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Structural Analysis of Historic Temple of Augustus in Ankara, Turkey

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ABSTRACT: The Temple of Augustus, one of the invaluable monuments survived from the Roman age, is located in Central Anatolia in the capital city of Turkey, Ankara. Ruins of the approximately 20 centuries old temple has reached to recent times with structural instability and expedited stone deterioration due to environmental conditions. Some of the inscriptions have been disappeared and the remaining ones are in danger of disappearing. Stability of the North wall of the temple is another major concern. Studies on temporary roof protection, stone conservation, site restoration, and structural monitoring are being studied by a multi-national and interdisciplinary team. This paper discusses structural concerns, nondestructive (ambient monitoring) testing results, and 3-D Finite Element Model (FEM) based analysis aspects of the project. Some retrofitting schemes are also suggested based on the structural problems.

1 INTRODUCTION

1.1 History of Augustus Temple

The Temple of Augustus, being one of the most important monuments of Roman age, is located in Ankara, Central Anatolia, Turkey. The temple is also known as Monumentum Ancyranum. Available information about the construction date of the temple goes back to years 30-25 B.C. After the conquest of Galatia (Asia Minor) by the first Roman Emperor Caesar Octavian Augustus, Ancyra (ancient name of Ankara) became the ruling center of Roman province. Referring to the glory of Caesar Octavian Augustus, a magnificent marble temple was built. Among the other Roman monuments, the Temple of Augustus has a special place. The temple owes its great fame to the inscriptions on its walls which were copied from the original inscriptions engraved on bronze pillars used to exist at the entrance of the mausoleum of Augustus in Rome. This inscription is called as Res Gestae Divi Augustus and it was engraved on the walls after the death of Octavian Augustus according to his will. The inscription is about the deeds and testaments of the emperor. Since the original inscription does not exist any more, the importance of the temple has significantly increased (Akurgal 1993).

1.2 The changes with time and current state of the monument

The monument has an H shaped plan and rests on a podium which is about 36m×55m. It used to have encircled by eight columns on the short side and fifteen columns on the long side. Additionally, four columns in front of the pronaos (entrance) and two columns on the backside just in the same axis where the walls of opisthodomos (backside) end used to exist. However, these columns are not present today. A reconstruction drawing according to excavation results carried out by Schede and Krencker (1936) is given in Figure 1.

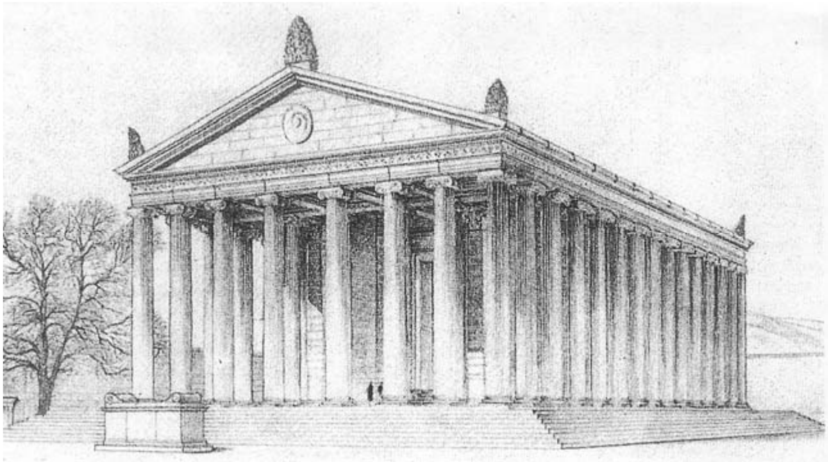

Figure 1 : Reconstruction drawing of the temple (Schede and Krenken 1936)

The temple exhibits classical roman architecture sign. It consists of a pronaos, a cella (room at the center) and an opisthodomos. The invaluable inscription was written on both of the pronaos walls. The corner of pronaos wall used to join northwest cella and almost half of the northwest cella wall was destroyed in 1834. The remaining part of the cella wall has been remarkably inclined towards the south-east direction. The wall dividing pronaos and cella still remains containing relatively less damaged gate through the temple. Additionally, the roof of the temple also does not exist anymore. The general view of the temple is shown in Figure 2 .

