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Experimental and numerical analysis of the global behaviour of the 1:9 scale model of the Old Bridge in Mostar

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Abstract. Composite nature of the masonry structures in general causes complex and non-linear behaviour, especially in intense vibration conditions. The presence of different types and forms of structural elements and different materials is a major problem for the analysis of these type of structures. For this reason, the analysis of the behaviour of masonry structures requires a combination of experimental tests and non-linear mathematical modelling. The famous UNESCO Heritage Old Bridge in Mostar was selected as an example for the analysis of the global behaviour of reinforced stone arch masonry bridges. As part of the experimental research, a model of the Old Bridge was constructed in a scale of 1:9 and tested on a shaking table platform for different levels of seismic excitation. Non-linear mathematical modelling was performed using a combined finite-discrete element method (FDEM), including the effect of connection elements. The paper presents the horizontal displacement of the top of the arch and the failure mechanism of the Old Bridge model for the experimental and the numerical phase, as well as the comparison of the results. This research provided a clearer insight into the global behaviour of stone arch masonry structures reinforced with steel clamps and steel dowels, which is significant for the structures classified as world cultural heritage.

Keywords: combined finite-discrete element methods; reinforced masonry arch structures; steel clamps and dowels

1. Introduction

Masonry arch bridges, significant both in cultural and historical terms, represent an essential part of modern transport infrastructure. From the civilisations of the ancient Middle East through the Romans and the middle Ages, up until the adoption and application of advanced construction materials, the arch is deeply rooted in the man-made architecture. The development of arch masonry can be accredited to the innovativeness of the builders and their determination to use the available techniques and materials in the most efficient and functional manner. The proper selection of materials (Aguilara *et al*. 2019), construction of arches and other elements of the structure were of

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Fig. 1 The reconstructed Old Bridge in Mostar - Southern view

crucial importance to ensure stability of a bridge, but also its resistance to various other effects. The analysis of these types of the structure deserves the attention of the scientific community.

Mathematical modelling and the analysis of such structures (Quagliarini *et al*. 2019) require a careful selection of available mathematical models that will realistically represent the interaction of all elements of the structure, as well as structural materials. In most masonry arch bridges, stone blocks and mortar are used as basic materials, and, in this particular case, there are also two new materials in the form of wrought iron clamps and dowels, as well as liquid lead, which were used to provide high-quality connection of the stone blocks. The clamps and dowels, as an example of strengthening of historical stone masonry structures, were found in ancient and medieval historical structures (Nikolić *et al*. 2019).

The accuracy of the results of numerical analyses considerably depends on a high-precision definition of all geometrical elements of the structure, their interconnectedness and the characteristics of each material involved in the modelling, since the variability of mechanical parameters of the materials describing the behaviour of such structures significantly affects the results of the conducted analyses. Different models have been developed to replicate the real behaviour of these structures with the highest degree of accuracy and the least number of assumptions. The basic models are divided into two-dimensional, which consider the interaction between the bridge arch and soil, and three-dimensional, which seek to represent the functioning of the structure as a whole. It is imperative that the mathematical model of the structure is in correlation with the real structure, as well as with the experimental models of the real structure. The introduction of the experimental models of real structures into the analysis to be used for the comparison with the mathematical models will ensure that the results of all conducted analyses reflect the real behaviour of the structure to the highest degree.

The Old Bridge in Mostar is a complex structure with a slender arch, constructed of stone blocks, with connection elements in the form of steel clamps and dowels. The bridge is located in a seismically active region. The analysis of the Old Bridge represents a genuine research challenge for the scientists in the field of masonry arch bridges but also for the wider scientific community.

1.1 The Old Bridge in Mostar, UNESCO World Heritage Site

The Old Bridge in Mostar was built in 1566. By Čelić and Mujezinović (1998) the builder of the

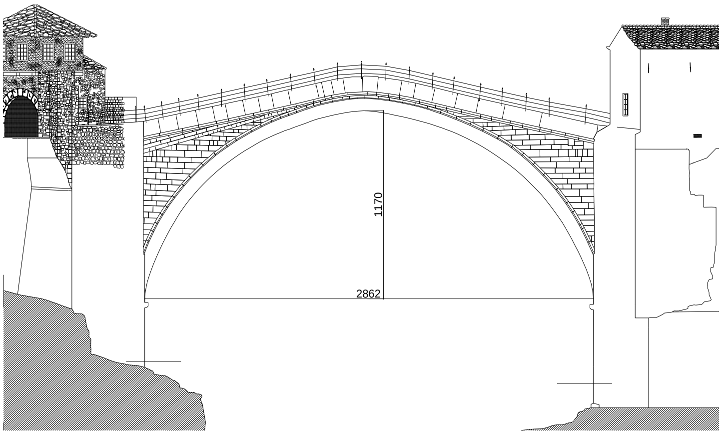


Fig. 2 CAD sketch - Southern view (cm)

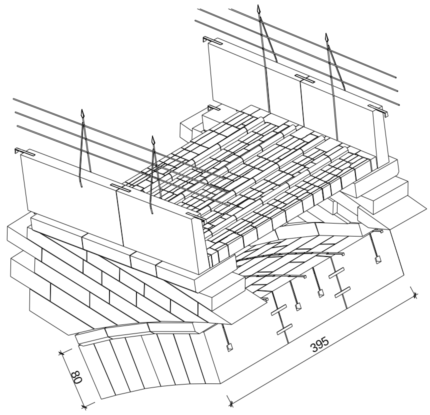


Fig. 3 CAD sketch - Cross section (cm)

bridge, Hajrudin, a student of the great Turkish architect Sinan, had been building this impressive structure for 9 years. For 427 years, the bridge had resisted all disasters until 1993 when it was demolished during the war in Bosnia and Herzegovina.

The reconstruction of the Old bridge was performed in the period from 1999 to 2004, by replicating all original geometrical elements and materials, construction methods and construction techniques. The Old Bridge in Mostar, shown in Fig. 1, together with the Old Town Area, was listed on the UNESCO List of World Heritage Sites in 2005.

The main structural element of the bridge is the load-bearing arch which is, considering its configuration, compressively loaded, thereby the stone blocks were adequate for this purpose. The northern span of the bridge arch is 28.71 m and the southern span is 28.62 m according to Čelić and Mujezinović (1998), shown in Fig. 2. The dimensions of the arch stones are 40x80x100 cm, conventionally arranged three to four rows over the depth of the vault. On average, show schematically in Fig. 3, the thickness of the vault is 80 cm and the width is 395 cm.

Due to the sizeable span and the properties of the structural material, the architect of the Old Bridge decided to introduce the central rib between the spandrel walls of the bridge. Thus, the bridge was made lighter with two hollows that reduced the weight of the bridge, while the stone rib additionally supported the bearing capacity of the entire structure. The bridge abutments and wing walls are of a typical wedge shape to resist the river action. The height of the abutments is approximately 6.50 m and the masonry of the bridge vaults commences from their ends. The wing walls of the bridge constructed above the abutments and up to the height of the spandrel walls protect the structure from the water impact. Stone spandrel walls that close the bridge and define the bridge face are approximately 60 cm thick. The cobblestone pavement was supported by the stiffening rib over the stone plates and is characterised by the transverse ribbed stairs to avoid slippage. The cobblestone paving was carried out in a layer of mortar that most likely had a waterproofing function. The footpath over the bridge is framed on both sides by the parapets made of stone plates, which are fixed to the final cornice in the plane of the spandrel walls. Afterwards, a wrought iron fence was added to the existing stone parapets. The transition on the faces from the arch to the spandrel walls was emphasised by decorative cornices.

