Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2023) 560-580

ECCOMAS
Proceedia

COMPDYN 2023
9th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Athens, Greece, 12-14 June 2023

STUDYING THE PERFORMANCE OF STONE MASONRY ARCH BRIDGES EMPLOYING IN-SITU MEASUREMENTS AND NUMERICAL PREDICTIONS

G.C. Manos[1], K. Katakalos[1], L. Kotoulas[1] and L. Melidis[1]

[1] Laboratory of Strength of Materials and Structures, Aristotle University
e-mail: gcmanos@civil.auth.gr

Abstract

The Stone masonry arch bridges used to be a very important part of the transportation system of the numerous communities living at the mountainous regions of Greece. The wide spread use of car transport after the mid-twentieth century dictated the construction of modern reinforced concrete bridges as part of a new road network. However, a new interest was generated in these structures that have the status of cultural heritage in need of preservation. The present study presents a series of in-situ measurements conducted at selected old stone masonry bridges, using up-to-date system identification techniques, in an effort to identify their dynamic characteristics in terms of eigen-frequencies, eigen-modes and damping properties. All these information is part of a data base that can be used in the future as a reference for identifying noticeable changes in these dynamic characteristics as part of a structural health monitoring effort for these bridges. Moreover, this information provides a basis for building realistic numerical simulations towards studying the structural behaviour of such stone masonry bridges and assessing their expected structural behaviour in extreme future seismic events. Selected in-situ measurements are presented together with their use in building numerical models of various levels of complexity. These numerical models are finally utilized in assessing the expected performance of specific case studies of stone masonry bridge structures in Greece towards meeting the demands of extreme events that include design earth-quake loads. The described system identification technique can also be linked to specific actions, such as earthquake activity, and thus serve as warning for specific maintenance counter-measure.

Keywords: Stone Masonry Bridges, In-situ Vibration Measurements, System Identification, Numerical Simulation, Foundation Deformability, Plaka Bridge Collapse.

ISSN:2623-3347
Peer-review under responsibility of the organizing committee of COMPDYN 2023.
doi: 10.7712/120123.10420.20883

1 INTRODUCTION AND PATHOLOGY

Numerous old stone masonry bridges are located mainly in the prefectures of Western Macedonia and Epirus and Thessaly in Greece (Gialeridis 1995, Grassos 2007, Milas 2016, Psimarni et al 2000). These bridges are examples of out-standing stone-masonry construction that was dominant for a long period in these parts of Greece (Figs. 1a and 1b). These stone masonry bridges today exist in a variety of conditions. A number of them have been maintained up to a point; these are usually located in places that are near sites that attracting visitors like the stone masonry bridge of Saint Vissarion near Pili-Trikalon in Thessaly. In other cases local communities have been instrumental in undertaking such maintenance works, like the stone masonry bridge of Aziz Aga. Both these bridges have been studied before by the authors of the present work. However, these maintenance works are carried out mainly by masons and does not involve an in-depth scientific procedure.

Fig. 1. The St. Vissariona stone masonry bridge

Fig. 2. The Aziz Aga stone masonry bridge

A number of stone masonry bridges have some of their parts destroyed due to various causes. The most usual cause is the erosion of the piers from the river flow. This can be a long term erosion that can also be suddenly amplified by flooding conditions, like the celebrated Plaka Bridge, which collapsed on the 1st Februay 2015 from peak flooding of Aracthos river. This bridge has been rebuilt in its original geometry as a traditional stone masonry bridge.

Fig. 3. The Plaka stone masonry bridge

A number of stone masonry bridges with collapsed parts have been rebuilt by substituting the collapsed part with reinforced concrete structural members. One such stone masonry bridge is the one depicted in figure . From the original four (4) arches the two ones at the left collapsed and were substituted by reinforced concrete slabs. Because the use of these bridges is limited to activities linked with traditional agricultural works they are mainly used as pedestrian bridges and therefore the permanent loads and the usual live loads pose low-level demands on their stone masonry or their reinforced concrete parts. However, this use creates the illusion that there is not real need for regular maintenance. This results that the conditions of these structure are usually in poor state; consequently, a next extreme action either from flooding or from an earthquake will have devastating effects and will most probably lead to severe structural damage or even collapse. The construction of these concrete parts not properly maintained have signs of concrete spalling and corrosion of the steel reinforcement, Moreover, the regions where these concrete slabs are supported by the stone masonry parts have also signs of deterioration of the masonry due to the way the environmental conditions influence these two different parts without removing the humidity and the water from rain or snow effectively. A solution to these problems would have been, apart from regular maintenance, to remove the reinforced concrete parts and rebuilt the original collapsed stone masonry parts with new stone masonry. This operation may have initial cost and construction difficulties. The construction difficulties arise from the fact that one needs to involve experienced stone masons, which is not so easy nowdays.

Fig. 4. The Koutsogianni stone masonry bridge with the collapsed part is being replaced with an RC deck

In an another stone masonry bridge the spans the river Sarantaporos (The Drosopigi bridge) despite the visible wide cracking at the bottom of the left pier the intervention dealt with with the stones of the deck together with rebuilding the side walls of this deck a higher level than before. This resulted in increasing the dead load without investigating whether this increase was favourable for the structural performance of load combinations which would include seismic forces. The total length is 42.0m with the clear span of the main arch is equal to 16.1m and the height 10m.

Fig. 5. The Drosopigi stone masonry bridge

There are a few cases of impressive stone masonry bridges which are today in a state of collapse. For these cases it is worth to examine the possibility to rebuild these stone masonry bridges in the original geometry employing traditional stone masonry construction techniques. Both the stone masonry bridges with reinforced concrete parts as well as the stone masonry bridges with collapsed parts they can be rebuild with traditional construction techniques initiating in this way a revival of such stone masonry construction which can also be applied to numerous stone masonry structures (churches, houses, etc.) that are in need of preservation, repair and reconstruction.

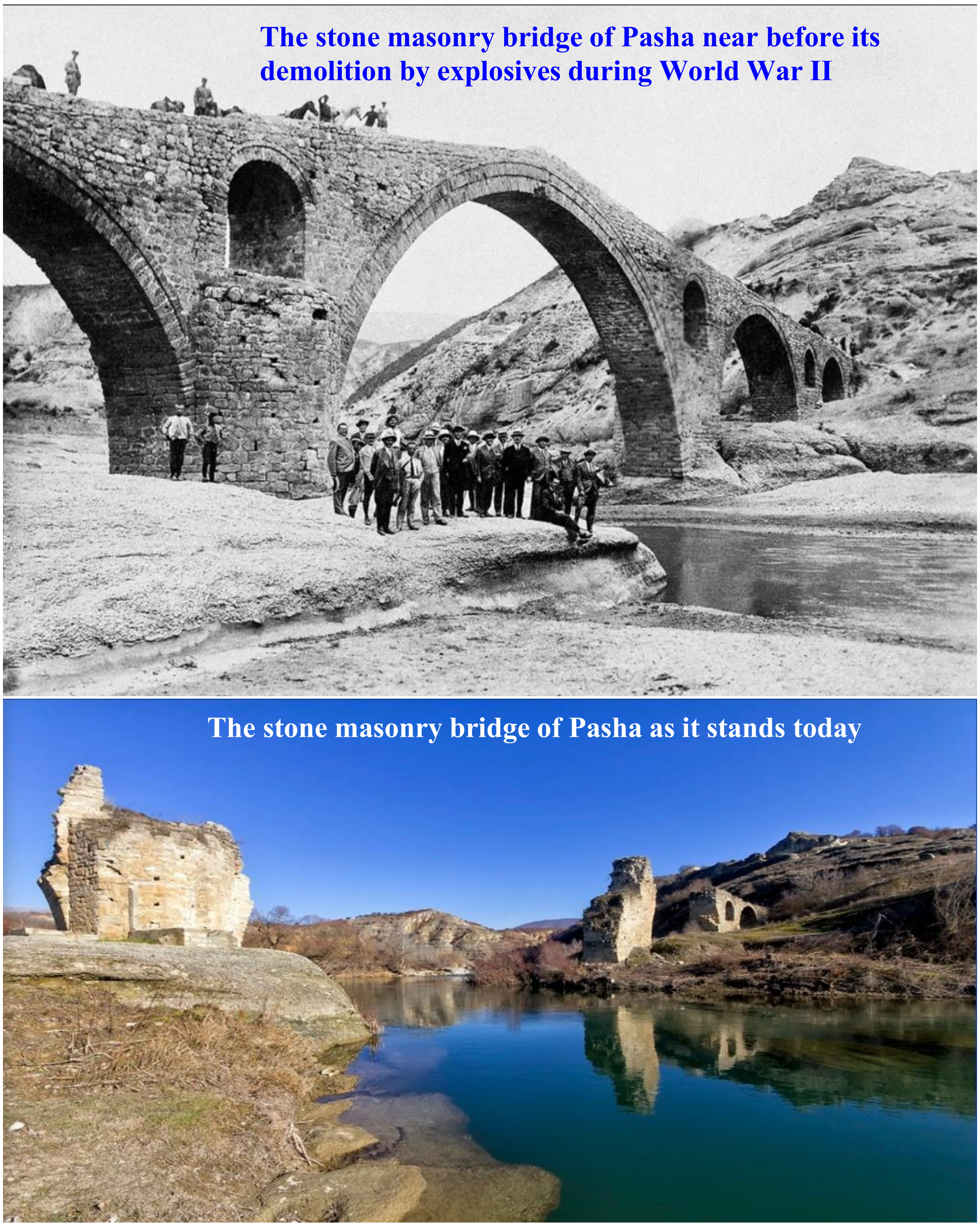


Fig. 6. The Pasha stone masonry bridge

Summarizing all the above the following important points can be followed in an effort to preserve these important stone-masonry structures.