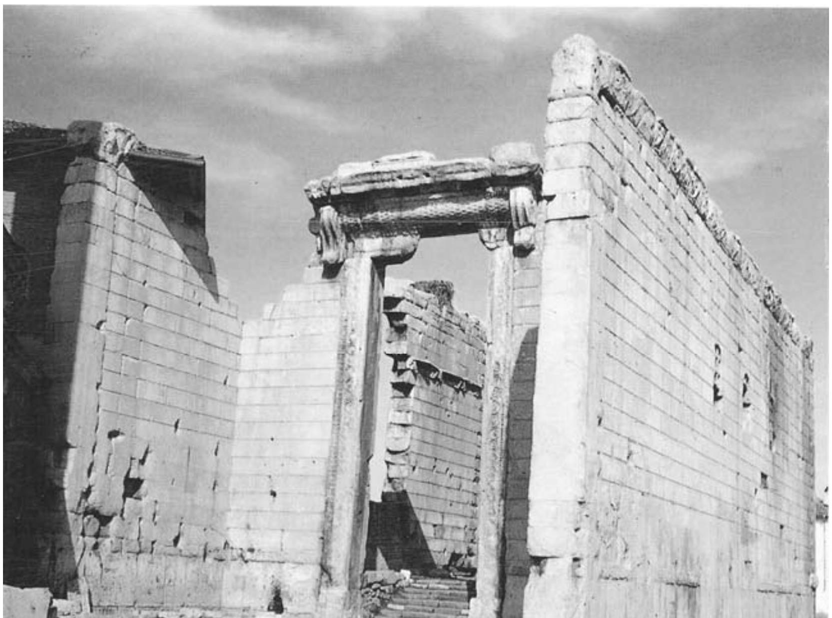

Figure 2 : General front view of the Temple of Augustus (Turkish Ministry of Culture Brochure)

In the 5^{th} century A.C., an apse had been added to the backside of the temple, the wall between cella and opisthodomos was destroyed and the temple was converted to a church. Later in the 15^{th} century A.C., Haci Bayram Mosque was built adjacent to the temple's North-West corner. Today, the region is very crowded with people who want to worship in the mosque. The Augustus Temple is also special since it coexists with a church and a mosque.

The current status of the temple poses several serious problems from structural and stone conservation points of view. The partially damaged North cella wall and entry gate lintel is in danger of collapsing. Some stone blocks located at the upper part of the wall of cella looks unstable and may fall down with strong wind or minor ground shakings. Furthermore, some parts of the inscriptions on the walls deteriorated due to harsh atmospheric conditions and presumably acid rains. Under heavy air pollution, the marble blocks degenerated to gypsum which can easily dissolve with rain. The temple was declared as a monument to be preserved by World Monument Found in 2000.

Turkish and Italian teams are working on a multi-disciplinary and multi-national basis for the conservation and protection of the inscriptions and structural retrofitting. Temporary roof to protect and preserve current condition is underway. Non-destructive testing, finite element analysis, and structural safety measures are also being conducted. The Turkish team consists of researchers from the Turkish Ministry of Culture and Tourism, Directorate General for Cultural Heritage and Museums, Museums of Anatolian Civilizations, and Middle East Technical University.

2 STRUCTURAL STUDIES ON AUGUSTUS TEMPLE

Structural studies concerning the Augustus Temple are mainly grouped under monitoring, modelling and analysis, and suggestions for preventive measures. Each one of the groups are further described under subheadings below.