For the construction of the Old Bridge vault, a stone *Tenelija* was used from the Mukoša site near Mostar. The compressive strength in a dry state was 32.90-45.00 MPa, while in the water-tight

Fig. 4 The Old Bridge assembly details

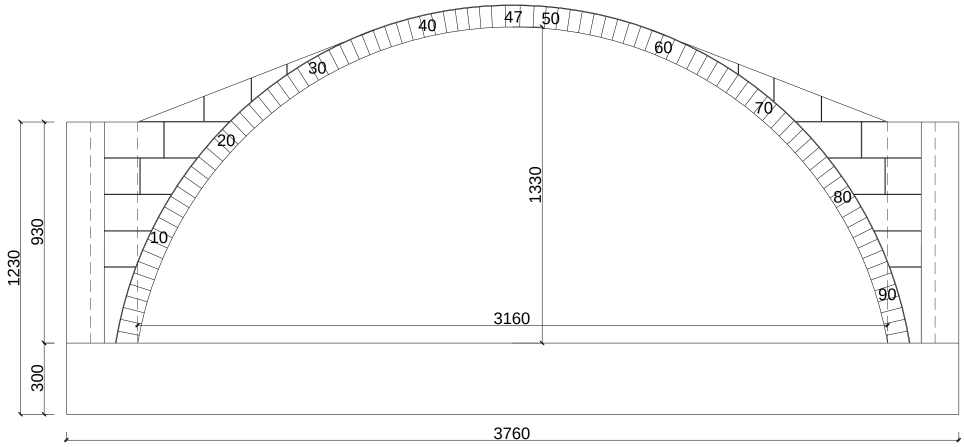


Fig. 5 Geometry of the model of the Old Bridge – front view (cm)

state the compressive strength was 30.80 MPa (Šaravanja *et al*. 2004). The mortar used during the construction of the bridge vault, according to the control tests carried out at the time of reconstruction by "IGH-Mostar" d.o.o. Mostar presented in references (Šaravanja *et al*. 2004), is composed of: lime paste 33%, sand 34%, broken brick 33%. The tests, according to the same source, provided the following results of the compressive strength of mortar: 1.1 MPa after 28 days, 1.6 MPa after 60 days and 1.9 MPa after 90 days (Šaravanja *et al*. 2004).

The technique of stone assembly by connecting elements, clamps and dowels with liquid lead as backfill was used in the construction of the original Old Bridge in Mostar both in 1567 and during its construction in 2004. The connecting elements shown in Fig. 4 were placed in the carved slots of the larger stone blocks, and the space between the stone elements and the connecting elements was filled with liquid lead Čolak (2016).

2. Experimental investigation

2.1 Geometry and design of the model

2.1.1 Geometry of the model

The model of the Old Bridge is built at the Dynamic Testing Laboratory located at the Institute

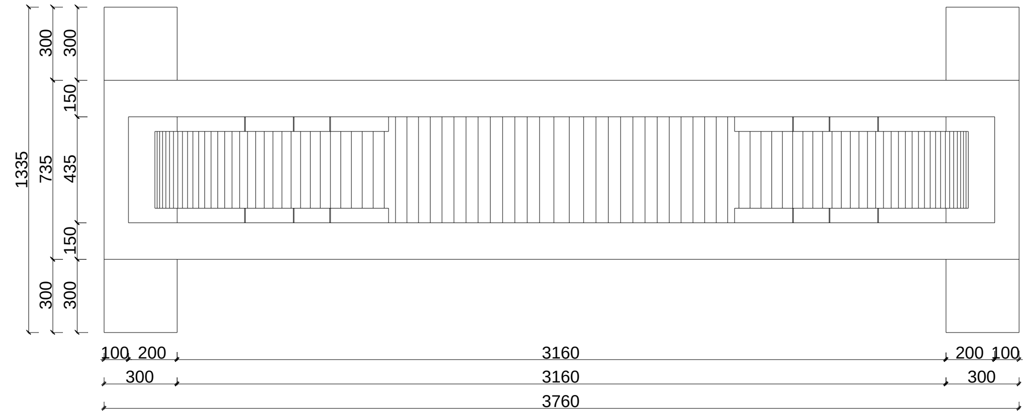


Fig. 6 Geometry of the model of the Old Bridge – top view (cm)

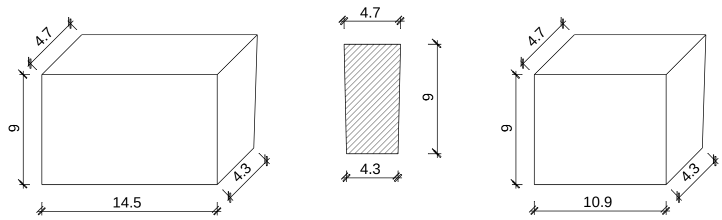


Fig. 7 Dimensions of the stone elements (cm)

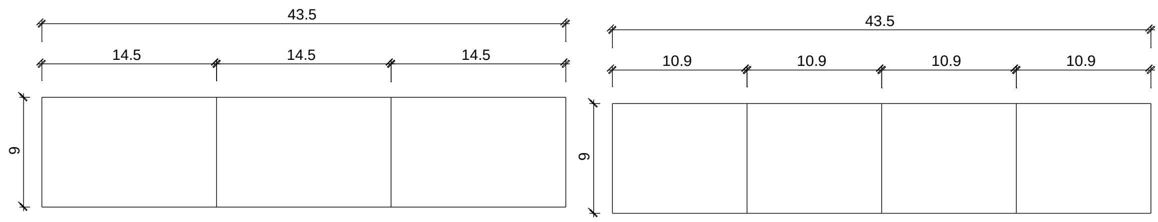


Fig. 8 The arrangement of the vault (cm)

of Earthquake Engineering and Engineering Seismology–IZIIS, Skopje, Republic of North Macedonia. The shaking table equipment at the Institute enables the programmed generation of translational vibrations in the horizontal and vertical directions.

The Old Bridge model is built in a 1:9 scale by Kustura (2018). The selected scale is also conditioned by the dimensions of the 5×5 m shaking table. The total length of the tested model with the foundation structure is 3.76 m, the span is 3.16 m, and the height of the arch from the foundation to the lower point of the vault is 1.33 m (see Figs. 5 and 6).

Two types of dimensions of the stone elements, shown in Fig. 7 were used for the construction of the bridge vault. A total of 324 pieces of stone elements, comprising 93 rows which formed the model vault, were prepared.

Rows were made as triple or quadruple rows, shown in Fig. 8. and a total of 92 rows were made alternately, while the central row was made of one stone element.