- Thorough investigation of the various parts especially the large main arch, its piers and their foundation.

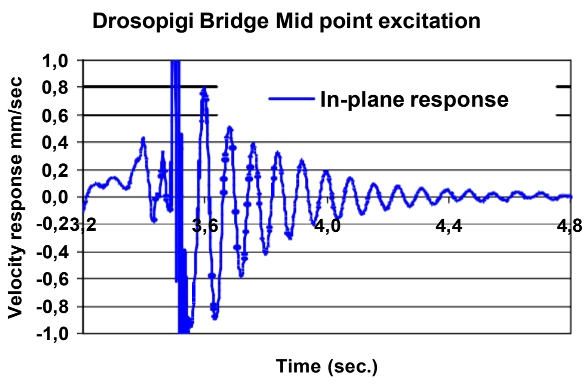
- Quantification of the extreme loading conditions such as flooding and earthquake actions.
- Use of in-situ testing towards a system identification process.
- Based on the system identification results the formation of a realistic numerical model.
- Employing this numerical model to perform numerical analysis in order to asses the critical areas that a repair – strengthening scheme should take into account. This analysis can initially employ linear-elastic assumptions combined with limit-state capacity scenarios before utilizing complex non-linear analysis procedures.
- Investigation of the materials in order to adopt repair and strengthening techniques compatible with the existing stone masonry.
- Use of in-situ testing after the repair and strengthening works are completed towards identifying the changes introduced to the system.

In what follows a number of specific stone masonry bridges are presented whereby some of the above steps were applied.

2 THE STONE MASONRY BRIDGE AT DROSOPIGI

The type of excitation that was employed, namely vertical in-plane excitation, was produced from a sudden drop of a weight on the deck of each stone masonry bridge (Aoki 2007, Manos 2015a, 2015b, 2016, 2017, Ozden et al 2012, Ruocci et al. 2013).

The level of this type of excitation was capable of producing mainly vertical vibrations; however, depending on the location of the stone-bridge that such an excitation was applied, horizontal vibratory response components could also be recorded. From the recorded three-component response the in-plane and out-of-plane eigen-frequencies and eigen-modes of each studied stone masonry bridge structure could be identified. The employed tri-axial velocity sensors had a sensitivity of 0.001mm/sec and a data acquisition system with a sampling frequency of 800Hz. The drop weight excitation in various locations combined with the placement of the sensors in selected locations was capable of capturing the in-plane as well as out-of-plane modes of response. A careful study of the numerous in-situ response measurements together with the assistance of numerical simulation tools and a back analysis process resulted for such stone bridges in their dynamic system identification. Figures 7 and 8 depict typical measurements of the out-of-plane and the in-plane respectively, together with the corresponding Fast Fourier Transform plots.



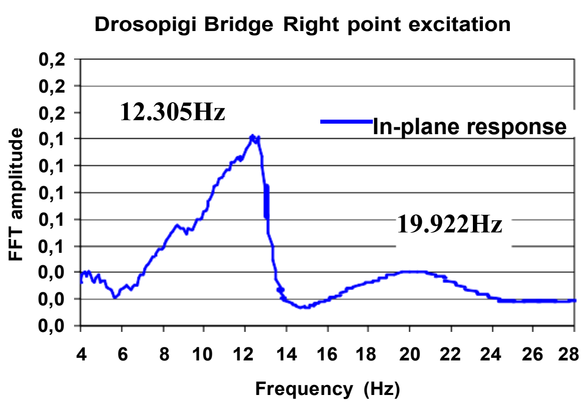


Fig. 7. The measured in-situ in-plane response at Drosopigi stone masonry bridge

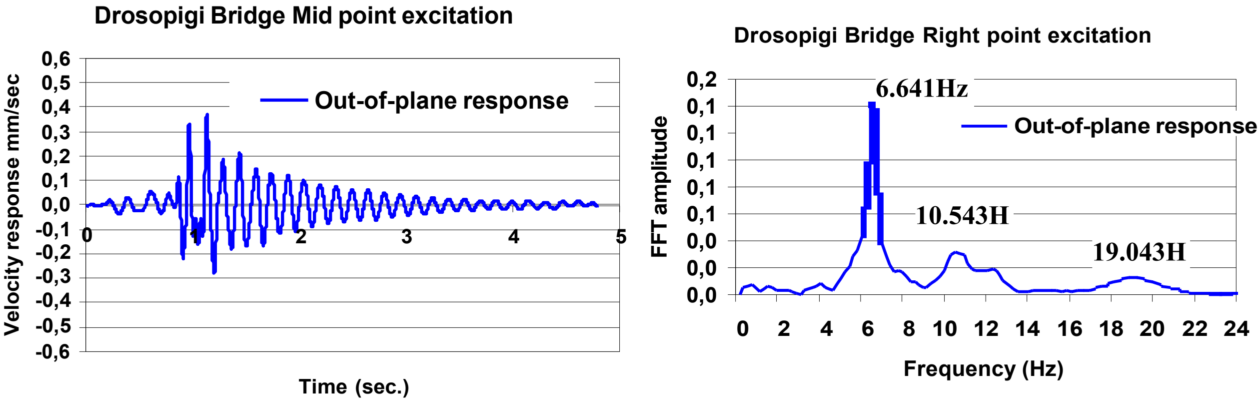


Fig. 7. The measured in-situ out-of-plane response at Drosopigi stone masonry bridge

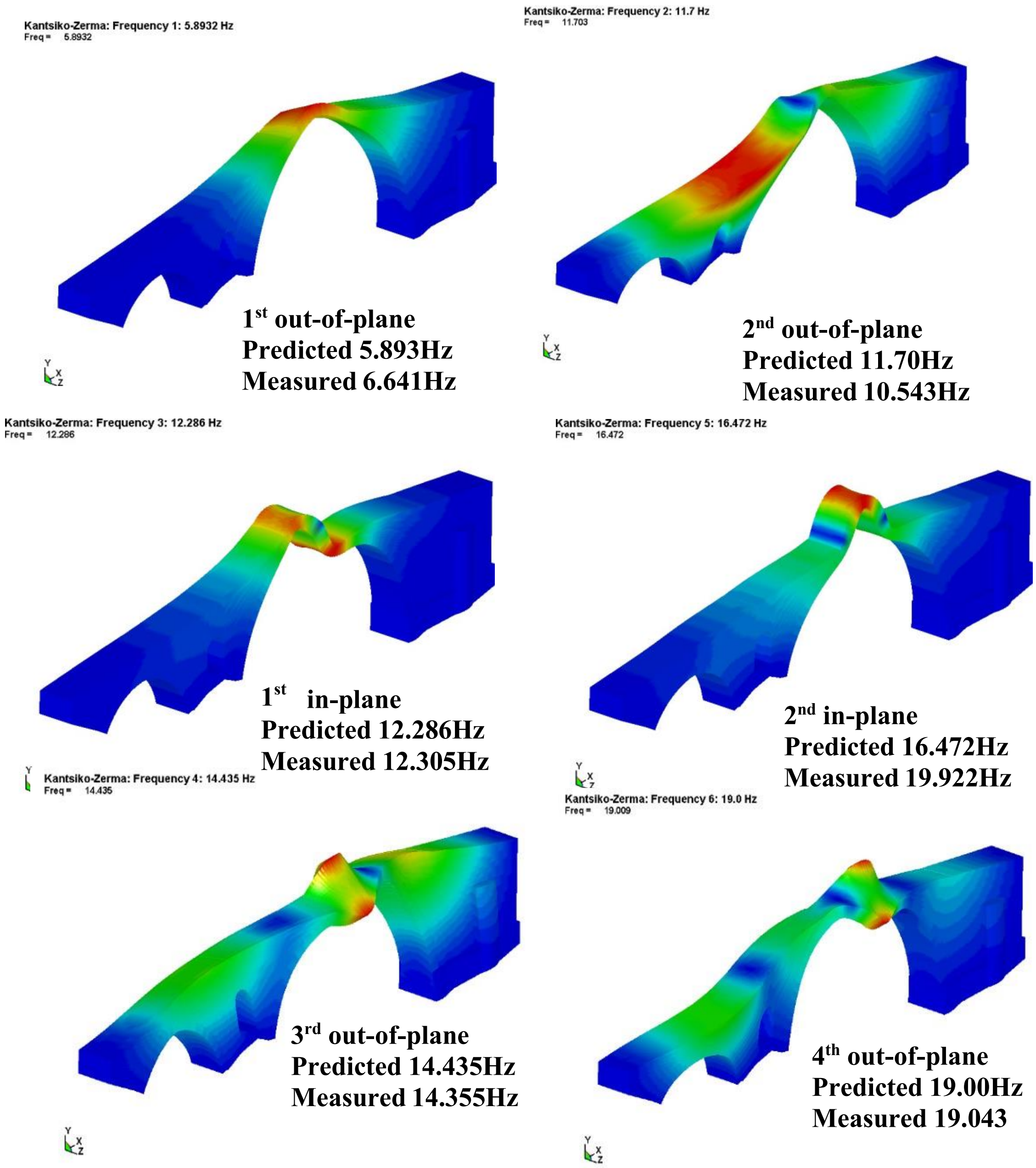


Fig. 9. The measured and predicted in and out-of-plane response at Drosopigi stone masonry bridge

