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Seismic Performance of a Masonry Heritage Structure

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Abstract*— World-wide experience from past earthquakes shows un-reinforced masonry structures are the most vulnerable and represent overall the largest threat to human life and property in future earthquakes. This highlights the structural inadequacy of buildings, especially unreinforced masonry buildings, to carry seismic loads and requires an urgent assessment of existing buildings in terms of the strength, expected performance and safety of existing buildings during earthquake as well as for carrying out the necessary rehabilitation. As it is a heavy, brittle material with low tensile strength and exhibits little ductility when subjected to seismic effects, unreinforced masonry is highly susceptible to earthquake damage than various other types of construction material. Unreinforced masonry buildings are usually characterized by sudden and dramatic collapse. Present study deals with an evaluation of the seismic performance of an old unreinforced masonry building structure. The 137 years old masonry heritage school building is located at Aligarh Muslim University, Aligarh (seismic zone IV). The building does not show any cracks under gravity loads. Since the historical building was built before the inception of seismic IS code, the point of concern is performance of building under seismic loads. In the present study, the building is modelled using finite element technique and its seismic evaluation is carried out using the commercially available Finite Element software assuming a homogeneous and nonlinear behaviour of the material. The building is subjected to different PGA levels (0.1g, 0.2g, 0.3g, 0.4g) as input ground motion to determine its seismic performance.The results thus obtained will be useful for detecting the weak failure zones of the buildings under future seismic forces and retrofit accordingly using proper retrofitting techniques.

***Index Terms*—Heritage masonry building, finite element modelling, seismic performance, peak ground acceleration.**

I. INTRODUCTION

The investigation of an old masonry structure is often combined with several difficulties. One aspect of difficulty is to find the original design plans of the structure. Over time, changes may have occurred to the structure. These might be structural modifications due to changes of use or combined with renovations. Not all modifications concern the structural system, but they often do. If modifications took place, they should be notified in the building chronology. Unfortunately, documentation on modifications of the structure is often not available either.

The engineer, who is investigating the structure, needs to find the required information by collecting all the data he can find on the structure. In case of an earthquake analysis, it may also be useful to find old records reporting of historical earthquakes in the region.

They may tell the engineer if the structure already underwent some seismic activity. The masonry characteristics of an old structure are also difficult to estimate, since there were no codes existing at the time of the construction, which would provide information on minimal requirements. If a material survey of the structure is too excessive, the engineer has to define the parameters using the provisions in the codes or by using reference values of similar structures. Masonry is defined as a composite, non-homogeneous and anisotropic material. It is a compound of masonry units bonded together with mortar. The units may be stones, bricks, adobe, tiles, stucco or precast blocks. The most effective use of masonry construction can be seen in load bearing structures where it performs a variety of functions, like supporting loads, subdividing space, providing thermal and acoustic insulation as well as fire and weather protection. But since mid-20th century, there were no engineering methods and codes available for the design of masonry buildings, the design of structural elements like thickness of walls, depth of footing, placing of steel or wooden beams, etc. was based on Thumb Rules. As a result walls used to be very thick and masonry structures were found to be very uneconomical beyond 3 or 4 stories. Being a heterogeneous material, behaviour of masonry depends on the mechanical properties of its components, the arrangement of the units, the interfaces between them and the interaction of these units with other structural members and materials used in the building (eg. concrete frames, timber or steel beams and columns and timber floors). Intensive theoretical and experimental research has been conducted to understand various parameters of masonry construction. Factors affecting strength, stability and performance of masonry structures have been identified, which need to be considered in design. In India, there has not been much progress in the construction of tall load bearing masonry structures, mainly because of poor quality of workmanship and materials[5]. Analysing and strengthening historical structures has always been a challenging task because of the geometrical complexity and lack of knowledge about the used material, structural modifications during the time and ageing of material. A better understanding of both gravity load transfer mechanism and lateral resisting system of such structures is the vital issue for a comprehensive structural analysis, understanding of the analysis results. With the development of computational methods, Finite Element Analyses has become the most important tool for the analyses of historical structures. Generation of a finite element model of the structure requires a good engineering experience to turn a complex geometry into a realistic geometrical simplification with a precise assumption of unknown inner-core materials.

