Materials Research Proceedings **26** (2023) 599-604 https://doi.org/10.21741/9781644902431-97

Influence of a hemp biocomposite reinforcement on masonry vaults dynamic response

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Keywords: Masonry Vaults, Biocomposite Reinforcement, Dynamic Behavior, Shaking Table Test

Abstract. In this paper the effectiveness of the application of a hemp biocomposite reinforcement at the extrados of a masonry barrel vault was investigated. To this aim, two specimens of unreinforced (UV) and reinforced (RV) masonry vaults were built having the same geometry with brickwork material and subjected to shaking table seismic tests. The comparison of the dynamic behavior between the two specimens was carried out by increasing the intensity of the seismic input, which was simultaneously applied on both the structures. The evaluation of the progressive damage induced by the seismic input was observed by visual inspections and natural frequencies decay estimated by experimental dynamic identification through the application of Operational Modal Analysis (OMA) techniques.

Introduction

Masonry vaults are common structural elements of the Italian architectural heritage, that in some cases are significantly vulnerable to seismic loads. For this reason, strengthening measures are often required to prevent damages or even collapses [1]. In the last decade, the use of traditional reinforcement techniques has been progressively replaced by Fiber Reinforced Polymers (FRP) bonded at the vault extrados/intrados. However, this approach has shown drawbacks mainly associated to the polymeric nature of matrix and physical compatibility between the matrix and the masonry support. Consequently, FRP strengthening evolved to innovative composite materials obtained by cement based matrix, i.e. Fiber Reinforced Cementitious Matrix [2,3]. Moreover, within the growing environmental sustainability issues, the scientific research is focusing on the development of more sustainable composite materials, based on vegetal fibers and natural matrix [4,5].

This paper presents the results of an experimental campaign aimed at verify the effectiveness of a biocomposite reinforcement applied on the extrados of a barrel vault in the increase of its strength. To this aim, two full-scale masonry barrel vaults were constructed with the same geometry and mechanical properties: one was unreinforced and the latter was reinforced at the extrados by continuous bidirectional hemp ropes bonded in a layer of cocciopesto matrix (i.e. a mix of ground clay bricks and organic binder). The two models were built and tested in the 3D shaking table of the Laboratory of Earthquake Engineering and Dynamic Analysis (LEDA) at Enna Kore University. Each vault was subjected to seismic and dynamic identification tests: the seismic load was given with increasing amplitude at the base of the two models while the dynamic identification tests were carried out after each seismic sequence in order to evaluate the variation of the dynamic properties, testifying structural damage.

The strengthening effectiveness was assessed by comparing the damages detected on the unreinforced and reinforced masonry vaults. Results showed that the proposed bio composite strengthening material is effective for improving the seismic performance of masonry vaults.

Description of the masonry vault specimens

The masonry vaults specimens were built in full scale, following the dimensions indicated in previous experiments made by [3]. One of them consists only by brickwork masonry (UV), while the other is strengthened with an hemp biocomposite reinforcement at the extrados (RV). More in detail, referring to the nominal dimensions, the span of the vaults is 291.6 cm and the rise 114.1 cm. Considering the thickness of the abutments, the total length of the structures at the base is 384.5 cm and the width in the out-of-plane direction is 207 cm. Both the specimens were built using standard bricks having dimensions of 5.5×12×25 cm, so that the thickness of the vaults is of 12 cm. An M15 class of mortar was used in the construction of masonry material with joints of about 1.5 cm in thickness.

The reinforcement system of the strengthened masonry vault is characterized by a biocomposite matrix made by a mixture of cocciopesto and resin in which a rectangular mesh net of hemp ropes is included. The composite material is then characterized by a significant tensile strength given by the hemp ropes and a particular elasto-plastic behavior given by the matrix in compression and bending loads [4]. The reinforcement was applied on the vault with a constant thickness of about 3 cm. In Figure 1 the two specimens fixed on the shaking tables of LEDA Laboratory of Enna Kore University are shown.

Figure 1. Photographic image of the unreinforced (UV) and reinforced (RV) masonry vaults fixed on the shaking table system of LEDA Laboratory of Enna Kore University.

