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SHEAR STRUCTURAL RESPONSE OF A PROTOTYPE STRENGTHENING SYSTEM DESIGNED FOR STONE MASONRY PANELS

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Abstract: This paper presents the set-up needed for an experimental study regarding the in-plane shear behaviour of stone masonry panels, strengthened with a prototype hemp reinforced mortar. Seven stone masonry panels will be designed and manufactured for this purpose: one unreinforced, three plastered on both sides and three plastered on a single side. The aim of this experimental study is to evaluate the effectiveness of the prototype hemp reinforced mortar in enhancing the shear strength and the displacement capacity of the stone masonry walls. In addition, the design and the manufacturing stages of the prototype hemp reinforced mortar have been carefully described, thus allowing an easy application of this TRM system on a large scale. Crucial aspects regarding the shear behaviour of stone masonry unstrengthen/strengthened walls, such as the quantification of the ultimate forces and displacements, the description of the dominant failure modes, and the characterization of the stress-strain state may be analysed by performing the envisaged experimental study based on the proposed set up.
Key words: stone masonry, textile reinforced mortars, hemp, digital image correlation system, monumental buildings.

1. INTRODUCTION

Stone masonry is one of the oldest and widely used structural system for civil buildings and historical constructions. Despite the convenient durability characteristics of the material (stone), the overall structural system is characterized by high seismic vulnerability, which frequently caused significant loss of life during recent earthquakes [1, 2]. The main reason of the poor structural behaviour of stone masonry constructions under seismic loading lies in the combination of low tensile strength and heavy inertia masses, features that can induce sudden and brittle failure modes. In fact, based on the data recorded from past catastrophic earthquakes, it can be stated that during a seismic event, the stone masonry structures may exhibit both in-plane and out-of-plain collapse of walls, characteristic failure modes that are often related to the lack of shear capacity [3].

In order to address the above-mentioned structural deficiencies, several strengthening techniques were developed, aiming to confer to the stone masonry constructions a global seismic response consonant to the safety performances indicated by standards. Among these strengthening techniques, the use of inorganic composite systems, generally referred to as textile reinforced mortars (TRMs), has increased over the last decade [4]. As a matter of fact, various acronyms were given by research teams to define the same kind of TRM system: textile reinforced concrete (TRC), fibre reinforced cementitious matrix (FRCM), inorganic-matrix grid (IMG), cementitious matrix grid (CMG), composite reinforced mortar (CRM), etc [5].

The TRM system has significant advantages compared to the well- established Fibre Reinforced Polymer (FRP) technical solution for external confinement of degraded concrete [6, 7], steel [8, 9], masonry [10, 11], or, even FRP elements [12-14], Such auspicious features are related to satisfactory mechanical performance, convenient fire resistance, reversibility, higher moisture permeability and compatibility with most of the masonry substrates [15]. Also, the typical failure mode of TRM strengthened masonry elements is characterized by a combined mechanism of progressive mortar cracking and slippage of the textile reinforcements, which results into an increased overall ductility. This characteristic failure mode consists in a stable and predictable mode of fracture, being preferred for the masonry structures located in earthquake prone areas.

Nowadays, the increasing awareness with respect to the environmental safety has materialized in gradually adapting the construction materials sector to more innovative and sustainable solutions [16]. Within this frame, the use of plant fibres (e.g., hemp) in strengthening applications as reinforcement system for mortars represents a feasible alternative to the use of composite inorganic fibres that reduces the overall environmental impact [17]. Thus, the favourable

properties of the TRM systems may be obtained at a much lower carbon footprint.
However, there are still several unaddressed issues regarding the structural behaviour of hemp-based TRM systems, such as the geometry of the hemp nets, the shape of the hemp transversal connectors, the mortar mixture and the possibility to apply the system only on one face of the wall (case specific to historical constructions with facades that need to be conserved). Moreover, there is still a lack of experimental programs to conceive a database so as to increase the overall confidence of designers in the structural efficiency of the hemp-based TRM systems when applied to masonry substrates. Within this frame, this paper presents the set-up needed to perform an experimental study on the shear capacity of stone walls strengthened by a prototype hemp-based TRM systems.

2. DESCRIPTION OF THE EXPERIMENTAL PROGRAM

The proposed experimental program aims to evaluate the in-plane shear performance of the strengthened stone masonry panels using a prototype hemp-based TRM system. Six stone masonry panels will be designed and manufactured for this purpose: three plastered on both sides and three plastered on a single side and, for comparison purposes, a benchmark stone masonry panel will be left un-strengthen throughout the study. The geometry of the benchmark stone masonry panel is presented in Figure 1.