2.1 Monitoring studies

The monitoring studies of the Augustus Temple consist of short term dynamic tests using ambient excitation and long term static measurements. The ambient vibration monitoring test was conducted to obtain the first fundamental vibration frequencies which will be used for Finite Element Model (FEM) calibration. The dynamic test was conducted on the North and South cella walls which are the two important and vulnerable walls of the structure. Partial collapse of the North wall imposes serious stability threat especially since the middle wall perpendicular to the North wall does not exist anymore (Fig 3). Although the South wall preserves its integrity, the 11m tall wall is laterally unsupported for about 22 m length. Dynamic ambient vibration tests were conducted on both walls in perpendicular direction to their planes.

Figure 3 : General front view of the North cella wall.

The first two natural vibration periods of the North and South walls were obtained by taking Fast Fourier Transform (FFT) of the measured time domain data and listed in Table 1. The modal vibration periods listed in Table 1 were used for analytical model calibration and structural identification (St-Id) studies.

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

	North wall seconds	South Wall seconds
First Mode	0.758	0.455
Second Mode	0.290	0.245

The long-term monitoring studies will initially concentrate on the tilt, temperature, and humidity measurements. Two tiltmeters will be placed at the North wall, which is found to be the most critical structural section of the temple. Measurements will be taken at every 60 minutes to measure daily and seasonal tilt changes. Measurements will reveal if the wall inclination is increasing over time and whether temperature has any effects on the tilt.

2.2 FE Modelling and structural analysis

The analytical model of the Temple of Augustus was constructed using shell elements and available SAP2000 analysis software of CSI (1995). The generated model successfully represents the simple geometry of the structure and distinguishes the thickness differences between the major parts of the monument. As seen in Fig 3, the North wall is composed of two parts, the lower part having smaller thickness than the upper part.

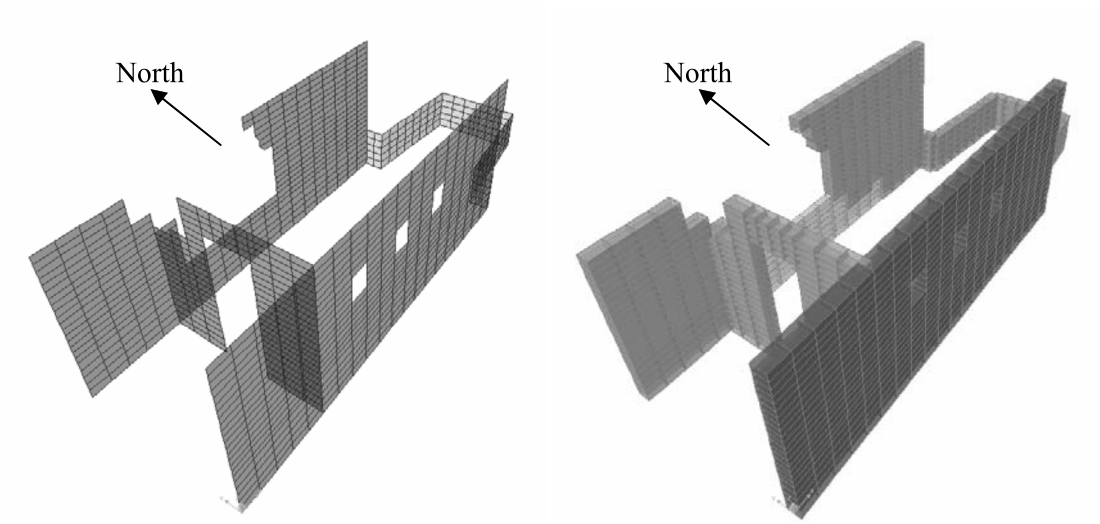

Figure 4 : General view of the FE model of Augustus Temple

The structural analysis of the Augustus Temple showed that the main modes of the two walls can be successfully obtained and calibrated against the experimentally obtained periods. Table 2 shows the analytically obtained periods which compare nicely with the experimental periods listed in Table 1. The analytically obtained mode shapes that correspond to the generated vibration periods in Table 2 are shown in Fig. 5. The first four modes of the calibrated analytical model indicate torsional, first bending, and second bending modes of the walls. Two additional bending modes found from the analytical model are also listed in Fig. 5.

