Comparative Study of Large and Medium Scale Mosque Models Tested on Seismic Shaking Table

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LISBOA 2012

SUMMARY:
Within the frame of the scientific cooperation between the Institute of Earthquake Engineering and Engineering Seismology (IZIIS), Skopje, Macedonia and the Kandili Observatory and Earthquake Research institute (KOERI), Istanbul, Turkey, a three year project entitled: "Harmonisation of the testing procedure of large scale and medium scale models on seismic shake table" is under realisation. In this paper the comparison between experimental results obtained for two models of a historical monument – a mosque constructed in different scales is presented. The models were made of same materials and same geometry. The scale factor of the model tested at IZIIS was 1/6, while that of the model tested at Kandilli was 1/10. Dynamic modeling theory for similarity was applied to both models neglecting the gravity forces. Based on the results obtained, a methodology for design and testing of medium and large scale models on shake tables has been proposed.

Keywords: harmonization, physical modelling, scaling factor, shake-table, damage pattern

1. DESCRIPTION OF THE ORIGINAL STRUCTURE

The Mustafa Pasha Mosque is located in the central area of Skopje. It is built in 1492. The planar dimensions are 20 x 20 m, and the dome's diameter is about 16 m. The massive walls and the drum of the dome are constructed of natural stones and bricks. The height of the main structure is about 22 m. The minaret is about 47 m high. The picture, plan and the cross sections of the mosque are shown in Figures 1.1 and 1.2.

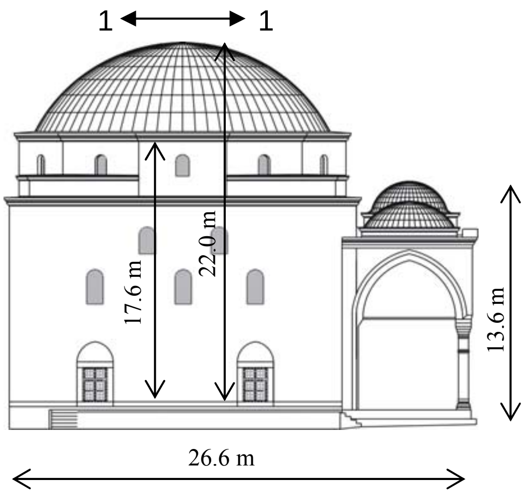

Figure 1.1 View of the Mustafa Pasha Mosque

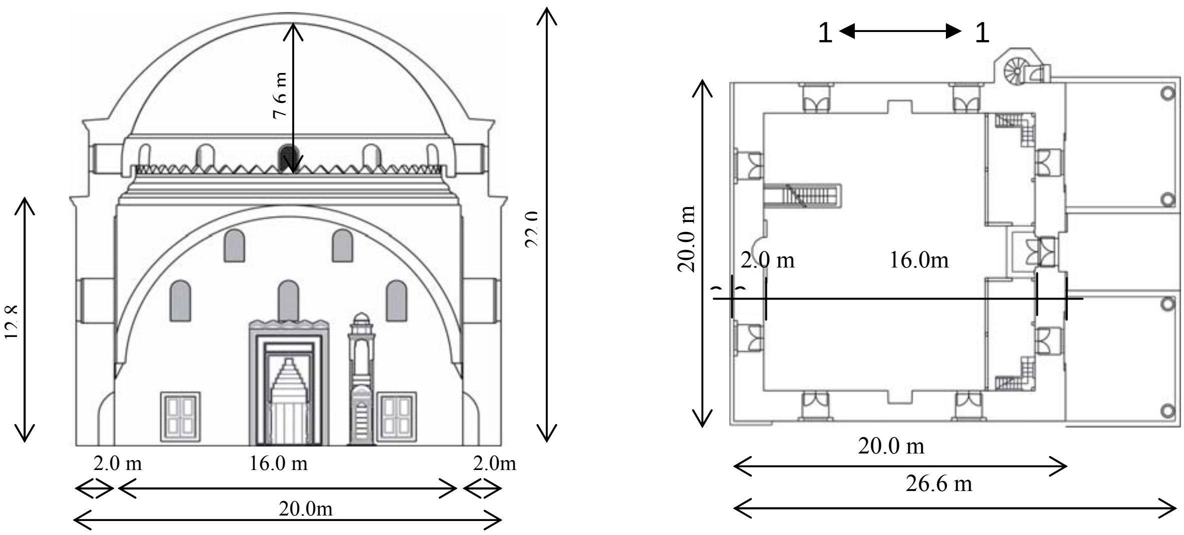

Figure 1.2 Vertical and horizontal cross-sections of the Mustafa Pasha Mosque

2. DESIGN OF THE MODELS FOR SHAKE TABLE TESTS

Considering the dimensions of the monument, as well as shake table characteristics, the geometric scaling factor for model dimensions is investigated.

