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FE Modelling and Dynamic Testing of Historic Aspendos Theatre in Antalya, Turkey

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ABSTRACT: Historic Aspendos Theatre is one of the most valuable monumental structures located in Antalya, Turkey, which has survived over 2200 years. Concerts and shows are still performed at Aspendos Theatre. Recent usage of high decibel amplifiers during concerts generates an increasing amount of concern about the structural safety of the theatre. This study attempts to investigate the effects of amplified beat frequencies of songs on the structure by conducting a detailed three dimensional (3D) Finite Element Model (FEM) of the theatre. The FEM is also used to simulate earthquake loading effects on the structure according to the Turkish Specification for Structures to be built in Disaster Areas. Dynamic non-destructive tests were conducted on the structure to obtain the first few resonant modal frequencies as 1.5Hz, 2.15Hz, and 3.5 Hz., which also fall in the same order with beat frequencies of many songs (1-2.8Hz). Comparison of measured frequencies against analytical models enables model updating and simulation of earthquake loads. Measured damping ratios are used in analyses. Although calculated earthquake induced forces are found to be the most critical loading condition as compared to the resonant sound induced vibrations, the stress levels of the two analyses were comparable. The maximum tensile stresses obtained from the most critical loading conditions were still within acceptable limits except for a few localized stress concentrations. The analyses results proved the obvious that the structure can resist earthquake forces of about 450 years of return period, since it is still standing after 2200 years from its construction. The relatively slender (40 m wide by 25 m high) front stage wall and the 3 m tall columns located over the top of the stage wall are considered to be the most critical and vulnerable sections of the Aspendos Theatre.

1 HISTORY OF ASPENDOS THEATRE

Historic Aspendos Theatre is located 38 km distance to Side which is a village of Antalya City. The theatre is constructed about 200 BC by architect Xenon who lived Aspendos city. The theatre has excellent acoustic properties and is one of the best preserved antic theatres. Theatre went under ruling of the Roman Emperor in 129 AC; however, many sculptures and parts of the theatre were dislocated during that time by politician Verres without damaging the main theatre building. Starting by 13th century, there are traces that the theatre went under ruling of Seljuk Turks. The Theatre has been renovated and restored during that time and used as a caravansary (kervansaray), which is one of the most important factors that the theatre remained in good condition until recent times. A caravanserai was a roadside inn where caravans could rest and recover from the day's journey (Wikipedia).

The good performance of the theatre located at earthquake (EQ) prone regions of Turkey for more than two millenniums is surprising and one of the driving forces of this study. Many studies conducted on the theatre so far concentrates on the acoustics of the building, but no studies were found on the FE modeling and EQ analysis of the structure (Lanckoronski, Pamphylien).

Figure 1 : Aspendos Theatre general inside view

2 OBJECTIVES AND SCOPE OF THE STUDY

The main objective of the study is to construct a representative analytical model of the historical Aspendos Theatre and conduct earthquake analysis using the Turkish code and provisions (Boz, 2006). Additional targets include vulnerability assessment of the structure against sound induced vibrations using dynamic test results. Therefore, the scope consists of

- 3D-FE modeling of the structure,
- Non-destructive field dynamic testing of the theatre,
- Earthquake (EQ) vulnerability assessment using FE modeling,
- Investigation of sound induced vibrations.

3 NON-DESTRUCTIVE TESTING OF THE THEATRE

Dynamic tests conducted on the theatre and material tests conducted on stones found on site similar to building blocks used in the building revealed the structural and material characteristics of the structure and building blocks. Stones found on site were used for ultrasonic velocity measurements to obtain elastic modulus values (Tuncoku, 2001). Mass and volume measurement of stones revealed unit mass of the material which will also be used in the modeling studies. Measurement of impact and ambient vibration revealed first few resonant frequencies and damping of the structure.