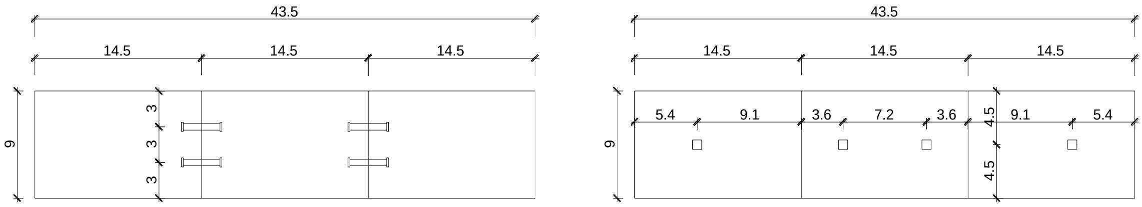


Fig. 9 Schematic layout of clamps and dowels (cm)

Table 1 Similitude requirements for the Old Bridge model

Scaling parameter	Scaling factor	Units	Prototype values	Model 1/9
Length	l_r	m	27.9	3.10
Time History	l_r	sec	60	6.67
Arch rise	l_r	m	11.9	1.33
Arch width	l_r	m	3.9	0.43
Time	l_r	sec	54	6
Frequency (longitudinal)	$1/l_r$	Hz	11.4	34.7
Frequency (vertical)	$1/l_r$	Hz	13.96	39.2
Gravity acceleration	neglected			
Mass density	1	kN/m^3	27	27
Strain	1	μstr	1	1
Input Acceleration (max.)	$1/ l_r$	g	0.25	2.4
Modulus of elasticity of stone	1	Mpa	$3x10^4$	$3x10^4$
Modulus of elasticity of steel	1	Mpa	$2.1x10^5$	$2.1x10^5$
Displacement	l_r	mm	1	1/9

The vault assembly method shown in Fig. 9 for the model followed the original vault assembly method of the prototype – the Old Bridge in Mostar. Clamps and dowels, as well as liquid lead, were used for connecting the stone blocks. The connecting elements, clamps and dowels, are also made to a 1:9 scale in relation to the actual structure.

2.1.2 Design of the model

The Old Bridge model is designed and constructed as a gravity force neglected model, Kustura (2018), with the use of stone, mortar and steel connecting elements materials of the equal or sufficiently similar properties as in the original structure. The physical model considered for the test is adequate, although the gravity forces neglected, because the stresses induced by gravity loads are small when compared to stresses induced by seismic forces. The stone *Varovnik* was used for the segments of the bridge vault, and Isomat-AK9 (initial tensile strength>0.50MPa) was used for mortar. The mechanical properties of the materials and some similitude requirements are provided below in Table 1.

It is obvious that there is some difference in the achieved and required frequency ratio model/prototype. The reasons for such difference are mainly due to the adopted scale, the thickness of mortar and its' strength that varies significantly with time, the way of supporting the arches, and probably the most important of all reasons is the way of construction of the prototype where each row of the arch has been compressed after placement, thus giving additional compactness and stiffness to the structure, that was not applied during the model construction.

What is important is that this difference in frequency is not influencing the main objective of this testing which is the investigation of the global behavior of the bridge model and the failure mechanism development.

2.1.3 Construction of the model

The model of the Old Bridge was constructed by preparing and placing the first blocks of stone on to the wooden formwork shown in Fig. 10(a) to confirm the adopted geometry of the model. The model was built following the rules of the prototype construction, where, besides the stone elements and clamps and dowels, liquid lead was used for filling effect (see Figs. 10 (b) and (c)). After the completion of construction, the model was mounted onto the shaking table test platform, shown in Fig. 11.

2.2 Instrumentation

The Old Bridge model was installed with 17 accelerometers, 11 relative displacement transducers

(a) (b) (c)

Fig. 10 Construction of the model

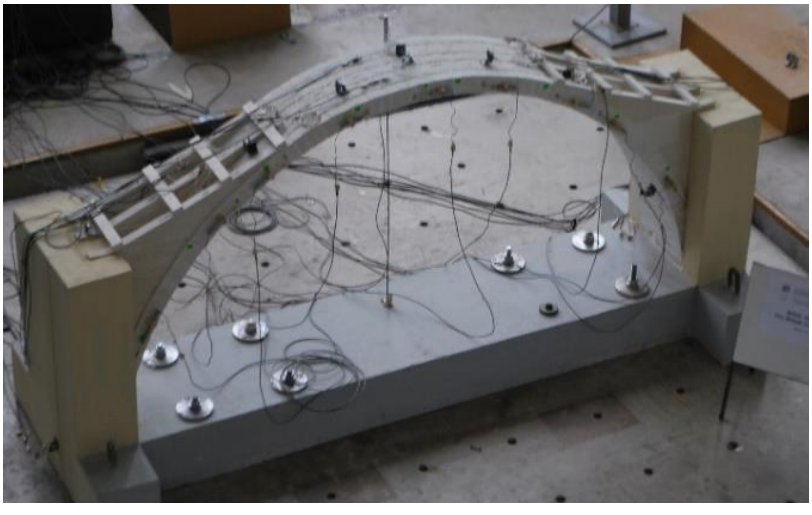


Fig. 11 The Old Bridge model in scale 1:9

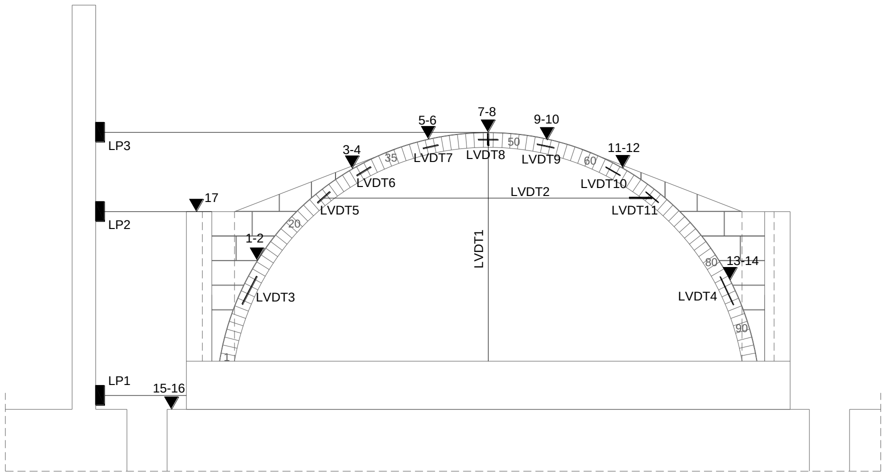


Fig. 12 Position of LPs (1-3), position of LVDT (1-11), position of accelerometers (1-17)

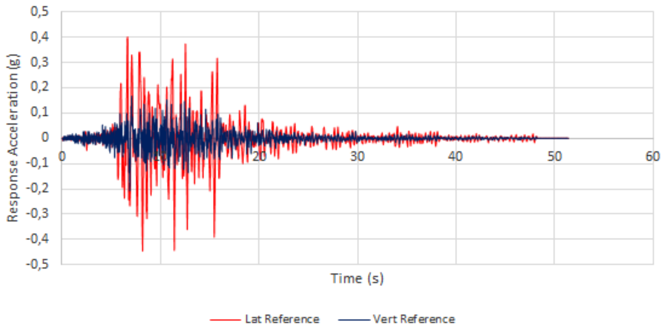


Fig. 13 Time history for Petrovac (Montenegro) earthquake 1979

(LVDT), and 3 absolute displacement transducers (LPs). In total, the instrumentation of the model included 31 measurement points, shown in Fig. 12 and the instruments were placed at the points of the greatest expected strains. These are the top of the arch points and the points of one-third zone of the arch.

