Computers and Concrete, *Vol. 18, No. 1 (2016) 099-112*
DOI: http://dx.doi.org/10.12989/cac.2016.18.1.099

Finite element modeling of the influence of FRP techniques on the seismic behavior of historical arch stone bridge

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(Received November 7, 2015, Revised March 11, 2016, Accepted April 6, 2016)

Abstract. Since the preservation of monuments is very important to human societies, different methods are required to preserve historic structures. In this paper, 3D model of arch stone bridge at Pont Saint Martin, Aosta, Italy, was simulated by 1660 integrated separate stones using ABAQUS® software to investigate the seismic susceptibility of the bridge. The main objective of this research was to study a method of preservation of the historical stone bridge against possible earthquakes using FRP techniques. The nonlinear behavior model of materials used theory of plasticity based on Drucker-Prager yield criterion. Then, contact behavior between the block and mortar was modeled. Also, Seismosignal software was used to collect data related to 1976 Friuli Earthquake Italy, which constitutes a real seismic loading. The results show that, retrofitting of the arch stone bridge using FRP techniques decreased displacement of stones of spandrel walls, which prevents the collapse of stones.

Keywords: historical stone bridge; spandrel walls; finite element simulation; ABAQUS; modeling; dynamic loads; earthquake resistant structure

1. Introduction

FRP is a composite material used to strengthen masonry structures against the most critical failures. Strengthening with FRP enhances stress resistance of the structure (Lourenço and Oliveira 2006 and Lorenzis, Dimitri, and Tegola 2007 and Saileysh Sivaraja *et al.* 2013).Until now, several buildings such as masonry buildings, bell tower, arch bridge, etc. have been retrofitted using FRP techniques. Current technology enhances strength of the stone arches and masonry structures, which is directly connected to the surface of the stone (Anania, Badalà, and D'Agata 2013 and Foraboschi 2004). In addition, the use of embedded FRP bars in mortar improved seismic

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http://www.techno-press.org/?journal=cac&subpage=8 ISSN: 1598-8198 (Print), 1598-818X (Online)

Fig. 1 The Roman Arch Bridge of Pont St Mart

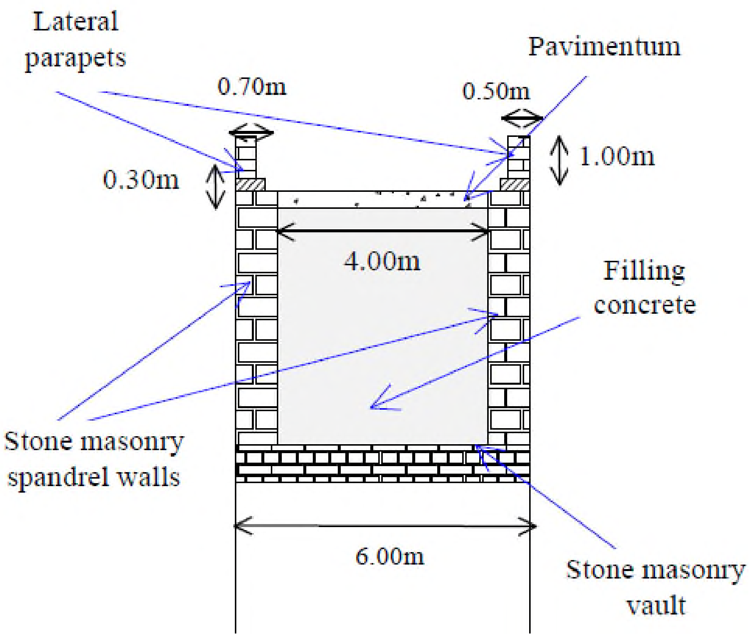
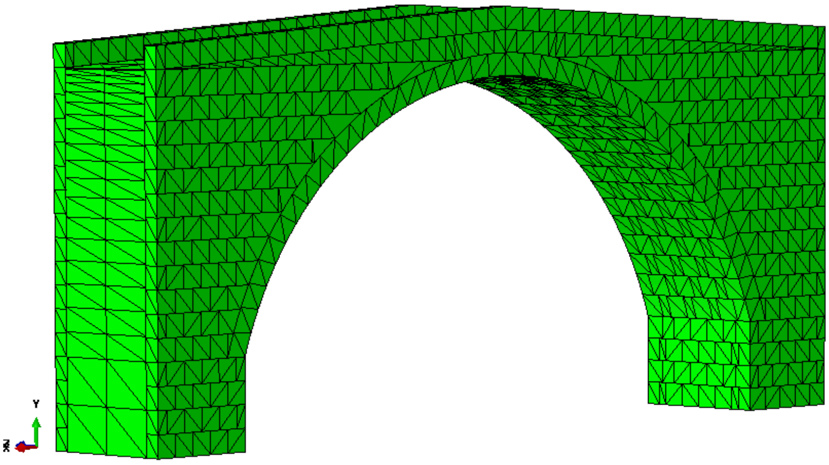