3.1 Material tests

Taking samples from the main theatre building was not possible for conservation purposes. However, similar stones existing on the site were found and tested in the laboratory. The properties of the stone samples are assumed to be close to the properties of building stones used in the theatre building. The irregular shapes stones were submerged into the water to find volume (V) and density (ρ) was calculated by simply dividing mass of the stones by the volume (2150 kg/m^3). The modulus of elasticity (E) was found by measuring ultrasound travel velocity which yielded 2350 MPa. The compressive strength of material is interpolated from a previous study (Tuncoku, 2001) conducted on compressive strength of similar stones and calculated to be about 12 MPa for the E value of 2350 MPa. The tensile capacity of the material is assumed to be about 1/10 of the compressive strength, and taken as 1.2 MPa. It should be noted that the joints between stones may transfer compression and shear only and may not transfer any tensile forces.

3.2 Ambient and free vibration dynamic tests

Dynamic tests were conducted on the theatre building to obtain the first few dominant vibration frequencies, which were compared against the analytical models. Comparison of experimental and analytical results enabled FE model validation and related calibration studies when combined with material test results. The dynamic tests were conducted at the ground floor levels of interior and exterior stage walls. Additional and better measurements were also taken from the top of the exterior stage wall by utilizing the ladder and bucket of a fire truck (Fig. 2). Dynamic tests were dominantly conducted by using an impact hammer to excite the structure. Although excitation of a 25 m tall, 40 m wide, and 1.8 m wide theatre wall seems impossible to be excited using a 5 kg impact hammer, successful free vibration acceleration readings were taken from the top and bottom of the wall (Fig. 3). The data acquisition system used in the study has a 24 bit analogue digital converter (ADC) system with force balance accelerometers down to 1 μg resolution and low noise cables.

Fast Fourier Transform (FFT) of the recorded time series revealed that the exterior wall of the theatre vibrates at about 1.5 Hz., 2.2 Hz., and 3.5 Hz. Comparison of the measured frequencies against Finite Element (FE) analysis results showed good correlation and indicated the corresponding mode shape of the measured frequency. The damping of the structure was also obtained from the measured dynamic measurements. Curve fitting techniques in time domain and half-power bandwidth method in frequency domain were used to obtain damping ratios, which were found to be in the range of 1%. The damping ratio of the theatre is considered to be low when compared to about 5% damping common to majority of the reinforced concrete buildings.

The dynamic vibration tests were conducted on the exterior wall only since there was no access to the inner (stage) wall. The inner wall dynamic modes were only recorded from the base of the wall which gave inferior results compared to recordings conducted at the top of the wall. The inner wall natural vibration frequencies were obtained as 0.87 Hz., 1.66 Hz., and 2.7 Hz.

