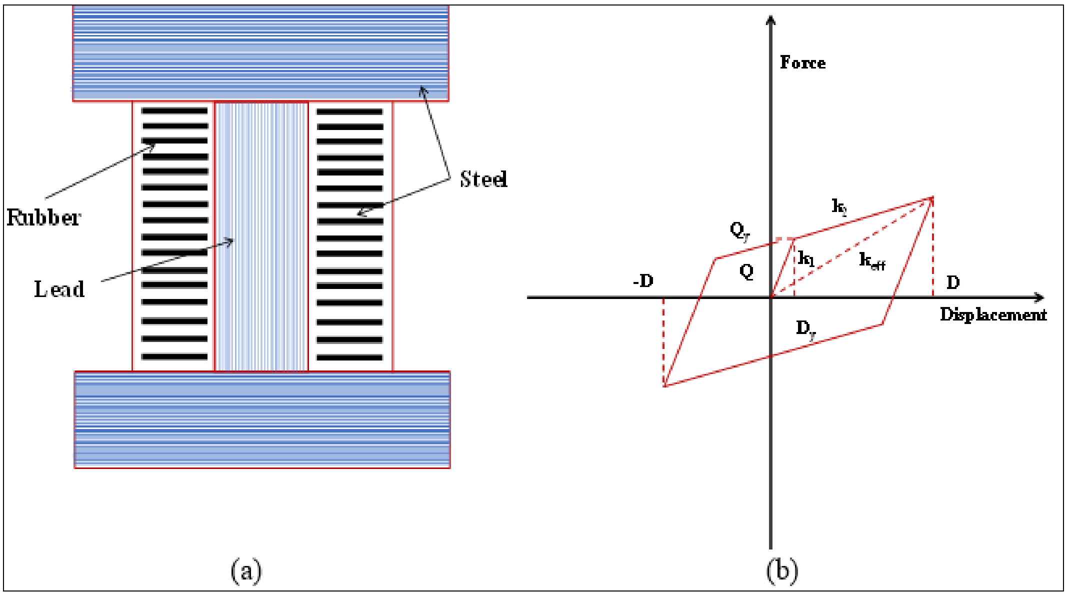


Fig 11: Lead rubber isolator: (a) components; (b) force-displacement curve.

$$k_1 = 6.5k_2 \quad (1)$$

$$k_2 = (F - q_d)/u_{(Be)} \quad (2)$$

$$q_d = q_0(\gamma_e)A_p \quad (3)$$

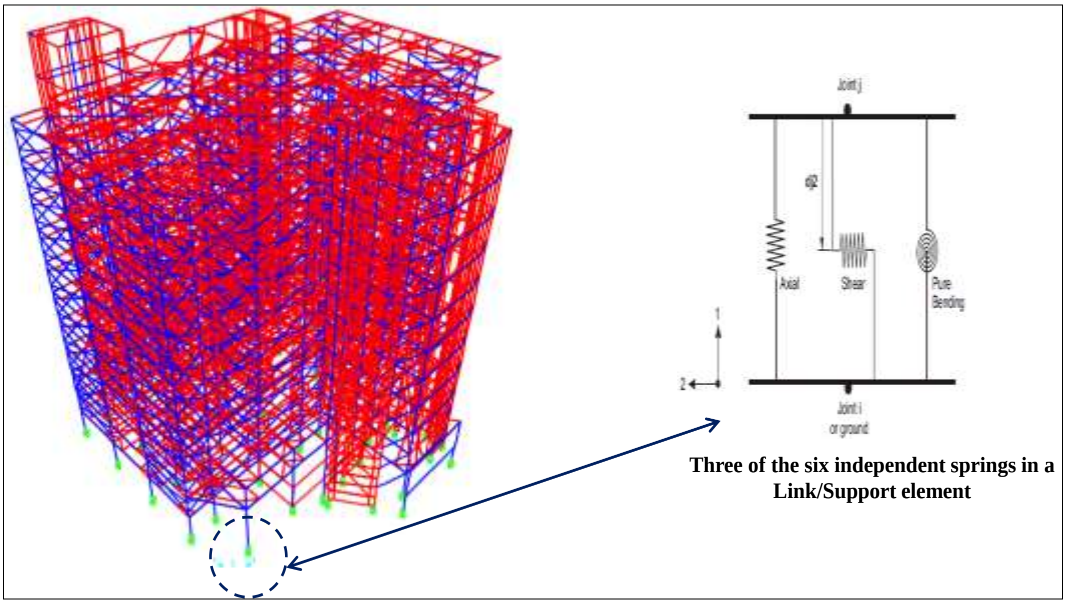
With,

$$q_0(\gamma_e) = b_0 + b_1\gamma_e \quad (4)$$

$$F = G_e A_e \gamma_e + A_p q_0(\gamma_e) \quad (5)$$

Where k_1 = initial stiffness; k_2 = post-yield stiffness; F = horizontal shear force necessary to produce horizontal displacement; q_d = characteristics strength of lead plug; u_{Be} = effective design displacement of the bearing; g_e = shear strain; A_p = cross-sectional area of the lead plug; G_e = nominal shear modulus of rubber material; b_0 and b_1 = model parameters.

