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DYNAMIC TIME HISTORY ANALYSIS OF STONE ARCH

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ABSTRACT

The present work is focused on time history analysis of the 102 years old Indo-Saracenic style *stone arch* of Senate hall, Allahabad University, India. The senate hall was constructed with old brick masonry and stone masonry in *Indo-Gothic*, *Hindoo* or *Hindu-Gothic*, *Mughal-Gothic*, *Neo-Mughal* style architecture. The main objective of the analysis is to identify the possible causes of existing damage and deformities in historical structure and actual behavior of stone arch during ground motion. Stochastic finite fault model is used to simulate the ground motion using regional parameter. The geometry of the stone arch is modelled by making use of both existing available drawing and survey performed on the structure. Nonlinear dynamic analysis is performed on detailed 3D Finite Element models. The stress variation throughout the arch is shown. The maximum deformation of 0.206 mm is observed at crown level of arch.

Keywords: Historical monuments; Stone arch; In-situ survey; Finite element modelling; dynamic time history analysis

1. INTRODUCTION

Allahabad city (25°28′ N latitude, 81°54′ E longitude), is 7th most populous city of Uttar Pradesh State, India [1]. The city original name was Prayag means "place of offerings" due to the Sangam (means meeting) of three ancient rivers viz., The Ganges, The Yamuna and The Sarawasti. The modern name was later given by Mughal Emperor Akbar in the year 1575 AD as 'Illahabad', now known as Allahabad [1]. The development of the city took place during the British rules and the Indian Maharajas in distinct ways from each other, made their individual efforts, to make the city flourish with monuments and buildings that embellish the cultural and historical value of the old city [2-3]. The city has many old historical monumental structures which were constructed with different classes of architectures and materials in different era. The present paper is focused on the 102-year-old stone arch, Indo-Saracenic style architecture, made up of stone and brick masonry is an integral part of Senate Hall of Allahabad University. The stone arches have been used as a load bearing components for supporting the roof of the structure. According to bureau of Indian standard [4], the Allahabad city is located in low-seismicity zone second and had experienced many earthquake events such as Bihar-Nepal earthquake, 1934 and Nepal earthquake, 2015. Due to 2015 Nepal earthquake, minor cracks were observed in stone arches of senate hall.

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In order to rehabilitate the old structures and to improve their performances during the seismic events, it is required to analyze them in detail. It is also well established that prior to mid of 20th century most of the old structures were not designed for the lateral loads. Further, old buildings are seriously affected even for small levels of lateral acceleration that generates small collapses on openings, joints, roof, stairs, domes, towers, walls, stone arches and decorative materials [5]. The quantitative analysis of the response of old masonry stone arch, for synthetically simulated ground motion using regional parameters such as stress drop, shear wave velocity etc., for the Allahabad city is performed. Further, time tedious nonlinear dynamic analyses is performed on 3-D model stone arch in ANSYS (14.0). The novelty of work is represented by the application of stochastic finite fault model in simulation of ground motion and using it for non-linear dynamic analyses for the complex geometries of stone arch. Figure 1 shows the stone arch of Senate Hall. The arch is constructed on the right side of the internal portion of Senate Hall. The Senate Hall is an administrative building that is an excellent example of English Colonial architecture amalgamated with Mughal architecture which make the form of Indo-Saracenic style architecture that needs to be protected.