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In this paper, masonry talk about traditional brick masonry often referred to as unreinforced masonry. The array of structures within this category is vast, ranging from historic stone structures to mortared brick structures still being constructed today. Many masonry structures are located in seismic regions, where earthquakes have exposed their vulnerability. Recent earthquakes have caused devastating loss of life and infrastructure. This problem is obviously not limited to the developing world. Despite their prevalence and their long existence, the behaviour of masonry structures under earthquake loading is still not well understood, and extremely hard to predict. The problem is challenging and it must be addressed. [6]

According to Sirajuddin et al. [4] Masonry structures fail miserably under lateral loading conditions like earth quakes and impact loads. Earthquake wave hitting perpendicular to the longer side of the wall is more vulnerable than that hitting parallel to the longer side of the wall. This is mainly due to the height to thickness ratio of the masonry wall. When the wave hit perpendicular to the longer side of the wall height to thickness ratio is much greater than when the wave hit parallel to the longer side of the wall.

Shyam Sundar Khadka [7] has taken old traditional building Shital Nivas as a case study for assessing its seismic performance. The whole building is not taken for the model due to modelling complexity and the interpretation of the results. The results obtained from the North wing 3- D model are generalized for the global behaviour of the whole building.

G. Angjeliu [8] analyzed former Italian Embassy to assess its structural response under horizontal loading. Their static analysis shows that the structure was able to withstand vertical loads.

Capozucca [10] concluded that Historic masonry walls have demonstrated high vulnerability and low shear capacity when exposed to seismic actions and the shear strength of masonry increases with the pre-compression up to a limit and becomes constant at higher pre-compression.

Parajuli et.al [11] study effects of various earthquake ground motions on finite element model (FEM). His results confirmed that existing masonry structure was found very weak in resisting seismic forces.

II. HISTORY OF HERITAGE BUILDING UNDERTAKEN

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, Uttar Pradesh, India. The School was founded in 1875 by Sir Syed Ahmad Khan, the famous educationist and social reformer. The foundation stone of school was laid down by a closest associate of Sir Syed, Maulvi Sami Ullah Khan, Secretary of the College Fund Committee, on May 24, 1875. 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 it's 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 and Fig 2 shows contemporary snapshot of north-west view and north-east view of STS High School respectively.

Fig 1: STS High School Front North- West view

Fig 2: STS High School Front North-East view

III. MATHEMATICAL MODELLING

The following modelling strategies can be adopted depending on the level of accuracy, simplicity desired and application field. (M Sirajuddin, et al.)

(1) *Detailed micro modelling*: Units and mortar joints are represented by continuum elements whereas the unit-brick interface is represented by discontinuous elements.

(2) *Simplified Micro modelling*: Expanded units are represented by continuum elements whereas the behaviour of the mortar joints and unit-mortar interface is lumped in discontinuous elements. These interface elements represent the preferential crack locations where tensile and shear cracking occur.

(3) *Macro-modelling*: Units, mortar and unit-mortar interface are smeared out in the continuum. It is more practice oriented due to the reduced time and memory requirements as well as user friendly mesh generation.

Fig 3 describes three types of modelling strategies of a masonry sample. Homogeneous macro-modelling is used for finite element modelling of masonry structure in this paper.

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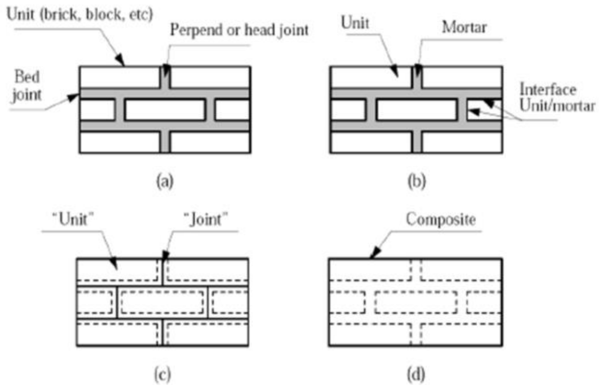

Fig 3: Modeling Strategies for Brick Masonry
a) typical masonry sample, b) detailed micro modeling, c) simplified micro-modeling, d) macro-modeling. (Lourenco, 2002) [9]

IV. EQUIVALENT STATIC ANALYSIS

The structure studied here is load bearing structure i.e. brick masonry structure. Since it is a very large structure, heterogeneous modelling of structure is not possible. So the brick and the mortar are considered as homogeneous units by taking the brick mortar prism.