Figure 2 : Dynamic impact modal testing

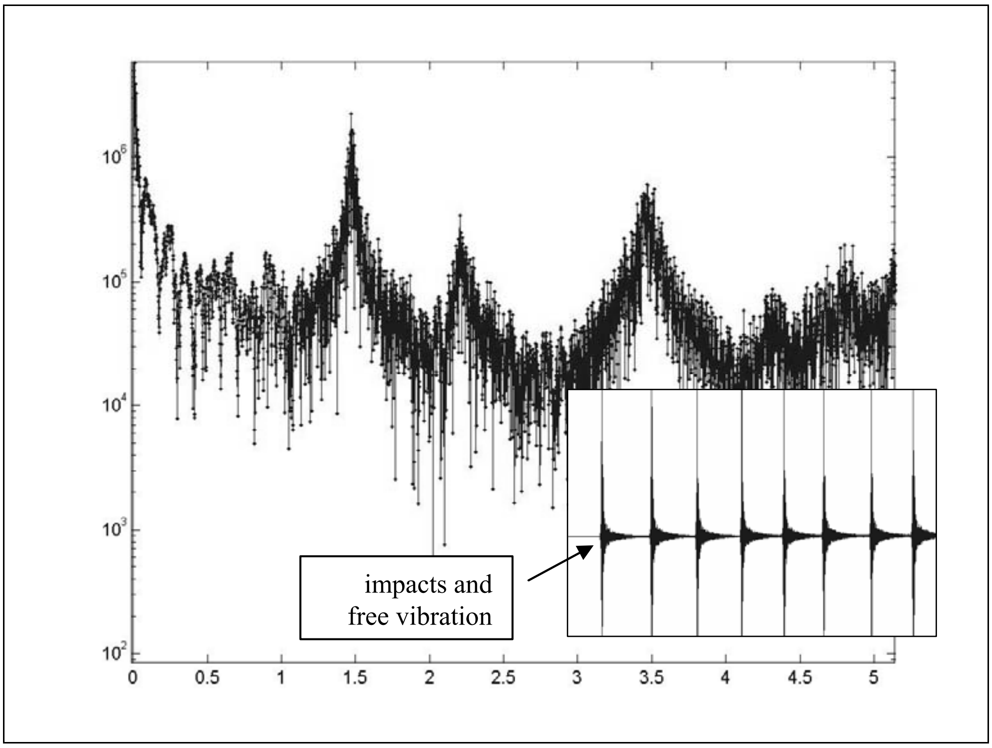

Figure 3 : FFT conversion of recorded impact free vibration data showing resonant frequencies.

4 FINITE ELEMENT MODELLING AND ANALYSIS OF THE THEATRE

FE model of the theatre building was generated using available drawings obtained from the Antalya Museum and actual geometric measurements conducted on site. Eight nodded solid elements were used to construct the FE model of the theatre (SAP2000 User's manual). The main theatre building was generated by using 12670 solid members and has about 63000 degrees of freedom (Fig. 4). The modal analysis results show acceptable correlation between the analytical and experimental frequencies (Table 1).

The FE model was used to simulate two different loading conditions:

1. sound induced dynamic loading at resonant frequencies,
2. earthquake loading on the theatre based on Turkish seismic code.

and each loading condition and relevant analyses results are explained below under each heading.

4.1 Sound induced dynamic loading at resonant frequencies

Although, considering sound induced forces exciting a large size masonry theatre building stage wall seems unrealistic to start with from an engineering judgement point of view, such a possibility was explored considering the building has low damping ratio and matching resonant frequencies with the beat frequencies of songs in general. The exterior wall damping ratio was calculated as 0.874% using advanced, commercially available ambient data post processing software ARTEMIS. Although interior wall top elevation was unreachable, the damping ratio is expected to be even smaller for the stage wall since it has smaller thickness.

The beat frequencies of 210 dance type songs fall in the range of 1.0 to 2.8 Hz by 96.2% (Structural Engineer 2000). Beat frequency studies on Turkish songs (e.g., Tarkan, Hande Yener, Pamela) and other selected international songs also support that finding. The pressure induced by sound sources is relatively small compared to other force sources such as earthquakes and wind. However, the lightly damped stage wall may go into resonance state, provided that the beat frequency matches with the natural frequency of the wall.

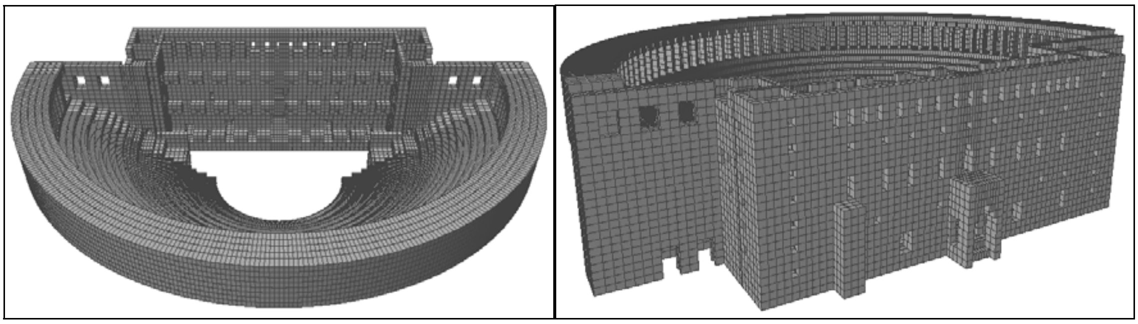

Figure 4 : General view of The Aspendos Theatre FE model.

Table 1 : The first two analytical natural vibration periods of the North and South walls.