2.3 Seismic loading characteristics

The dynamic excitation was applied simultaneously in the longitudinal (Y) and vertical (Z) directions.

For seismic testing, the accelerogram of the Petrovac (Montenegro) earthquake from 15 April 1979 shown in Fig. 13 was applied, which was scaled in time domain by the factors 1:9, 1:6 and 1:3 for the purposes of testing and for the excitation of the model vibrations in the resonant state, Kustura (2018).

A total of 39 tests were conducted shown in Table 2, of which 14 were conducted for the purpose of periodically determining dynamic characteristics and assessing the model stiffness degradation (Random and Sweep), while the other 25 tests were seismic tests designed for monitoring the model response and the development of the failure mechanism (Kustura *et al*. 2018).

Table 2 Basic characteristic of conducted tests

Mark	Type of excitation/input intensity/SF	Mark	Type of excitation/input intensity/SF
Test_01	Random / 3-55Hz / a=0.01g / X	Test_21	Random / 3-55Hz / a=0.01g / V
Test_02	Random / 3-55Hz / a=0.01g / Z	Test_22	Petrovac / Y=1.49g / Z=0.75g / SF 1:9
Test_03	Sweep / 3-55Hz / a=0.01g / X	Test_23	Petrovac / Y=1.79g / Z=0.85g / SF 1:9
Test_04	Sweep / 3-55Hz / a=0.02g / X	Test_24	Petrovac / Y=1.90g / Z=0.90g / SF 1:9
Test_05	Sweep / 3-55Hz / a=0.02g / X	Test_25	Petrovac / Y=2.1g / Z=1.6g / SF 1:9
Test_06	Sweep / 3-55Hz / a=0.02g / X	Test_26	Random / 3-55Hz / a=0.01g / H
Test_07	Petrovac / Y=0.04g / Z=0	Test_27	Random / 3-55Hz / a=0.01g / V
Test_08	Petrovac / Y=0.02g / Z=0	Test_28	Petrovac / Y=2.10g / Z=1.25g / SF 1:9
Test_09	Petrovac / Y=0.07g / Z=0.05g	Test_29	Petrovac / Y=2.30 g / Z=1.50g / SF 1:9
Test_10	Petrovac / Y=0.14g / Z=0.12g	Test_30	Petrovac / Y=2.38g / Z=1.8g / SF 1:9
Test_11	Petrovac / Y=0.27g / Z=0.20g	Test_31	Petrovac / Y=0.38g / Z=0.15g / SF 1:6
Test_12	Random / 3-55Hz / a=0.01g / H	Test_32	Petrovac / Y=0.74g / Z=0.30g / SF 1:6
Test_13	Random / 3-55Hz / a=0.01g / V	Test_33	Petrovac / Y=1.35g / Z=0.60g / SF 1:6
Test_14	Petrovac / Y=0.24g / Z=0.16g / SF 1:9	Test_34	Petrovac / Y=2.40g / Z=0.90g / SF 1:6
Test_15	Petrovac / Y=0.44g / Z=0.38g / SF 1:9	Test_35	Random / 3-55Hz / a=0.01g / H
Test_16	Petrovac / Y=0.51g / Z=0.40g / SF 1:9	Test_36	Random / 3-55Hz / a=0.01g / V
Test_17	Petrovac / Y=0.69g / Z=0.45g / SF 1:9	Test_37	Petrovac / Y=0.40g / Z=0.20g / SF 1:3
Test_18	Petrovac / Y=1.01g / Z=0.50g / SF 1:9	Test_38	Petrovac / Y=1.24g / Z=0.46g / SF 1:3
Test_19	Petrovac / Y=1.25g / Z=0.65g / SF 1:9	Test_39	Petrovac / Y=2.30g / Z=1.15g / SF 1:3
Test_20	Random / 3-55Hz / a=0.01g / H		

2.4 Results of experimental investigation

Due to a substantial number of measuring points (31 in total) and the number of tests (39 in total), a large number of results was yielded by the experimental research in terms of the history acceleration diagram, oscillation frequency, absolute and relative displacement of the structure. For the purpose of this paper, the following test results were selected: Test_16 related to the linear behaviour, Test_22 where the first cracks occurred, Test_33, Test_34, Test_38 where the cracks further developed and Test 39 where the model collapsed.

As previously stated, the results presented in this paper and shown in Fig. 14 represent the time history of the horizontal displacement at the top of the arch for the selected test. The failure mechanism is presented later in the text.

3. Numerical analysis

The numerical analysis of the Old Bridge model was performed by the numerical model for dry-stone masonry structures based on the combined finite-discrete element method which can simulate the movement of stone blocks, their fracture and fragmentation, yielding and extracting of the clamps and dowels, and the collapse mechanism of the structure. The model was developed for non-reinforced and reinforced dry-stone masonry structures and recently applied in various examples of 2D and 3D masonry structures (Smoljanović *et al*. 2013a, Smoljanović *et al* 2013b, Smoljanović *et*

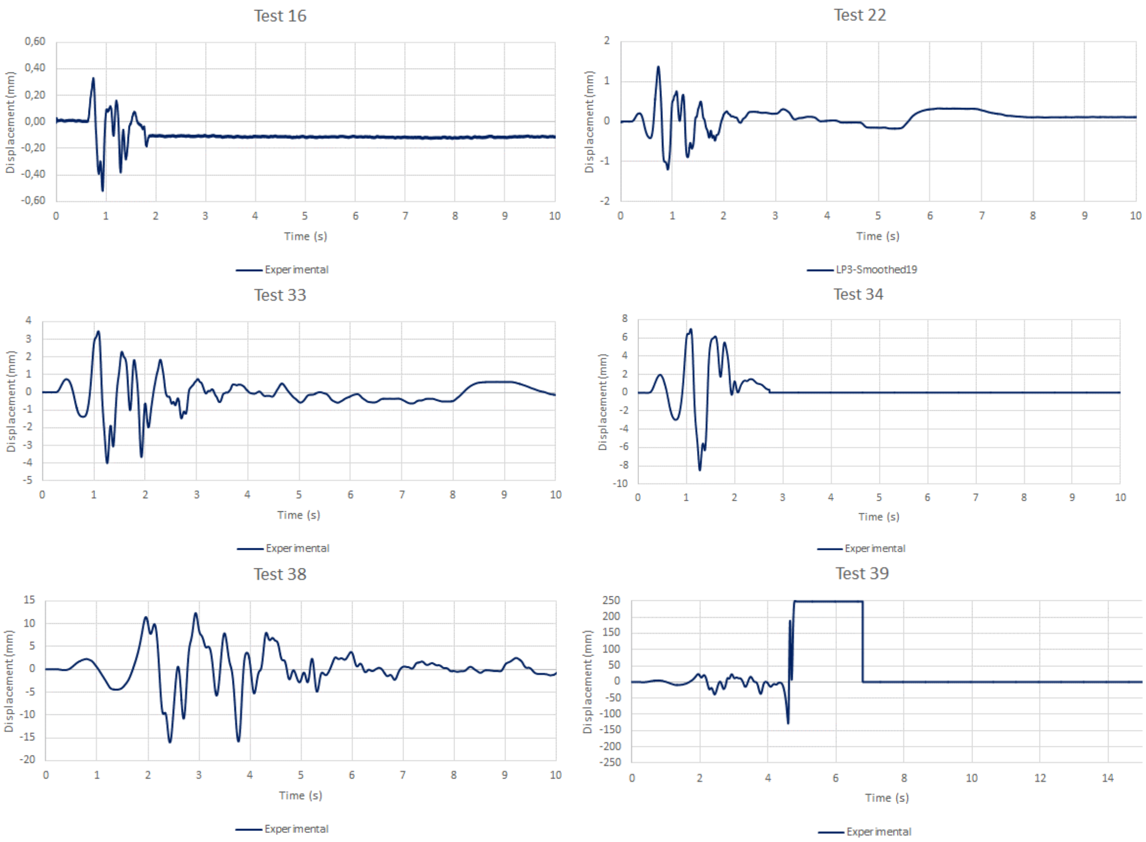


Fig. 14 Time histories for the horizontal displacements at the top of the arch

al. 2015, Smoljanović *et al*. 2018).