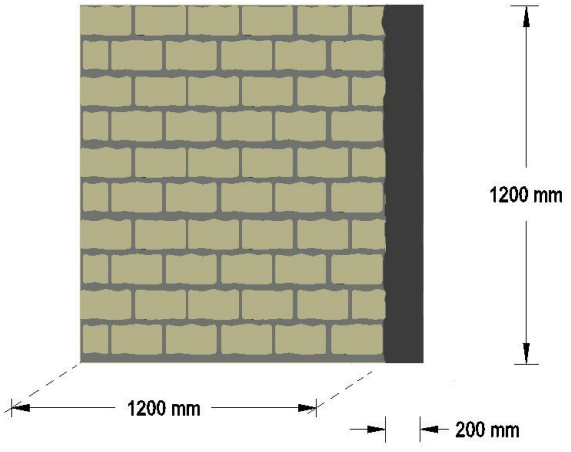

Fig. 1. Unstrengthen stone masonry panel. Benchmark configuration

The prototype hemp-based TRM system consists in the application of a self-supporting lime mortar matrix reinforced with 50 mm x 50 mm hemp net with the thread thickness of 4 mm, surrounding the panel. The jacketed panel surfaces will be interconnected by means of through-wall 10 mm hemp anchors. In the case of the stone masonry panels reinforced on one side, the anchorage will be made at half the thickness of the element, while for the panels that will be reinforced on both sides, the anchorage will be made on the entire thickness of the wall. In both cases, the end parts of the hemp cords will be spread in a circular pattern with a diameter of 200 mm. Also, in both cases, the parts of the hemp cords that will be inserted in the panels will be impregnated with mortar, until the holes are filled. The geometrical configuration of the strengthened stone masonry panels is presented in Figure 2.

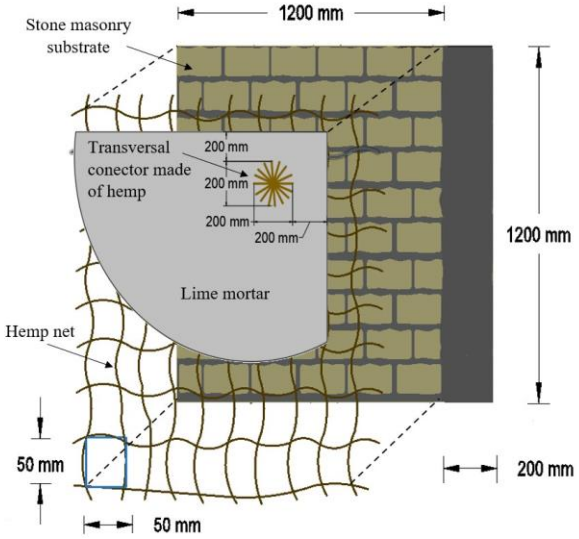

Fig. 2. Geometrical configuration of the strengthened stone masonry panels

3. MATERIALS PROPERTIES

The masonry panel walls will be made with semi-profiled stone units from Zupăita quarry, Șcheia Village, Iași, Romania (figure 3). The quarried stone blocks are about 4 - 6 m thick and were extracted from significant depths ranging from 6 to 20 m.
Among the monumental buildings that were constructed with stone units from Zupăita quarry, we list only a few that are of major importance, namely: the Church of The Three Hierarchs in Iaşi (built in 1639), the Lion Monument in The Copou Garden of Iaşi (13.5 meters high, built in 1841), part of the works performed at The Alexandru Ioan Cuza University of Iași and The Metropolitan Church of Iaşi and the tombstones of the Jewish Cemetery in Iași. It is also worth mentioning that stone units from Zupăita quarry were used for the reconstruction of the middle tower of the Church of St. Spiridon in Iaşi [18].
The mortar that will be used for the assemblage of the stone masonry panels and the one mixed for the TRM strengthened system are different, having distinct material properties.

Fig. 3. Semi-profiled stone units extracted from Zupăita quarry

The mortar mixture designed for the assemblage of the stone masonry panels will be made by mixing 1 part lime with 1.5 parts sand. This mix will be left to dry for at least 5 minutes. After that, the water will be slowly added until the desired consistency is reached. In the case of the mortar designed for the TRM strengthened system, perlite will be added in the previously mentioned mix. Perlite is an amorphous volcanic glass with a high-water content, typically formed by the hydration of obsidian. Due to its low density, perlite may increase the covering capacity and workability of the lime mortar, which is important for reducing costs and increasing the thermal performances. The mixture of the strengthening mortar was designed based on an experimental program that will be presented in a future article.

As mentioned before, the strengthening mortar will be reinforced with hemp fibres. As a crop, hemp grows quickly and yields more fibres compared to cotton or flax [19]. Also, the hemp crops require no toxic substances, as pesticides and fertilizer, being classified as a green (organically) harvest [20]. The harvested hemp fibres are separated either by using manual retting methods (field and water retting) or by using chemical retting methods (enzymes additions). The retting process is defined as the braking of the pectic material, which binds together the fibres to the flax stem, and separating the fibres. After the retting process is finished, the fibres are spun to manufacture continuous yarns. The hemp fibres yarns are characterized by high tensile strength (~690 MPa) and low density (~1.4 g/cm3).

