An Investigation on Feasibility of Proposed Isolation System for an Unreinforced Masonry (URM) Heritage Building Subjected to Seismic Excitation

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Abstract- An analytical study to determine the effectiveness of elastomeric base isolation technique over fixed base of an old Unreinforced Masonry (URM) heritage school building has been carried out. Finite Element (FE) model for the heritage URM school building was developed with assumptions that the masonry building is homogeneous and the material behaviour is linear. The building was subjected to El- Centro earthquake as input ground motion in both X and Y directions to determine its seismic performance. The stresses obtained under gravity and earthquake loading (Nonlinear Dynamic Loading) were compared with permissible stresses available in Indian code. Results were found satisfactory under gravity load due to huge mass but few tension failures was observed at critical locations (like corners, top of door and windows etc.) under seismic action in addition to gravity loading. Therefore, to reduce the exceeding stresses in weak zones elastomeric bearings namely, Lead Rubber Bearing (LRB) and High Damping Rubber Bearing (HDRB) were designed as per International Building Code and used in the numerical model of URM heritage building. Many trials for placement of bearings at critical locations were performed to reach a final conclusion on the basis of reduction of stresses. Percentage (%) reductions in direct principal stresses and shear stress for base isolated models (using LRB and HDRB) with respect to fixed base were calculated.

Keywords- Heritage Structure, URM, Seismic Analysis, LRB, HDRB.

I. INTRODUCTION

India has an affluent historic background which is well depicted from various pious, educational and political buildings standing over decades in various old cities of the country. Among which most of the historical structures are made of Unreinforced Masonry (URM). The protection and strengthen of these historical buildings is an imperative need in order to preserve them for upcoming generations. But, prior to any retrofitting it is first required to assess the seismic performance of heritage building. According to Valente et al. [1] the structural assessment of historical buildings is a complex and articulated problem based on different activities. Castori et al. [2] carried out the seismic assessment of monumental masonry building: the Civic Museum for which they adopted three modelling strategies; equivalent frame model, rigid macro-block model and finite element model and Hadzima-Nyarko et al. [3] performed the seismic vulnerability assessment of an old historic masonry building using damage index.

Strengthening and assessment of characteristics of heritage structures is a challenging job due to unavailability of codes during their time of erection. Also, their material survey is too extreme and hence the engineer needs to describe parameters using present codes available or take the reference values of parallel structure.

Various restoration programs are running under the Archaeological Survey of India (ASI) but, these traditional methods of restoration/retrofitting perturb the inherent properties and unique beauty of the structures and hence limit its relevance in case of heritage buildings. Therefore, a most suitable rather an outstanding method - Base isolation technique has been used in the present study as it does not impinge on the architectural exquisiteness of the building facade. Coupling of the isolator with the superstructure enhances the flexibility of the total isolated structural system. Hence, the technique lengthens the structures natural time period away from the predominant frequency of the ground motions, thus evading catastrophic responses caused due to resonance.

There are a range of types of base isolation systems from simple pure friction to complex bearing systems and dampers which have been used in the past in various buildings of countries like Japan, U.S.A., and China etc. Steel rubber laminated bearing was developed in 1960s in Japan [4]. Also, in early 1980s development in rubber technology lead to new rubber compounds which were termed High Damping Rubber (HDR) [5]. Sarbah [6] has used lead rubber bearing isolators, LRB 400, LRB 500 and LRB 600 to isolate the model developed in SAP2000 software of masonry – reinforced concrete office building for the Internal Revenue Service in the Huating County of the Pingliang City in China. Old masonry Chapel building of Rikkyo University (Japan) has been retrofitted using combination of the laminated natural rubber bearing and the red bar damper. Total numbers of the natural rubber bearing are thirteen and two kinds of 50cm and 60cm diameters have been used. Also, ten of the red bar dampers are used which are located around the natural rubber bearings [7]. Way and Howard [8] discussed the rehabilitation of Mackay school of Mines. The building as of now rests on 67 high damping rubber bearings. A large number of masonry buildings with seismic isolation, with number of floors between 5 and 8 have been realized in Beijing [9]. Shamim et al. [10] investigated the effectiveness of pure friction isolation on a heritage school building by numerically introducing the sand layer between the super structure and plinth beam. The isolation system resulted in a reduction of principal stresses to about 75% considering coefficient of friction as 0.5.