This numerical model was used for the simulation of the dynamic response of the model of the Old Bridge in Mostar, subjected to seismic load, which is shown further in the paper. The geometry of the model used in the numerical analysis is presented in the previous sections.

3.1 Basis of combined finite-discrete element method

The combined finite-discrete element method (FDEM) (Munjiza *et al*. 1995, Munjiza *et al*. 2004) is intended to simulate the defragmentation process considering the deformable blocks subject to breaking, which may result in the fragmentation of one block into several blocks during the analysis. The deformability of the discrete elements is enabled by discretising each one by their own finite element mesh. Material non-linearity was modelled by the contact elements inserted between the mesh of triangular finite elements, thus simulating the occurrence and development of cracks. The inclusion of all mentioned effects is ensured by developing the algorithms that, at any time step, include the detection and interaction of a contact, the monitoring of the state of stresses and strains in the finite and contact elements, the occurrence and development of cracks, the integration of the equation of motion over time including large displacements and rotations, and the visualisation of said effects.

One of the important parameters whose evaluation can substantially affect the accuracy of the results is the value of the penalty coefficient, which is significant for the issues where the force-displacement dependence is monitored. Due to the use of the penalty method for calculating the contact forces, the combined finite-discrete element method contains a solution error in the analysis of those issues when the force-displacement relationship is monitored. The penalty coefficient regulates the value of penetration of one finite element into the other during contact interaction, but also the value of separation of finite elements before the crack occurrence. The penalty coefficient value eliminating the value of the error directly affects the duration of calculation, while the selection of a higher value of the penalty coefficient, due to the usage of explicit integration of motion equations, results in a shorter time step leading to a several times longer calculation time. In the numerical examples provided by the combined finite-discrete element method, it is necessary to evaluate the minimum value of the penalty coefficient that will reduce the relative displacement error to an acceptable level (Smoljanović *et al*. 2015).

The second important parameter is the value of the damping coefficient resulting in the loss of energy in the dynamic contact of two discrete elements, which can significantly affect the behaviour of masonry stone structures during earthquakes. In the combined finite-discrete element method, damping is also used in the static analysis for the avoidance of the dynamic effects due to the application of a monotonously increasing load. In order to properly assess the value of the damping coefficient that will be used in the numerical analysis, it is necessary to have a vast knowledge of all the effects that damping can cause in the structure.

3.2 Discretisation of a dry-stone structure with steel clamps and bolts

The dry-stone masonry structure is observed as a set of discrete elements, where each stone block is discretised by its own mesh of triangular elements, and the contact elements are implemented at the places of potential cracks (Muniza *et al*. 2000, Munjiza *et al*. 1998) considering the Coulomb law of friction (Xiang *et al*. 2009). Material non-linearity, fracture and fragmentation are considered through the contact elements which are implemented within the finite element mesh of each block.

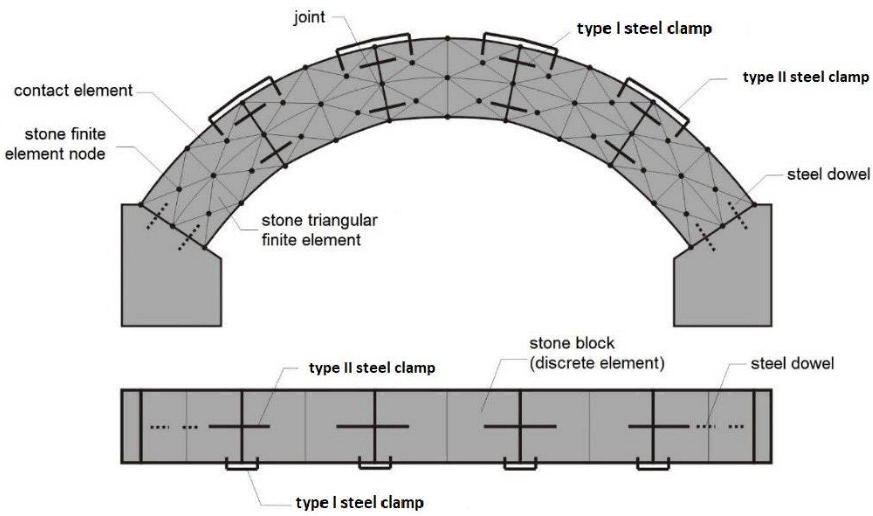


Fig. 15 Discretisation of a stone arch with installed clamps and dowels [11]

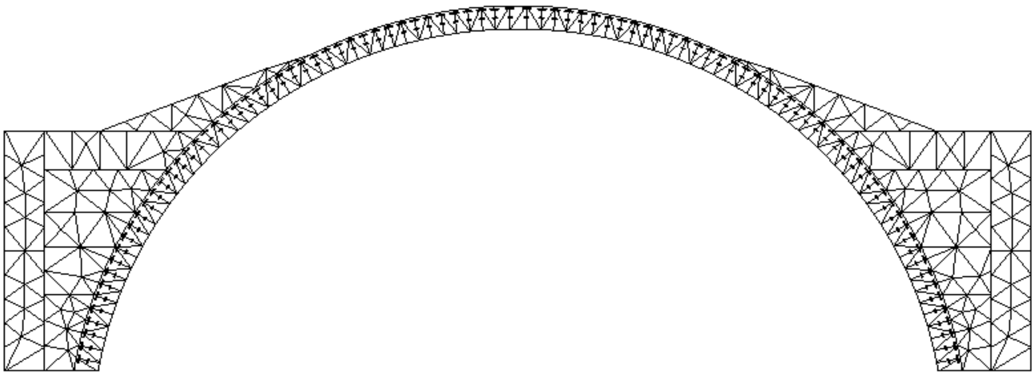


Fig. 16 Discretisation of the Old Bridge model

Steel clamps type I and II and steel dowels were modelled with one-dimensional element dowels (Smoljanović *et al*. 2015) which can be placed in arbitrary positions inside the stone finite elements, shown in Fig. 15. Type I steel clamps are placed perpendicularly to the front surface of the wall, while type II steel clamps, used in this analysis, are placed along the structure, usually on the upper side of the arch of stone masonry bridges. Steel dowels are also used as connecting elements in this analysis. A detailed description of geometrical and material models of the clamps and dowels can be found in literature (Smoljanović *et al*. 2015).

3.3 Input parameters for numerical analysis

The discretisation of the Old Bridge model shown in Fig. 16 is generated by a Y-2D computer programme with the implemented numerical model for steel clamps and bolts.