2.1. Scaling factors of the large-scale model for testing on IZIIS shake table

The scaling factor of the model of the Mustafa Pasha Mosque is 1/6. The dimensions at the base of the Mustafa Pasha Mosque are 20.0 x 20.0 m. Its height is 22.0 m. The total mass of the mosque is about 5200 tons. Thus, in 1/6th scale, the model should be about 24.0 tons with additional 5.0 tons for the foundation mass. This is within the range of shake table's payload capacity of 40 tons. Considering the height of the mosque, in 1/6th scale, the height of the model should be about 3.7 m, which is below the 10m-height limit of the laboratory. Considering the mosque's base dimensions, in 1/6th scale, the model base will be 3.3 x 3.3 m, which is also within the 5.0 x 5.0 m dimensions of the shake table.

Although the gravity forces neglected, the physical model considered for the test is adequate, because the stresses induced by gravity loads are small and negligible when compared to stresses induced by seismic forces. This is typically the case when the lateral load resisting system consists primarily of shear walls, which carry little vertical load except through boundary elements. The input accelerations will be within 0.6-1.2 g, which is within the range of table capacity (max 1.5 g).

2.2. Scaling factors of medium scale model for testing at KOERI shake table

Considering the geometry and the payload capacity of the KOERI shake table, the scaling factor of the model was reduced to $1/10^{th}$. The mass of the model is about 5.0 tons with an additional mass of 2.0 tons for the foundation, which is within the range of the payload capacity of 10.0 tons. The dimensions of the base of the model are 2.0 x 2.0 m. The height of the model is 2.2 m, which is within the dimensions of the table (3.0 x 3.0 m). The input accelerations used are within 1.0 g, which is in the range of the table capacity (max 2.0 g).

The model parameters and scaling factors for the $1/6^{th}$ and $1/10^{th}$ scale models are shown in Table 2.1.

Table 2.1." Gravity forces neglected" similitude laws for the model of the Mustafa Pasha Mosque in Skopje

Scaling parameter	Scaling Factor	Units	Prototype Values	Adopted values	
				Model 1/6	Model 1/10
Length	l_r	m	20/20	3.3/3.3	2.0/2.0
Time history	l_r	sec	60	10	6
Natural frequency	l_r^{-1}	Hz	3.0	18	30
Gravity acceleration	neglected				
Input acceleration	l_r^{-1}	g	0.1-0.2g	0.6-1.2g	1.0-2.0 g
Mass density	1	kN/m^3	19.0	19.0	19.0
Strain	1	μstr	1	1	1
Modulus of elasticity	1	MPa	6800	6800	6800
Compressive strength	1	MPa	27	27	27
Shear strength	1	MPa			
• Stone	1	MPa	0.15	0.15	0.15
• Brick	1	MPa	4.7	4.7	4.7
• Mortar	1	MPa	0.1	0.1	0.1
Displacement	l_r	mm	1	1/6	1/10
Force	l_r^2	kN	1	1/36	1/100

3. TESTING OF THE 1/6TH SCALE MODEL AT IZIIS SHAKE TABLE

3.1. Objectives of the testing

The testing was performed within the PROHITECH FP-6 project, realised in the period of 2004-2008. The main objective of the project was to investigate experimentally the effectiveness of the proposed reversible technology for strengthening and increasing the seismic resistance of these types of historical monuments. According to that, the seismic shaking table testing was performed in three main phases:

Phase 1 - Testing of the original model under low intensity level with the objective of provoking damage to the minaret only.

Phase 2 - Testing of the model with strengthened minaret under intensive earthquakes, with the objective of provoking collapse of the minaret and damage to the mosque.

Phase 3 - Testing of the strengthened mosque model until creating heavy damage.

3.2. Initial dynamic characteristics of the model

First, the dynamic characteristics of the model are identified by means of ambient vibration method, measuring the low-amplitude vibrations at 14 points by Ranger seismometers, as shown in Figure 3.1. The Fourier amplitude spectra for the minaret and for the mosque are given in Figure 3.2. The natural frequency of the minaret was 6.6 Hz, while that of the mosque was 12.8 Hz.