Table 2 : The first two analytical natural vibration periods of the North and South walls.

	North wall seconds	South Wall seconds
First Mode	0.7578	0.4549
Second Mode	0.2896	0.2452

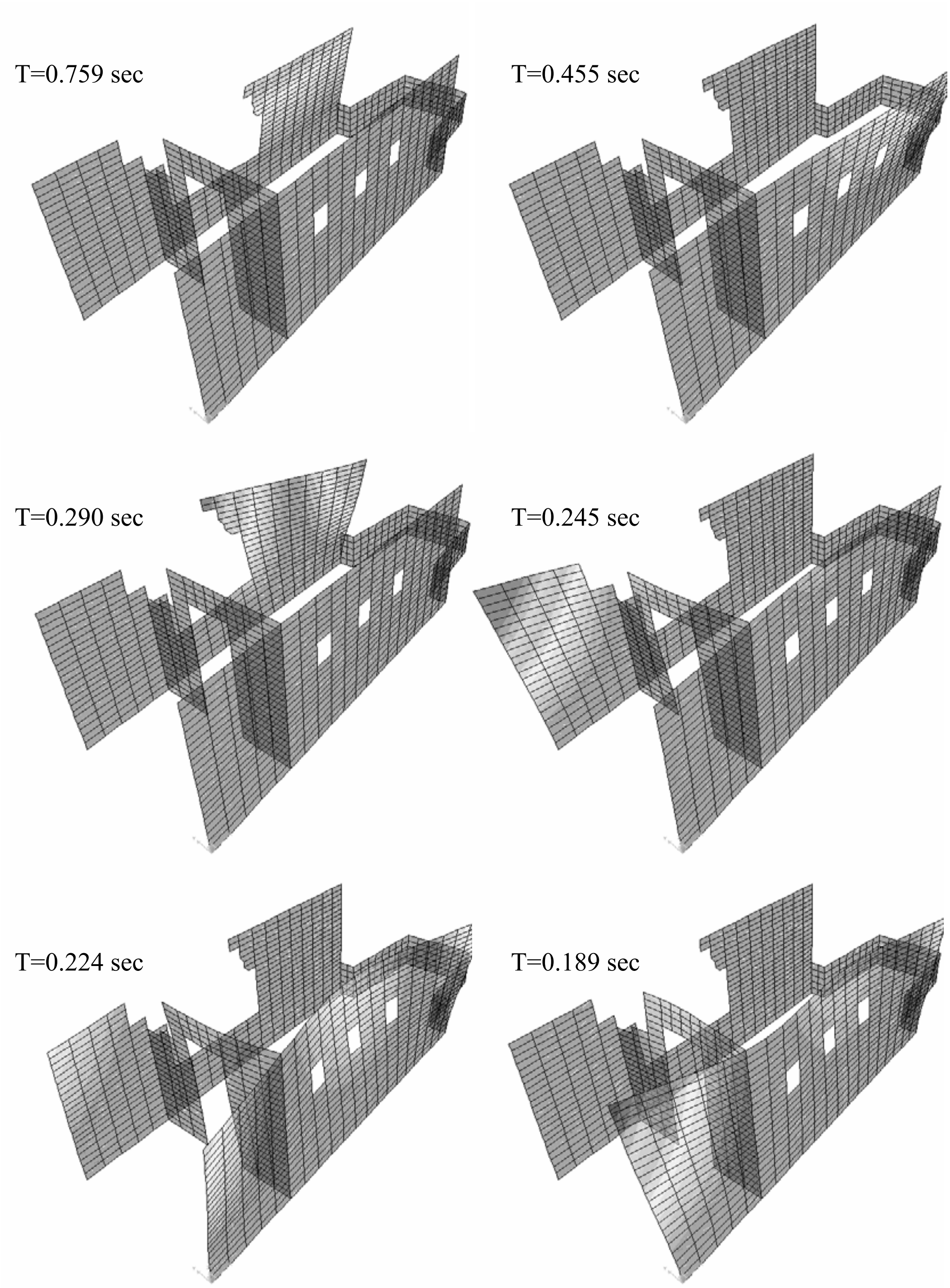

Figure 5 : Calibrated FE model simulated mode shapes

The parameters during the calibration were selected to be a) thickness, b) unit mass, and c) modulus of elasticity of the walls. Since the analytical model calibration was only based on the ambient dynamic measurements of the Augustus Temple, a number of different analytical models were obtained that lead to similar results. The common property of all calibrated models was found to be a constant that would relate stiffness and mass as a ratio. The stiffness of the temple walls can be simplified as the bending stiffness which is a function of modulus of elasticity (E) × moment of inertia (I). Variable 'I' is related to width (ω) × thickness cube (t^3). The mass is a function of unit mass (ρ) × area (A= ω × t). The length and height of the walls are considered to be constant for both variables. The ratio between the stiffness and mass of structural systems leads to the general period definition as shown in Equation 1. Simplification of the fore mentioned equations lead to a constant (C) for the Temple of Augustus walls as shown in Equation 2. The C constants for the North wall upper part, lower part, and South wall were obtained as 6.076E-07 s^2/m^4, 1.861E-06 s^2/m^4, and 5.155E-07 s^2/m^4, respectively. Considering the unit mass (ρ) as 2700 kg/m^3 for marble, wall thickness (t) as 0.85 m for the North wall, and modulus of elasticity (E) as 6.15 GPa, periods shown in Fig. 4 are obtained. The lower part of the North wall were calibrated to have an average thickness of 0.485 m, and South wall average thickness as 0.923m. Relatively low E value obtained for the walls is purely analytical and should be supported by material tests conducted on the samples. Nevertheless, low E value of the wall may be an indication of material deterioration and or additional flexibility generated by stone connections.