These homogeneous masonry units are analysed using very fine meshing of plate elements in the software with the above given properties.

Typical floor plans of the building are shown in Fig 4. As seen from figure, Ground floor and First floor plan are almost similar. All the walls in the structure except veranda walls are 12 inches thick while veranda walls are 9 inches thick. Height of ground floor is 16ft 10inches and height of first floor is 15ft 1inch while height of first floor veranda wall is 12ft 7inches. The building rests on a very firm soil with about 1.5 m deep masonry strip footing. Hence the support condition is taken as fixed in the STAAD PRO software. Masonry columns are provided in the buildings. Some are solid and some are hollow from inside. Hollow columns are not considered in the software design model. Building is having arched roof supported on iron girders which are resting on masonry walls.

In the software model beams are considered over walls and roof load is applied. The building is almost symmetrical and therefore only half of the building is considered for analysis. The results obtained will be generalized for the whole building. 3D view of the building modelled using plate elements in STAAD Pro is shown in Fig 5.

V.NUMERICAL STUDY

The seismic analysis of building is done using equivalent static method as described in the code IS 1893(Part I): 2002, [2] in which seismic effect, that is, a horizontal force is considered as the percentage of the total weight of the building. In this method, dynamic forces, which act on the structure during the excitation, are converted into equivalent horizontal force. As per IS Code 1893(Part I): 2002, the building is located in seismic zone IV (Z=0.24). Being a school building the importance factor, I and Response Reduction factor, R for load bearing structures is taken as 1.5 each. The present structure is analysed using STAAD Pro V8i software, under the various load combination mentioned in IS 1905:1987 [1]. Elastic Modulus and Shear Modulus are calculated as per ref. [3]

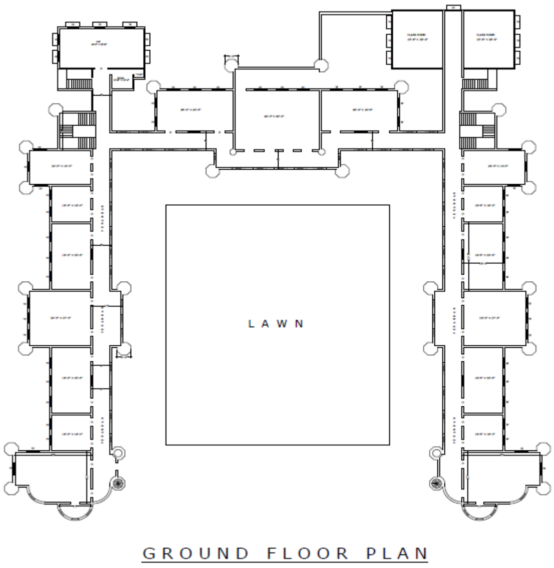

Fig 4: Typical Floor Plan of the Building

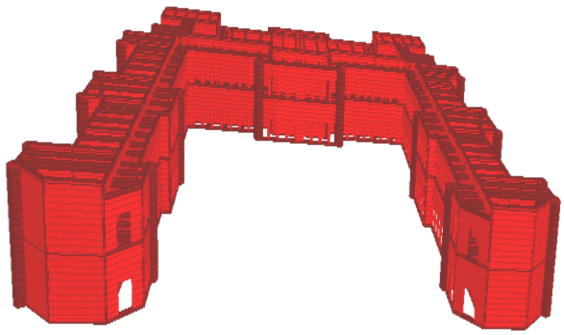

Fig 5: 3D model of the building in STAAD Pro using Plate elements

Some bricks fetched from the site are tested in the universal testing machine and the following results are obtained for material properties as shown in Table I.