3.3. Shake table test results

Testing in this phase was performed under low shaking intensities in order to provoke damage only in the minaret. Under the scaled Montenegro Earthquake with peak acceleration of 2%g, the first horizontal crack appeared at the base of the minaret, as shown in Figure 3.3. In the following tests with intensities up to 10% g, damage on the main structure was observed. The reason for the damage was because the dominant frequency of the applied excitation was close to the natural frequencies of the minaret and the mosque.

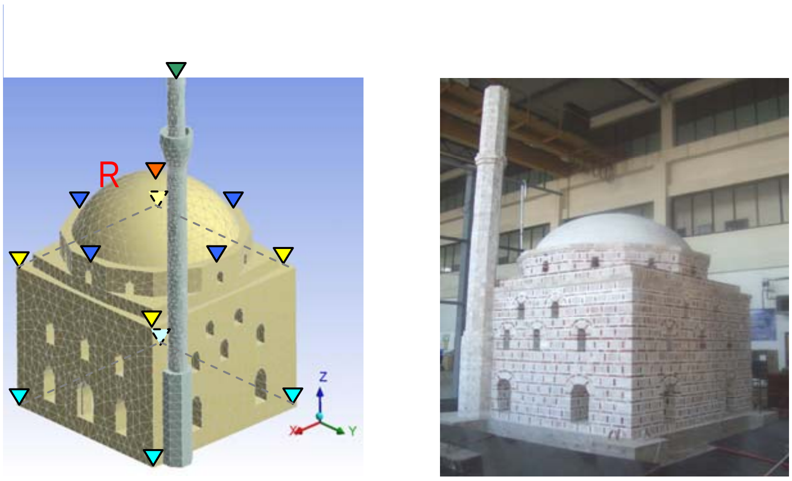

Figure 3.1 Measuring points for ambient vibration test at IZIIS

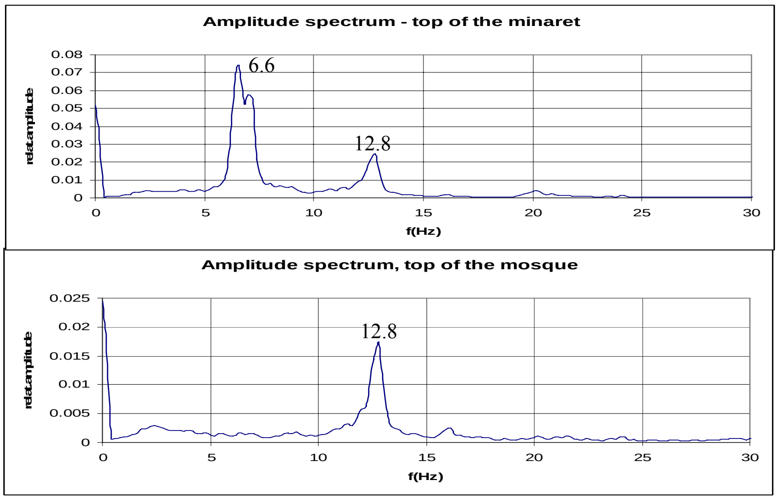

Figure 3.2 Fourier amplitude spectra from the ambient vibration tests of the model

Figure 3.3 Horizontal crack at the base of the minaret

Pictures of the damaged model are presented in Figure 3.4, while measured response characteristics for input intensities of 2%g and 10%g are given in Figures 3.5-3.8.

The time that the horizontal crack on the minaret appeared can be seen in the acceleration and displacement time histories recorded at the top of the minaret (Figure 3.7). During the last test with input intensity of 10% g, this crack developed into a complete hinge, as seen in the top displacement time history, such that the minaret was vibrating freely, reaching the maximum absolute displacement of 9mm. The maximum displacement at the top of the mosque was 2.6mm.

