Homogenous Finite Element Modelling and Seismic Analysis of A Massive Unreinforced Masonry Heritage Building and Its Proposed Rehabilitation

Saba Shamim, Shakeel Ahmad, Rehan A. Khan

Abstract: An Unreinforced Masonry Heritage school building situated at Aligarh Muslim University, Aligarh has been investigated for possible seismic failures using SAP2000 Finite Element Software. The school building being a massive and complex structure has been modelled using homogenous modelling approach. The material was considered to be homogenous and isotropic. The natural frequencies and mode shapes were computed using modal analysis. The building was then subjected to seismic ground motions in both X and Y directions to determine its seismic performance. The results showed that the building was safe under gravity loading but some weak zones were found under earthquake loading. In order to conquer the exceeding stresses a rehabilitation study has also been performed to see its effectiveness on the Heritage school building model which proved to be satisfactory.

Keywords: Heritage building, URM, Seismic analysis, Rehabilitation

I. INTRODUCTION

Most of the historical structures in India are made of Unreinforced Masonry (URM). The structural analysis of historical masonry buildings is particularly a complex issue since the engineer has to deal with many unknowns (geometry, material properties, structure condition, elements connection, stiffness of horizontal diaphragms, building history, etc.) [1]. The masonry heritage school building (as suggested for pilot study) Minto Circle, officially Syedna Tahir Saifuddin High School (STS High School) is a 137 years old building. It is a semi-residential high school under Aligarh Muslim University at Aligarh.

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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 (Fig. 1).

Fig. 1. STS High School (North-East Wing)

In order to protect the historical structures from seismic vulnerabilities it is required to explore a retrofitting method which does not affect the architectural beauty of heritage building. Base isolation is an excellent alternative over the traditional retrofitting techniques which cause disruption in various parts of buildings. There are various types of base isolation systems such as frictional isolation system comprising pure friction, friction pendulum, resilient friction isolation and elastomeric bearing isolation system comprising laminated rubber bearing, lead rubber bearing, high damping rubber bearing etc.

Prior to any historical restoration or protection operation it is first required to carry out modelling and seismic analysis of the structure. With the advancement in the computational technology, Finite element Model (FEM) has become a strong tool for modelling of masonry structures. Finite element modelling and seismic analysis using SAP2000 software of URM building (Shital Niwas, Nepal) has been carried out by Khadka [2]. The mechanical properties of the masonry and timber used for analysis are tabulated in Table 1.

Seismic assessment of the former Italian Embassy in order to determine its structural response under horizontal loading has been performed previously [3]. The SAP2000 finite element software was used to model the structure and seismic behaviour of the building was investigated by a nonlinear static procedure. Ahmad S. et al. [4] modelled a masonry heritage building using homogeneous macro-modelling with plate elements in the software STAAD pro. for studying its behaviour under gravity and seismic loading. Due to restrictions on extraction of bricks from the heritage building for determining its material properties,

they have used suitable reference values from the recent literature.

The use of pure friction base isolation technique in URM structure by providing a sliding interface at the plinth level to permit relative motion between the superstructure and the substructure has been studied earlier [5]. Nanda [6] suggested base isolation system for architectural temples. He separated the super structure of the temple from pedestal by a smooth friction layer in the form of marble/marble interface. Nearly 50% K was observed at the roof level at the cost of 30 mm base sliding displacement. Yekrangnia et al. [7] investigated the efficiency of frictional base isolation retrofitting technique on performance improvement of URM school building. He considered frictional coefficients as 0.2, 0.5 & 0.8 representing the low, moderate and high (brick to brick) friction. The model was subjected to three linearly increasing harmonic excitations with different frequencies simulating the dominant frequencies of a typical earthquake records in low, moderate and high frequencies (5, 10 & 20 Hz).

In literature there are number of works on seismic analysis of masonry buildings but very few studies have been performed on pure friction isolation system as rehabilitation technique for heritage buildings. Therefore, it will be interesting to explore the effectiveness of the proposed rehabilitation technique on masonry heritage building.