Table I: Material Parameter

Properties of Material	Value
Unit Weight of Masonry(kN/m3)	20
Compressive strength of masonry units(MPa)	15
Prism strength of masonry, f_m (MPa)	10
Elastic modulus of masonry, E (MPa)	5500
Shear modulus, G (MPa)	2200
Poisson's ratio, µ	0.2

Using the above material properties, various mode shapes and stresses in the structure are obtained from the finite element model.

A. Analysis of Modes shapes and Frequencies

Natural frequencies and mode shapes of the building have been obtained through modal analysis approach using STAAD Pro.The first 5 frequencies of the building obtained by Modal Analysis have been shown in Table II. The first three mode shapes are shown in Fig 6. It is seen that the natural frequencies are closely spaced.

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Table II: Natural Frequencies

Mode	Frequency (Cycles/ sec)	Time Period (sec)
1	4.181	0.23918
2	4.222	0.23688
3	4.345	0.23016
4	4.766	0.20984
5	5.361	0.18655

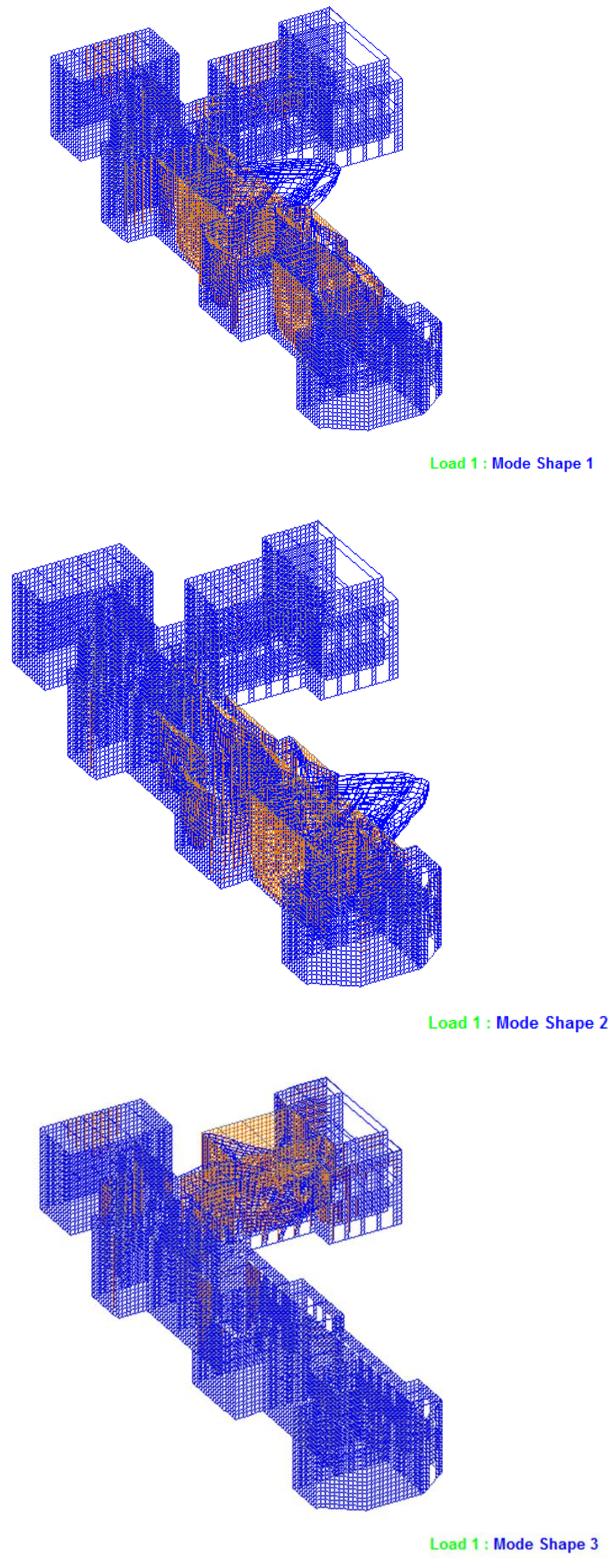

Fig 6: First three Mode Shapes

B. Analysis of stresses under Gravity loading

As seen from Fig 7, most part of the structure remains under compression within permissible limits as given in IS 1905:1987 while tensile stress is exceeded at a very few locations i.e. beam wall junctions at the