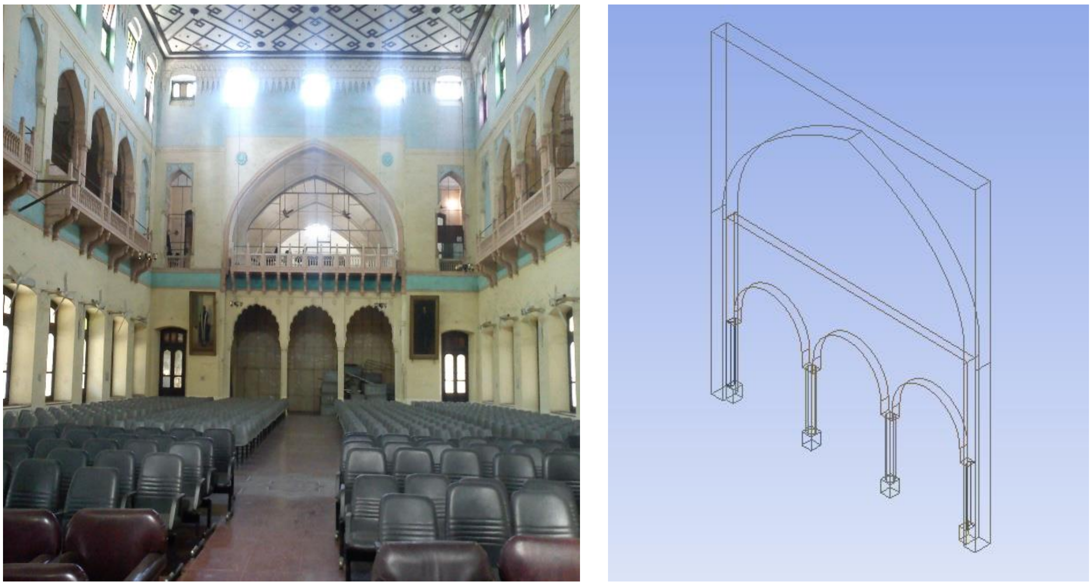


Figure1. Stone arch view of senate hall

2. SENATE HALL ARCH AND ITS RECONNAISSANCE

The masonry construction is one of the ancient construction techniques which is still opted in rural areas of undeveloped nation of the world. As per the technical report [6], more than 70 percent of the structures in the world are masonry structures. The Senate Hall arch is a good example of load bearing (masonry wall and stone arches) structure constructed in 1915 (102-year-old). The senate hall structure was designed by British engineer “Sir Swinton Jacob” (who also designed the Victoria house in Kolkata) and construction was started in 1910 and completed in 1915.

Reconnaissance survey shows that the components of different height, width and thickness are provided to support the masonry roof of ground floor and first floor. The stone material is used in arches, front facades, octagonal columns, stairs, balcony, flooring and decorative materials of senate hall structure. At present, the quality of stones is deteriorated. The major and minor cracks were observed in stone arches and facades of the structure. The major cracks are observed in the arch joints, crowns and stone columns. The size of cracks was approximately 3.0 mm as shown in figure 2(a-i). Some parts of the buildings are closed due to the deteriorated material at both ground floor and first floor level.