As previously stated, the penalty and the damping coefficient are the most important numerical parameters which significantly influence the model calculation. The penalty coefficient value, which was assumed in the numerical analysis at 3×10^{10}, is the recommended value for the numerical analysis of masonry stone structures using the FDEM method according to (Smoljanović *et al*. 2015). The damping coefficient is determined by the geometric and material properties (modulus of elasticity E, finite element size h, material density ρ) by the expression (Smoljanović *et al*. 2015)

$$\bar{\mu}_{kr} = \frac{2}{\sqrt{3}} h \sqrt{E\rho} \tag{1}$$

The mechanical properties of the stone elements used in this numerical model are associated with the mechanical properties of the stone *Varovnik* used for the experimental part of the research. The calibration of the numerical model was performed by modifying the yield and the ultimate strength and deformation of the steel elements, clamps and dowels. The basic parameters used as input data in the numerical analysis are provided in Table 3.

For the numerical analysis, the same type of seismic load is used (accelerogram of the Petrovac earthquake scaled 1:9, 1:6 and 1:3 in time domain). Same as for the experimental phase, Test_16, Test_22, Test_33, Test_34, Test_38 and Test_39 are selected for the presentation of the results obtained by the numerical analysis.

3.4 Results of the numerical analysis

Table 3 Basic input parameters for numerical analysis

Stone		Steel	
Elasticity Module, E (MPa)	3×10^4	Elasticity Module, E (MPa)	$2{,}1\times10^5$
Poisson coefficient, v	0.3	Cross-sectional area of clamp, A (m^2)	0.000008
Density, ρ (kg/m^3)	$2{,}66\times10^3$	Cross-sectional area of dowel, A (m^2)	0.0001
Penalty coefficient	3×10^{10}	Length of clamp entering the stone, L (m)	0.007
Static coefficient of friction, μ_{st}	$6{,}5\times10^{-1}$	Yield strength, fy (MPa)	70
Dynamic coefficient of friction, μ_{din}	$6{,}5\times10^{-1}$	Deformation at yield strength, ε_{sh}	0.0017
Damping coefficient, μ	2×10^5	Ultimate strength, fu (MPa)	90
		Limit deformation, ε_u	0.05
		Deformation at failure, ε_{br}	0.095

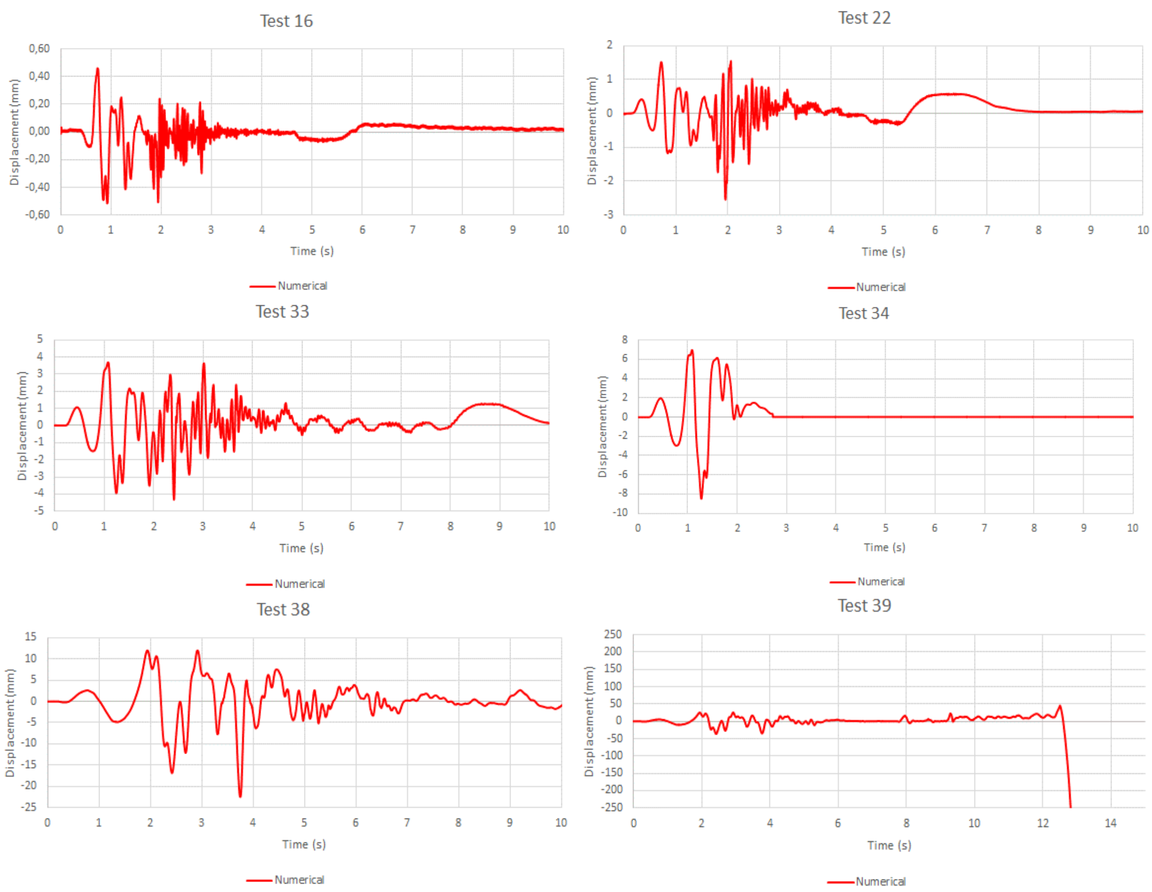


Fig. 17 Time histories of the horizontal displacements at the top of the arch

In this section, the time history of the horizontal displacement at the top of the model for the selected test is presented in Fig. 17. The failure mechanism of the model is presented later in the text.