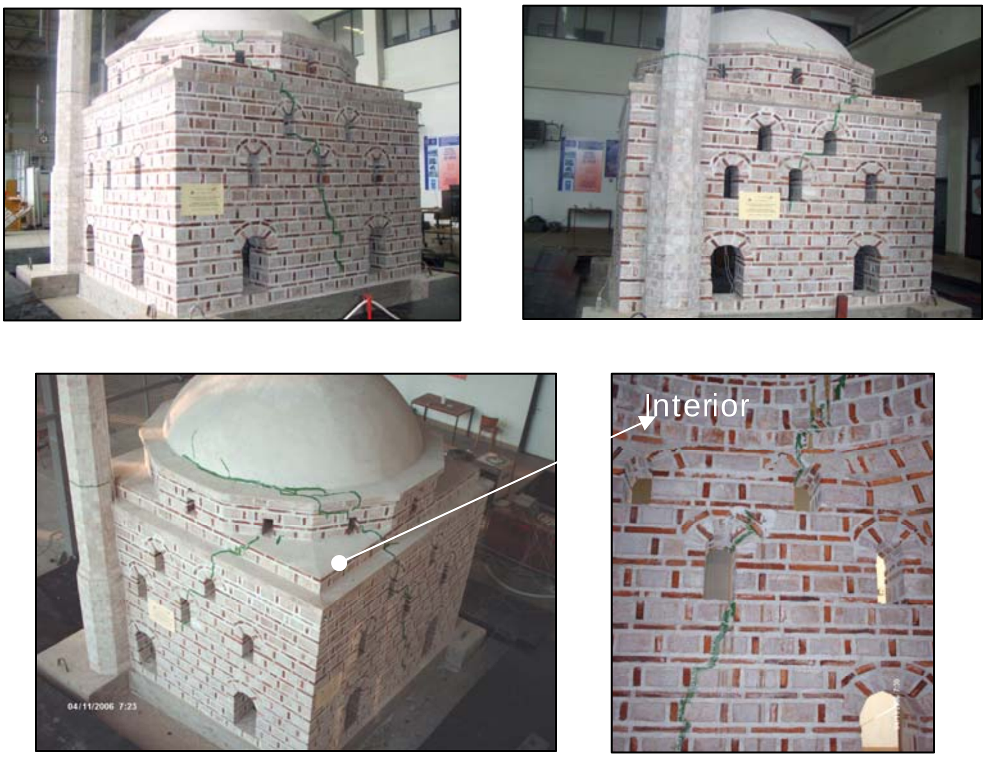

Figure 3.4 Damage to the model after phase 1 testing

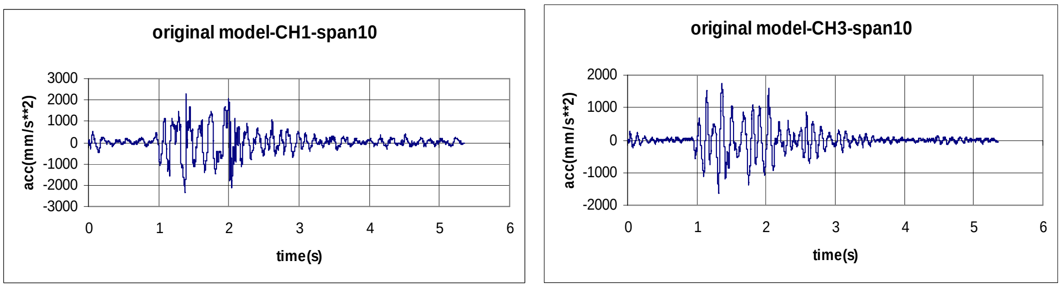

Figure 3.5. Acceleration response at the top of the minaret (left) and at the top of the dome (right) for 2%g input

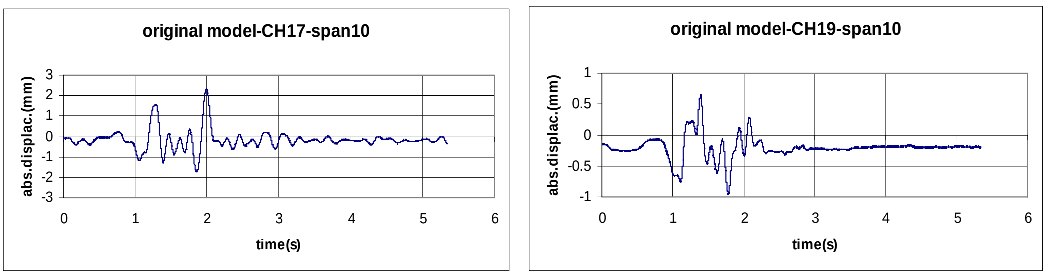

Figure 3.6. Displacement response at the top of the minaret (left) and at the top of the dome (right) for 2%g input