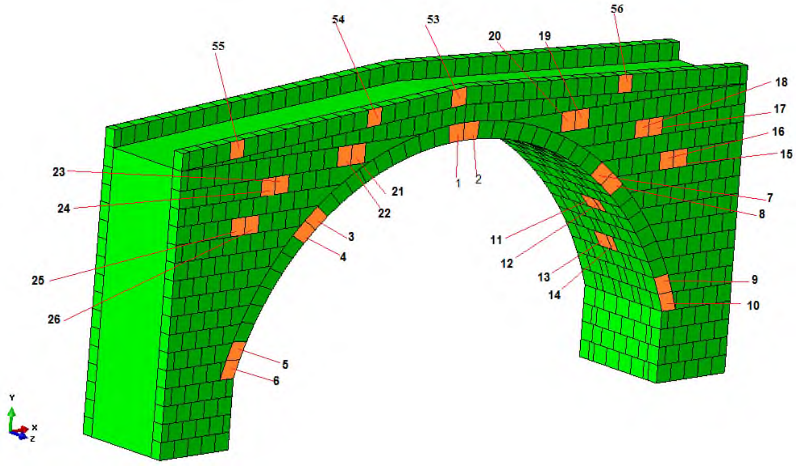
Fig. 2 Bridge cross section (Frunzio, Monaco, and Gesualdo 2001)

performance and integrity of stones (Milani and Bucchi 2010).

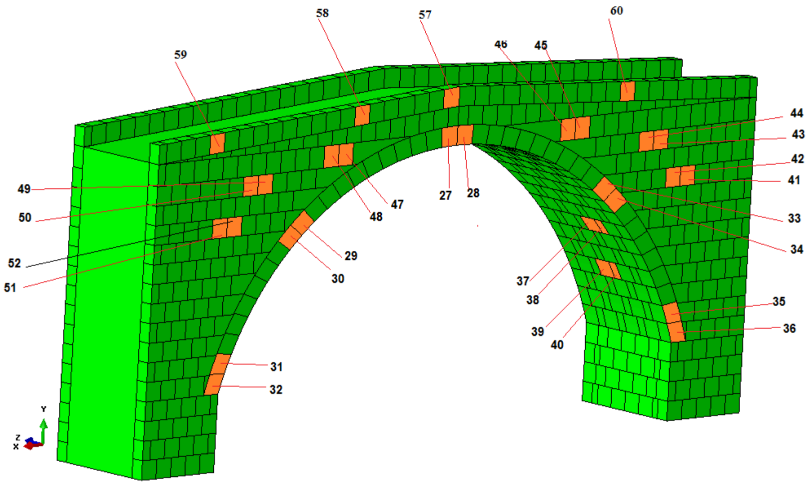
This research involves a structural analysis of an arch stone bridge in Saint Pont Martin, Aosta, located in LYS Valley, Italy, which is currently in good condition (Franciosi 1986). Stones from Rome have been used to construct the bridge. The span of bridge is 31.4 m and its radius is 16.5 m radius, as shown in Fig. 1. Fig. 2 shows the cross-sectional view of the bridge. (Frunzio, Monaco and Gesualdo 2001 and Page and Ives 1991).



(a) Tetrahedron quadratic mesh of the bridge (C3D10M)



(b) Right wall



(c) Left Wall

Fig. 3 numbering of finite element model in ABAQUS software

Table 1 Material properties

Material	Modulus of elasticity (N/mm^2)	Poisson ratio	Cohesion (N/mm^2)	Friction Angle (°)	Density (kg/m^3)	Compressive yield stress (N/mm^2)	Dilation Angle (°)
Arch	3000	0.2	1.2	50	1600	6.6	35
Spandrel walls	2500	0.2	1	48	1400	5.2	32
Filling	1500	0.05	0.5	32	1300	1.8	17
Foundation	7000	0.25	1.8	58	1300	12.55	40
FRP	22000	0.3	--	--	--	--	--

2. Finite element model

2.1. Behavioral model of materials

Most materials used in the bridge were cut stones. Four different materials were used in the construction of the bridge, with its structural elements arch, walls, filling materials, and foundations, with the characteristics reported in Table 1 (Frunzio, Monaco and Gesualdo 2001). In addition, major efforts were made to formulate yield criteria in order to express the behavioral model of various materials over the past 100 years. Most of such criteria are good for only one particular material. In several cases, theory of plasticity of stone is based on Drucker–Prager yield criterion. (Yu *et al.* 2006)

To model masonry materials by finite element method, masonry materials (brick-stone) were modeled either as a continuous environment or a discontinuous environment where blocks are separated by mortar or contact elements, thus sliding between blocks may be possible. This analysis method requires very extensive computational work for real world structures. However, it is a valuable method, compared with time-consuming and costly experiments. Modeling of the behavior of contact between the blocks is an effective and efficient method for numerical simulation of masonry structures. Although, due to lack of archaeological knowledge, other modelling could be acceptable.

In this study, for seismic retrofitting the FRP is used. The FRP were modeled using 4100 “shell” elements, and for this purpose “S4R" element with 4 nodes and 6 degrees of freedom (three translational and three rotational) per node was chosen from the element library of the “ABAQUS.CAE". The thickness and length of FRP was about 1.0 mm and 0.5 m, respectively. Since the models used both shell and solid elements, “shell-to-solid couplings” were used to transition from FRP elements to stone elements. Each internal constraint of the shell-to-solid coupling distributes the forces and moments acting at its shell node as forces acting on the related set of coupling surface nodes on the solid elements.