In figure 9 a comparison is presented between the measured eigen-frequency values, as they were derived from the analysis of numerous in-plane and out-of-plane in-situ response measurements with the corresponding numerically predicted values utilizing a 3-D numerical model formed with solid finite elements by Simos [ ]. As can be seen a reasonable agreement was obtained between the numerically predicted values with the corresponding measured values.

3 THE STONE MASONRY BRIDGE AT RODOCHORI (TSOUKARI)

The same in-situ methodology used before was also utilized for this stone masonry bridge. This bridge has five arches; from left to right there are initially two small arches then one medium size arch followed by the main arch (4th arch) with a clear span equal to 12.4m and a clear height of 5.5m.

Fig. 11. The Rothochori (Tsukari) stone masonry bridge

The fifth stone masonry arch collapsed some time ago and was replaced by a reinforced concrete slab. The collapse of this 5th arch followed the right slope erosion by the river flow. This slope was relatively unstable because it was formed by relatively soft soil deposits. The right abutment was replaced by a RC wall supporting the right end of the concrete deck. The fourth stone masonry pier was supplemented at its right side also with a RC wall. This is shown in figure 11. The numerical simulation of this structural formation is shown in figure 12. With green colour is the parts built with stone masonry whereas with blue colour the reinforced concrete parts are shown. All these parts were supposed to be in full contact.

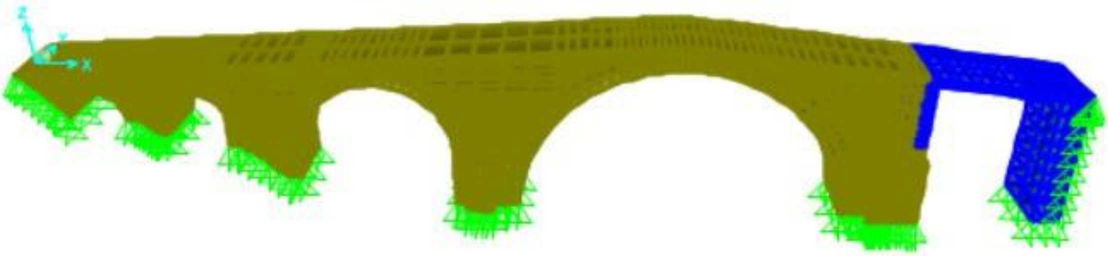


Fig. 12. The numerical simulation of the Rothochori (Tsukari) stone masonry bridge with the RC parts

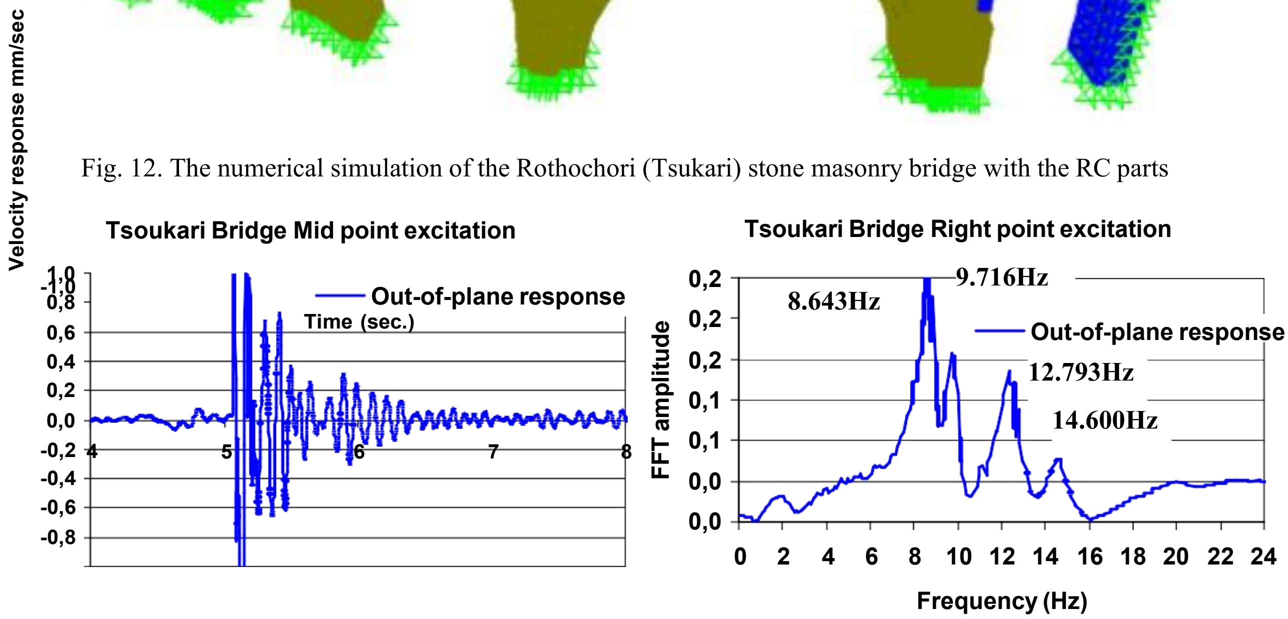


Fig. 13. The measured in-situ out-of-plane response of the Tsukari stone masonry bridge

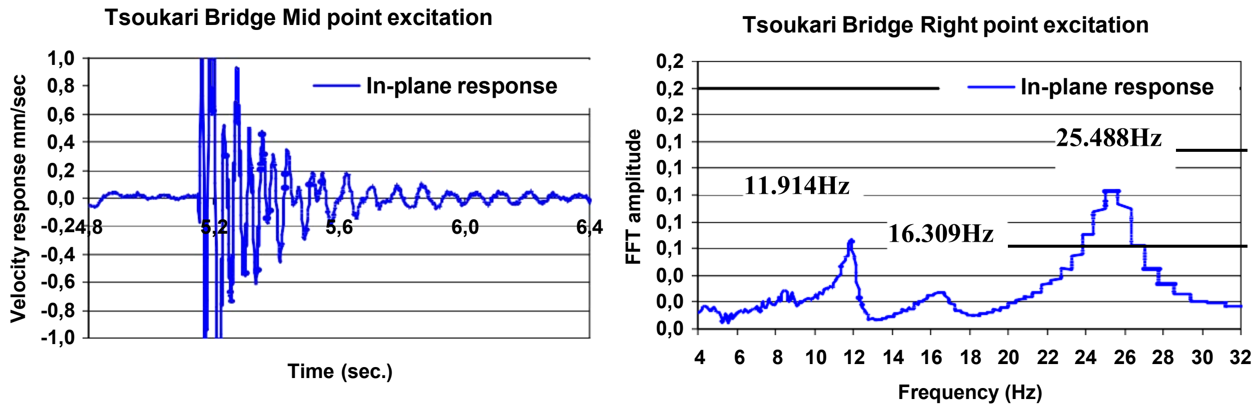


Fig. 14. The measured in-situ in-plane response of the Tsukari stone masonry bridge

The drop weight excitation in various locations combined with the placement of the sensors in selected locations was capable of capturing the in-plane as well as out-of-plane modes of response. A careful study of the numerous in-situ response measurements together with the assistance of numerical simulation tools and a back analysis process resulted for such stone bridges in their dynamic system identification. Figures 13 and 14 depict typical measurements of the out-of-plane and the in-plane respectively, together with the corresponding FFT plots for the Tsukari stone masonry bridge with the RC parts.