	Experimental Hz.	Analytical Hz.
Interior First Bending	(too noisy)	0.87
Exterior First Bending	1.5	1.47
Interior Second Bending	1.7(noisy)	1.66
Exterior Second Bending	2.2	2.36
Interior Third Bending	2.8 (noisy)	2.71
Exterior Third Bending	3.5	3.76

The sound pressure level (SPL) is calculated as a function of decibel (dB) which is a logarithmic unit to describe the ratio of intensity. The minimum pressure that can be felt by human ear is 2e-5 N/m^2, called as "threshold of hearing", and shown with letter P_o. The pressure created by a sound source is described by dB as and is defined a multiple of hearing threshold P_o. For instance, a speaker in disco from 1 m distance might generate about 100 dB sound, which would translate to 2 N/m^2 (Pa) pressure. The relationship between pressure and dB is given in Eq. (1) below:

$$P = P_o \cdot 10^{\left(\frac{SPL}{20}\right)} \quad (1)$$

The pressure created by multiple speakers can be combined together. If the sources are coherent (exactly the same frequency and phase) they can be directly summed up. Otherwise, SRSS approach is used to combine incoherent sources.

Although the permitted sound pressure level is 90 db in Aspendos Theatre, the measurement is carried out at front row seats (or further back) which are at least 25m away from the wall. The sound pressure is inversely proportional with the distance square. For example, the SPL might be $(25)^2$ times larger at 1m away from the speakers (which is about the distance between the wall and speakers), as compared to the SPL at 25m away from the speakers. SPL level of 625 times large is equivalent to 55.92 dB which is additive to 90 dB. Therefore, about 145 dB pressure might be obtained on the stage wall, which is equivalent to 198 Pa. Considering the distance between speakers and upper elevations of the wall, a uniform pressure of 63 Pa is considered in the analysis. The pressure is assumed to be exactly matching the first vibration frequency of the stage wall which is about 0.87 Hz, a little bit lower than the minimum expected beat frequency range of songs (1 to 2.8 Hz). The dynamic amplification of the stage wall displacement is considered as 1/(2×(damping ratio)) times the static displacement (Chopra, 1995). The amplification factor at resonance state would be equal to 1/(2×0.08) which is 62.5 times the static displacement. A uniform pressure of 63 Pa is assumed to act on the whole surface of the stage wall, being amplified by 62.5 times at the resonant state creating an equivalent pressure of about 3950 Pa. The maximum stresses developing on the stage wall are calculated to be in the range of 1.5 MPa as shown in Fig. (5).

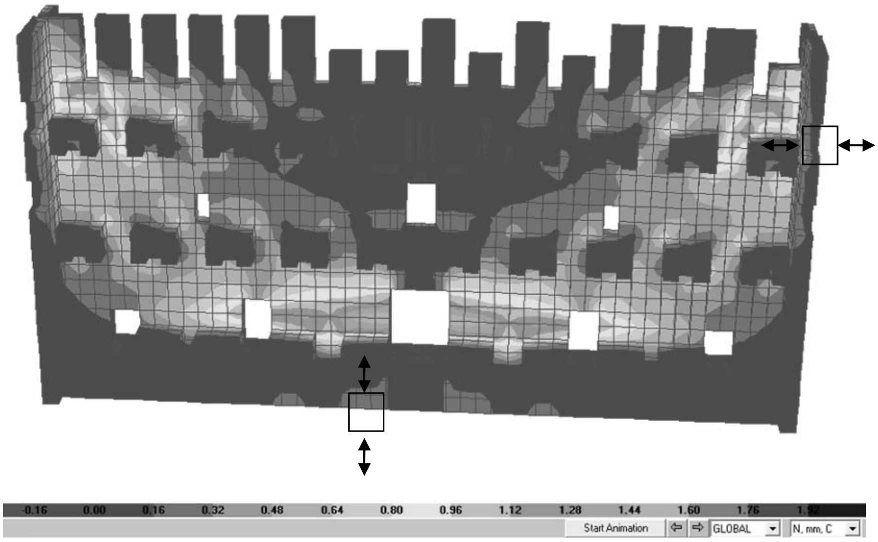

Figure 5 : Maximum (tensile) stresses generating at the stage wall due to sound induced forces

The stresses developing at the same location due to self weight (dead load) is in the order of 0.9 MPa which is about 0.6 MPa smaller than the tensile stresses generated in vertical direction by the resonant sound induced pressure. Stresses developing at the corners of the stage wall are also in the range of 1.2 MPa which are not balanced by any dead load stresses. The stresses generating at the upper corners of the stage wall (Fig. 5) are in the same order of tensile material capacity of 1.2 MPa as described in Section 3.1. Special care should be taken to keep SPL lower than 115 dB at the surface of the stage wall with 20 dB safety margin (instead of measuring the SPL at around seats) and not allowing drums or songs with beat frequency of 0.87, 1.47, 1.66 Hz (e.g., BeeGees: Staying Alive has 1.7 Hz beat frequency).