Experimental setup

In order to investigate the effectiveness of the proposed reinforcement technique during earthquakes, an extensive experimental campaign was carried out on the 3D shaking table system at the Laboratory of Earthquake engineering and Dynamic Analysis (L.E.D.A.) Research Institute of “Kore” University [6]. This system consists of two identical 6 degrees of freedom (DOFs) 4×4

m shaking tables that can operate separately and simultaneously, and with asynchronous or synchronous motion.
The two specimens were equipped with two measurement systems. The first consists of MEMS accelerometers of 1 V/g in sensitivity deployed on the structures with two different configurations. In Configuration 1 the two vaults were instrumented with the same setup as illustrated in Figure 2(a) using 22 sensors, while Configuration 2, characterized by 28 sensors deployed as illustrated in Figure 2(b), was used only for the RV for high values of dynamic loads. The second measurement system is an optical-based equipment, through which the displacement time histories of specific markers installed on the vaults have been recorded by means of an innovative three-dimensional motion tracking. It consists of a set of eight high-speed, high-resolution cameras operating in the infrared field and reflective markers placed appropriately on the two vaults.

The dynamic input load was the acceleration records acquired by the seismic station of Norcia (Central Italy) during the earthquake of October 30th in 2016: both horizontal and vertical measured acceleration time histories (Figure 3) were used as input for the shaking table system. The choice of this seismic input was due to its peculiarity in the strong vertical acceleration time history, which causes significant damages in the city of Norcia and other neighboring towns [7,8].

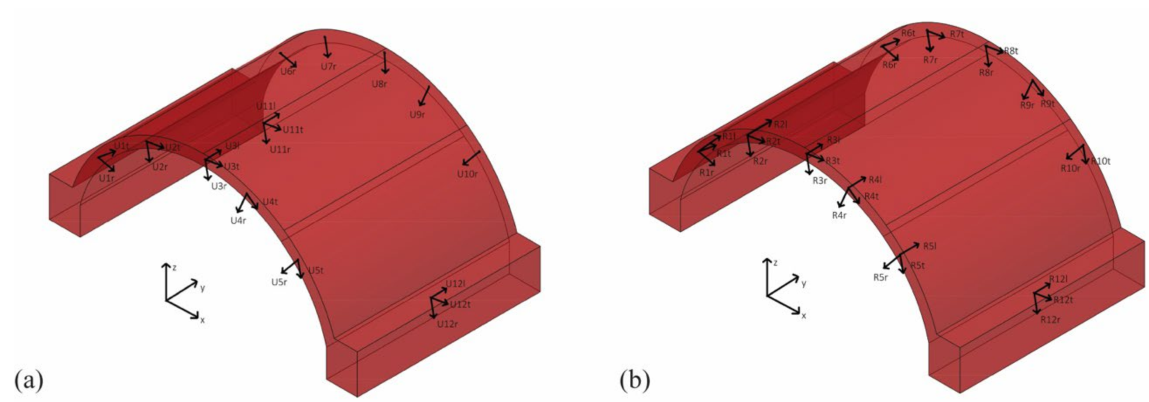


Figure 2. MEMS accelerometers layout installed on the specimens according the Configuration 1 (UV and RV) and the Configuration 2 (RV).