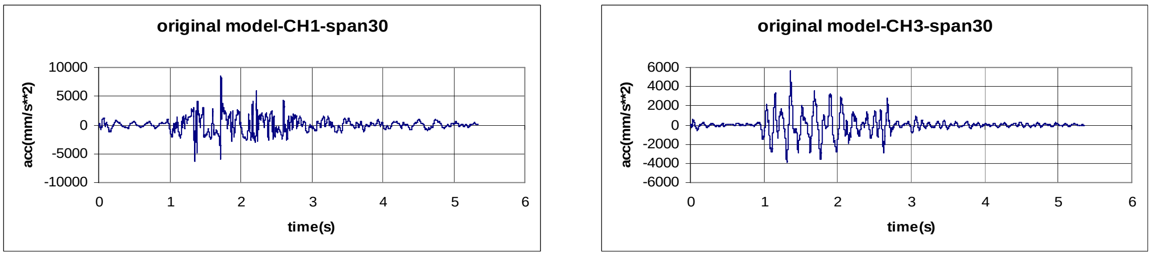

Figure 3.7 Acceleration response at the top of the minaret (left) and at the top of the dome (right) for 10%g input

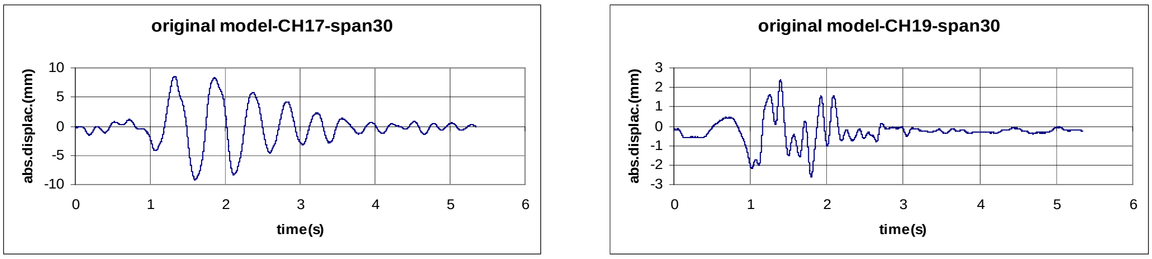

Figure 3.8 Displacement response at the top of the minaret (left) and at the top of the dome (right) for 10%g input

4. TESTING OF THE 1/10TH SCALE MODEL AT KOERI SHAKE TABLE

4.1. Objectives of the testing

The testing was performed within the scope of the on going bilateral project between Macedonia (IZIIS) and Turkey (KOERI). The main objective of the project was to investigate experimentally the influence of scaling factors of model geometry on test results. The shake table testing of the 1/10th scale model was planned to be performed in two main phases:

Phase 1 - Testing of the mosque model with the objective of provoking damage to the minaret and mosque.

Phase 2 - Testing of strengthened mosque model to verify the effectiveness of the applied strengthening method.

The first phase was completed in November 2011. The second phase is currently underway, which will be completed by the end of 2012.

In this paper, the Phase 1 results are outlined.

4.2. Initial dynamic characteristics of the model

After placing the model on the shaking table, dynamic characteristics of the model are determined by means of ambient vibration tests, measuring the vibrations at several locations of the model by Guralp accelerometers. The instrument layout is shown in Figure 4.1. The Fourier amplitude spectra of the minaret are presented in Figure 4.2. The natural frequency of the minaret was 12.0 Hz, while that of the mosque was 22.0 Hz.

4.3. Shake table test results

Testing in this phase was performed with low intensities in order to provoke damage to the model. The input intensity of the Montenegro Earthquake was scaled to 0.02-1.0g and applied to the model in several steps. The first horizontal crack appeared at the base of the minaret at 0.08g, as shown in

Figure 4.3. In the following tests with intensities up to 1.0 g, damage on the main structure became also visible.

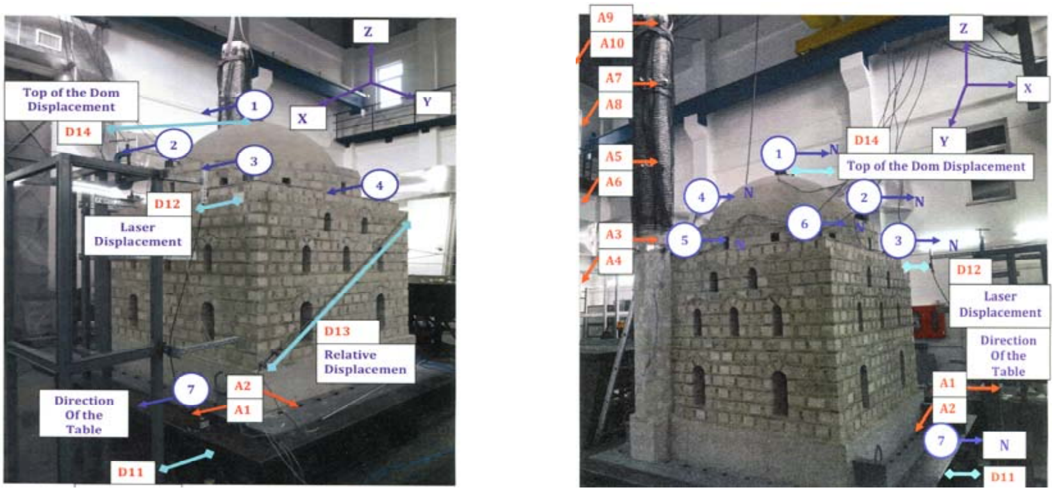

Figure 4.1 Measuring points for ambient vibration test of the 1/10th scale model at the KOERI shake table laboratory