4.2 Earthquake induced forces and analysis

The Aspendos Theatre is located on a zone 3 seismic area based on "Specification for Structures to be Built in Disaster Areas, part III - Earthquake Disaster Prevention", zone 1 being the worst of 5 level scale (Turkish Seismic Code). The spectral acceleration coefficient is taken as 0.2 (relating to 20% of gravitational acceleration). The soil conditions are accepted to be rock or stiff soil (Z2) with spectrum characteristic periods, T_A and T_B as 0.15 sec and 0.40 sec.

The FE analysis results for the dead load plus earthquake response spectrum loading indicate that 475 year earthquake with amplified damping ratio (in the range of 1%) creates about 3 MPa stresses localized at the base of the walls (Fig. 6). The stress concentrations at the corners and middle of the wall in horizontal direction are in the range of 1.5 MPa. The earthquake analysis creates larger tensile stresses compared to the sound induced stresses as explained in Section 4.1.

5 CONCLUSIONS

The Aspendos Theatre being one of the most valuable ancient theatres that survived over 2200 years and still being fully functional today has been dynamic tested and analytically modelled. The first natural vibration frequencies of the exterior wall are obtained as about 1.5 Hz., 2.2 Hz., and 3.5 Hz. The FE model, modal frequencies are compared against the measured values and found to be in close agreement with the measurements. Using the analytical model of the theatre main building, effects of sound induced dynamic forces and earthquake forces are studies. Analyses results indicated that tensile stress concentrations exceeding the assumed 1.2 MPa tensile stress capacity develops at the bottom, upper corners, and upper middle section of the inner (stage) and exterior walls. Stresses generated during a 2000 year return period earthquake is expected to be 3 to 4 times larger than the material tensile capacity, causing cracks and possible local damage to the structure. The theatre building must have gone through repair work in its history and well maintained to be in such a good shape today.