The main objectives of the paper are to (i) Experimentally validate the FE results on SAP2000 (ii) model the heritage building using FE tool (iii) determine seismic response of fixed base model (iv) determine seismic response of base isolated models (v) compare the effectiveness of suggested rehabilitation technique over fixed base FE model.

II. MATERIAL PROPERTIES

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 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- I have been taken from a recent literature [2] on seismic analysis of a similar hundred years old masonry building in Nepal. Nepal is located very near to India so a similarity can be observed in the material, workmanship, techniques, climate and other structural parameter justifying its incorporation in our case.

Table- I: Material Properties

Properties	Masonry
Young's Modulus (MPa)	1708
Poisson's ratio	0.15
Mass Density (KN/m³)	2100
Compressive Strength (MPa)	4.0
Tensile Strength (MPa)	0.4

A. Architectural Specifications

The plan of the heritage 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 Fig. 2 and 3. The other required specifications are listed below;

- Height of ground floor =5130.8 mm (16 ft 10 inch)
- Height of first floor = 406.4 mm (15 ft 1 inch)
- Height of first floor veranda wall =3835.4 mm (12 ft 7 inch)
- Ground floor wall thickness =304.8 mm (12 inch) thick
- First floor wall thickness= 228.6 mm (9 inch) thick
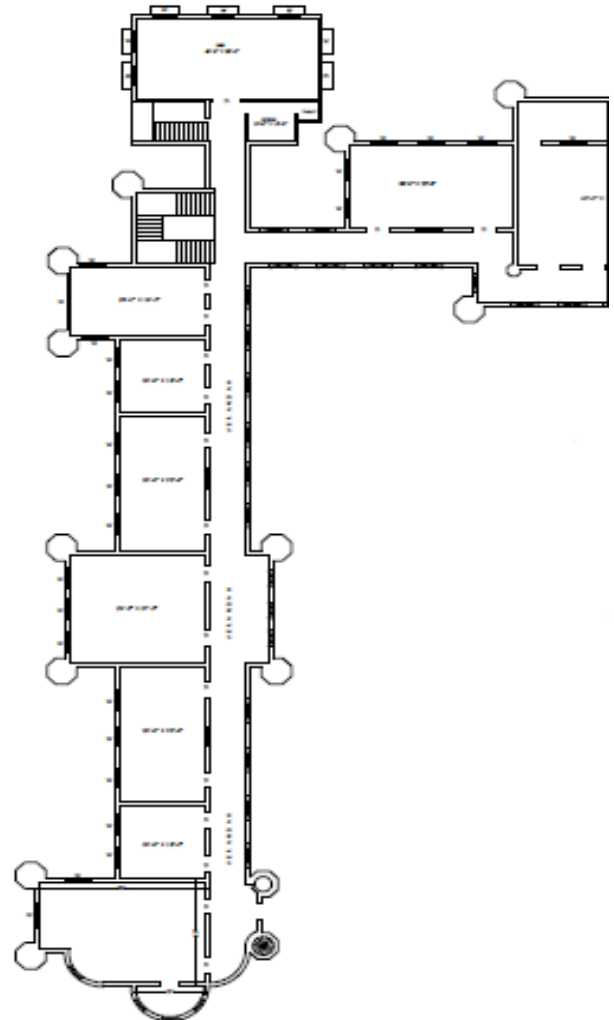- All Verandah walls thickness= 228.6 mm (9 inch) thick.