$$T = \frac{1}{2\pi}\sqrt{\frac{m}{k}} \text{ (sec)} \tag{1}$$

$$C = \frac{\rho}{E \times t^2} \text{ } (s^2/m^4) \tag{2}$$

Unfortunately, analytically and experimentally obtained vibration periods of 0.76 sec, 0.46 sec, 0.29 sec, and 0.24 sec mostly coincide with the response spectrum generated for the site conditions. Considering a dense sand, gravel, or silty clay soil conditions (Type B or C soil, Turkish seismic code, Specifications for Structures to be Built in Disaster Areas, 1997) and Z2 or Z3 site class, T_A and T_B are found to be equal to 0.15 sec and around 0.4-0.6 sec, respectively. The spectrum coefficient S(T) comes close to 2.5 which is the highest amplification factor in the spectrum for the measured structural periods. The earthquake analysis using the relevant response spectrum and 0.3g ground acceleration (reduction factor R was taken as 1.0), maximum of about 12 MPa tensile stress is calculated at the base of the North wall. Maximum dead load stress on the same wall is only about 0.4 MPa indicating that the stone and its joints will experience excessive tensile stresses, far beyond limits, in the order of 8 to 11 MPa. About 2000 year old masonry construction with missing tension connectors between blocks has no chance but collapse during a possible earthquake. Preventive measures against earthquakes are strongly recommended for collapse prevention. Future monitoring results will reveal wall inclination changes over time which might be affected by busy street traffic vibrations, differential settlement, wind, eccentric support conditions, and/or small earthquakes.