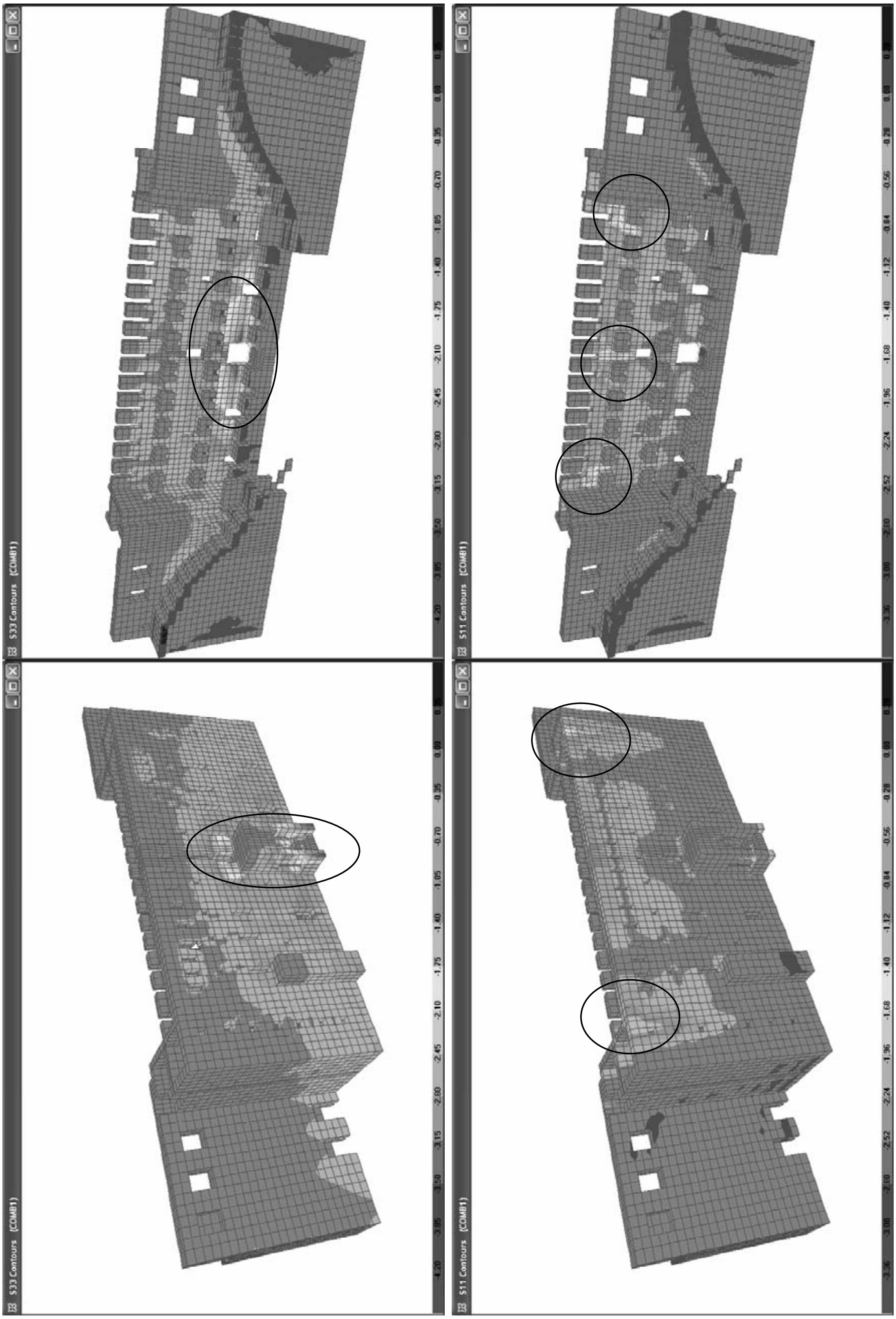

Figure 6 : Maximum (tensile) stresses generating at walls due to DL+EQ induced forces

Sound induced stresses found to be larger than expected especially since the theatre walls are unsupported for 40 m width and 25 m height with very low damping. 1.2 m and 1.8m thick walls might be vulnerable to electronically amplified, high volume sounds that would have beat frequencies that exactly match the natural frequencies of the walls; especially the interior (stage) wall of 0.87 Hz. When integer multiples of excitation frequencies (song beat frequencies) match with integer divisions of structural modal frequencies, the structure might also go into resonance state. For instance, a song with 1.4 Hz beat frequency might excite the third bending mode of the stage wall, which is at about 2.8 Hz. Second bending mode of the stage wall can be best excited when stereo speakers play drums at 1.7 Hz beat frequency with 180 degrees phase difference between left and right speakers or when half of the speakers located on left or right sides of the stage do not work.

The FE analysis results for the dead load plus earthquake response spectrum loading indicate that 475 year amplified earthquake (since damping ratio is about 1%) creates about 3 MPa stress concentrations localized at the base of the walls and middle entrance door columns (Fig. 6). The stress concentrations at the corners and midsection of the walls in horizontal direction are in the range of 1.5 MPa. The earthquake analysis creates larger tensile stresses compared to the sound induced stresses; however, both stresses are in the order of maximum assumed tensile stress of the material (1.2 MPa).

The study concludes that The Aspendos Theatre is not invincible and may experience medium damage during a possible earthquake. The reduction coefficient (R) was taken as 1.0 for the evaluation study, which might be about 3 or more as the structure starts to experience inelastic deformations and crack formations. The first natural periods of the inner and exterior walls are about 1.15 sec and 0.68 sec., respectively, both being larger than T_b=0.40 sec.; therefore, any damage would cause them shift further in the period axis reducing earthquake spectral accelerations. Lower period modes usually has smaller amount of mass participation and have smaller contribution in EQ response. The study also highlighted that sound induced vibrations may be critical provided that certain conditions are met. Authorities should be careful in defining rules for the theatre usage based on this study (i.e., keeping SPL at stage wall level smaller than 115 dB including safety margin); moreover, controlling and enforcing those rules. Vibration monitoring of stage wall may also be feasible to continuously monitor vibrations, then automatically detect and give warning signals if resonance conditions occur.

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