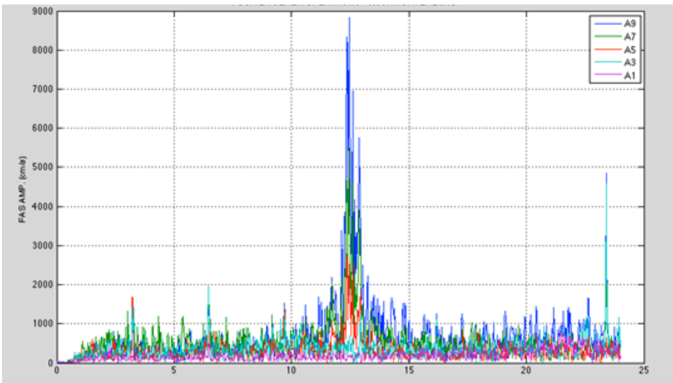

Figure 4.2. Fourier amplitude spectra from ambient vibration tests of the 1/10th scale model at the KOERI shake table laboratory along the minaret, f=12.0 Hz.

Figure 4.3. Horizontal crack (marked with red) at the base of the minaret (left). Further damage can be seen on the upper part of the minaret and also on the drum at the base of the dome (left). Damage to the dome and to the walls as seen from the interior of the model is shown on the right.

Selected response time histories for peak input intensities of 0.08g and 1.0g are given in Figures 4.4 and 4.5. The exact time that the horizontal crack appears in the minaret base can be identified from the acceleration, velocity and displacement time histories recorded on the upper part of the minaret. During the final test with input intensity of 1.0g, this crack completely developed into a full hinge causing the minaret vibrate freely and independently from the mosque. This can be seen in Figure 4.5. The maximum absolute displacement at the top of minaret was 1.2cm.

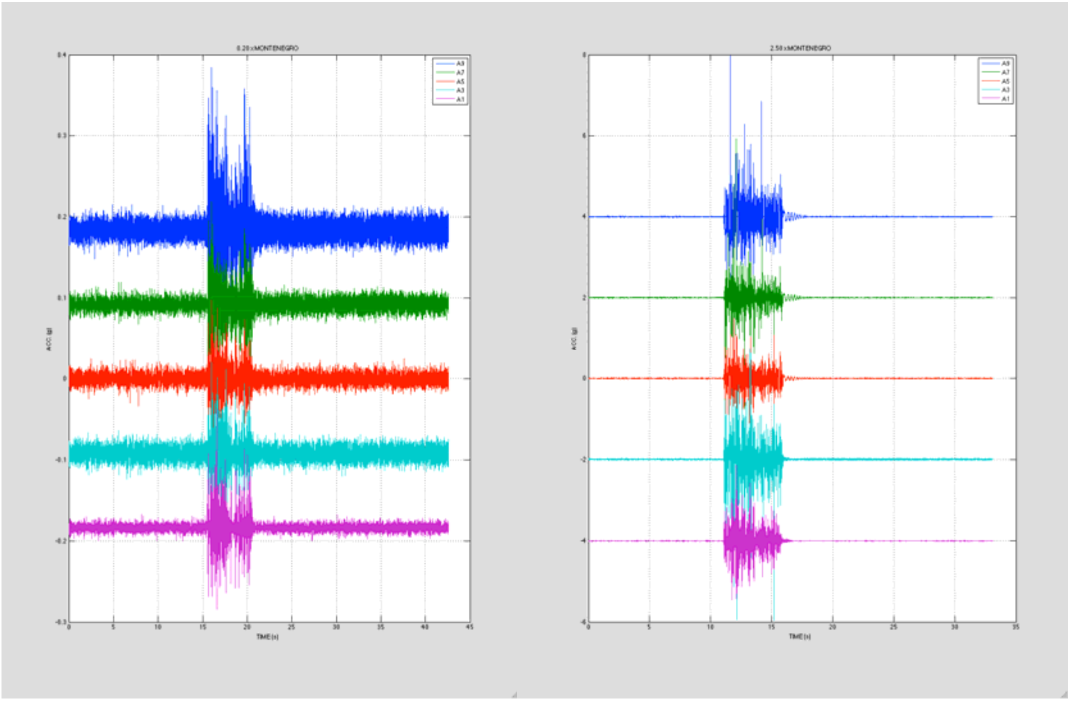

Figure 4.4. Acceleration response along the minaret for 0.08g (right) and 1.0g (left) input