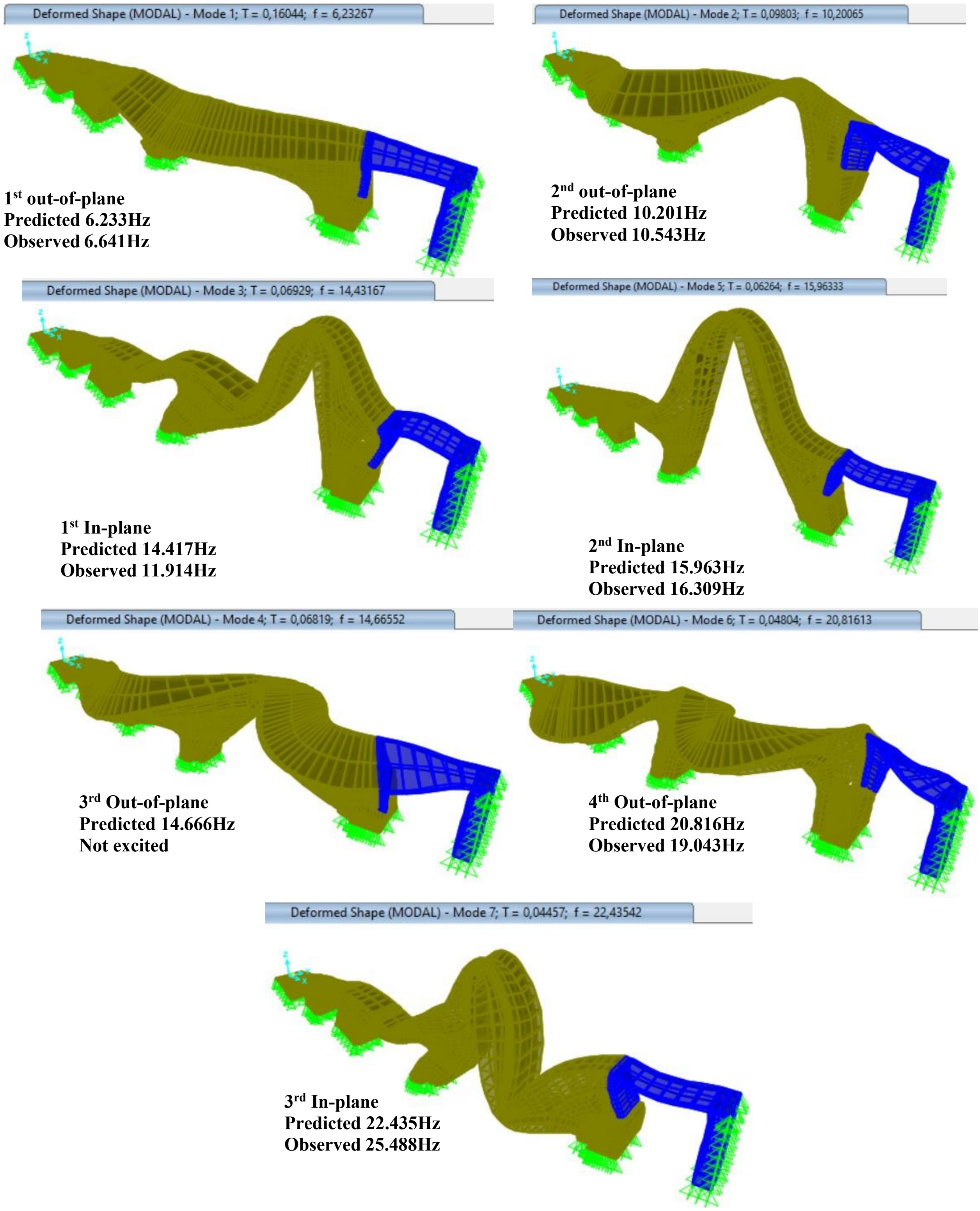


Fig. 15. The measured and predicted in and out-of-plane response of Tsoukari stone masonry bridge

In figure 15 a comparison is presented between the measured eigen-frequency values, as they were derived from the analysis of numerous in-plane and out-of-plane in-situ response measurements with the corresponding numerically predicted values utilizing a 3-D numerical model formed with solid finite elements. As can be seen a reasonable agreement was obtained between the numerically predicted values with the corresponding measured values. Table 1 lists the first eight eigen-modes and the corresponding eigen-period values. In addition, the corresponding modal mass ratio (%) values are also listed.

TABLE: 1 Modal Participating Mass Ratios Tsoukari stone masonry bridge with RC parts

		Period (sec)	UX	UY	UZ	SumUX (in-plane)	SumUY (out-of-plane)	SumUZ (In-plane)
Mode	1	0,1604	0	**42%**	0	0	42%	0
Mode	2	0,0960	0	2.1%	0	0	44.1	0
Mode	3	0,0693	**44%**	0	0,2%	44%	44.1	0.2%
Mode	4	0,0682	0	12%	0	44%	56.1	0.2%
Mode	5	0,0626	3.3%	0	**16%**	48.3%	56.1	16%
Mode	6	0,0480	0	0	0	48.3%	56.1	16%
Mode	7	0,0446	0	0	6.1%	54.7%	56.1	23%
Mode	8	0,0409	0	9.4%	0	**54.7%**	**65.5**	**23%**

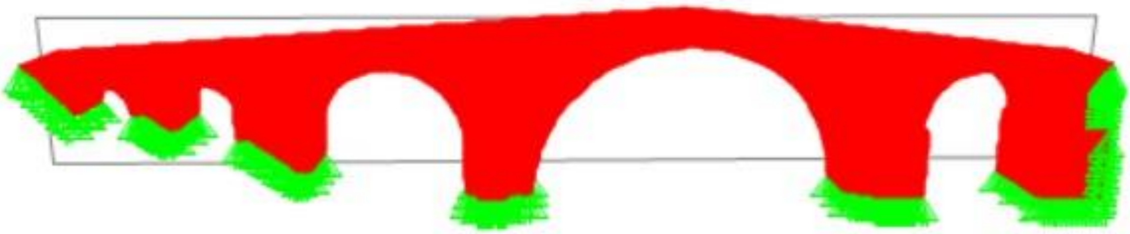
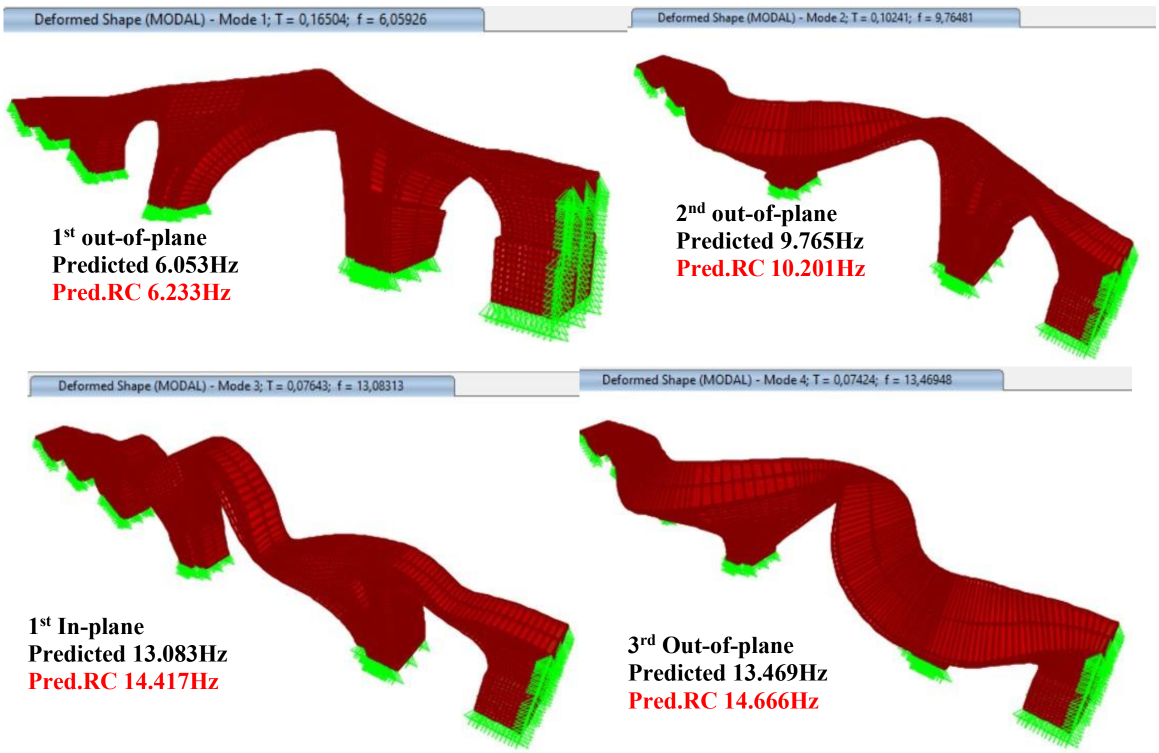


Fig. 16. The numerical simulation of the Rothochori (Tsukari) stone masonry bridge with repaired 5th arch