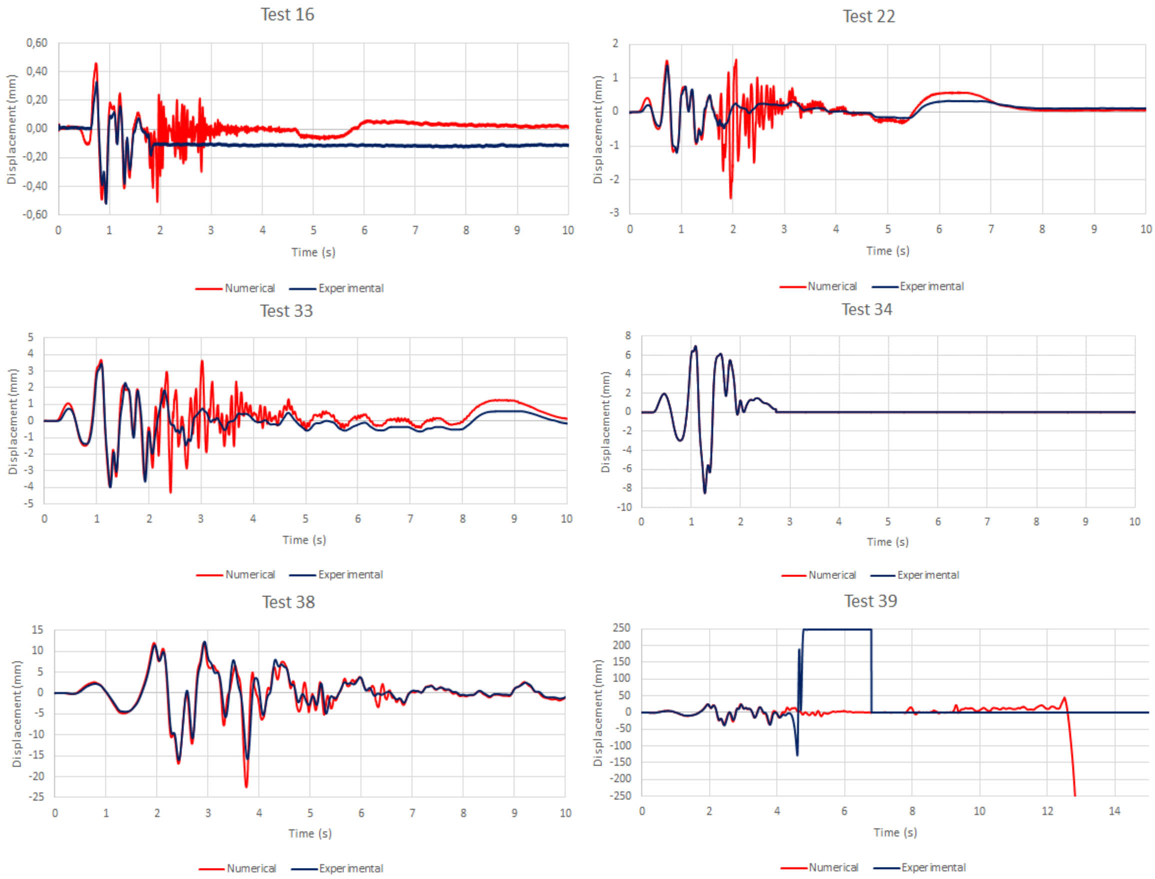


Fig. 18 Comparison of the time histories of the horizontal displacements at the top of the arch

4. Comparison of the experimental and numerical results

The comparison of the obtained displacement results is limited to selected tests and characteristic points at the top of the arch, including the comparison of the model failure mechanism of the model for Test_39.

4.1 Comparison of the absolute horizontal displacement at the top of the arch

Further in the text, shown in Fig. 18 is presented the comparison of the time histories of absolute horizontal displacements obtained during the experimental testing and the displacements obtained by the numerical analysis.

4.2 Comparison of the failure mechanism

In the following section, the failure mechanism and response of the Old Bridge model is analysed in terms of the input load that resulted in the collapse of the structure, for both the experimental and the numerical phase. Initial stage of model is shown in Fig. 19. The failure and collapse of the