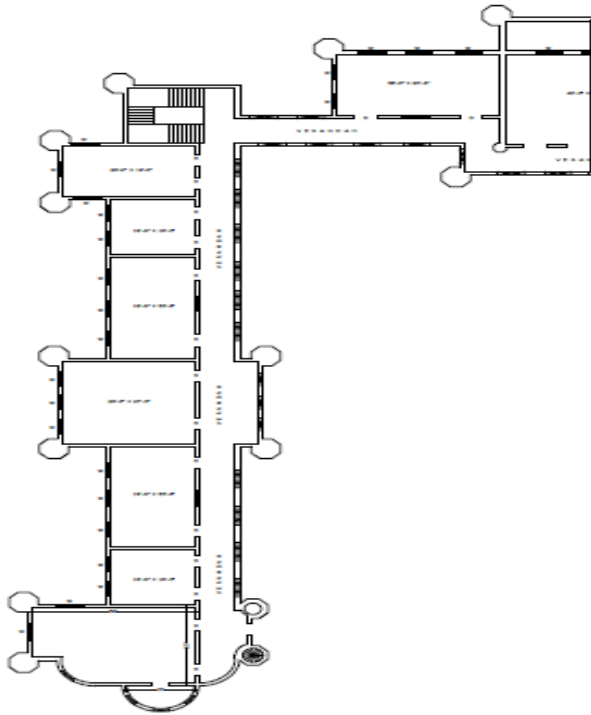**Fig. 1. Ground floor plan of North-East wing**

Fig. 2. First floor plan of North-East wing

III. FINITE ELEMENT MODELLING (FEM) OF HERITAGE BUILDING

Finite element modelling (FEM) is one of the strongest computational tool for modelling composites like; masonry. Finite Element (FE) modelling is basically of two types; homogenous modelling and heterogeneous modelling. In homogenous modelling the masonry unit and the mortar element are considered to be smeared and are assigned an an isotropic or anisotropic material. It is suitable for large scale models. Heterogeneous modelling is more suitable for small models were units and mortar are modelled separately. Since, the heritage school building is quite enormous hence, homogenous macro modelling of simply North –East wing was carried out. A FE macro model was developed in SAP 2000 software wherein the masonry units were modelled using **4- node shell element** which is by default available in SAP2000**.** Spyrakos and Francioso [8] and Khadka [2] have also used 4 – node shell element to model masonry. Ahmad S. et al. [4] modelled the same masonry heritage school building using plate elements in STAAD pro software.

Fig. 4 shows the Three-Dimensional (3D) view of finite element (FE) model developed in SAP2000 software. 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 building rests on a very firm soil with about 1.5 m deep masonry strip footing. Hence, the support condition was taken as **fixed** in the SAP 2000 software. The model was generated using 23017 shell elements, 6385 frame elements, 23276 joints with 872 restraints in SAP 2000.
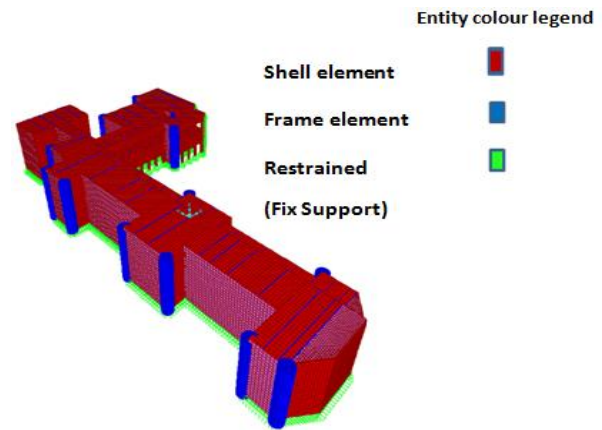

Fig. 3. Three-Dimensional view of FE model

IV. VALIDATION STUDY

The static analysis of the FE model with its base restrained (fixed) is been carried out in order to assess the present state of the structure under gravity loads. As per **IS 1905- 1987** [10] permissible values of Compressive stress is 1.1 MPa, Tensile stress is 0.07 MPa and Shear stress is 0.25 MPa.