II. SCHOOL BUILDING TAKEN FOR STUDY

Syedna Tahir Saifuddin High School (STS High School) is about 140 years old heritage school building. It is a semi-residential high school situated in the campus of Aligarh Muslim University, Aligarh (India). Its original name was the "Mohammedan Anglo Oriental Collegiate School" The School grew in M.A.O. College in 1877 which in 1920 became the Aligarh Muslim University by an act of the Central Legislature. The School bore the name, Muslim University High School, but became popularly known as Minto Circle after the then Viceroy of India, Lord Minto, who generously funded the construction for its new buildings. In 1966, the school was named after the then Chancellor Syedna Tahir Saifuddin, and hence forth known as S.T.S. High School. The contemporary snapshot of North-East view of STS High School is shown in Figure 1.

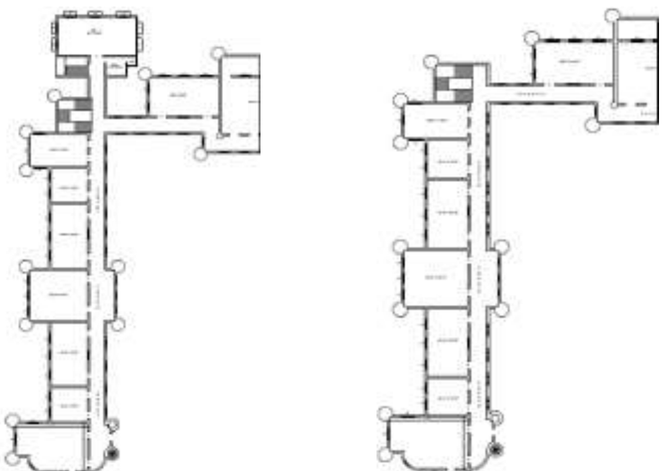
Figure 1: North East view of STS high school

In order to determine the mechanical properties of existing masonry, test prisms shall be extracted from an existing wall, transported to a laboratory, and tested in compression, tension etc. But, in present study, the URM school building is a heritage structure hence it was not allowed to haul out the bricks from there. Therefore, the material properties of brick masonry as shown in Table 1 have been taken from a literature [11] on seismic analysis of a similar hundred years old URM building in Nepal. Nepal is located very near to India so a similarity can be observed in the material characteristics, workmanship, techniques, climate and other structural parameter justifying its incorporation in our case.

Table 1- Material Properties [10]

Material	Young's Modulus (MPa)	Poisson's Ratio	Mass Density (kg/m^3)	Compressive Strength (MPa)	Tensile Strength (MPa)
Brick Masonry	**1708**	**0.15**	**2100**	**4**	**0.4**

The drawing of the school building was arranged from the Building Department of Aligarh Muslim University, Aligarh. The ground floor plan, first floor plan of the heritage building are shown in Figure 2. The other required specifications are; Height of ground floor =5130.8mm, Ground floor wall thickness =304.8mm thick, All Verandah walls thickness= 228.6mm thick, Height of first floor = 406.4mm, Height of first floor veranda wall =3835.4mm, First floor wall thickness= 228.6 mm thick.



(a) (b)

Figure 2: (a) Ground Floor Plan of North-East Wing (b) First Floor Plan of North-East Wing

III. FINITE ELEMENT MODELLING AND ANALYSIS

There are various types of Finite Element (FE) modelling techniques; homogenous, heterogeneous, micro, macro and detailed macro modelling. Since, the structure under study is very huge hence, homogenous macro modelling of simply North –East wing was carried out. A FE macro model was developed in SAP 2000 [12] wherein the masonry units were modelled using 4- node shell elements which are by default available in SAP2000. These elements have also been used by Khadka [11] and Spyrakos and Francioso [13] to model masonry. Figure 3 shows the 3D view of model developed in SAP2000. Building is having arched roof supported on iron girders which are resting on masonry walls. The iron girders on which the walls are resting were modelled using frame elements. The support condition was taken as fixed since; building rests on a very firm soil with about 1.5 m deep masonry strip footing. A total of 23017 shell elements, 6385 frame elements, and 23276 joints with 872 restraints were generated in SAP 2000 software.