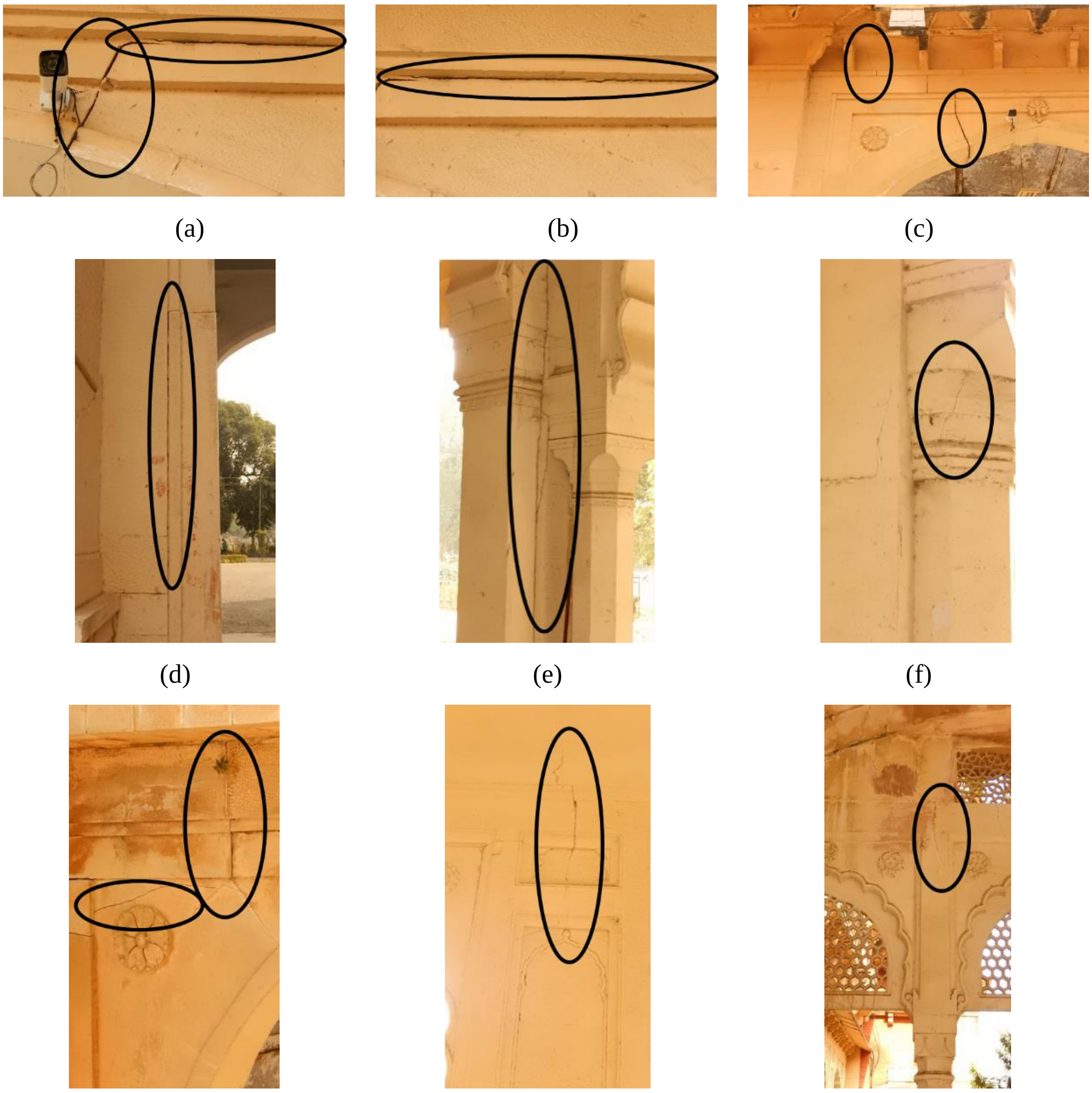

(a) (b) (c) (d) (e) (f) (g) (h) (i)

Figure 2. Major and minor cracks observed in stones

3. FINITE ELEMENT MODELLING OF STONE ARCH

Modelling of the stone arch is performed using data sets obtained from survey, CAD drawings, and consultation with the engineer-incharge of the Allahabad University. Firstly, by geometric survey of the stone arch, all the dimensions are validated with the available CAD drawing. The dimensions are measured with the help of Disto-metre and tape. Figure 3 shows that the arch is a combination of two types of arches that is supporting the ground floor and first floor of the senate hall roof. The first level is having 03 numbers of small arches with semicircle arch having radius of 1.4m while the main arch is having radius of 4.88m. The small arches are supported on 2.13m high stone columns. The top arch is supported at the level of 6.10 m. The span of arch is 10.67 m. The meeting hall roof is supported by the stone arch. The three arches on the ground level are supported on 2.13 m high 0.45m diameter column, and main arch is supported on 0.60m square column on both end. The thickness of main arch and small arches are 0.61m and 0.31m respectively. The stone arches are in good condition due to their proper maintenance.

The modeling of stone arch is performed using finite element software ANSYS workbench (ANSYS 14.0). The geometry of stone arch is created using the homogeneous behavior as shown Fig 4. The stone arch is modelled in ANSYS with fine meshing solid elements 186 and 187. Analyses of arches are performed by choosing 20-Noded and 10-Noded 3D solid element. The main reason to choose 3D

20-Noded solid Element is to capture the quadratic displacement behavior. The element supports plasticity, hyper-elasticity, creep, stress stiffening, large deflection and large strain capabilities. It also has mixed formulation capability for simulating deformations of nearly incompressible elastoplastic materials, and fully incompressible hyper-elastic materials. The material properties such as density, Young's modulus and Poisson's ratio are obtained from the literature survey of old historical monumental structures [7].