The analysis of FE model under gravity load shows that the stresses (Fig. 5) are within the permissible limits as per the Indian code. Hence, it can be concluded that the model is safe under gravity load and thereby, validating the Finite Element (FE) model of the heritage building under study.
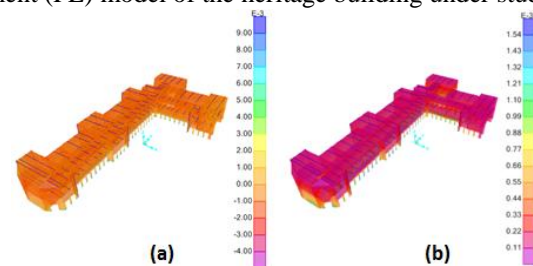

Fig. 4. (a) Direct principal stresses (b) Shear stress due to gravity loads (MPa).

V. SEISMIC ANALYSIS

The Modal and Time History Analysis of fixed base FE model were performed wherein the El-Centro earthquake ground motion data (by default available in SAP2000) was given as the seismic input in both X and Y directions. 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. [11] addressed the structural safety of a masonry world heritage building in Germany using a FE model. Authors have also performed the modal analysis using ABAQUS software. And, the results were compared in terms of maximum principal stresses.

The natural frequencies (Table- II) of first three modes obtained by modal analysis were found to be closely spaced.

Table- II: Natural Frequencies

Mode	Frequency (Cycles/ sec)	Time Period (sec)
1	8.35073	0.11975
2	8.75441	0.11423
3	8.87466	0.11268

Most part of the structure remains under compression under seismic loading. The maximum values of compressive and tensile stresses were 2.734 and 0.758 *MPa* respectively in X direction and 3.760 and 1.380 *MPa* respectively in Y direction (Fig. 6). The tensile and compressive stresses were exceeding at few places like at the beam wall joints and bottom edge of the walls.
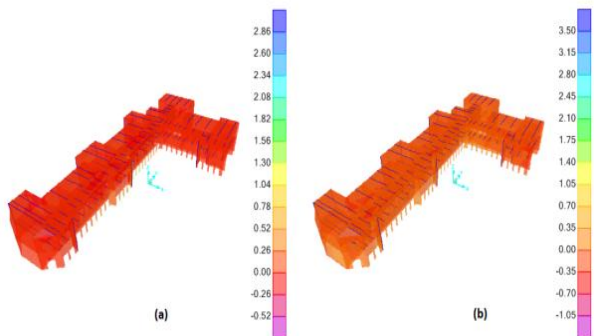

Fig. 5. Direct Principal Stresses (MPa) due to seismic load in (a) X direction (b) Y direction.

Also, some walls were found to be failing due to exceeding shear stress mostly at bottom corner and edge of the walls. The maximum value of shear stress was 0.452 *MPa* in X direction and 0.596 *MPa* in Y direction (Fig. 7).
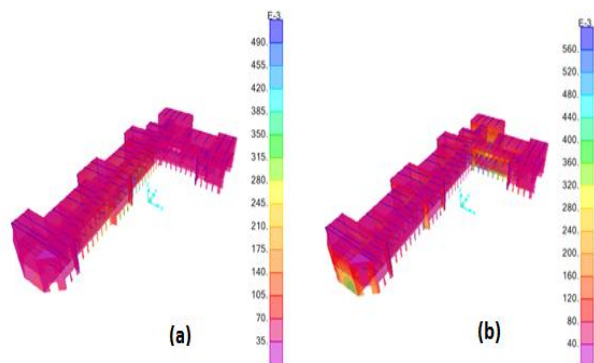

Fig. 6. Shear Stress (MPa) due to seismic load in (a) X direction (b) Y direction.

VI. REHABILITATION OF HERITAGE BUILDING USING PURE FRICTION (P-F) ISOLATION TECHNIQUE

Modal analysis of fixed base FE model showed that first three natural frequencies (Table- II) of the heritage building are closely spaced and also, the time period is within the range of 2 seconds which makes the heritage building suitable for rehabilitation using base isolation technology. P-F base isolation using sand layer was implemented in the study. Sand is very cheap, natural material and is physically and chemically stable against all the forces and chemical agents which are normally expected to encounter during life time of the structure. Also, it does not require any maintenance. Sand layer acts as a soft layer between base of

the structure and hard foundations. During earthquake excitation, the structure acts as a non-sliding structure till base shear achieves the value equal to limiting friction force. When base shear exceeds the value of limiting friction force, the structure starts sliding on the sand layer. Due to sliding motion of the structure, the part of energy of earthquake excitation gets dissipated in the sand layer and remaining energy reaches to the super-structure [12].