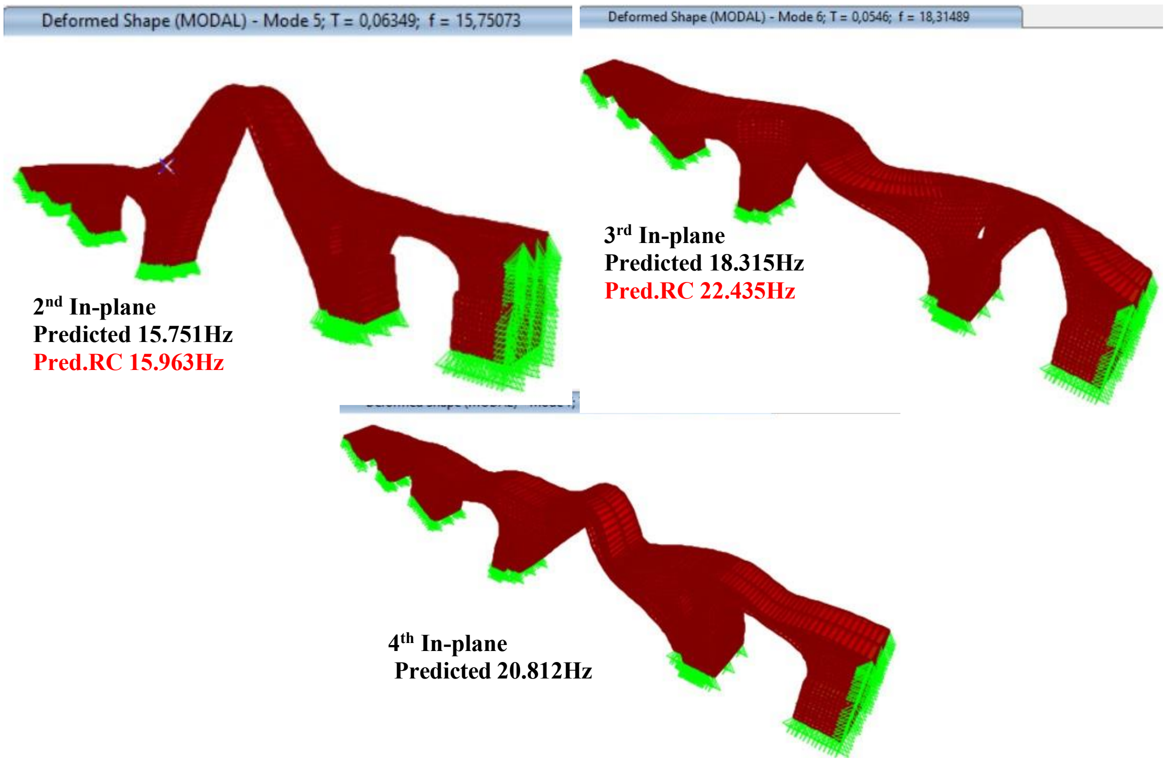


Fig. 17. The measured and predicted in and out-of-plane response of Tsoukari stone masonry bridge. This numerical model simulates this bridge having the concrete parts replaced with stone masonry traditional construction.

In figure 16 a numerical model us depicted simulating the Tsoukari bridge having the 5th collapsed arch being rebuilt with traditional stone masonry construction techniques having removed before the RC parts. In figure 17 the obtained eigen-modes and eigen-frequencies for this model are shown. In the same figure the eigen-frequency values obtained for this model are listed in black colour whereas the corresponding values for the numerical model of the Tsoukari bridge as it stands today with the RC parts are also listed with red colour. As can be seen the reconstructed stone masonry bridge becomes stiffer in the out-of-plane response and more flexible in the in-plane response than the existing bridge with the RC parts. Table 2 lists the first eight eigen-modes and the corresponding eigen-period values. In addition, the corresponding modal mass ratio (%) values are also listed for this reconstructed with traditional stone masonry construction bridge

TABLE: 2 Modal Participating Mass Ratios of Tsoukari stone masonry bridge with the RC parts being replaced by stone masonry built with traditional construction

		Period (sec)	UX	UY	UZ	SumUX	SumUY	SumUZ
Mode	1	0,1650	0,000	**0,370**	0,000	0,000	0,370	0,000
Mode	2	0,1024	0,000	**0,008**	0,000	0,000	0,380	0,000
Mode	3	0,0764	**0,470**	0,000	0,002	0,470	0,380	0,002
Mode	4	0,0742	0,000	**0,150**	0,000	0,470	0,530	0,002
Mode	5	0,0635	0,001	0,000	**0,120**	0,470	0,530	0,120
Mode	6	0,0546	0,000	0,000	0,000	0,470	0,530	0,120
Mode	7	0,0480	0,000	0,000	0,099	0,490	0,530	0,220
Mode	8	0,0437	0,000	0,025	0,000	**0,490**	**0,550**	**0,220**

4 THE STONE MASONRY BRIDGE AT ANTHOCHORI (PRAMORITSA)

This is a four arch stone masonry bridge near Anthochori that spans the river Pramoritsa with a total length of about 50m. Its main arch has a clear span equal to 15.45m and a height of 8.65m. Its deck has a clear width of 2.3m and a total width of 2.70m. The in-situ testing of this bridge was performed after it was repaired with a careful repointing of its mortar joints. This bridge is shown in figure 18 together with the numerical model built to simulate its dynamic and earthquake response.