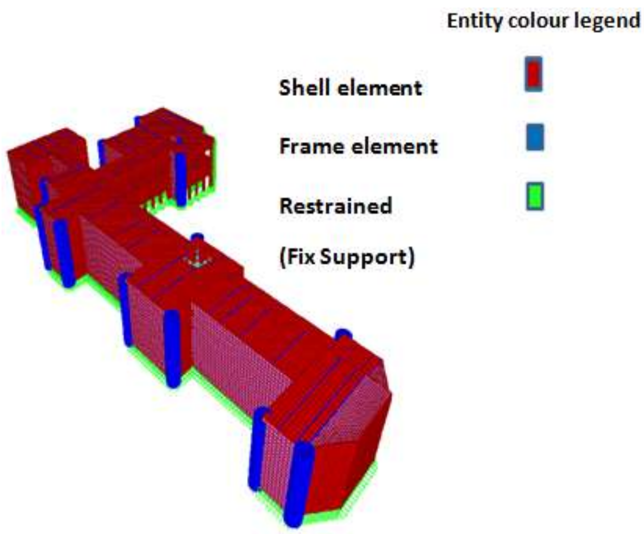


Figure 3: 3D View of Model

3.1 Analytical study of heritage building- fixed base-

As per IS 1905- 1987 [14] permissible values of Compressive stress is 1.1MPa, Tensile stress is 0.07MPa and Shear stress is 0.25MPa. The present state of the heritage building under gravity load was assessed by carrying out static analysis with its base fixed, which showed that the building is safe under gravity load. The maximum values of compressive, tensile and shear stresses were 0.01MPa, 0.005MPa and 0.0016MPa respectively (Figure 4) which is well within the code limits. Thereby, validating the developed FE model of the heritage building.

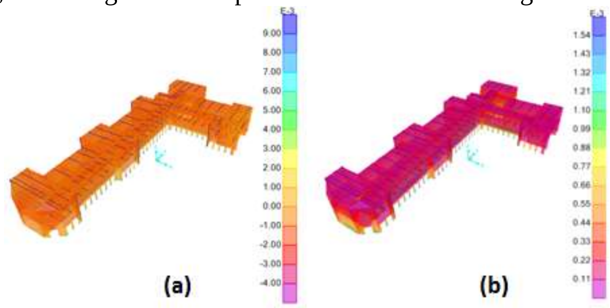


Figure 4: (a) Direct Principal Stresses (b) Shear Stress Under Gravity Load.

Thereafter, Time History Analysis was performed wherein the El-Centro earthquake ground motion data (Figure 5) was given as the seismic input in both X and Y directions. The ground motion was scaled to match the response as per Indian code provisions.

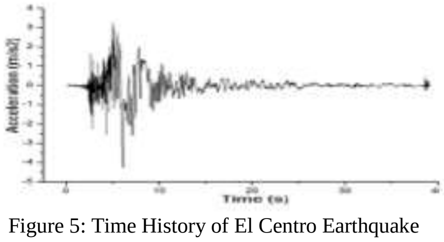


Figure 5: Time History of El Centro Earthquake

3.2 Modal analysis- fixed base-

The dynamic characteristics, natural frequencies and mode shapes were obtained by Modal analysis. It is important to carry out modal analysis of such a structure whose experimental study is not possible as in present case of heritage school building. Modal analysis determine the different time periods at which structure will resonate naturally. If the natural frequency of structure matches the frequency of earthquake the building may continue to resonate resulting in large structural damages. Compan et al. [15] has also performed the modal analysis using ABAQUS software of Chapel of the Würzburg Residence.

Modal analysis of heritage school building showed that first three natural frequencies are closely spaced and also, the time period is within the range of 2 seconds which makes the heritage building suitable for retrofitting using base isolation technology. The natural frequencies and modal participation factors (P_K) of first three modes are shown in Table 2.