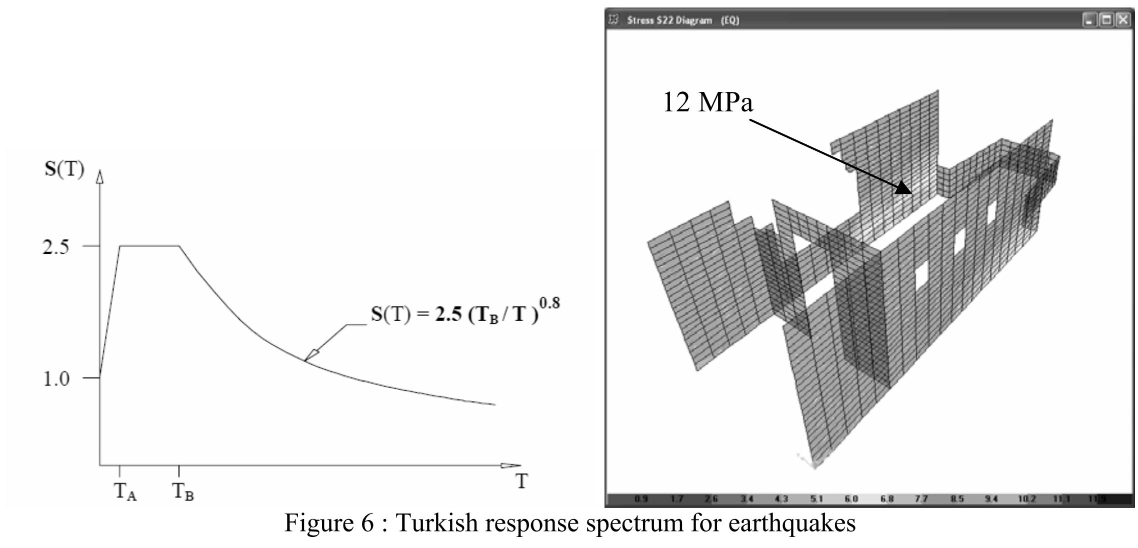

Figure 6 : Turkish response spectrum for earthquakes

2.3 Structural stability issues and suggestions for preventive measures

The damaged section of the North wall exhibits structural instability and poses vulnerability against lateral forces. The 11 meter high wall is only supported from the base and slightly inclined towards South (Fig. 3). The stability of the rocks at the top of the wall is another threat for pending damage (Fig. 3). It is recommended that the stones that are not stable at the top of the North wall and at the entrance gate should be carefully removed and placed on ground against falling off on their own. The North wall should also be laterally supported with strong A-frames (Fig. 7); however, the supports may be placed a few centimetres away from the wall without touching it. The frame support would be ready to support the wall if the stability is lost due to wind, earthquake, or other unforeseen effects.