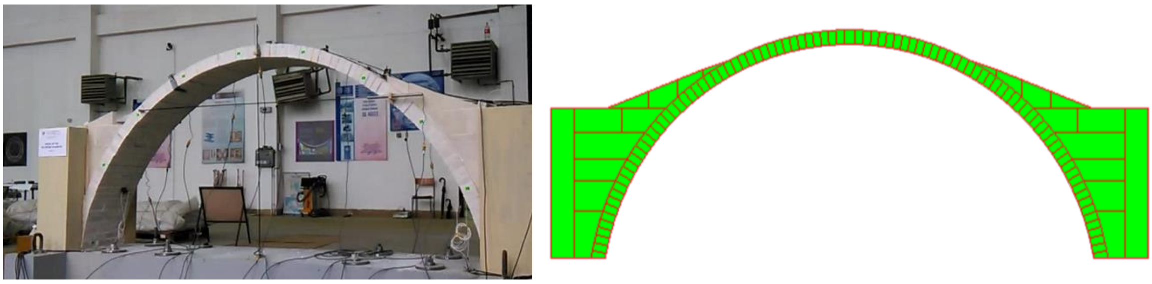


Fig. 19 Initial stage

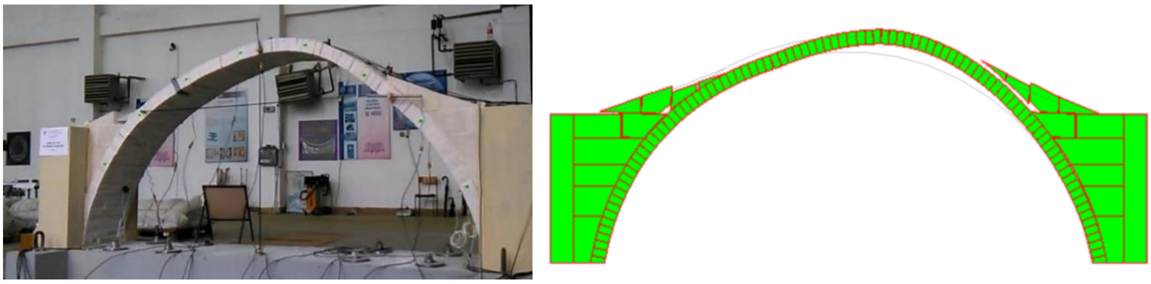


Fig. 20 Mode shapes and failure mechanism for Test_39–initial cracks

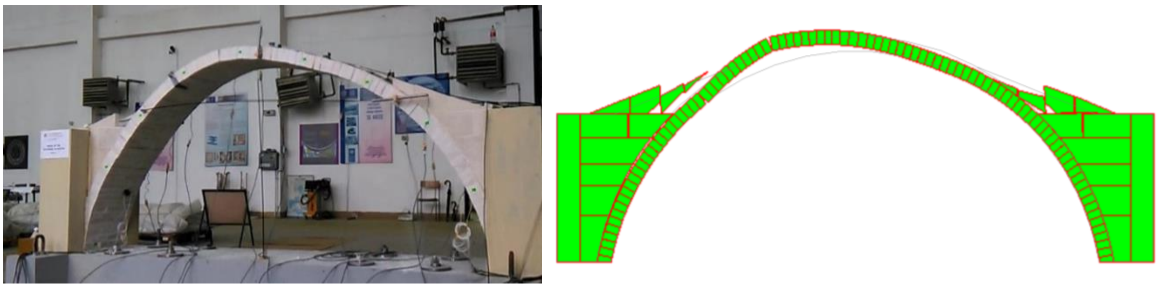


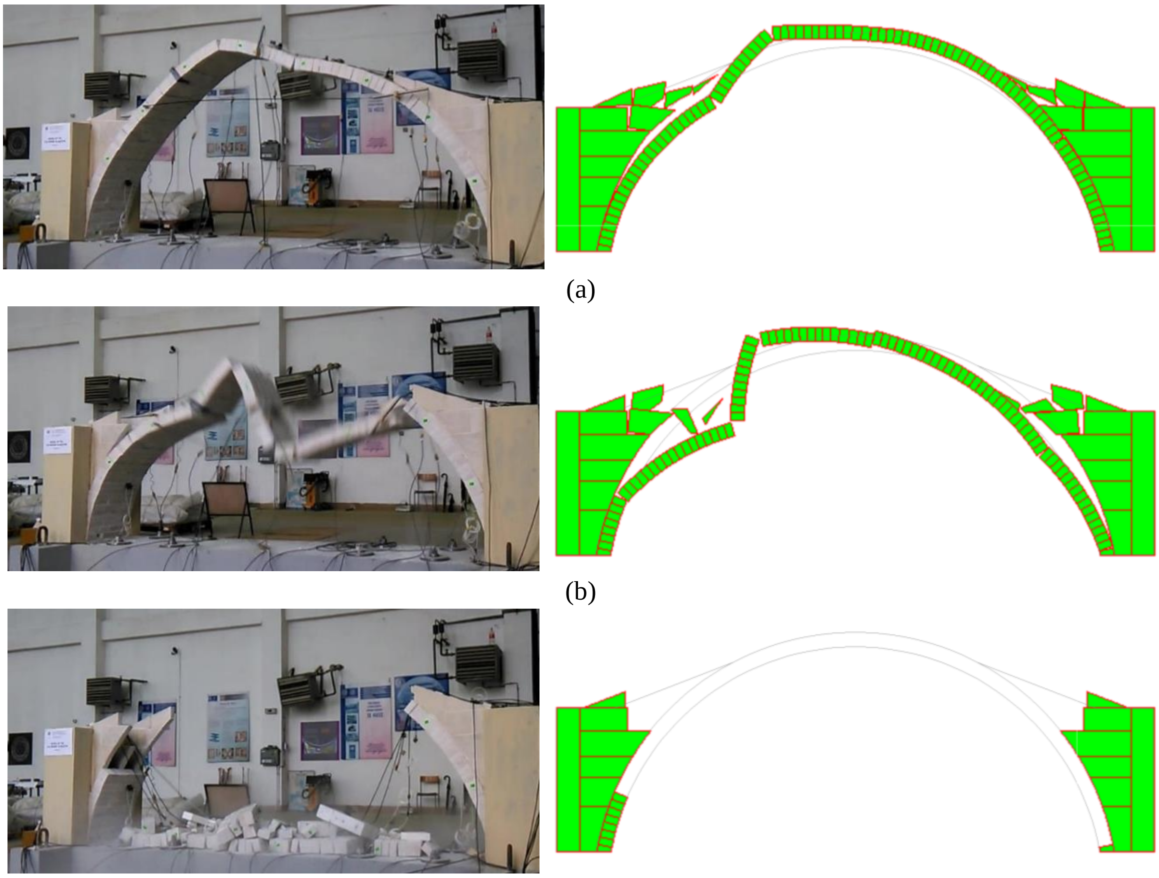
Fig. 21 Mode shapes and failure mechanism for Test_39–crack development

structure occurred for Test_39, or for the input acceleration of the Petrovac earthquake of 2.27 g scaled to the 1:3 ratio in Time domain.

The experimental tests and the numerical analyses show that the initial phase of the model failure is characterised by the deformation and separation of the spandrel wall elements, shone in Fig. 20 and the lifting of the model arch.

With the further increase of the input load, the structure increasingly deformed and the model arch was significantly lifted, shown in Fig. 21 for both the experimental and the numerical analysis. Pronounced deformations of the model arch also resulted in the cracks in the one-third zone points of the arch and near the top of the arch. They first occurred on one side of the arch and, with further deformation, they symmetrically occurred on the other side of the arch.

By further loading, the connections failed at the top of the arch zone and in the one-third zone points, followed by the separation of the bridge vault from the spandrel walls and the collapse of the structure (see Figs. 22 (a)-(c)), Kustura (2018).



(a)

(b)

(c)

Fig. 22 Mode shapes and failure mechanism for Test_39–collapse of the model

5. Conclusions

This paper presents experimental and numerical analysis of the global behaviour of the 1:9 scale model of the famous Old Bridge in Mostar.

The experimental investigation provided useful information about the mechanism of damage and failure. A considerable number of time history diagrams of accelerations, frequencies, absolute and relative displacements and strains at 31 measuring points for all 39 excitations provide useful data for further analysis regarding efficiency of the connecting elements between the stone units, which had a special role in protecting the structure from collapse.

Numerical modelling based on the combined finite-discrete element method (FDEM method) with a possible modelling of contact interaction, energy dissipation during impact, block deformability, fracture and fragmentation is suitable for determining the global behaviour and establishing the failure mechanism.

In summary, the following items should be emphasised:

- 25 seismic tests were performed until the total collapse of the model with the gradual increase in the input intensity from 0.04 g to 2.40 g, with different time scaling factors – 1:9, 1:6 and 1:3,

in order to provoke resonant conditions and intensive vibration of the model;
• A stable vibration was observed for the maximum real intensity of Petrovac earthquake, 0.44 g.
• The effectiveness of the connecting elements (clamps and dowels) for the significant improvement of the seismic stability, increased load bearing and deformation capacity as well as for enabled successive development of the failure mechanism was detected and confirmed;
• The last test with an input acceleration of 2.30 g (which is far from a realistic intensity) resulted in significant displacements, pulling-out of the connecting elements from the holes, loss of stability and consequential total collapse of the model;
• The time histories of displacement at the top of the arch obtained by the numerical analysis are fairly consistent with the results obtained by the experimental phase;
• The observed differences of the response curves in time regarding the displacements of characteristic points of the Old Bridge model can also be explained by the fact that the input parameters of the numerical model are the same through all conducted tests, whereas in the experimental testing, the characteristics of the model are different in relation to the previously conducted one as a result of specifying multiple dynamic excitations in sequence for each following test;
• The global behaviour of the model related to mode shapes, occurrence of damage and failure mechanism agrees rather well with the experimental studies;
• The level of input excitation at which the model failure and collapse occurred is the same for the experimental tests and the numerical analyses.

We can say that the importance of this research reflects in new knowledge of the complex behavior of this type of structures under dynamic loads when the effects of applied connection elements are considered. The originality of this work reflects in the fact that such a complex research on stone masonry arch structures, which also involved detailed experimental modeling of clamps/dowels-lead-stone connection elements. An additional value of presented work is in the fact that most structures with such structural characteristics are usually a part of historical heritage structures, and it is our obligation to better understand their behavior under dynamic loads.

6. Guidelines for further research

There are various possibilities for further research of seismic resistance of masonry arch structures that would allow researchers to obtain more results experimentally and thus increase the accuracy of the conducted analyses. Some of these are as follows:
• Soil-structure interaction is significant for understanding the complex behaviour of masonry arch bridges, hence the future research should further investigate and shed more light onto this issue;
• Micro-modelling of interaction in the connection – stone, connecting elements, lead - is another activity that requires certain answers and consideration of local effects;
• The applied testing procedure and the applied technique of model construction will be helpful to future similar research. The observed damage and the development of cracks for different levels of dynamic loads can be useful for improving the existing regulations defining or proposing procedures for the rehabilitation and reconstruction or monitoring of the masonry arch structures. In addition, determination of the most vulnerable zones on a masonry arch model could be also useful for defining the monitoring procedure on these types of structures;

• The performed research is a valuable contribution to a more comprehensive understanding of the behaviour of masonry arch bridges, as well as their future preservation;
• In case of the Old Bridge in Mostar, the current situation is that there are no observations on the bridge other than geodetic ones, therefore we strongly suggest the installation of the on-line monitoring system on the bridge at the characteristic points. Considering the observed cracks on the bridge vault, it is strongly recommended to perform ambient vibration measurements to explore the bridge natural frequencies, mode shapes and damping coefficients, in order to set a realistic mathematical model for performing a detailed and precise numerical analysis.

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