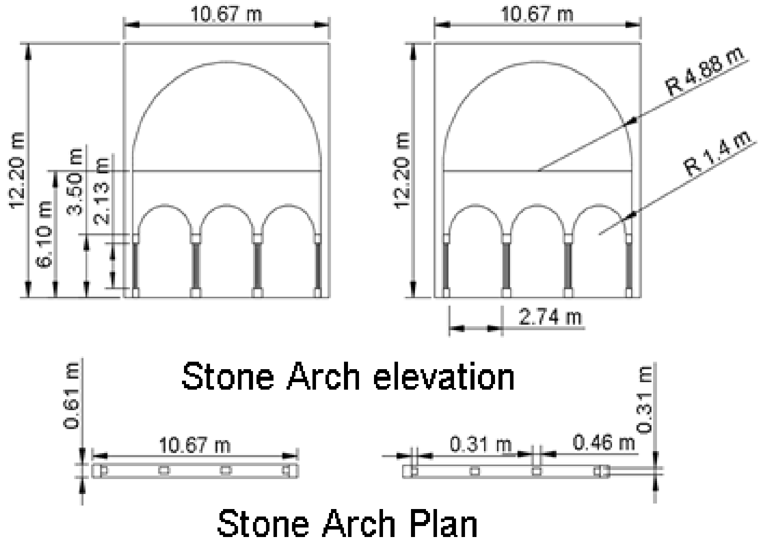


Figure 3. Plan and elevation view of stone arch

The analysis is performed on the structure only after performing the convergence test with the meshing size 50mm. Altogether, the Finite Element (FE) stone arch model is having 1,68,690 nodes and 38,258 elements. The stone piers of main arch and vault were modelled as fixed at the base where as sides of the column are consider as not restrained along x-direction.

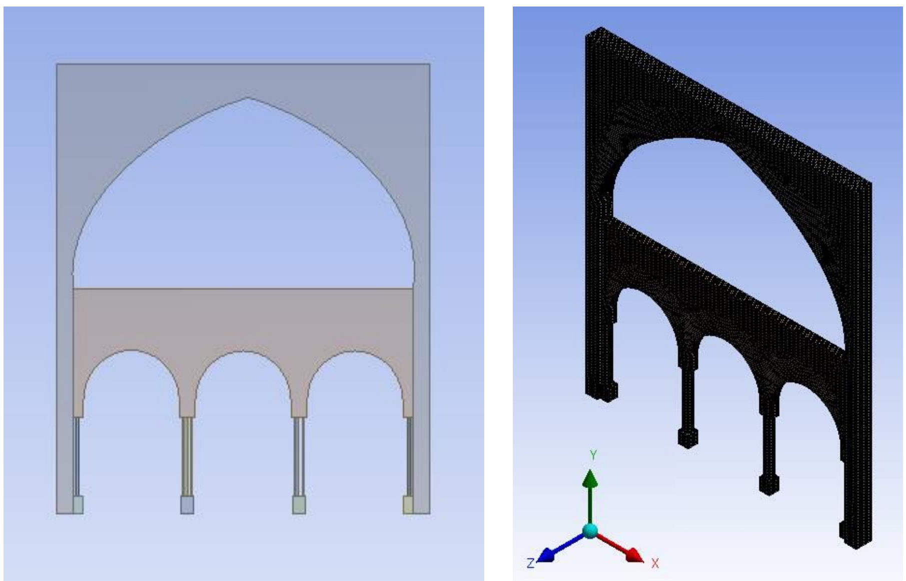


Figure 4. Finite element modelling of stone arch

4. SITE SPECIFIC DYNAMIC TIME HISTORY

Due to non-availability of strong motion data for Allahabad city, synthetic ground motion was simulated using stochastic method of Boore (1983) [9]. The target ground motion amplitude spectrum, which depends on magnitude, distance and duration properties is given by Motazedian and Atkinson (2005) [10],

$$A_j(r,f) = \frac{R_{\theta\phi}.F.V}{4\pi\rho v_s^3}.(2\pi f)^2.\frac{M_{0ij}}{\left[1+\left(\frac{f}{f_{0ij}}\right)^2\right]}.G.e^{\frac{-\pi f r_{eff}}{v_s Q(f)}}e^{-\pi k f} \quad (1)$$

Where $A_j(r,f)$, target amplitude spectrum corresponding to distance (r) and frequency (f), $R_{\theta\phi}$ is radiation pattern constant (average value of 0.55 for shear waves), F denotes free surface coefficient (generally taken as 2), V is partitioning coefficient of shear waves into two components (generally taken as $\sqrt{2}$), ρ is density of rock at source (fault), v_s= shear wave velocity at source, M_{0ij}= seismic moment related to the ijth sub fault, $f_{0ij}(t)$ = corner frequency related to ij^{th} sub-fault at time t, $N_r(t)$ = number of ruptured sub-faults at time t, $M_{0,avg}$ = average sub fault moment due to each fault = $M/_N$, N = total number of sub-faults, G = geometrical spreading function, r_{eff} = effective distance of sub fault from the site, $Q(f)$ = quality factor at frequency f, and k= high frequency diminution filter, kappa [11-16]. The ground motion time history for Allahabad city with PGA of 1.291 m/sec^2 is simulated for Allahabad fault is shown below in Fig. 5.