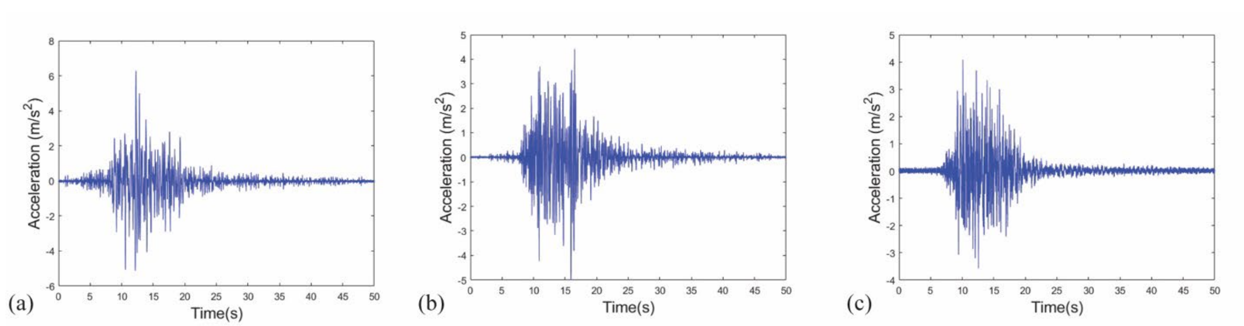
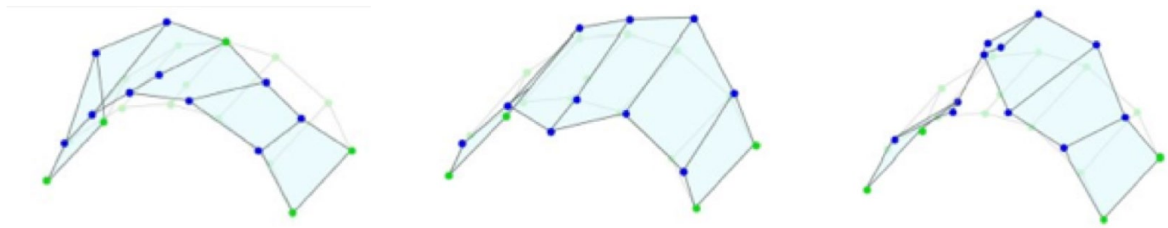


Figure 3. Acceleration time histories recorded by NOR seismic station on October 30th of 2016 used as seismic input during the tests.

Mode 1 Mode 2 Mode 3



f_1^{UV}=18.36 Hz
f_1^{RV}=19.14 Hz

f_2^{UV}=25.00 Hz
f_2^{RV}=27.54 Hz

f_3^{UV}=37.40 Hz
f_3^{RV}=37.80 Hz

Figure 4. First natural frequencies and related mode shapes identified for UV and RV speciment in undamaged condition.

The input load was applied simultaneously to both the specimens thanks to the laboratory facilities, which allow to use coupled shaking tables. The seismic tests were performed scaling the amplitude of Norcia acceleration time histories by different Scale Factors (SF) ranging from 0.2 to 0.4 for the UV and from 0.2 to 2.30 for the RV, with progressive steps of 0.1 SF. Between each step of the increasing seismic load, Ambient Vibration Tests were carried out through operational modal analysis techniques to identify and localize the progressive damage developed in the structures. It should be noted that, taking into account both the added mass and the stiffness of the composite, the reinforcement system did not increase significantly the first natural frequencies of the vault in undamaged condition (Figure 4), so that the energy amount transmitted to the structure can be considered almost the same for both UV and RV.

Analysis of the results

As described in the previous Section, the seismic tests were performed by using two configurations of the sensors layout. In Configuration 1 the deployment of the sensors was equal for both the UV and RV. With this configuration, only two values of the seismic input SF were used, i.e. 0.2 and 0.4. After the first dynamic test no damages occurred on both the specimens, while the second dynamic test induced the activation of a kinematic 4-hinges mechanism on the UV specimen. However, after the rocking motion, the UV did not reach the collapse. In Figure 5 the position of the four hinges is indicated in the front and behind sides of the vault (Figures 5(a) and 5(b)), while Figure 5(c) and 5(d) show the development of the hinges through the width of the vaults, which clearly appear as cylindrical hinges. At the same step, the RV specimen did not show any significant damage.

After the achievement of the critical equilibrium condition for the UV, the test continued only for the RV specimen, with a sensor deployment described by the Configuration 2. By increasing the intensity of the seismic input, the first damages occurred on the structures at a value of SF equal to 2.20, with mortar detachments at the intrados. During the dynamic motion of the further step (i.e. SF equal to 2.30) significant damages occurred: a series of cylindrical hinges activated along the development of the vault and a sliding failure at the right impost (Figure 6(a)); sliding and debonding failure at the crown of the vaults and cylindrical hinge at the left impost (Figure 6(b)); opening of other hinges and increasing of the developed damages (Figures 6(c) and 6(d)).

The results of the AVTs carried out after each step of dynamic tests highlighted a decrease of the natural frequency due to the damage of about 45%, 30% and 10% for the first three modes of UV specimen and of about 65%, 55% and 35% for the first three modes of RV specimen, but, at the same time, with an increase of strength of about 5 times.