roof level and at the bottom most corners of walls due to combined effect of Dead load and Imposed load. The maximum value of tensile stress is 0.594 N/mm^2 reached at a very few positions otherwise tensile stresses in the structure are also within the acceptable range. Shear stresses in the structure due to gravity loading are within acceptable limits. The permissible shear stress value is 0.5 MPa, which is not exceeded anywhere.

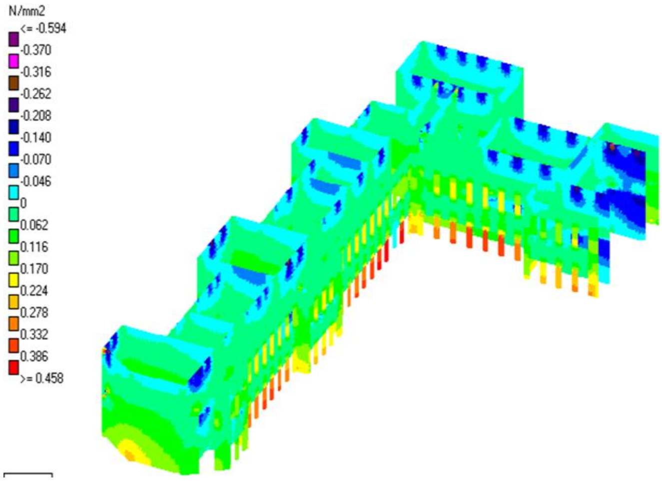

Fig 7: Direct Principal Stresses due to Gravity Loads

C. Analysis of stresses under seismic loading

The structure is analysed for various load combinations of dead load, imposed load and seismic load for masonry buildings as given in IS 1905: 1987. The building is subjected to different PGA levels (0.1g, 0.2g, 0.3g, 0.4g) as input ground motion to determine its seismic performance. As seen from Fig 9 and Fig 10, due to seismic load in X and Y direction respectively, most part of the structure remains under compression within permissible limits. As for the gravity loading, here also tensile stress is exceeded at a few places as seen from figures.

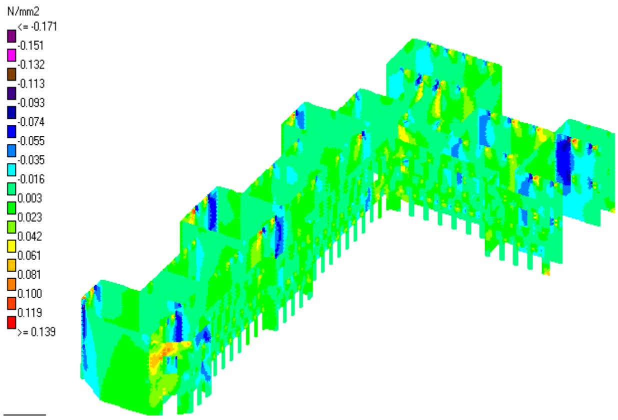

Fig 8: Shear Stresses due to Gravity Loads

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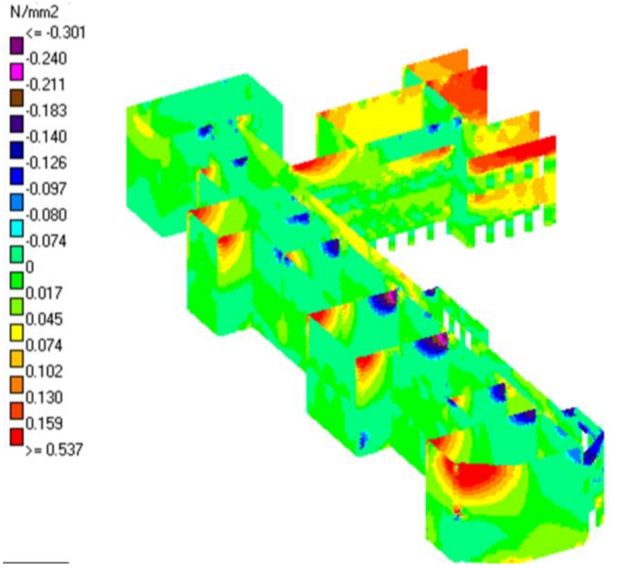