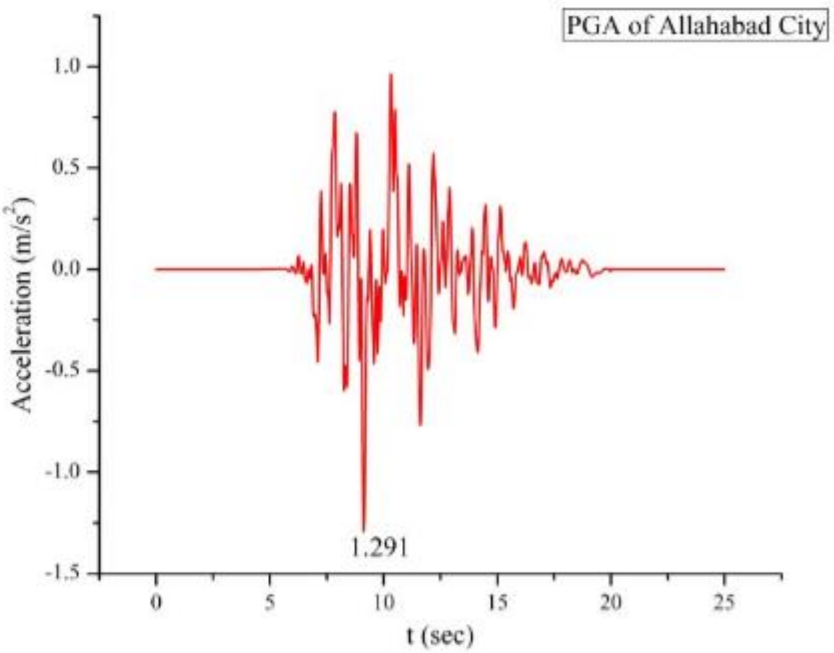


Figure 5. Time history analysis in stone arch

5. ANALYSIS

Geometrical survey is utilized for modelling the stone arch. The dynamic responses are analyzed on the crown of arches located on ground floor and first floor. Many studies suggest that application of different simulation models may provide possible solution to the complications involved in analysis of seismic performance of any masonry structure [17]. The seismic responses can be interpreted more comprehensively by combining the dynamic response [18]. In present work, site-specific simulated time history analysis shows the responses of any stone arch at different critical points.

The Transient analyses (Time History Analysis) are observed to be more significant than Response Spectrum Analysis as much as dynamic equilibrium is satisfied at each time step. Time-history analysis based on time step integration is often the most reliable approach to evaluate a finite element model dynamic response, provided that the damping value and the stress-deformation relationship are accurately considered, as well as material properties. The results are evaluated at four most valuable points considered at stone arch shown (Fig.6), A at ground floor level; B at first floor level; C at first floor arch crown and D of ground floor arch crown. The dynamic analysis is performed in the Z-direction of stone arch with limited computational system (24 GB RAM and 8 core processor) for 26 hours. The time integration is set in 500 sub-steps at each component of arches.

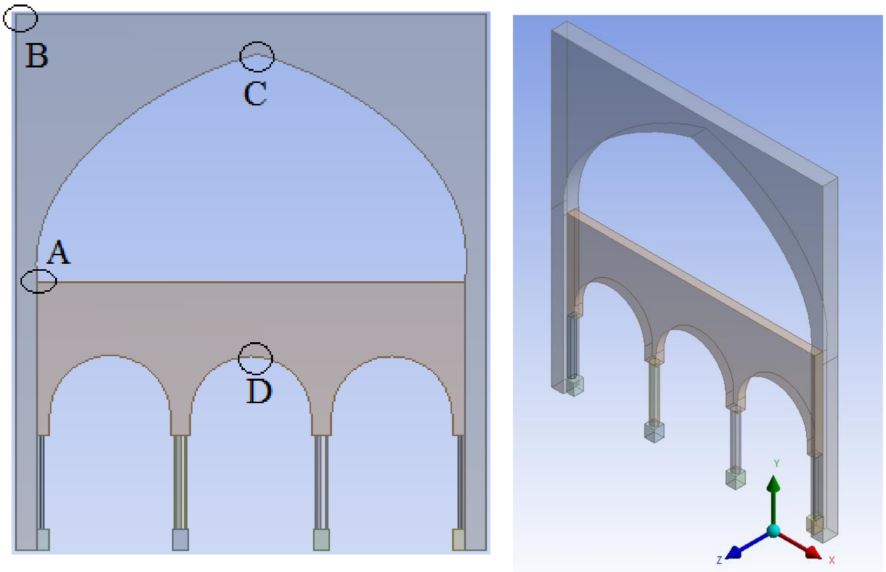
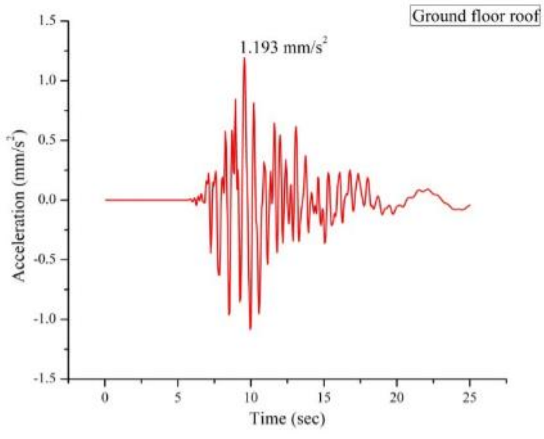