Table 2: Natural Frequencies and Modal Participation Factors

Mode	Natural Frequency (Cycles/ sec)	Time Period (sec)	P_K
1	8.35073	0.11975	50.167
2	8.75441	0.11423	-9.115
3	8.87466	0.11268	7.364

3.3 Seismic analysis- fixed base-

Seismic analysis showed that most part of the structure remains under compression. The maximum values of compressive, tensile and shear stresses (Figure 6 and Figure 7) are 2.734MPa, 0.758MPa and 0.452MPa respectively in X direction and 3.760MPa, 1.380MPa and 0.596MPa respectively in Y direction. Although, most part of the building observes no damage except the inner veranda piers, bottom of the outer corner walls, some areas around the large opening and stair cases. The mode of failure in masonry depends on the direction and magnitude of the direct and shear stresses. In general, historical buildings fail due to the de-bonding of mortar-brick joint resulting in the separation of bricks from the wall, tensile failure causing joints to open and frictional sliding. The exceeding value of compressive stress can lead to the toe crushing of masonry piers. Diagonal tension cracks near the openings are the result of the exceeding tensile stress whereas, exceeding shear stress can result into sliding, rocking or over turning of the walls.

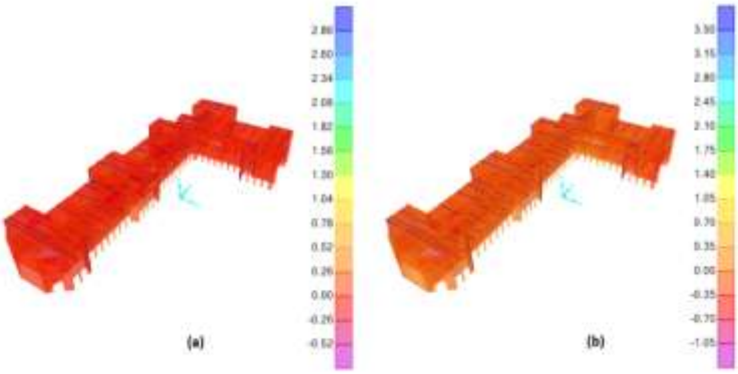


Figure 6: Direct principal Stresses in (a) X direction (b) Y direction

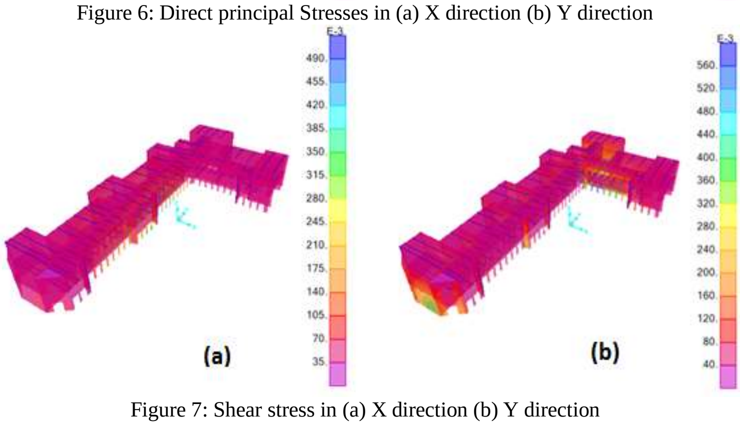


Figure 7: Shear stress in (a) X direction (b) Y direction

IV. BASE ISOLATION – ELASTOMERIC BEARINGS

There are various types of bearings available in this technically advancing world. The two major functions of these isolators are to lengthen the natural time period of structure and decrease its acceleration response to seismic forces. Here Lead Rubber Bearing (LRB) and High Damping Rubber Bearing (HDRB) have been used for the analytical study. LRB provides elastic restoring force and the required damping can be generated by using suitable size of lead core. Performance of LRB can be maintained throughout repeated strong earthquakes, with proper resilience and reliability. HDRB is another type of elastomeric bearing whose vertical stiffness is several hundred times the horizontal stiffness due to the incidence of inner steel plates. Steel plates provide high vertical stiffness as well as restrict the rubber from bulging while horizontal stiffness of the bearing is guarded by the low Shear Modulus (G) of elastomer. The damping in

the bearing is improved by adding up extra-fine carbon block, oils and other fillers. The parallel action of linear spring and viscous damping are the overriding features of HDRB system.
Previous studies showed that, in order to optimize the building both from the economic and structural points of view, the number of isolation devices should be limited and they should be mainly deployed at the intersections of the bearing wall5 [16]. As a result, a rigid structure under the walls of the first floor should be realized. This rigid structure is usually built in reinforced concrete and so the foundations, and should be able to transmit the static and dynamic actions from the superstructure to the isolation devices.
Hence, beam of dimension 302.8mm x 302.8mm was modelled under the superstructure at plinth level for proper installation of bearings. Both the bearings namely; LRB and HDRB were designed as per International Building Code [17]. The properties of the rubber used for the design is shown in Table 3. The schematic diagrams of LRB and HDRB are shown in Figure 8 and Figure 9.