2.2. Numerical model of the bridge

The bridge was modeled as 1660 separate stones. The numbering of selected blocks are presented in Fig. 3. By using penalty method, the coefficients of friction between the stones and coefficient of friction between the stones and mortars were 0.7 and 0.6, respectively. All materials were modeled using Drucker–Prager failure criterion model. In this study, the bridge was analyzed

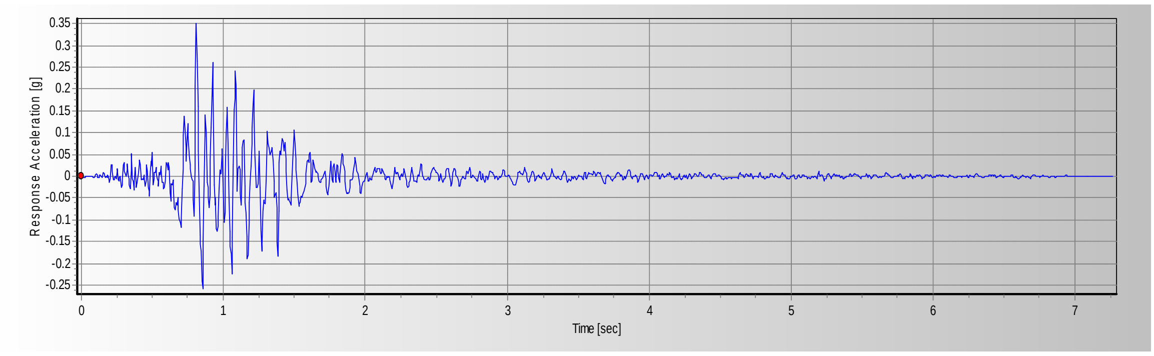


Fig. 4 Seismic acceleration

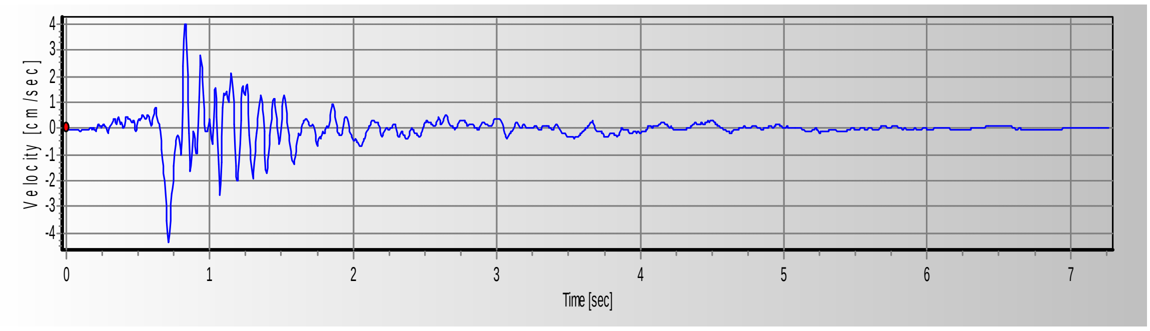


Fig. 5 Seismic velocity

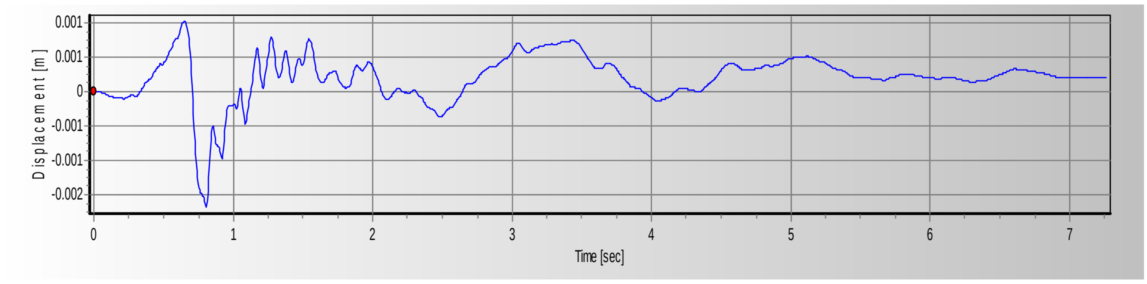


Fig. 6 Seismic displacement

under seismic and dead load, in presence and absence of FRP. All surfaces of the arch and spandrel wall were retrofitted using FRP, and the interaction between FRP and surface of stones was analyzed using solid shell coupling. Specifications of FRP are provided in Table 1.

2.3 Earthquake

Since the objective of this research was to study a method of retrofitting arch stone bridge, a real seismic loading was required. For this purpose 1976 Friuli Earthquake, Italy, was used. The earthquake data was obtained using seismosignal software. This was an 8 magnitude earthquake with duration of 7 seconds, as shown in Figs. 4 to 6. Seismic loading was applied to the bridge in z direction.