Fig 9: Stresses due to seismic loads (Earthquake in X direction)

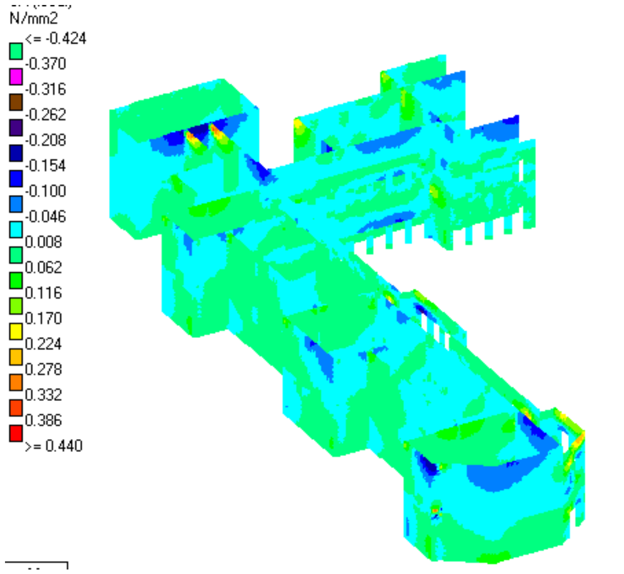

Fig 10: Stresses due to seismic loads (Earthquake in Y direction)

Table III: Maximum value of stress reached for different values of PGA

PGA	Direct Stresses (N/mm2)				Shear Stresses (N/mm2)	
	Seismic loading in X direction		Seismic loading in Y direction		Seismic loading in X dir	Seismic loading in Y dir
	Comp-ressive	Tensile	Compr-essive	Tensile		
0.1 g	0.441	0.424	0.559	0.594	0.445	0.452
0.2 g	0.627	0.452	0.853	0.594	0.445	0.452
0.3 g	0.941	0.684	1.279	0.834	0.466	0.452
0.4 g	1.255	0.919	1.706	1.154	0.621	0.487

Table III shows maximum values of stresses reached for different Peak Ground Acceleration (PGA) levels of 0.1g, 0.2g, 0.3g and 0.4g under seismic loading in X and Y direction. It can observed that maximum compressive stresses for all PGA levels are within permissible limits but tendency of structure to fail in tension increases with increase in PGA level.

VI. CONCLUSIONS

- The masonry heritage building is modeled using homogeneous macro-modeling with plate elements in the software STAAD Pro. The finite element model is analyzed for both gravity and seismic loading.
- The first 5 natural frequencies of the building are obtained by Modal Analysis. It is seen that the first 4 fundamental frequencies are closely spaced while 5th frequency is somewhat widely spaced.
- The building does not show any cracks under gravity loads. Considering all the Load cases, the structure remains in compression within permissible compressive stresses (2.5 MPa) for all values of PGA levels.
- Permissible shear stresses (0.5 MPa) are exceeded for PGA of 0.4g for seismic loading in X direction. The maximum value reached is 0.621 MPa.
- But tendency of structure to fail in tension increases with increase in PGA level. Only at a few places tensile stress is exceeded (> 0.14 MPa), mostly at the corners of walls at bottom and roof level and at beam-wall junctions.
- The portions around the openings were found to be highly vulnerable in all cases.
- The structure is safe under static loading, only few weak zones are seen which can be retrofitted accordingly using proper retrofitting techniques.
- Finally, it is also evident from the different scenarios discussed above that damage zones in the walls of the present masonry building will vary depending upon the seismic excitation to which the structure is subjected, geometry of walls and material properties of the masonry work. Therefore, recommendations regarding strengthening of various locations of walls of a particular building can be only made after the numerical model of the structure under the given conditions are thoroughly investigated.

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