Table 3: Rubber Properties of Bearings

Rubber Properties	Values	
	LRB	HDRB
Hardness	IHRD45	IHRD45
Elongation At Break, $\in_B$	500%	500%
Young’s Modulus, E (MPa)	1.8	1.8
Shear Modulus G, (MPa)	0.54	0.54
Modified Factor, K	0.8	0.8

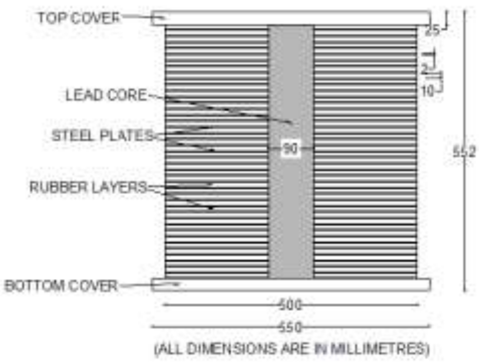


Figure 8: Schematic Diagram of LRB

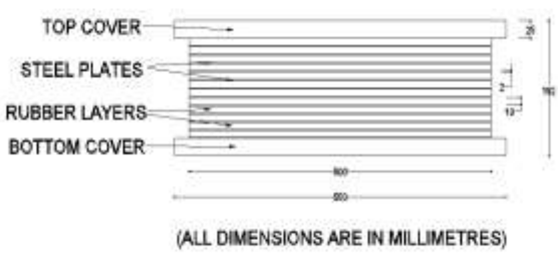


Figure 9: Schematic Diagram of HDRB

4.1 Modelling of bearings in SAP2000

The bearings were modelled using ‘link and support properties’ option wherein Rubber Isolator is selected in ‘link/support type’. The provided beams and location of the bearings are shown in Figure 10. Several trials were performed to decide the position of bearing on the basis of reduction in stresses. A total of 85 lead rubber bearings and 51 high damping rubber bearings having diameter 500mm have been used. Non-linear time history analysis is carried out in SAP2000 software to see the effect on the structure under seismic loading. The heritage building is subjected to same El-Centro earthquake as in case when the building was analyzed with fixed base.

4.2 Modal analysis

Typical earthquake ground acceleration period lies in the range of 0.1-1.0seconds. Therefore, the structures having their natural period in this range (as in our case of pilot building, Table 2) are more prone to the phenomenon of resonance. For such a structure base isolation is the most suitable method of protection as it increases the time period of the structure >1.5seconds (usually 2-3seconds). The first three natural frequencies obtained by modal analysis for LRB and HDRB are shown in Table 4. The time period is shifted compared to fixed base in case of both LRB and HDRB.

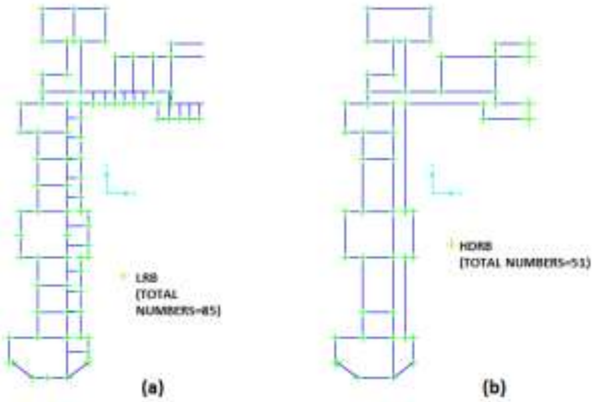


Figure 10: Beams At Plinth Level and Position of Bearings (a) LRBs (b) HDRBs

Table 4: Natural Frequencies

Bearing	Mode	Natural Frequency (cycles/sec)	Time Period (sec)
LRB	1	0.41721	2.39687
	2	0.49449	2.02230
	3	0.64402	1.55276
HDRB	1	0.27337	3.65803
	2	0.39024	2.56251
	3	0.53998	1.85191

4.3 Seismic analysis- LRB

Due to seismic load in X direction, maximum values of compressive, tensile and shear stresses are 0.086MPa, 0.047MPa and 0.017MPa respectively (Figure 11). Due to seismic load in Y direction, maximum values of compressive tensile and shear stresses are 0.151MPa, 0.081MPa and 0.023MPa respectively (Figure 12). The compressive and shear stresses are within the permissible limits of Indian code [14]. Tensile stresses exceed very few places near the bottom of wall around the bearings of some piers.