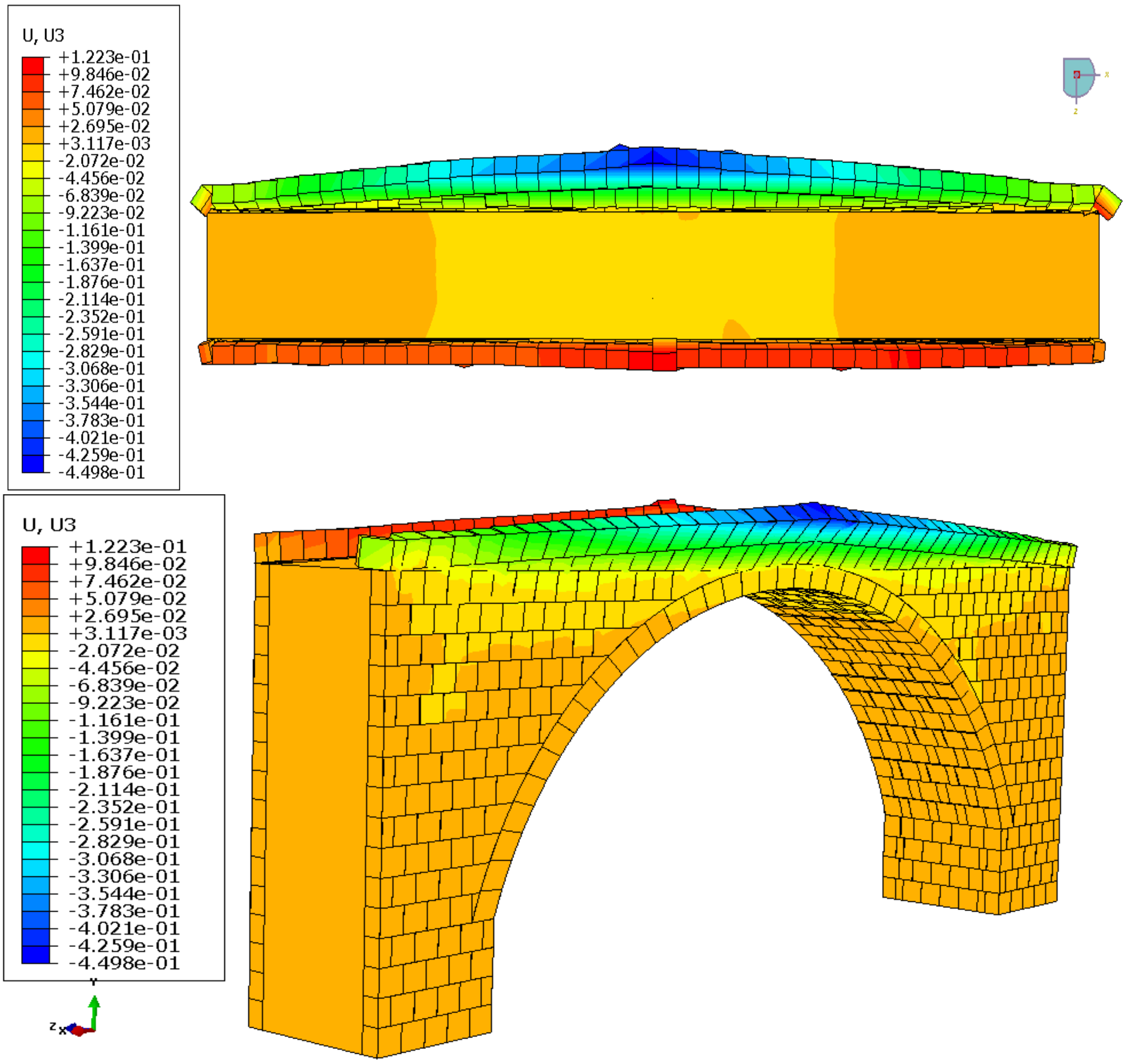


Fig. 7 Displacement(m) in the Z direction of the bridge retrofitted with FRP

3. Results and discussions

The maximum displacements of blocks in z direction before and after retrofitting with FRP are shown in Figs. 7 and 8. As can be seen, retrofit of bridge structures using FRP significantly reduces the displacement of stones. Experimental results demonstrated that strengthening of masonry with FRP has a very significant effect on the arch resistance against the earthquake. This effect may increase arch's strength by 20 times (Baratta and Corbi 2007, Tao, Stratford and Chen 2011)