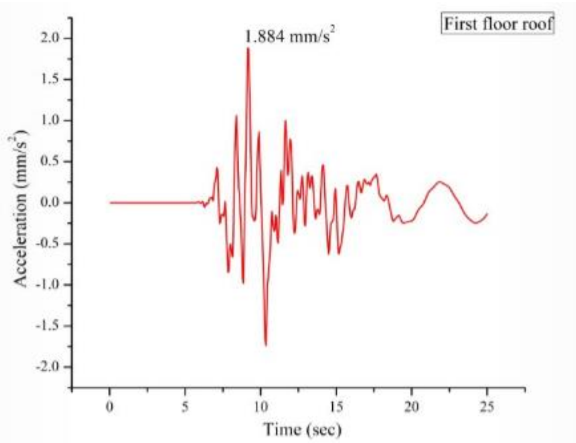
Figure 6. Results observed at critical points of stone arch

6. RESULTS AND DISCUSSION

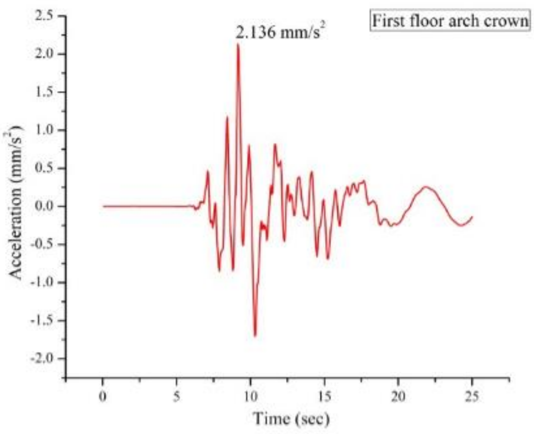
The acceleration time history response is observed at points (A, B, C, and D) as shown in Fig.6 for input motion in the z-direction of the stone arch. The acceleration response of each level is shown in Fig.7. The results show that at all the levels, i.e. ground floor, first floor, first-floor arch crown and ground floor arch crown of the stone arch is de-amplifying (Fig 7a-d). The acceleration response of ground floor de-amplify to 1.193m/s^2 at the 6.10m height due to the point (A) and at point B of the first floor it de-amplify to 1.884mm/s^2. Further at point C and D the de-amplification are 2.136 mm/s^2 and 2.486 mm/s^2 respectively.