Using the above equations and data, thirty-one BI devices have been designed having maximum size of 1300 mm x 1300 mm and the smallest one is 250 mm x 250 mm. In SAP2000, isolators are modeled using link/support element option. The shearing behavior is incorporated based on the model proposed by Park *et al.* (1986) [15] and extended for seismic isolation bearings by Nagarajaiah *et al.* (1991) [13].



Three of the six independent springs in a Link/Support element

Fig 12: Analytical model of base isolated AB.

For the elastomeric bearing (Rubber isolator) option in the link element, nonlinear (Bilinear) properties can be assigned to the two horizontal shear directions, but only linear elastic behavior is accommodated for the remaining axial and three rotational directions. Fig. 12 represents the analytical model of retrofitted hospital with the detailing of link connection.

Performance of retrofitted hospital building using base isolation devices

The retrofitted AB (RAB) is also analysed to investigate the vulnerability of the repaired hospital building. For this reason, static and dynamic analyses have been done similar to the benchmark hospital building. After that, the structural responses are compared with the codes.

Static analysis

The RAB is subjected to earthquake loading considering the seismic zoning coefficient of Z = 0.15g and Z = 0.28g. From the analysis, it is observed that the maximum floor displacement is reduced due to the application of base isolation devices as a retrofitting strategy. In the case of AB, it was observed that eight columns failed for a seismic zoning coefficient of Z = 0.28g. However, for RAB, the exceeded DCR values of failure columns remain less than the unit.

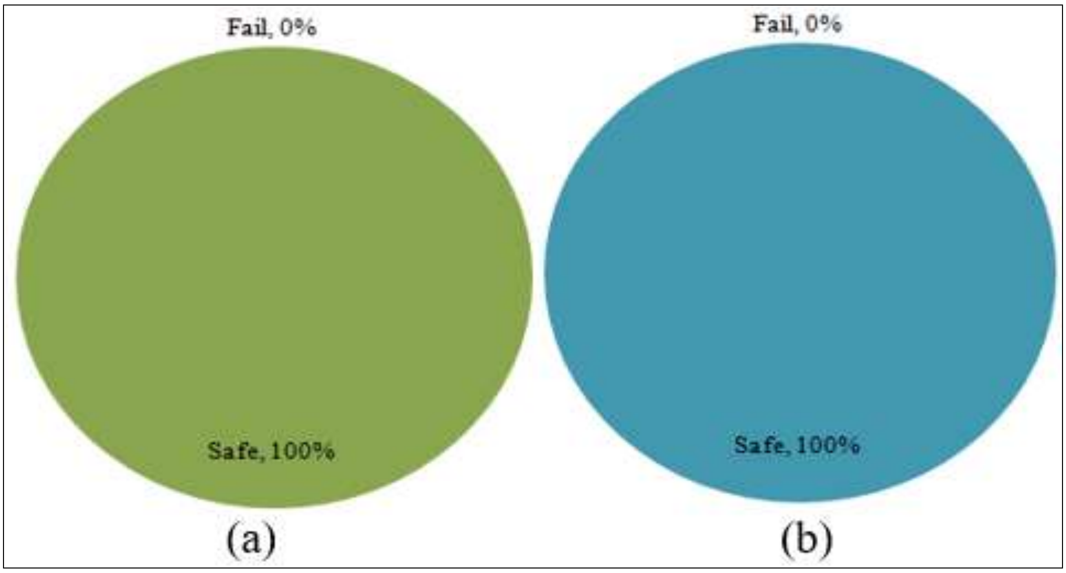


Fig 13: Number of columns fail in base-isolated AB for (a) Z = 0.15g and (b) Z = 0.28g.

Fig. 13 represents the percentage of column failure of RAB for seismic zoning coefficients of 0.15g and 0.28g. From these figures, the building became safe for a seismic zoning coefficient of 0.28g due to adopting the proposed retrofitting strategy.

Linear time history analysis

The mathematical model of RAB is analysed for 36 ground motions whose PGA varies from 0.1625g to 0.785g. From Fig. 14, it is clear that the maximum floor displacement of the RAB is 50.9 mm, which is permissible as per the BNBC displacement limit for this hospital building. The requirement of reinforcement of structural members for all considered time history loading is also calculated for RAB. After that DCR values of columns are computed and compared with that of benchmark hospital buildings. The calculated DCR value of columns of retrofitted hospital buildings shows that all columns remain safe for these time history loadings. These results provide sufficient evidence that the proposed retrofitting method is effective in reducing the seismic effect on the existing vulnerable hospital building and will keep it functional even after severe earthquake.