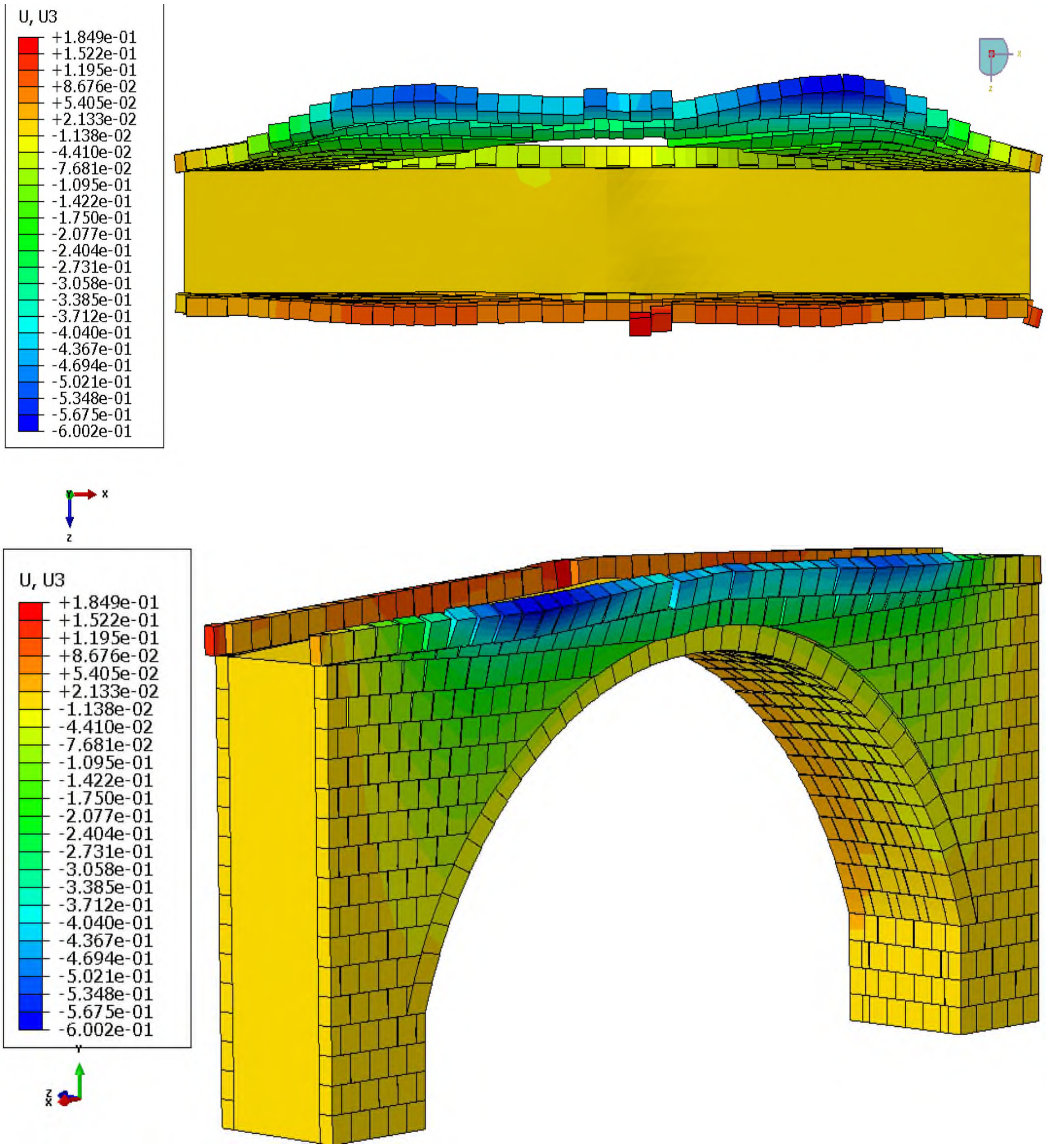


Fig. 8 Displacement(m) in Z direction of non-retrofitted bridge

Obtained results from the stone bridge that was under seismic load, indicates that the blocks on the right wall of the bridge before retrofitting with FRP has been little displacement. However, the displacement of the blocks with the FRP reinforcement has been reduced dramatically. (Figs. 9 and 10)