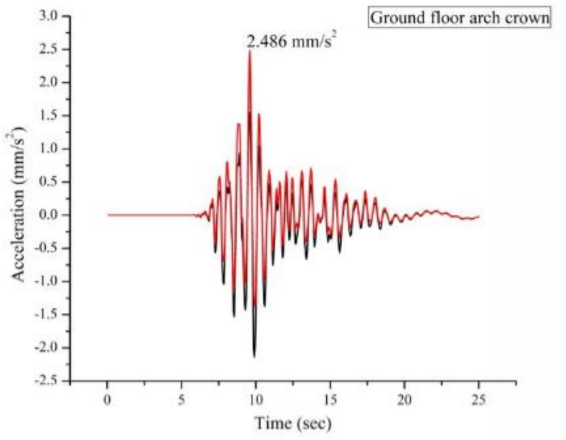
(a) Ground floor response of stone arch



(b) First floor response of stone arch



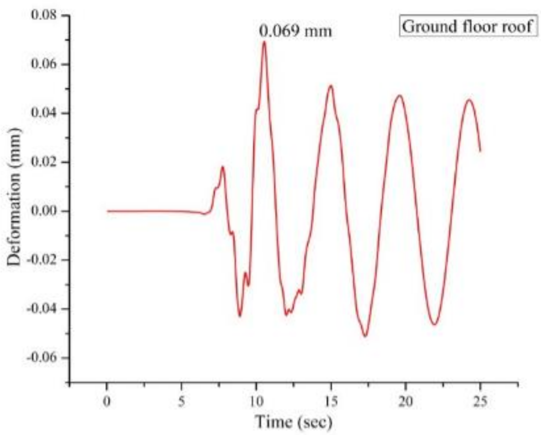
(c) Acceleration response of first floor arch crown



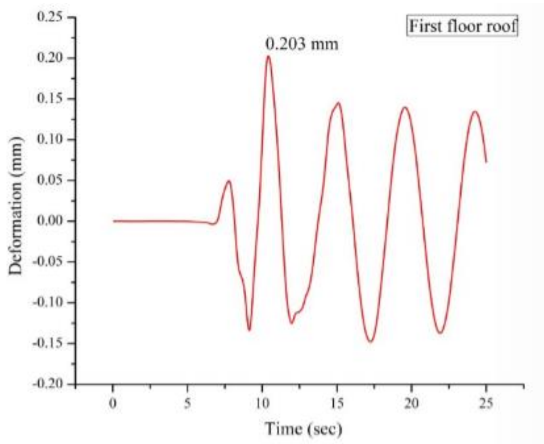
(d) Acceleration response of ground floor arch crown

Figure 7. Acceleration response of stone arch

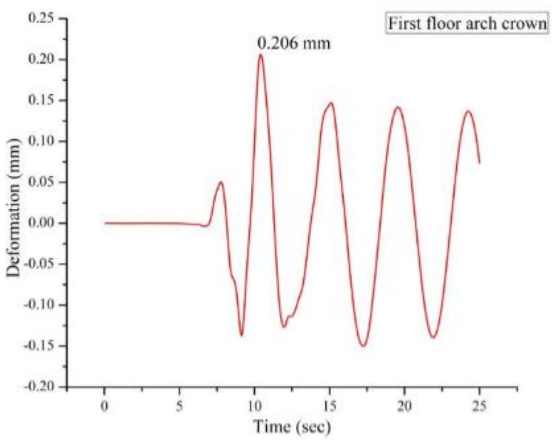
Deformation responses of stone arches are shown (Fig 8). The maximum deformation is observed at first-floor arch at crown 0.206mm. The minimum deformation 0.069mm has observed at corner of ground floor roof. The deformation is 0.203mm on first floor roof. Outer arch has been constructed from continuous parts with ground floor and first floor.



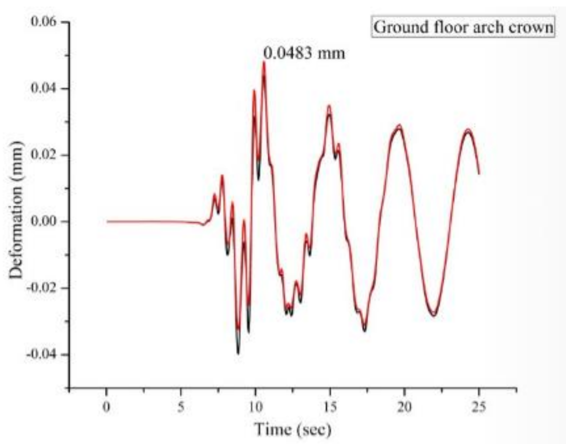
(a) Ground floor deformation of main arch column



(b) First floor roof deformation of arch



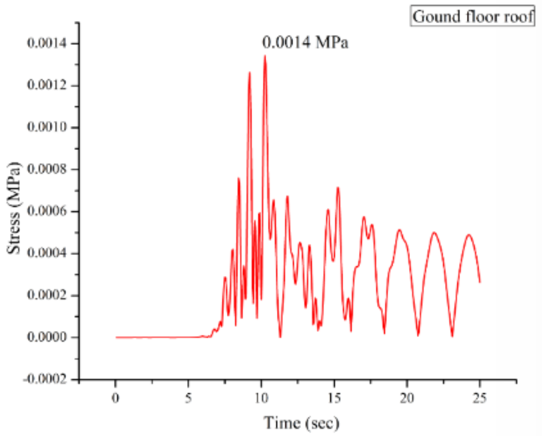
(c) First floor crown deformation of stone arch