For the seismic analysis six models were considered. In first three models sand layer was introduced at the brick-brick interface at plinth level and in later three models parallel beams of dimension 302.8mmx302.8mm were modelled under the entire superstructure at the plinth level and sand layer was introduced at the beam-beam interface with varying values of coefficient of friction (μ) viz., 0.2, 0.35 and 0.5. Sand layer was modelled using 'link and support properties' option available in SAP2000 wherein 'Friction Isolator' was selected in link/support type. The frictional isolator was developed for restricted base sliding of 5mm to avoid the overturning or tilting of structure.

After the application of proposed rehabilitation technique similar seismic analysis were performed in the six models having varying frictional coefficient and surface conditions. Seismic analysis of the rehabilitated model (having Beam-Beam interface coefficient of friction μ=0.2) was found to have the maximum values of direct principal compressive and tensile stresses as 0.146 and 0.077 *MPa* respectively in both X and Y directions (Fig. 8(a)). Direct principal compressive and tensile stresses do not exceed the permissible limit in most parts of the structure. The maximum value of principal shear stress was 0.029 *MPa* (Fig. 8(b)) which is well within the permissible limit of IS-code.
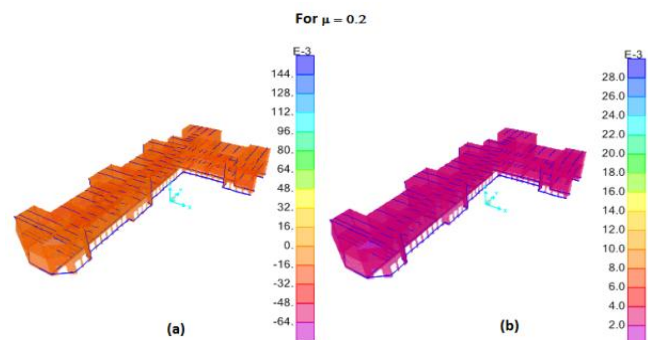

Fig. 7. (a) Direct Principal Stresses (MPa) due to seismic load in X and Y directions (b) Shear Stress (MPa) due to seismic load in X and Y directions.

Similarly, the seismic load was applied in both X and Y directions in remaining models and the stresses obtained after the analysis are summarised in Table- III.

Table- III: Stresses in X and Y directions.

Type	μ	Stresses (MPa)		
		Type	*X Direction*	*Y Direction*
Brick-Brick interface	0.20	Direct principal tensile	0.296	0.351
		Direct principal compressive	1.216	1.444
		Shear	0.114	0.215
	0.35	Direct principal tensile	0.915	0.221

		Direct principal compressive	0.211	0.948
		Shear	0.130	0.135
	0.50	Direct principal tensile	0.168	0.181
		Direct principal compressive	0.697	0.803
		Shear	0.099	0.114
Beam-Beam interface	0.20	Direct principal tensile	0.077	0.077
		Direct principal compressive	0.146	0.146
		Shear	0.029	0.029
	0.35	Direct principal tensile	0.091	0.091
		Direct principal compressive	0.340	0.340
		Shear	0.078	0.078
	0.50	Direct principal tensile	0.092	0.092
		Direct principal compressive	0.372	0.372
		Shear	0.077	0.077

VII. RESULTS AND DISCUSSION

The seismic analysis of Finite Element (FE) model of the heritage school building developed in SAP2000 software showed no failure zones except the beam-wall joint; bottom corner and edge of walls. 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