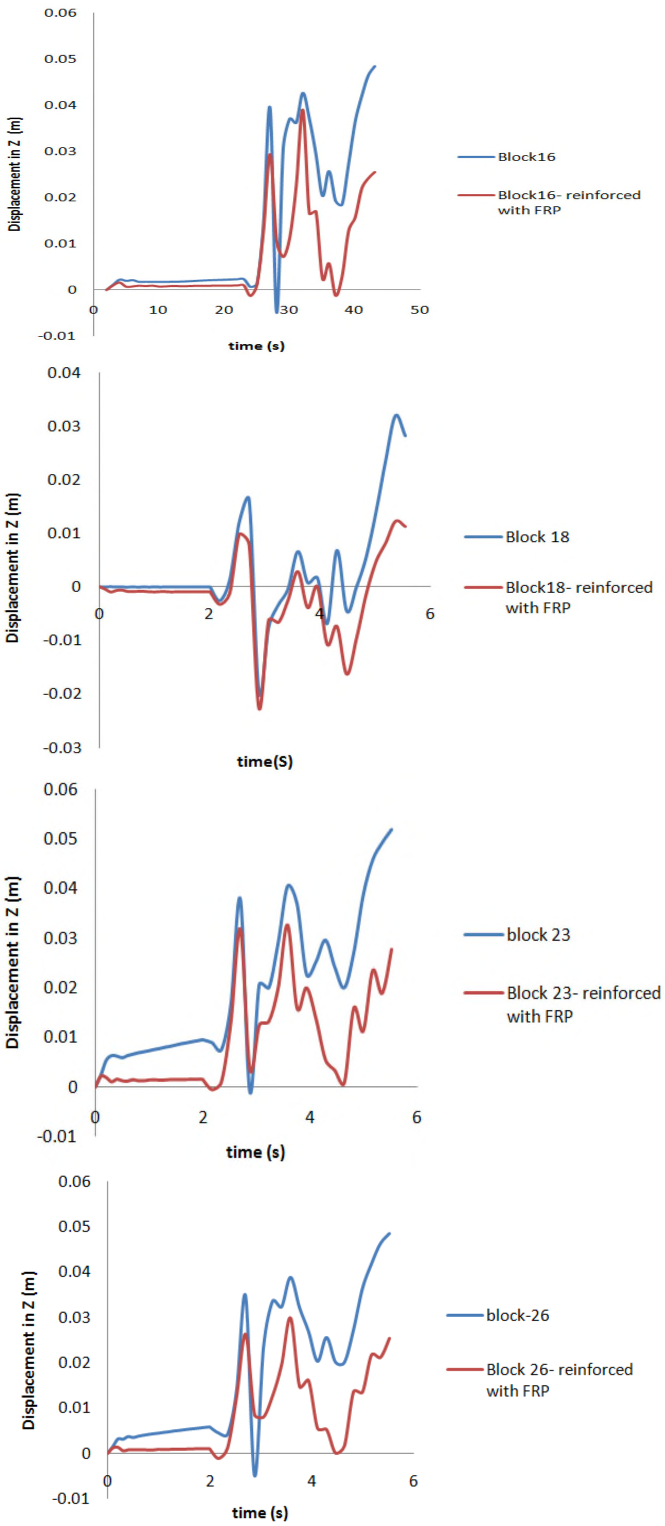


Fig. 9 Displacement(m) in the Z direction of the right wall of bridge

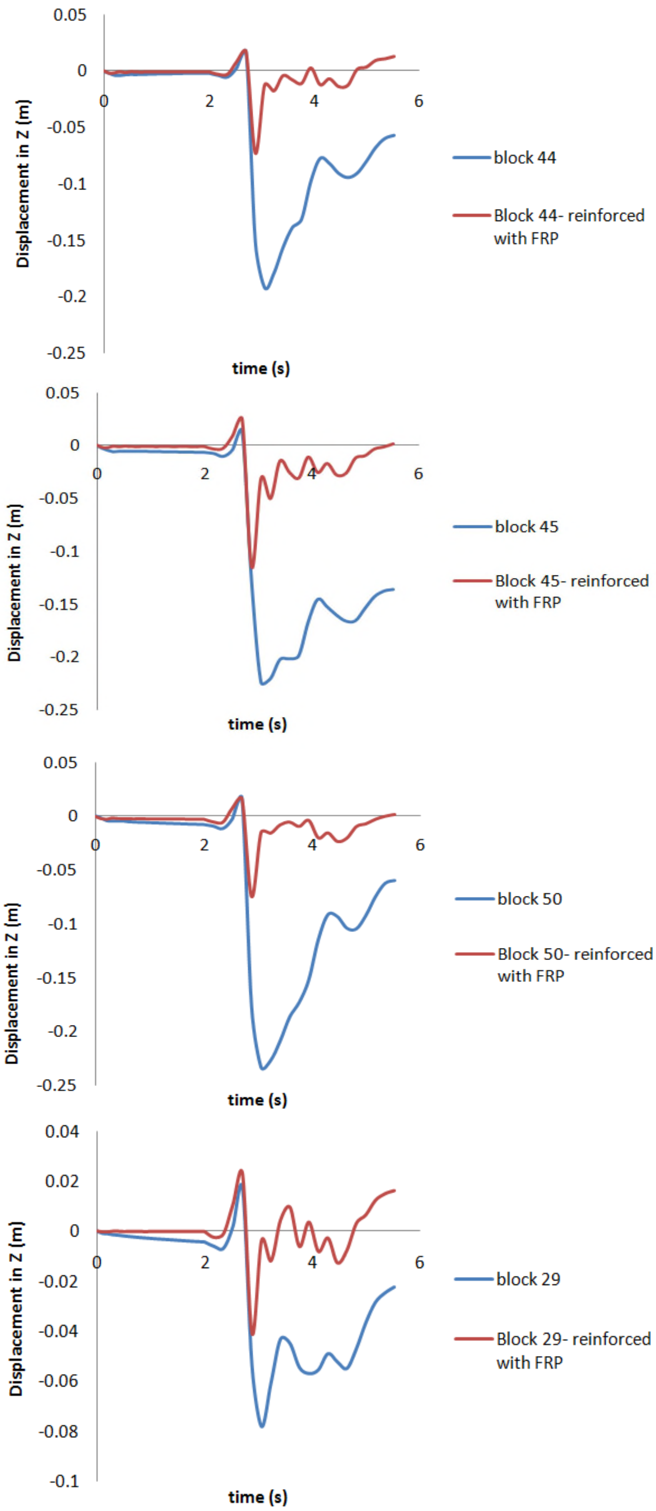


Fig. 10 Displacement(m) in the Z direction of the left wall of bridge

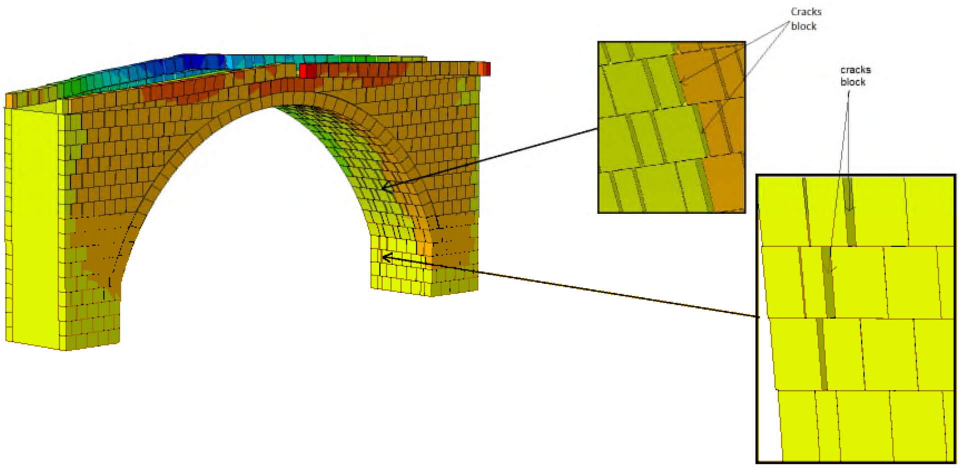


Fig. 11 Expansion of cracks in the bridge

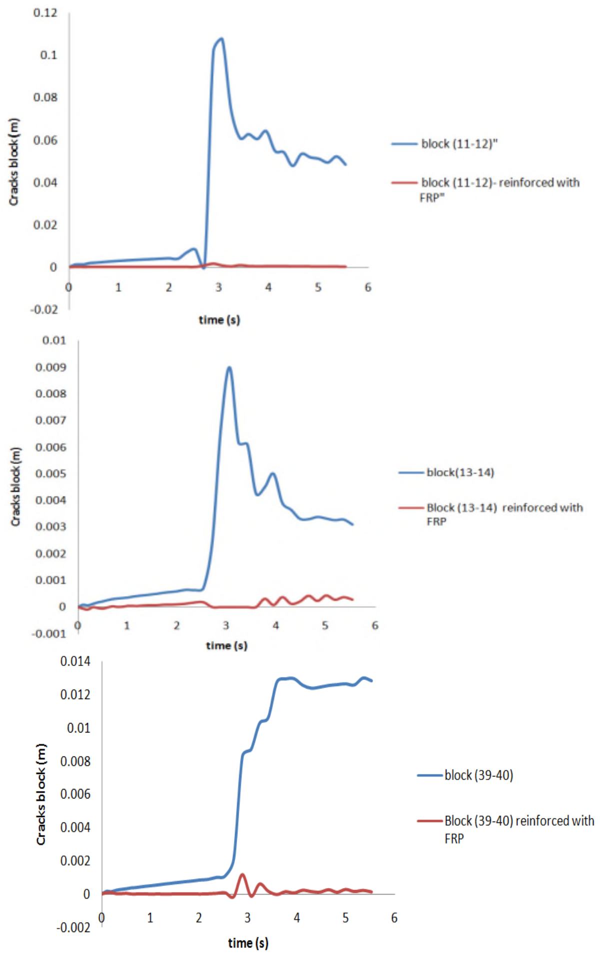


Fig. 12 Cracks (m) between the blocks before and after retrofitting

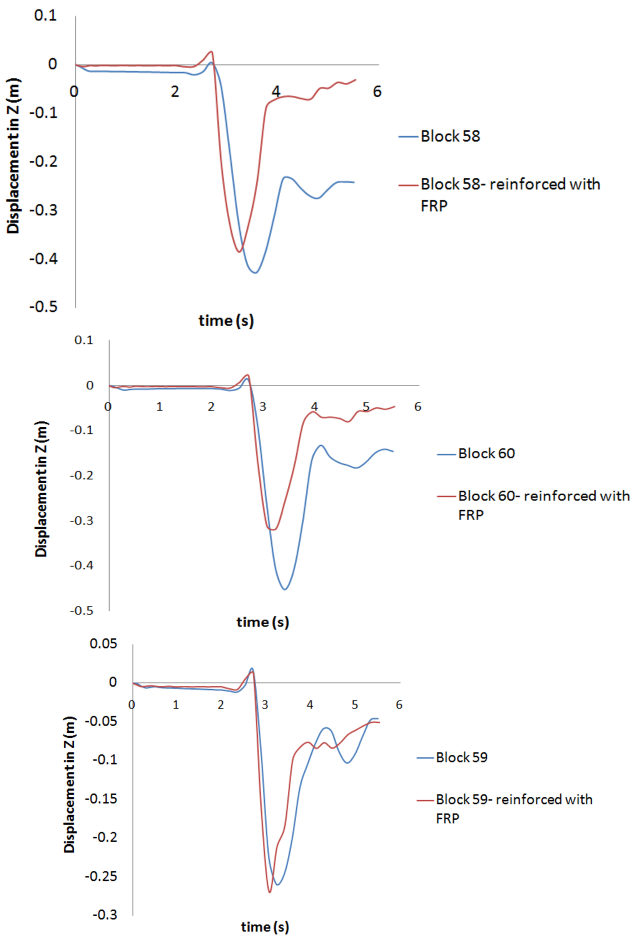


Fig. 13 Displacement(m) in the Z direction of the left parapets of bridge

Obtaining results from the left wall show that the displacement of some blocks before retrofitting with FRP is up to 0.25 meter that causes destruction of the bridge. By retrofitting the left wall using FRP, the displacements of wall blocks effectively reduced and at the maximum is about 0.1 meter that preserves the lateral wall of the bridge. (Fig. 10) Therefore, good tensile strength of FRP increases the integrity and solidarity of the blocks. Consequently, the walls of the bridge retrofit using FRP decreased 50% displacement in the Z direction, which helps maintaining the structure of the bridge after an earthquake.