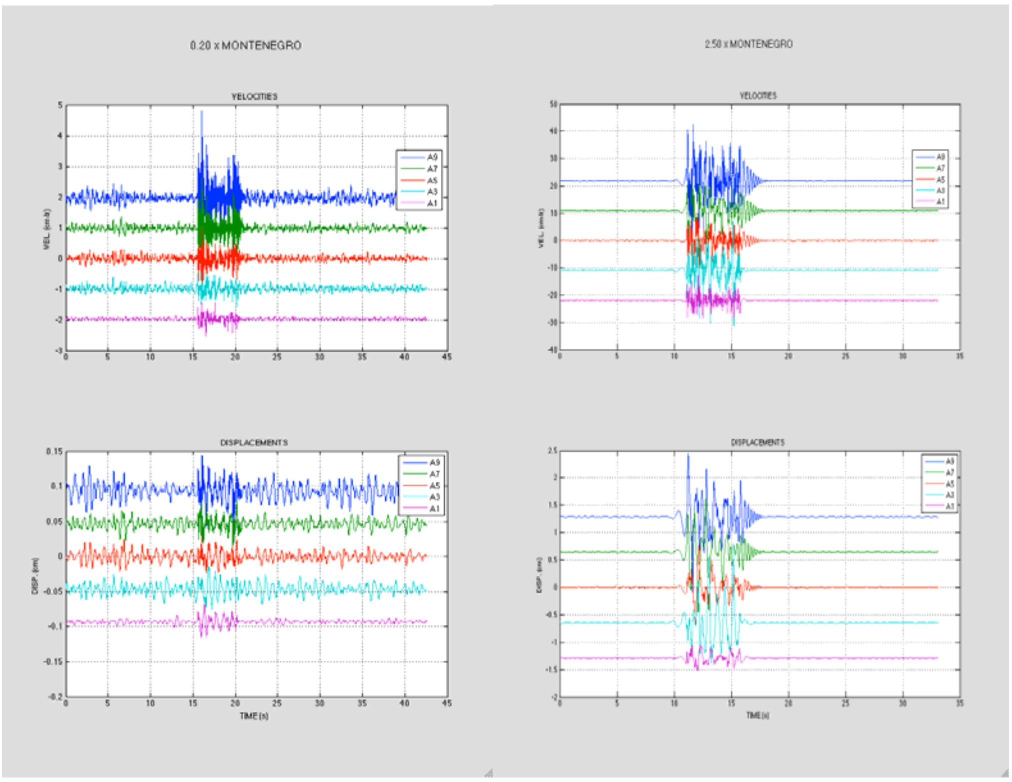

Figure 4.5. Velocity and displacement responses along the minaret for 0.08g (right) and 1.0g (left) input

5. COMPARISON OF THE RESULTS FROM THE 1/6TH AND 1/10TH SCALE MODELS

5.1. Comparison of the dynamic properties of the models

The dynamic properties of the two models were measured before the shake table tests by ambient vibration tests. Figure 5.1 compares the FAS of both models. Table 5.1 shows the natural frequencies of the models obtained for the minaret and the mosque. According to the similitude law, the ratio of the natural frequencies should be 10/6= 1.67. As it can be seen, obtained frequencies closely satisfied this requirement, which implies that the design of the models is compatible with the similitude laws.