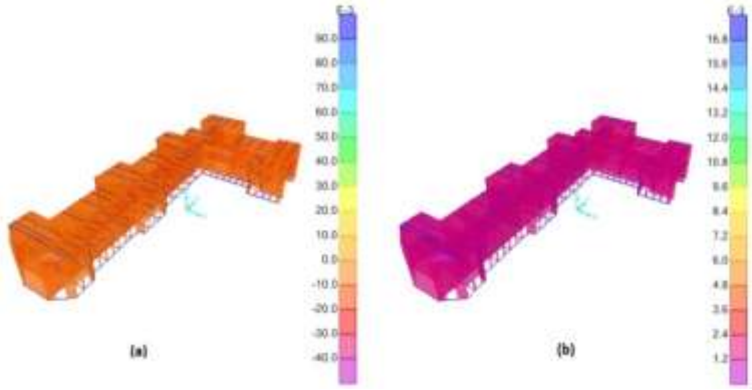


Figure 11: (a) Direct Principal Stresses in X Direction (b) Shear Stress in X Direction for LRB.

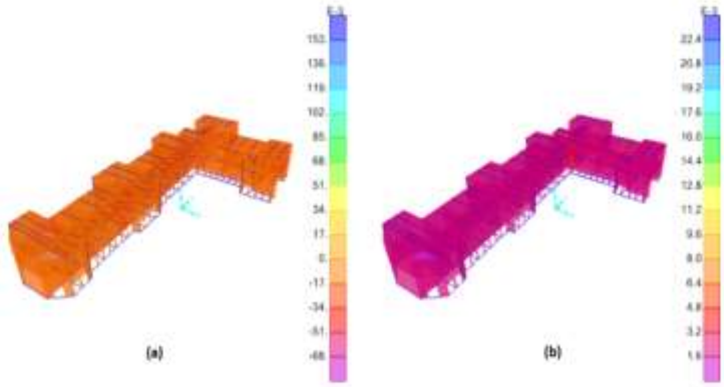


Figure 12: (a) Direct Principal Stresses in Y Direction (b) Shear Stress in Y Direction for LRB.

4.4 Seismic analysis – HDRB

Due to seismic load in X direction, maximum values of compressive tensile and shear stresses are 0.024MPa, 0.012MPa and 0.004MPa respectively (Figure 13). Due to seismic load in Y direction, maximum values of compressive, tensile and shear stresses are 0.063MPa, 0.032MPa and 0.009MPa respectively (Figure 14). The stresses are within the permissible limits of IS code [14].

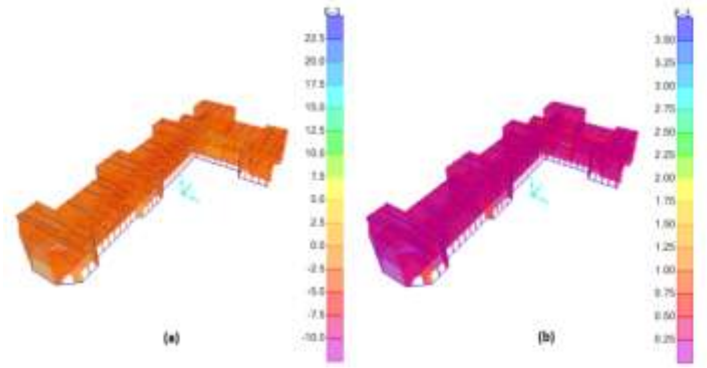


Figure 13: (a) Direct Principal Stresses in X Direction (b) Shear Stress in X Direction for HDRB.