The cracks between the blocks in consequence of the loss of strength and adhesion of the mortar has been created (Fig. 11). Therefore, to prevent cracks, the researchers offer a number of ways. One of these methods is retrofitting bridges using FRP. Reducing adhesion between the blocks is a factor of destruction of the bridge. In addition, preventing the cracks between the blocks, keeping the bridge safe, in dealing with accidental loads such as earthquakes, scouring and treated.

The results of this study suggest that the use of FRP retrofitting bridges in earthquake is one of the appropriate procedures. They show that the cracks of some blocks before retrofitting with FRP

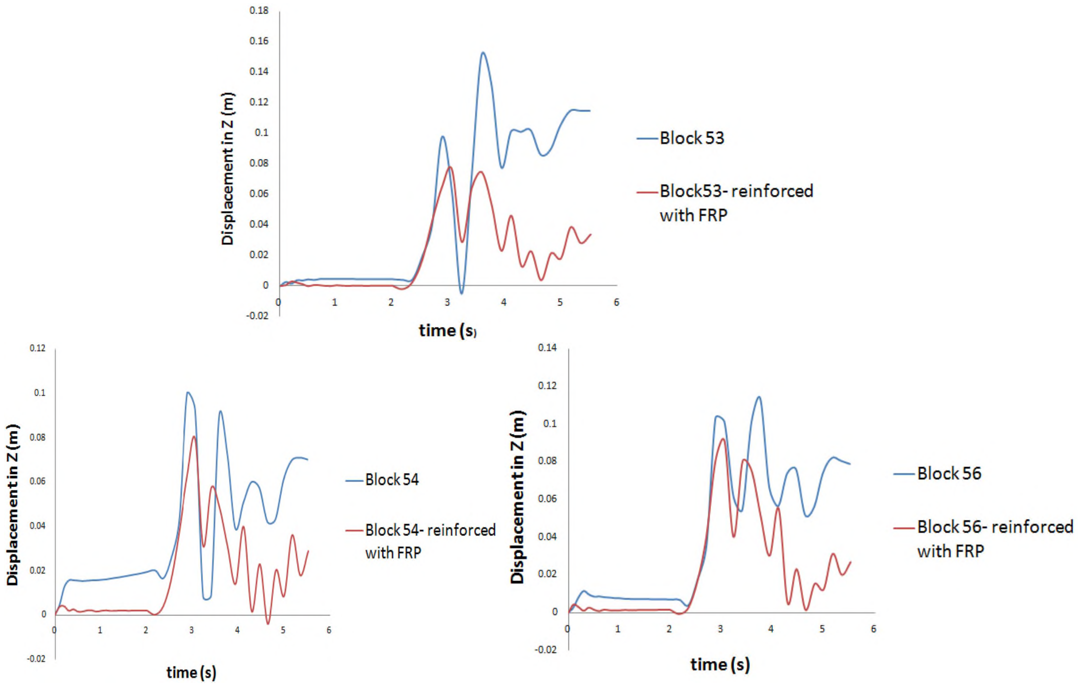


Fig. 14 Displacement(m) in the Z direction of the right parapets of bridge

is up to 0.12 meter. These cracks can cause damage to the bridge structure which led to the complete collapse of the bridge structure. By retrofitting using FRP, the cracks of wall blocks effectively were reduced. (Fig. 12) High tensile strength of FRP in both directions reduces the displacement of blocks. Hence, retrofitting bridges using FRP decrease up to 90 percent of cracks. This increases the seismic capacity of the bridge significantly.

In addition, the results show that the maximum displacement of left parapets blocks of the bridge before retrofitting with FRP is about 0.45 m, which leads to the bridge parapet collapse progression or to damage larger than acceptable. With parapet retrofitting using FRP, maximum and minimum displacement of left parapets blocks is obtained as 0.39 and 0.26 m, respectively. Although, it reduces the lateral displacement parapet bridge, it could not prevent from collapsing parapet. (Fig. 13). Furthermore, the maximum displacement of right parapets blocks without FRP is 0.16 m. With parapet retrofitting using FRP, maximum and minimum displacement of left parapets blocks is obtained as 0.10 and 0.08 m, respectively, which, provides a robust repair method for damaged parapets. (Fig. 14)

4. Conclusion

This research involved a structural analysis of an arch stone bridge in Saint Pont Martin, Aosta, Italy. Based on the results from the numerical study, the following conclusions can be drawn:

1. By retrofitting the bridge spandrel wall using FRP, the displacements of wall blocks effectively reduced that preserves the lateral wall of the bridge. Therefore, good tensile strength of FRP increases the integrity and solidarity of the blocks. In addition, the walls of the bridge retrofit

using FRP decreased 50 percent displacement in the Z direction, which helps maintaining the structure of the bridge after an earthquake.

2. Retrofitting of arch stone bridge using FRP reduces expansion of stones of arch bridge structure, which in turn stabilized the structure of the bridge. The results show that the cracks of some blocks before retrofitting with FRP is up to 0.12 meter. However, by retrofitting using FRP, the cracks of wall blocks effectively were reduced. Hence, retrofitting bridges using FRP decrease up to 90 percent of cracks. This increases the seismic capacity of the bridge significantly.

3. The results show that the displacement of left parapets blocks of the bridge before retrofitting with FRP leads to the bridge parapet collapse progression or to damage larger than acceptable. With parapet retrofitting using FRP, the displacement of parapets blocks is reduced and it provides a robust repair method for damaged parapets.

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