The rehabilitation of the heritage building using P-F Base isolation technique has proven to be an effective and economical method for protection of heritage building against seismic (earthquake) loads. The study indicates appreciable reduction in stresses in first three models (Brick-brick interface friction; 0.2, 0.35 and 0.5) and optimal reduction in stresses in later three models (Beam-Beam interface friction; 0.2, 0.35 and 0.5) compared to fixed base. The direct principal tensile stress was exceeding at few places at the re- entrant corners of the inner face walls in first three models. The percentage reduction in various stresses in X direction and Y direction compared to fixed base of the proposed six models are shown in the Fig. 9 and 10 below.
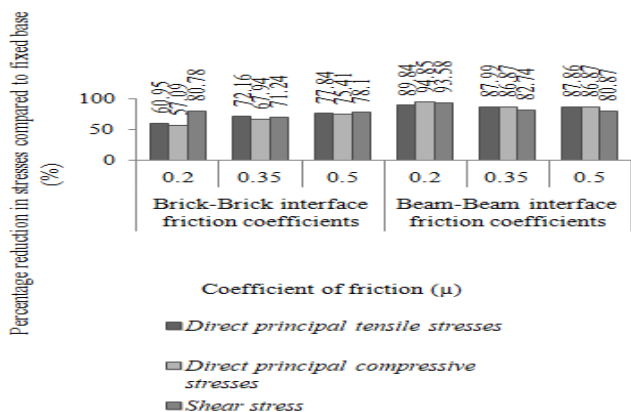

Fig. 8. Percentage reduction in stresses in X direction compared to fixed base.
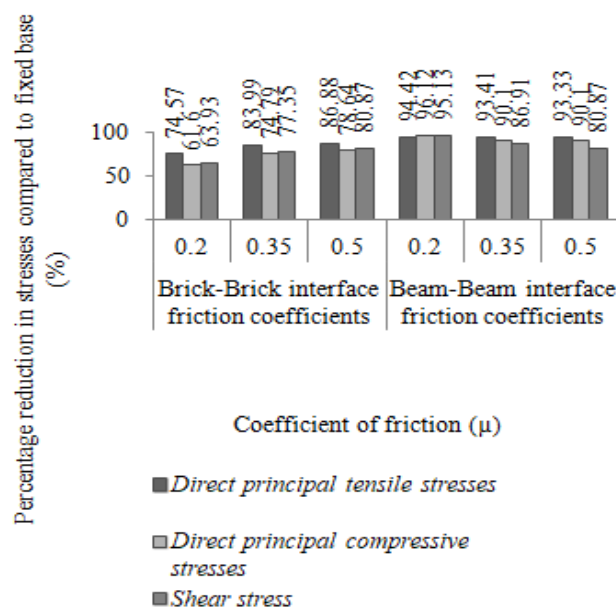
Fig. 9. Percentage reduction in stresses in Y direction compared to fixed base.

VIII. CONCLUSIONS

- Finite element (FE) model of the heritage school building has been developed in SAP2000 and was found to be safe under gravity load thereby, validating the model under study.
- The seismic analysis of the FE model showed some week/failure zones which are unavoidable in case of heritage structures. Hence, a most suitable rehabilitation technique has been proposed.
- It can be seen and concluded that to conquer the limitations of weak strength of masonry and architectural features of heritage building P-F base isolation technique is an excellent rehabilitation method.
- The fundamental time period of the structure is increased when using suitable base isolation system in comparison to the fixed base structure.
- Advantage of P-F isolation system is that compared to other rehabilitation techniques which are expensive and disturbing, this method is economical and feasible.
- The presented details of six models make it possible to be implemented in existing buildings, adding more advantage to its feasibility.
- On increasing the friction coefficient the stresses are reduced but sliding of super structure over the sub-structure is amplified which can cause considerable damage to sanitary fittings, mechanical and electrical equipments of the building. But, these damages are more bearable over the structural damages considering life safety. However, use of flexible connections in piping systems and loose electrical cables can reduce such non-structural damages.

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Retrieval Number: F7340038620/2020©BEIESP
DOI:10.35940/ijrte.F7340.038620
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