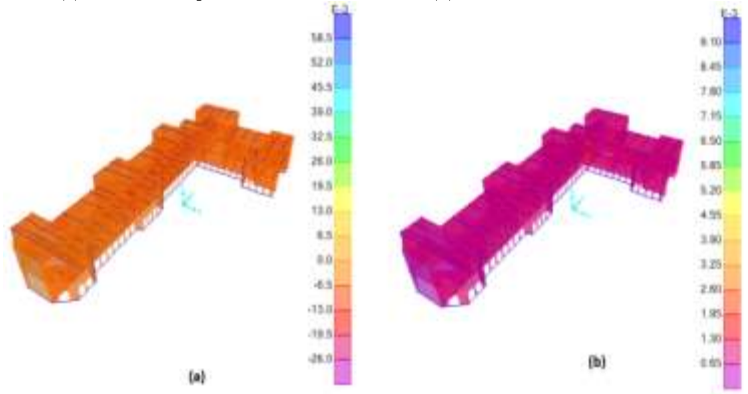


Figure 14: (a) Direct Principal Stresses in Y Direction (b) Shear Stress in Y Direction for HDR

V. RESULTS AND DISCUSSION

Compared to the fixed base response elastomeric base isolation has greatly reduced the stresses in URM heritage school building proving it to be an effective technique for the restoration of heritage buildings against seismic vulnerabilities. It has been observed that HDRBs are more effective with just 51 bearings and higher percentage of reduction in stresses compared to LRBs. Percentage reductions in stresses in both X and Y directions of base isolated model using LRB and HDRB compared to fixed base model are shown in Figure 15 and Figure 16.

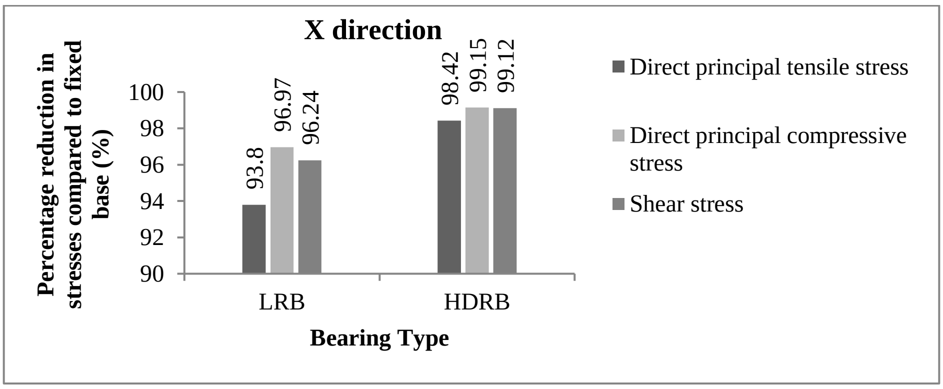


Figure 15: Percentage reduction in stresses compared to fixed base in X direction

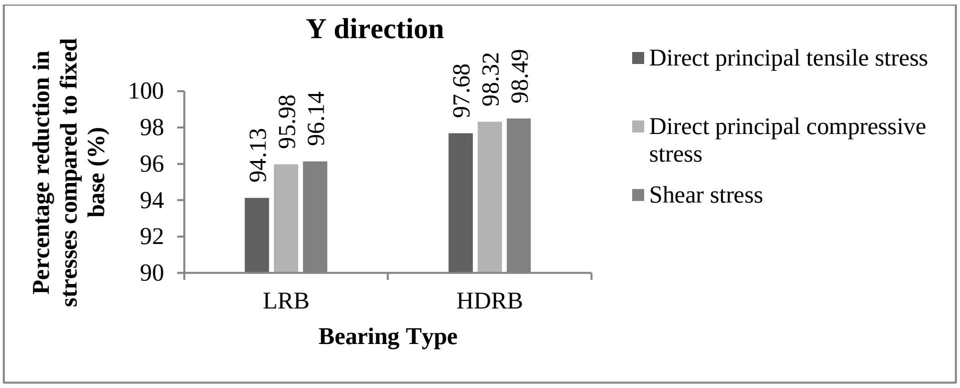


Figure 16: Percentage reduction in stresses compared to fixed base in Y direction

VI. CONCLUSIONS

It can be concluded that elastomeric base isolation is a successful technique for the retrofitting of heritage buildings. However, extra engineering work in order to analyze and design the elastomeric isolation system is required. Also, bearings are quite expensive but can be considered as a wise and healthy investment for future.

VII. ACKNOWLEDGMENT

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CONFICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest.

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