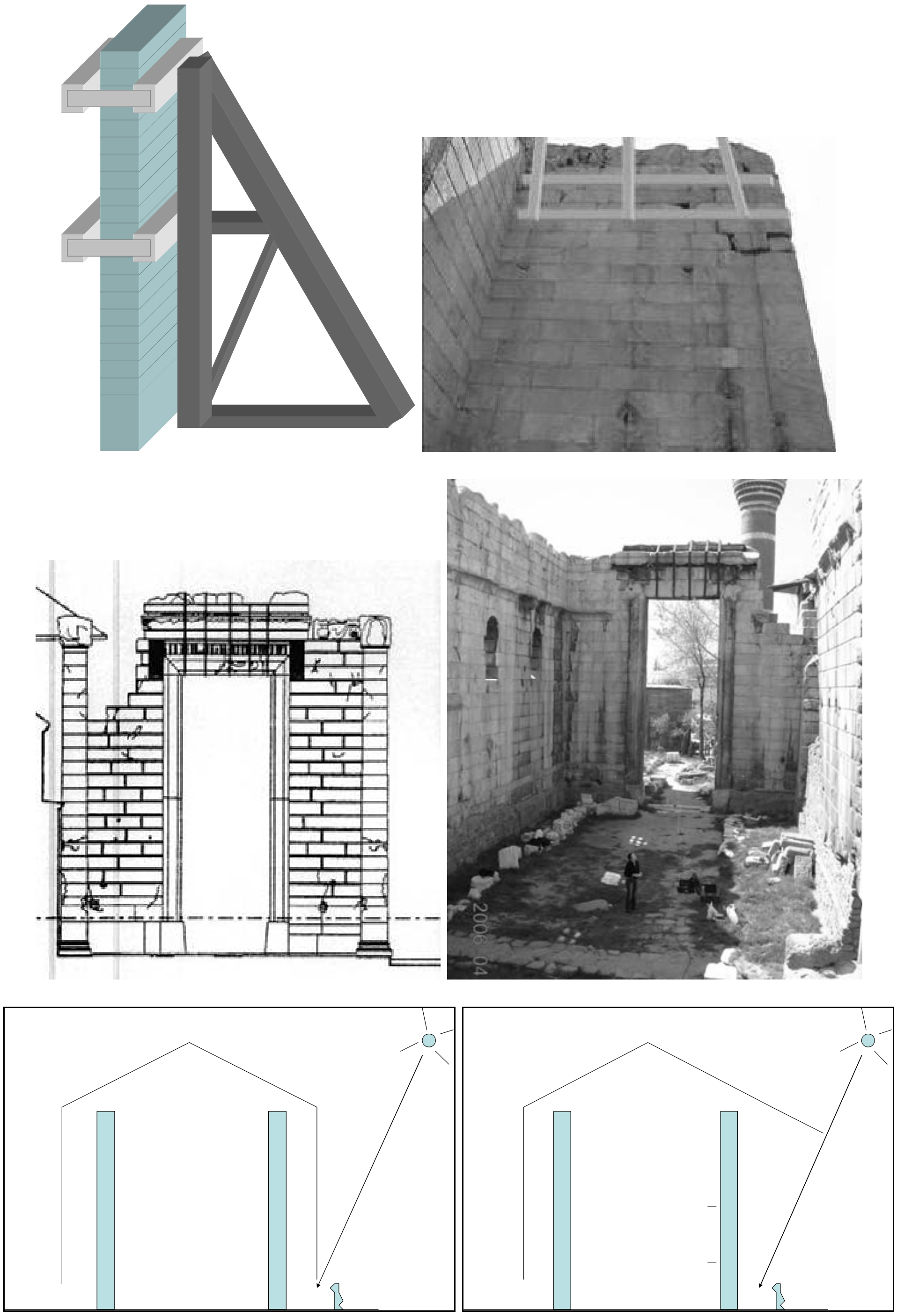

Figure 7 : Possible preventive measures for the Temple of Augustus.

South-West wall, which is located outside the temple gate, has visible cracks which are dominantly excited by the T=0.189 sec (5.3 Hz) mode (Fig. 5) which is also located at the highest range of the response spectrum. A steel mesh-frame might be placed on the South-West wall upper corner to prevent out-of-plane failure and slow down any possible shear failure (Fig. 7). Although the entrance gate lintel was strengthened in the past using steel belts, it presents a dangerous condition (Fig. 7) since the beam is heavy, damaged, poorly supported, and supporting belts are heavily rusted in their current state. For preservation of temple's current state and prevent any further damage to the stone blocks and inscriptions, the temple may be covered using a temporary roof which would prevent rain and direct sunlight exposure while permitting proper ventilation. Two possible roof cover options are shown in Fig. 7.

3 CONCLUSIONS

Structural analysis and preliminary dynamic tests of the Temple of Augustus showed that the first vibration periods of 0.76 sec, 0.46 sec, 0.29 sec, 0.24 sec, 0.224 sec, and 0.189 sec mostly coincide with the response spectrum generated for the site conditions which has T_A and T_B values 0.15 sec and 0.4-0.6 sec, respectively. The earthquake analysis results indicated that tensile stresses are in the range of 6 MPa to 11 MPa and generated at the bottom of the walls; North wall being the most critical structural section of the temple. Such large tensile stresses cannot be tolerated by masonry walls and collapse is expected during an earthquake defined by the Turkish seismic code, Specifications for Structures to be built in Disaster Areas (1997). Other structural problems associated with the entrance gate lintel and South West wall corner needs immediate attention. The North wall should be laterally supported as a safety measure. Structural health monitoring related studies will start in 2006 summer and continue to measure any possible long-term changes in the wall inclination.

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