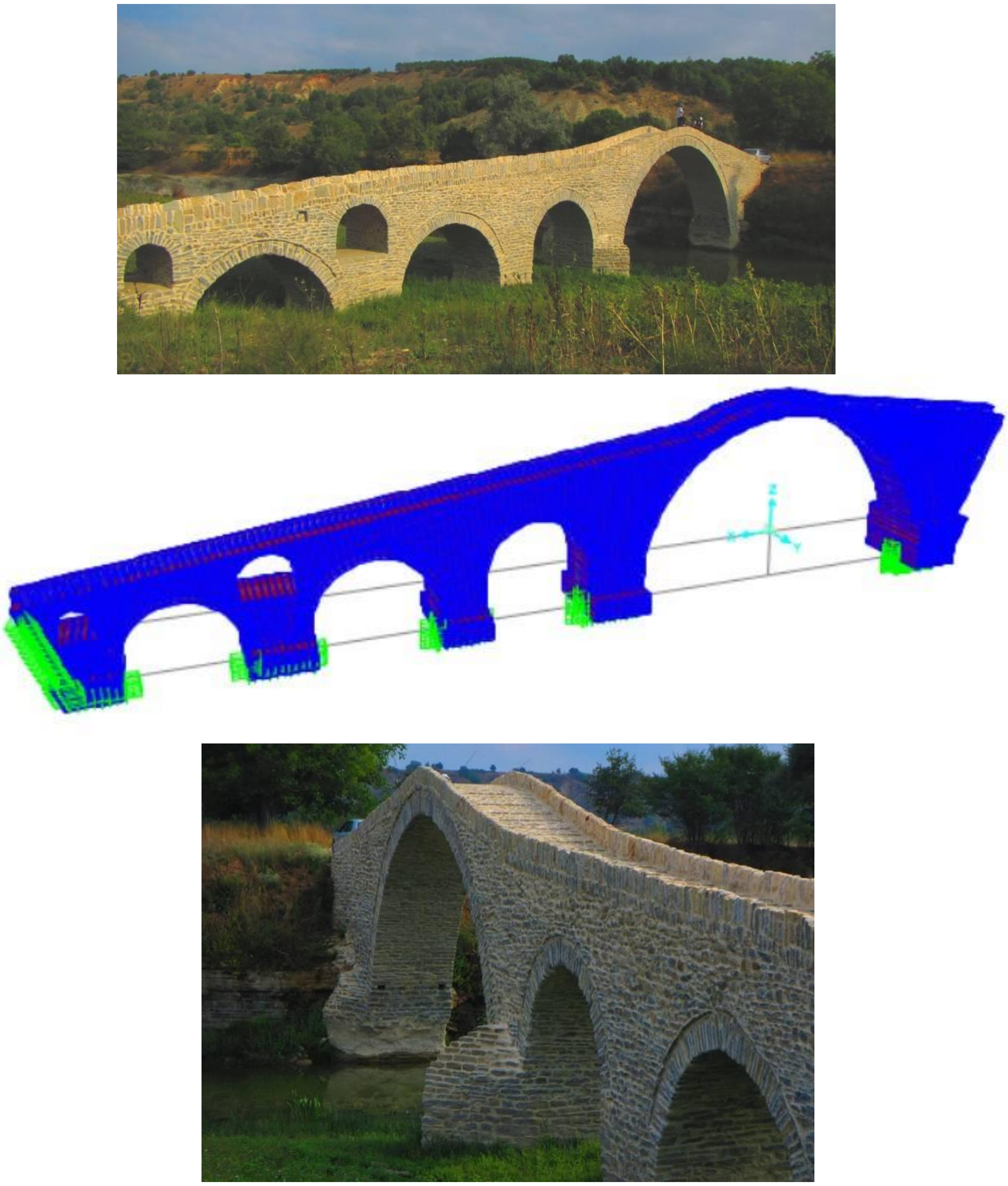


Fig. 18. The Anthochori (Pramoritsa) stone masonry bridge and its numeral model

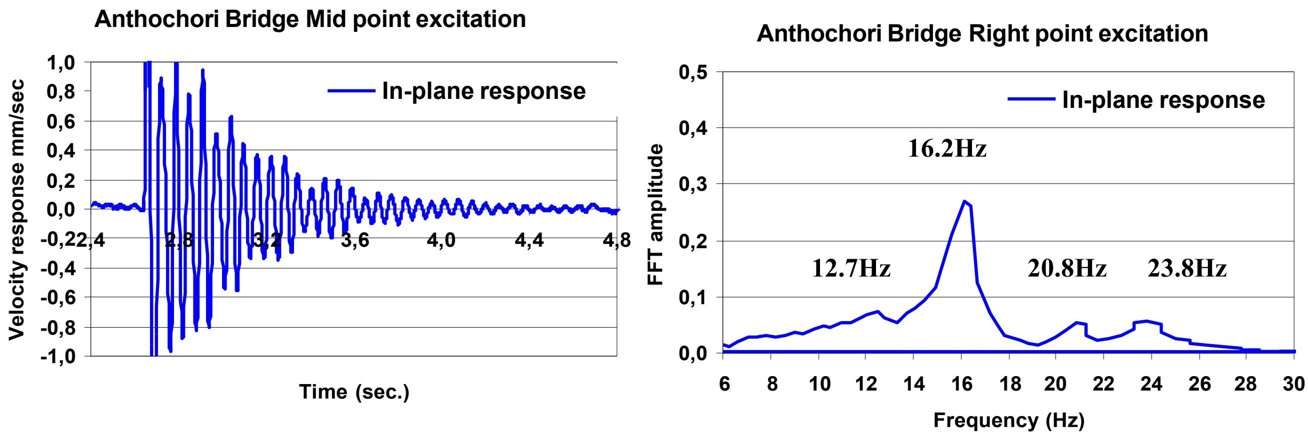


Fig. 19. The measured in-situ out-of-plane response of the Anthochori stone masonry bridge

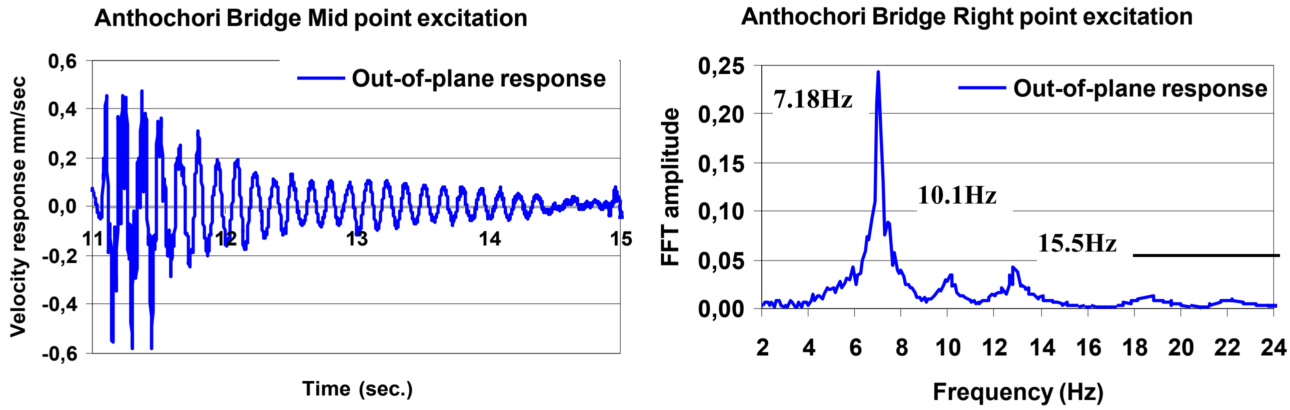


Fig. 20. The measured in-situ in-plane response of the Anthochori stone masonry bridge

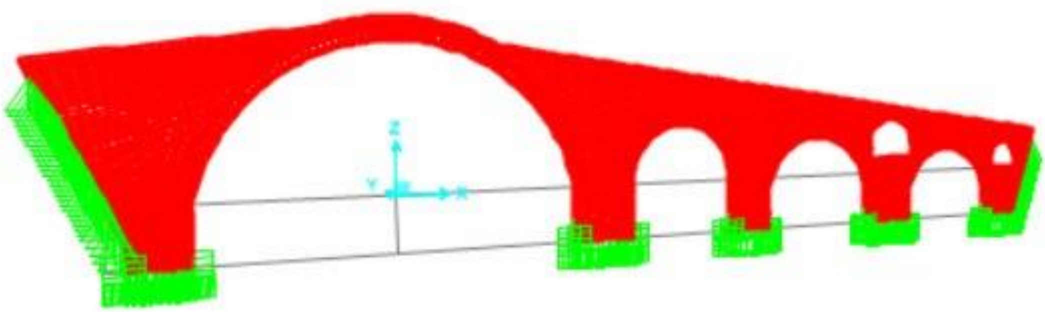


Fig. 21. The numerical model of the Anthochori (Pramoritsa) stone masonry bridge

In figure 22 the numerically predicted eigen-modes and the corresponding eigen-frequency values are shown. In the same figure the eigen-frequency values obtained from the in-situ response measurements depicted in figure19 and 20 are also listed. As can be seen, reasonably good agreement is achieved between the predicted and the measured eigen-frequency values.

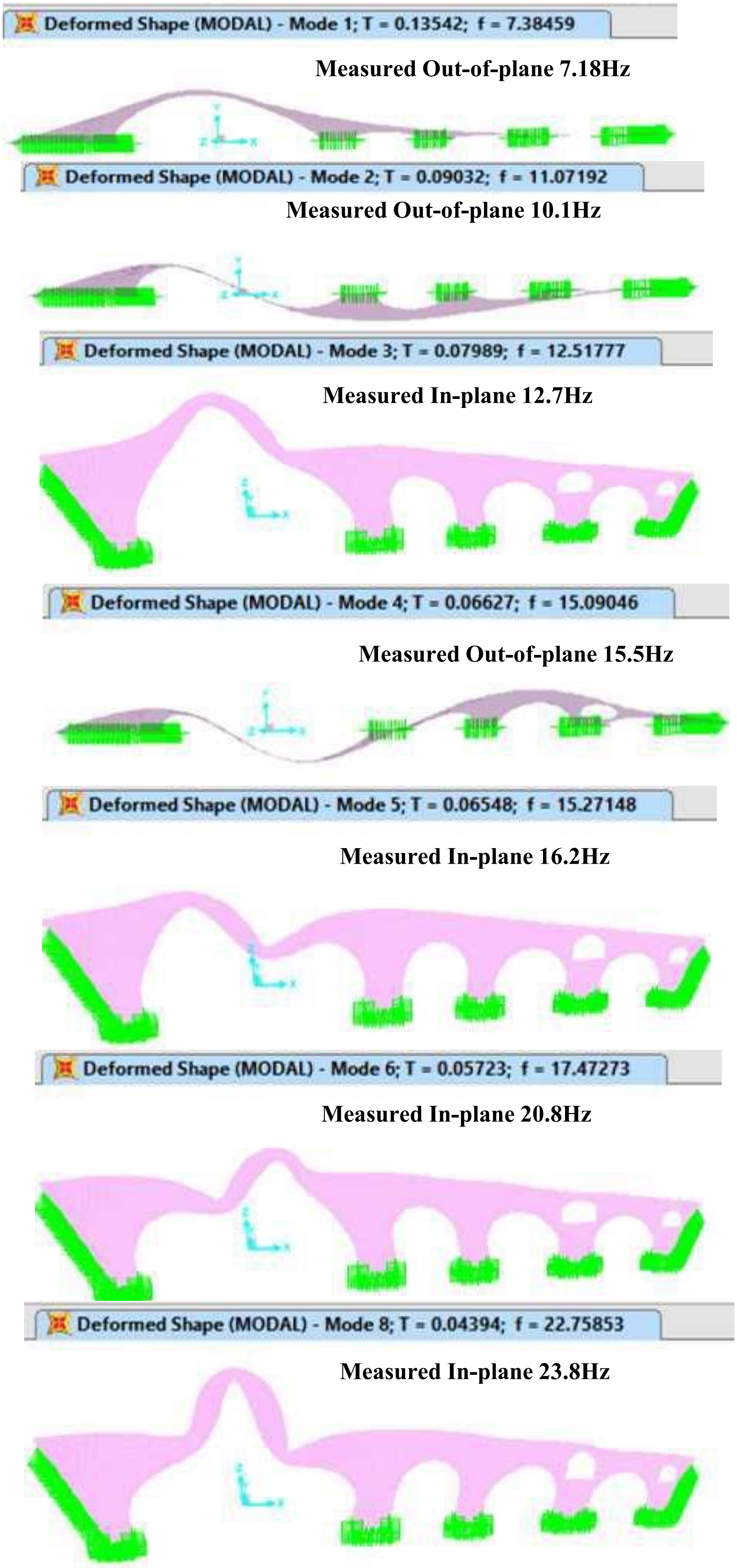


Fig. 22. The eigen-modes and the eigen-frequencies (measured and predicted) for the Anthochori bridge

Table 3 lists the modal mass participation ration of the first 12 eigen-modes.