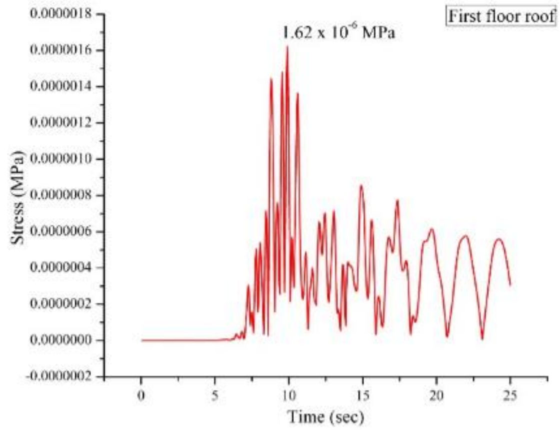
(d) Ground floor crown deformation of stone arch

Figure 8. Deformation response of stone arch

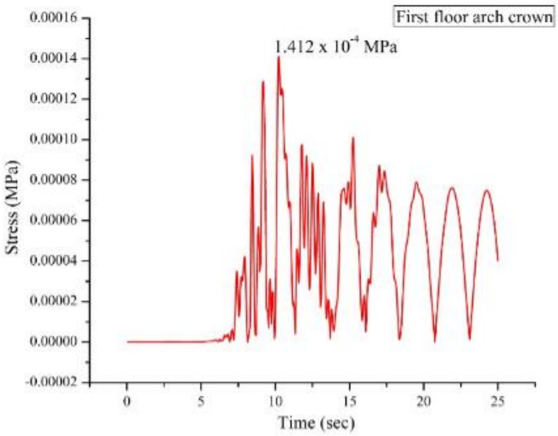
Further, the stresses response of stone arch has observed at maximum on ground floor roof level (0.0014 MPa) as shown (Fig. 9a). The overall stress has generated on the base of the stone arch of (0.0021 MPa) shown (Fig. 9e).



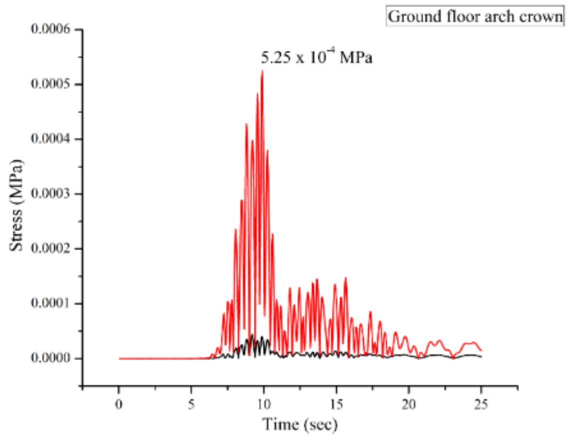
(a) Ground floor roof stress of arch



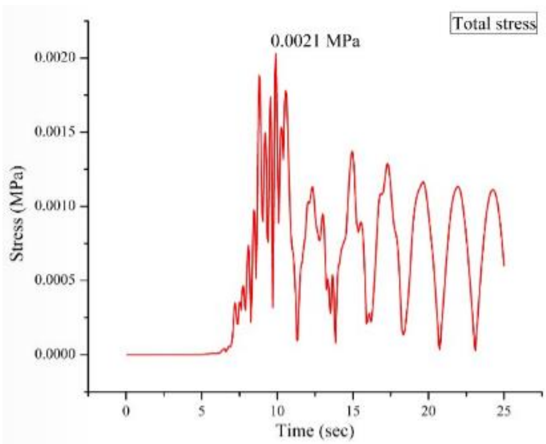
(b) First floor roof stress of arch



(c) First floor arch stress at crown



(d) Ground floor arch stress at crown



(e) Overall stress of the stone arch

Figure 9. Stresses in stone arch

7. CONCLUSIONS

The dynamic response is estimated for 12.20m high stone arch of Senate Hall, Allahabad University. The stochastic finite fault model is used to generate acceleration time history for Allahabad city by using the regional parameters such as stress drop, shear wave velocity, surface drop and pulsing percentage. It is observed that the response of the two level stone arch, de-amplify the ground motion significantly at all the level. The deformation response is negligible and stress generated due to the motion is insignificant. The simulation results were observed to be very conservative. Further, detail analysis is required for accurately analyzing the model.

8. ACKNOWLEDGMENTS

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