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Figure 5. Damage configuration developed on the UV specimen after the application of a seismic input with SF equal to 0.4.

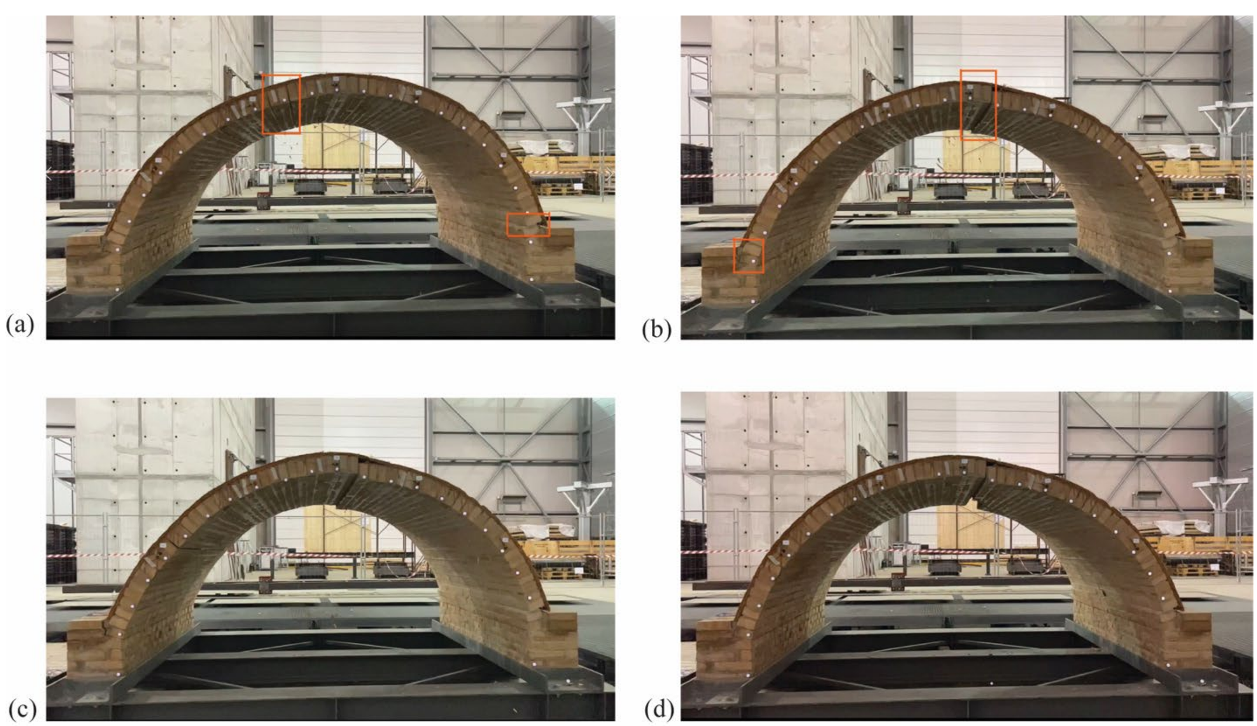

Figure 6. Damage configuration developed on the RV specimen after the application of a seismic input with SF equal to 2.3.

Conclusions

In this work the effectiveness of an hemp biocomposite reinforcement applied on a masonry barrel vault was investigated by means of shaking table tests carried out on two full scale specimens: unreinforced (UV) and reinforced (RV) masonry vaults. The reinforcement consists of hemp ropes included into a composite matrix made by cocciopesto and resin material. The seismic input was applied simultaneously on both the structures with a progressive increase of the intensity. The results highlighted a significant increase in strength of the RV specimen, on which significant damages occurred with the application of a scale factor of 2.30 to the seismic input, if compared to the UV specimen, in which a kinematic mechanism occurred with the application of a scale factor of 0.40 to the seismic input. Moreover, by means of visual inspections and frequency decay estimation as indicator of damage parameter, it was observed that UV specimen was characterized by very localized damages with small intensity, which essentially correspond to the activation of hinges, while RV specimen shown a more spread damage pattern, in some case with great intensity and in large displacements, but without reaching the collapse.

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