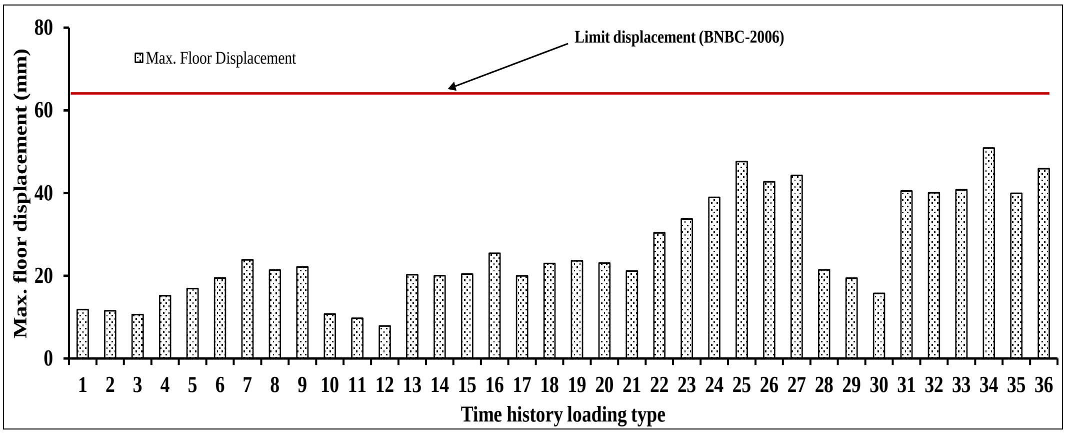


Fig 14: Variation in maximum floor displacement of base isolated AB with time history loading type.

Response spectrum analysis

The RAB is analysed for response spectrum loading and structural responses are calculated for all RS loading. The top floor displacement of the hospital building was remarkably reduced and remained within the limiting value due to the implementation of retrofitting strategy for all RS loading except for RS_36 which is demonstrated in Fig. 15. It is also calculated the DCR values of all structural members of RHB and it is found that the values are less than the unit value for all members. Nevertheless, for strong ground motion, it is observed that the BI device exceeds the allowable limit.

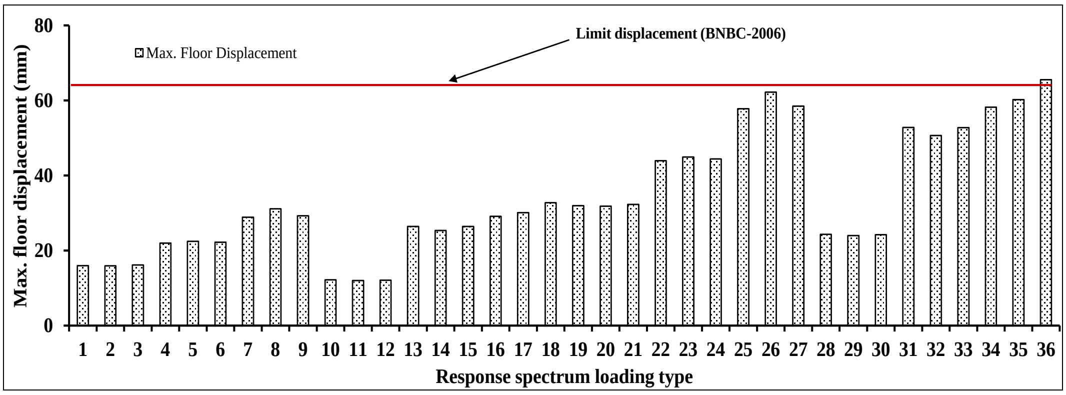


Fig 15: Variation in maximum floor displacement of base isolated AB with response spectrum loading type.

Conclusions

From the preliminary and detailed assessment of the considered hospital building, it is confirmed that the existing hospital building is safe as per BNBC-1993 [4]; however, it is vulnerable to earthquake load suggested in the revised BNBC. The implementation of BI devices as a retrofitting strategy is effective in reducing the seismic effect on the hospital building and thus the retrofitted hospital building becomes safe for seismic load suggested in BNBC-2006 [5]. Therefore, the vulnerability of existing hospital buildings in Bangladesh particularly those that were constructed prior to 1993 must be investigated and a proper retrofitting strategy needs to be implemented if required.

Credit authorship contribution statement

Md. Abul Hasan: Conceptualization, Methodology, Investigation, Writing – original draft. Md. Basir Zisan: Writing – review & editing, supervision. Biplob Kanti Biswas: Writing – review & editing.

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Declarations

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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