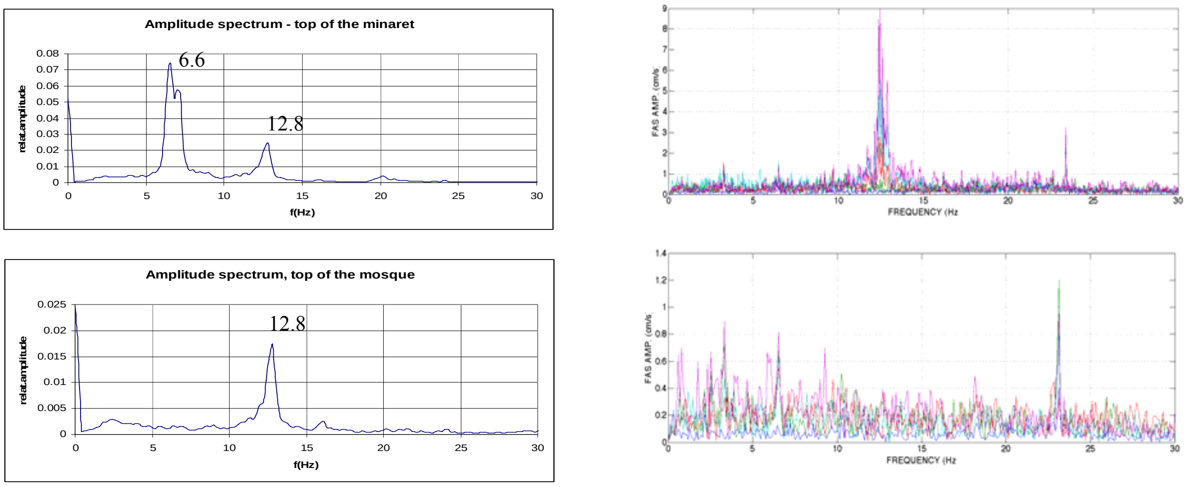

Figure 5.1. FAS for the 1/6th scale model (left) and the 1/10th scale model (right)

Table 5.1. Comparison between natural frequencies of the 1/6th and 1/10th models

Substructure	1/6th Scale Model	1/10th Scale Model	Required ratio	Obtained ratio
Minaret	6.6 Hz	12.0 Hz	1.7	1.8
Mosque	12.8 Hz	23.0 Hz	1.7	1.8

5.2. Comparison of the damage distribution on the models

Shake table tests of the models were performed under the same earthquake record, the 1979 Montenegro Earthquake. According to the similitude law, the time history of the earthquake was compressed six times, while the peak amplitude was amplified six times. In the case of the 1/10th scale model, the time history of the earthquake was compressed ten times, while the peak amplitude was amplified ten times. The seismic excitations with different intensities created similar crack patterns on both models. Namely, the minarets in both models suffered horizontal cracks at the bottom part near the joint with the main structure of the mosque, while diagonal cracks appeared between the window openings and on the domes (Figure 5.2), which confirm again the correctness of the design approach as “adequate model with gravity force neglected”.

6. CONCLUSIONS

Comparison between two models shows that very good compatibility is obtained for the dynamic characteristics of the models and the damage distribution. Although there are some discrepancies in the acceleration and displacement responses, the differences are still within an acceptable range. Thus, it can be concluded that the information received from the models is consistent with each other, and with that of the original structure, even if the geometry scale is different.

Figure 5.2. Comparison of damage distribution of the models (1/6th scale model on the left, 1/10th scale model on the right)

ACKNOWLEDGEMENTS

This project is supported by TUBITAK of Turkey and Ministry of Education and Science of Macedonia. It is partially supported by the Ministry of Development of Turkey. We thank Mr Oktay Çırağ, Mr Ahmet Korkmaz, Mr Nafiz Kafadar, Mr Ekrem Ulusoy, Mr Mehmet Vefa Bektaş of KOERI for their help with the shake table test of KOERI model. We also thank Mr Eren Kalafat and Mr Korhan Oral of Ulus Yapı, Istanbul for the construction of the KOERI model.

REFERENCES

Krstevska, L., Tashkov, L., Gramatikov, K., Landolfo, R., Mammana, O., Portioli, F. and Mazzolani, F.(2008) Shaking table tests on the large scale model of Mustafa Pasha Mosque without and with FRP. **Proceedings** *of the sixth international Conference on Structural Analysis of Historic Construction* - SAHC2008, 2-4 July, Bath, United Kingdom, p.p.383-391

L. Krstevska, LJ. Tashkov, K. Gramatikov, F. Mazzolani, R. Landolfo(2009). Shaking Table Test of Mustafa Pasha Mosque Model in Reduced Scale. **Proceedings**, *Protection of Historical Buildings, Conference Prohitech* 09, Rome, Italy, 2009, Taylor & Francis Group, London, ISBN978-0-415-55803-7, **Vol 2**, pp 1633-1640

L.Krstevska, Lj. Tashkov, K. Gramatikov, R. Landolfo, O. Mammana, F. Portioli, F. Mazzolani(2010) Large scale experimental investigation on Mustafa-Pasha mosque. *Journal of Earthquake Engineering*, **Volume 14**, Issue 6 July 2010, pages 842-873 (IF 1.049)