Table 3. Modal participation mass ratios

	Period	UX	UY	UZ	SumUX	SumUY	SumUZ
	Sec	In-plane	Out-of-plane	In-plane	In-plane	Out-of-plane	In-plane
MODE 1	0,135	0	**35.2%**	0	0	35.2%	0
MODE 2	0,090	0	**7.0%**	0	0	42.2%	0
MODE 3	0,080	**28.5%**	0	0,9%	28.5%	42.2%	0.9%
MODE 4	0,066	0	**16.2%**	0	28.5%	58.4%	0.9%
MODE 5	0,065	0,5%	0	**3.7%**	29.0%	58.4%	4.7%
MODE 6	0,057	**0,099**	0	**6.5%**	38.9%	58.4%	11.2%
MODE 7	0,049	0	0,2%	0	38.9%	58.6%	11.2%
MODR 8	0,044	**14.2%**	0	5.1%	53.1%	58.6%	16.3%
MODE 9	0,040	0	**9.1%**	0	53.1%	67.7%	16.3%
MODE 10	0,035	0,3%	0	**4.9%**	53.4%	67.7%	21.2%
MODE 11	0,034	0,2%	0	**27.1%**	53.5%	67.7%	48.3%
MODE 12	0,034	0	0,1%	0	**53.5%**	**67.8%**	**48.3%**

In addition to the dynamic modal analysis a dynamic spectral analysis was also performed based on the design spectra Type-1 and Type-2, as they are defined by Euro-Code 8 and the Greek Code for Seismic Design ([10] to [16]). The peak design ground acceleration was set equal to 0.16g and the soil conditions category B. The response modification coefficient was set equal to q=1.5 for unreinforced masonry. An amplification factor was introduced in order to compensate the fact that the twelve (12) eigen-modes included in this numerical analysis mobilize either in-plane or out-of-plane a ratio quite smaller than the total mass of the structure. The load combinations included the following:

COMB1 or COMB3 = Dead + Earthquake-x RS (in-Plane) + 0.3* Earthquake-y RS (Out-of-plane). (COMB1 or COMB3) is for design response spectrum Type1 or Type2, respectively.

COMB2 or COMB4 = Dead + Earthquake-y RS (out-of-Plane) + 0.3* Earthquake-x RS (in-plane). (COMB2 or COMB4) is for design response spectrum Type1 or Type2, respectively.

TABLE 4: Base Reactions

OutputCase	CaseType	StepType	GlobalFX	GlobalFY	GlobalFZ
Text	Text	Text	Tonf	Tonf	Tonf
DEAD	LinStatic		0,0	0,0	**1018,6**
Ex EQ Type1	LinRespSpec	Max	141,3	0,0	44,7
Ex EQ Type2	LinRespSpec	Max	141,3	0,0	44,7
Ey EQ Type1	LinRespSpec	Max	0,0	169,1	0,0
Ey EQ Type2	LinRespSpec	Max	0,0	169,1	0,0
COMB1	Combination	Max	141,3	50,7	1063,3
COMB1	Combination	Min	-141,3	-50,7	973,8
COMB2	Combination	Max	**42,4**	**169,1**	1032,0
COMB2	Combination	Min	**-42,4**	**-169,1**	1005,1
COMB3	Combination	Max	141,3	50,7	1063,3
COMB3	Combination	Min	-141,3	-50,7	973,8
COMB4	Combination	Max	**42,4**	**169,1**	1032,0
COMB4	Combination	Min	**-42,4**	**-169,1**	1005,1

The definition of the seismic excitation characteristics for including them in the evaluation of the earthquake performance of stone masonry bridges is a relatively complex issue. Simos and Manos [26] studying the earthquake performance of the Konitsa stone masonry bridge included in addition to the ground motion recordings of the 1996 Konitsa near-field earthquake, four additional earthquakes (two with the characteristics of near field and two those of a far field) were introduced and their damageability was compared. This study revealed that far-field earthquakes were shown to be far more destructive than their near-field counterparts. For the Anthochori stone masonry bridge only the Euro-code design spectra were included in the numerical analysis considering only the horizontal components of the seismic forces. Due to the range of the eigen-frequencies for the most significant eigen-mode the base shear for Type-a and Type-2 design response spectra lead to the same base shear values in either in-plane (x-x) or out-of-plane directions. The most demanding in terms of tensile stress fields are combinations COMP-2 and COMP-4 which introduce horizontal seismic forces in the out of plane directon. The resulting tensile stress fields in the s22 direction (normal to horizontal bed mortar joints) are depicted in figure 23 for COMP-2 and COMP-4, being almost identical. The maximum tensile stress value is approximately equal to 1.0MPa and it appears at the foot of the mid-pier which is founded within the river bed.

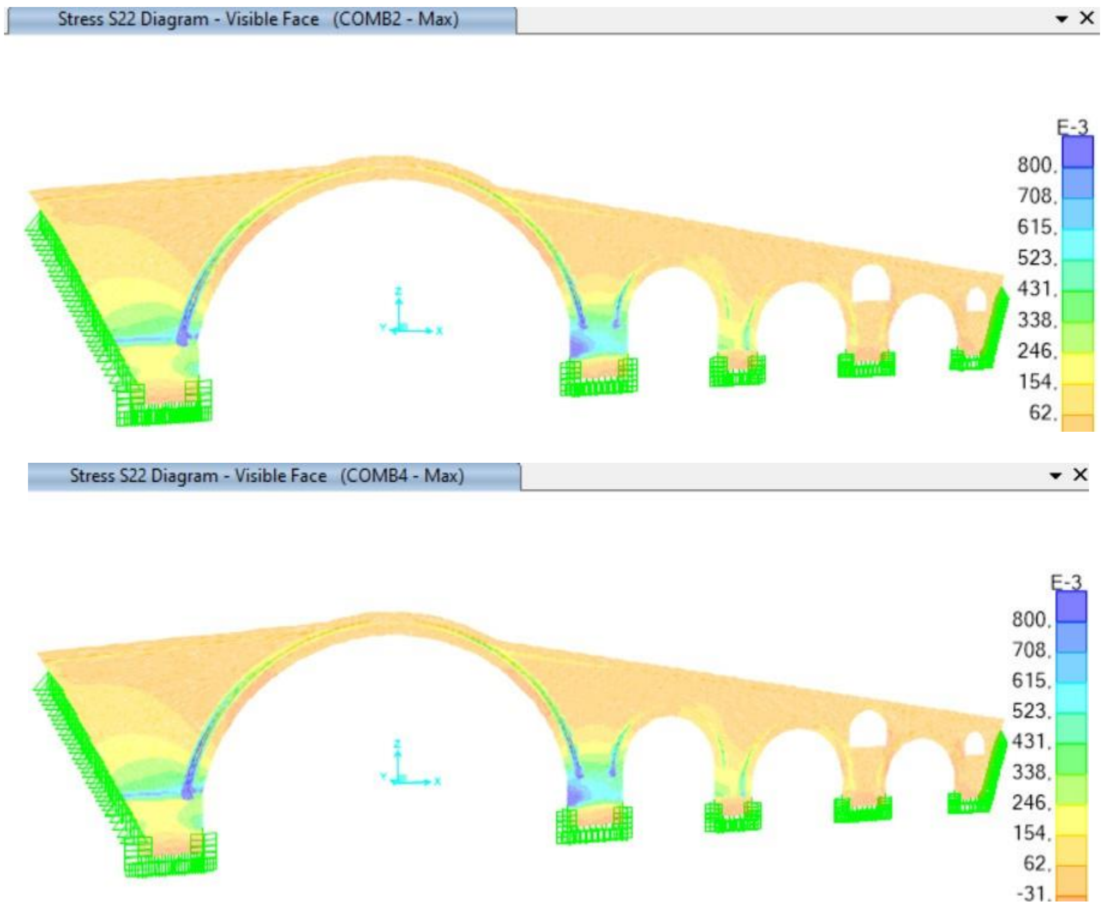


Fig. 23. The The resulting tensile stress fields in the s22 direction (normal to horizontal bed mortar joints) for the Anthochori bridge

5 CONCLUSIONS

- Stone masonry construction has a long tradition in many places worldwide. Stone masonry bridges built many centuries ago are one such example. Despite the rigidity and resilience of stone masonry bridges they are in need of maintenance in order to preserve them as part of the built cultural heritage. Towards this end in-situ measurement campaigns were conducted on a number of stone masonry bridges in order to identify their dynamic characteristics in terms of eigen-frequencies, eigen-modes and damping properties. This information is believed to represent a valuable basis for building realistic numerical simulations of the structural behaviour of such bridges as well as for their structural health monitoring.
- The actual conditions of each stone-masonry bride in its super-structure and its supports must be carefully considered.
- The flexibility of the foundation, which may be partly attributed to long or short term erosion of the bridge footings, results in detrimental response for the Plaka bridge. These predicted peak tensile stress values are well beyond the stone masonry strength. Consequently, they could well have contributed towards the February 2015 collapse.
- The simplified numerical analyses yielded numerical predictions of bridge deformations and stresses that are useful in understanding the structural behaviour and the structural damage potential for such masonry structures.
- The peak tensile values predicted when design seismic forces were applied can be of considerable magnitude thus indicating the severe potential structural damage for this old stone masonry bridge from the design earthquake. The most vulnerable parts of the bridge, as obtained from the location of the peak tensile stress concentration, is a wide area at the crest of the main central arch of the bridge as well as at the abutment near the foundation.
- The integrity of the stone masonry in various parts of the bridge is an additional maintenance issue of considerable importance. Intervention recommendations for such stone masonry bridges should include clauses for applying preparatory actions of measurements and analyses like the ones included here together with established principles that govern a major retrofitting / maintenance effort for cultural heritage together with effective retrofitting / maintenance techniques that are proven to be durable.
- The described system identification technique can also be utilized in identifying changes of stiffness that may be linked to specific actions, such as earthquake activity, and thus serve as warning for certain maintenance counter-measures.
- Results form advanced non-linear numerical analyses ([26], [27], [28]) show that such numerical simulations can reproduce in a realistic way the collapse failure scenario and support the hypothesis that the most-likely cause of the collapse of the Plaka bridge.

REFERENCES

[1] Aoki T., et al, (2007), "Theoretical and Experimental Dynamic Analysis of Rakanji Stone Arch Bridge, Honyabakei, Oita, Japan," 7th International Conference on Motion and Vibration Control, MOvIC 04.

[2] Drosopoulos G.A., Stavroulakis G.E., Massalas C.V., (2006) "Limit analysis of a single span masonry bridge with unilateral frictional contact interfaces," Engineering Structures 28 (2006) 1864–1873.

[3] EAK (2000), Provisions of Greek Seismic Code 2000 , OASP, Athens, December 1999. Revisions of seismic zonation introduced in 2003.

[4] Eurocode 8 (2004) - Design of structures for earthquake resistance – Part 1 and Part 2: Bridges, DRAFT No 3. European Committee for Standardization; 2004.

[5] Galeridis A. (1995) “The Stone Masonry Bridges in Thessalia”, Technical Chamber of Greece, Eptalofos, Athens, Greece (In Greek).

[6] Gazette of the Greek Government (1967), (ΦΕΚ 352/Β/31-5-1967) and (ΦΕΚ 194/Β/21-2-2000), (in Greek).Grassos G. (2007), “The stone masonry arch bridges of Greece”, Center of environmental education Makrinitsas, Editor G. Grassos, ISBN: 978-960-98043-9-4, (in Greek). http://kpe-makrin.mag.sch.gr.

[7] ITSAK (2019) Institute of Engineering Seismology and Earthquake Engineering (ITSAK), Data Base of Greek Earthquake Strong Motions.

[8] Kiyono J., et al. (2012), “Seismic Assessment of Stone Arched Bridges,” 15 WCEE, Lisboa, Portugal, 2012.

[9] Korompilias D., (2015), “Study of the inelastic behaviour of the Konitsa bridge using an inelastic model for masonry and applying strengthening methods,” PhD Thesis, Univ. Of Patras, Greece, (in Greek).

[10] Manos G.C. (2011), “Consequences on the urban environment in Greece related to the recent intense earthquake activity”, Int. Journal of Civil Eng. and Architecture, Dec., Volume 5, No. 12 (Serial No. 49), pp. 1065–1090.

[11] Manos G.C. et al. (2015a), “Field experiments for monitoring the dynamic soil-structure-foundation response of model structures at a Test Site” Journal of Structural Engineering, American Society of Civil Engineers, Special Issue “Field Testing of Bridges and Buildings, D4014012, Vol. 141, Issue 1, January 2015.

[12] Manos G.C. and Kozikopoulos E., (2015b) “In-situ Measured Dynamic Response of the Bell Tower of Agios Gerasimos in Lixouri-Kefalonia, Greece and its Utilization of the Numeri-cal Predections of its Earthquake Response”, COMPDYN 2015, Greece.

[13] Manos G.C., Kotoulas L., Soulis V., Felekidou O. (2015c), “Numerical Simulation of the Limit Non-Linear Behaviour of Unreinforced Masonry under In-plane State of Stress from Gravitational and Seismic Actions”, COMPDYN 2015, Greece.

[14] Manos G.C., Nick Simos N. and Kozikopoulos E. (2016) “The Structural Performance of Stone-Masonry Bridges”, Chapter 4, Structural Bridge Engineering, ISBN 978-953-51-2689-8, Print ISBN 978-953-51-2688-1, http://dx.doi.org/10.5772/64752.

[15] Manos G.C., Kozikopoulos E.,Kotoulas L., Simos N. (2017), “In-situ Measurements Related to the Performance of Stone Masonry Bridges in Greece”, COMPDYN 2017, 6th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, M. Papadrakakis, M. Fragiadakis (eds.), Rhodes Island, Greece.

[16] Manos G., Simos N., Lambri-Gaitana N. (2019), “Dynamic and Seismic Behaviour of Stone Masonry Brisges in Greece Utilizing In-situ Measurements and Numerical Predictions”, COMPDYN 2019, 7th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, M. Papadrakakis, M. Fragiadakis (eds.), Crete, Greece.

[17] Milas Iraklis, (2016), "Stone Bridges", Ethnos Travel Book, Ethnos Publications, ISBN:978-960-577-122-5 (in Greek).

[18] Ozden Caglayan B., Kadir Ozakgul and Ovunc Tezer, (2012), "Assessment of a concrete arch bridge using static and dynamic load tests" Structural Engineering and Mechanics, Vol. 41, No. 1 (2012) 83-94

[19] Papazachos B.K. and Papazachou K. (1989) "Earthquakes in Greece", Ziti publishers, Thessaloniki, Greece, (In Greek).

[20] Psimarni K., Georgopoulos A., Balodimos D.D. (2000), "Development of a Geographic In-formation System for the Traditional Bridges of Central Zagori,", Report to the Municipal-ity of Zagori, in Greek.

[21] Ruocci G., Quattrone A., Zanotti Fragonara L., Ceravolo R., De Stefano A., (2013) "Experimental Testing of a Masonry Arch Bridge Model Subject to Increasing Level of Damage", IRIS, Chapter 6, Industrial Safety and Life Cycle Engineering, VCE Vienna Consulting Engineers, www.vce.at, ISBN 978-3-200-03179-1.

[22] SAP2000, Integrated Software for Structural Analysis and Design, Computers and Structures Inc.

[23] Sevim Barıs, et al., (2011), "Finite element model calibration effects on the earthquake re-sponse of masonry arch bridges," Finite Elements in Analysis and Design, 47 (2011), 621–634

[24] Simos N. and. Manos G.C, (2013), "Numerical Analysis of Seismic Response of Natural Stone Arch Bridges-Field Observations and a Case Study," COMPDYN 2013, http://www.eccomasproceedings.org/cs2013/

[25] Simos N., Manos G.C., Kozikopoulos E., Kotoulas L. "On the Assessment of the Plaka Bridge Collapse using Non-linear Analysis Preventable or Doomed?", COMPDYN 2017, 6th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, M. Papadrakakis, M. Fragiadakis (eds.), Rhodes Island, Greece, 15–17 June 2017.

[26] Simos N., Manos G.C., Kozikopoulos E. (2018), "Near- and far-field earthquake damage study of the Konitsa stone arch bridge", Engineering Structures 177 (2018) 256–267, https://doi.org/10.1016/j.engstruct.2018.09.072.

[27] Manos G., Simos N., Psyrras G. (2020), "Investigating Stone Masonry Arch Bridges in Greece Employing In-situ Measurements and Numerical Predictions" Prohitech, Athens, Greece.

[28] Manos G., Simos N., "Studying the Performance of Stone Masonry Arch Bridges Employing In-situ Measurements and Numerical Predictions", COMPDYN 2021, 8th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, M. Papadrakakis, M. Fragiadakis (eds.), Athens, Greece, June 2021 .