The development of the 2d architecture hemp fabric net (made by knitting hemp yarns) was carried out through the use of a specialised CAD systems (Gemini), [21] and a multigauge electronic flat knitting machine (CSM 502 HP 2.5), (figure 4), [22]. Using the CAD system, it was automatically generated the most adequate nesting plan for the hemp grouping and distribution of fibres. Also, during the design stage, there were set the tracking product evolution points for the prototype hemp fabric. This strategy implies both restore points and model timeline/branch, tools that allow for further optimization regarding the hemp fibres distribution, in the directions of primary importance, usually where the highest stresses occur. The flat knitting machine that was used for manufacturing the hemp fabric is equipped with friction feed wheels, which ensured a reduced thread tension during the cutting and sewing processes [22]. Also, the machine gauge can be adjusted such that to change the needle during the sewing process, if needed. The needle bed is mounted on a racking device which enables a course up to four inches. The take-down system of the machine consists in various adjustable roller segments for main, upper and comb take-downs. Also, the thread holding is composed of 8 clamping and cutting units, thus ensuring the possibility of manufacturing large fabrics. These features are considered the key factors in the transition process from prototype to mass production.

Fig. 4. CSM 502 HP 2.5 multigauge electronic flat knitting machine [22]

4. SPECIMENS PREPARATION

As mentioned before, the masonry panels will be made of semi-profiled stone units and mortar composed of lime and sand. The thickness of the bed, head and vertical joints will not be constant, since the stone masonry is irregular. Before applying the prototype hemp-based TRM strengthening systems, the surfaces of the panels will be cleaned of dust and loose materials. After wetting the surface of the panels, the first layer of lime mortar will be overlaid. Once the hemp reinforcement layers are applied, the whole system will be anchored in the stone masonry. In order to insert the hemp fibre cords, holes will be drilled through the stone masonry panels and the loose material will be removed with compressed air. The inserted parts of the hemp cords will be impregnated with strengthening mortar up to the saturation point. Once the holes are filled, the excess mortar will be removed with a trowel. After the application of the prototype hemp-based TRM system, all the stone masonry panels will be secured in specially designed fixtures and stored in laboratory conditions.

5. EXPERIMENTAL SET-UP

After all the components are cured, the panels will be instrumented for the loading stage. The shear tests will be performed using a PR-500 no.15 test machine. The tests will be force controlled at a rate of 5 kN/min loading speed. During the application of the force several parameters will be monitored: the relative displacement in horizontal and in vertical direction (recorded with two linear variable displacement transducers (LVDTs), the variation in time of the applied force, the initiation and the development of the failure modes. In order to monitor these parameters, the testing machine is equipped with two acquisition systems (DAQs), (figure 5).

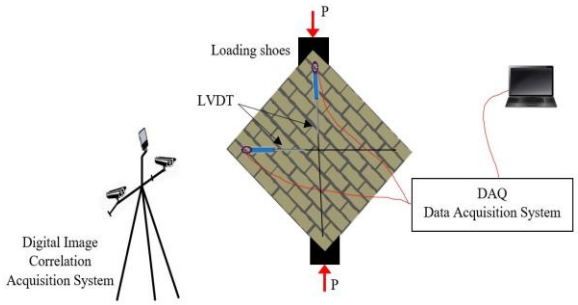

Fig. 5. Experimental set-up of the stone masonry panel

The first data acquisition system provides a classic, basic voltage measurement that will be signal conditioned after the tests are done [23]. The second data acquisition system utilize a Digital Image Correlation (DIC) measurement technique to determine the variations in shape (contour), displacements and strains for the panels [24]. Thus, a stereoscopic camera setup will be used for the surface contour measurements.

The DIC DAQ is able to automatically determine the maximum of the correlation array between the pixel intensity array subsets on two corresponding images. The maximum of the correlation array is the integer translational shift between them. Thus, the displacements can be automatically determined by calculating the relative difference in the contour states over the measurement series. After that, the strain variations are computed from the two quantities already determined (shape and displacement).

As the name implies, the digital image correlation principle works by interacting a series of digitally acquired images, which will be successively taken during the testing of the masonry panels (figure 5). This process can function only through the recognition of a custom pattern on the panel's surface. The camera digitizes the stochastic dots pattern on every pixel as a discrete grey-level intensity. Thus, black dots will be painted on the surface of the panels, in the region of interest (nearby the loaded diagonal).

A benchmark image will be taken for an initial measurement, which is considered as the original state of the specimen's shape. The deformation of the panel's shape is quantified by comparing a sequence of measurement images relative to the benchmark image (figure 6). Thus, once a center pixel corresponding to the benchmark image is identified, through the search function, on the images taken to the deformed masonry panel, the movement and the deformation are described using a shape function attributed to the grey-level intensity variables.

The DIC DAQ consists in two perspective cameras whose lenses point on the stone masonry panel surface (figures 6 and 7).

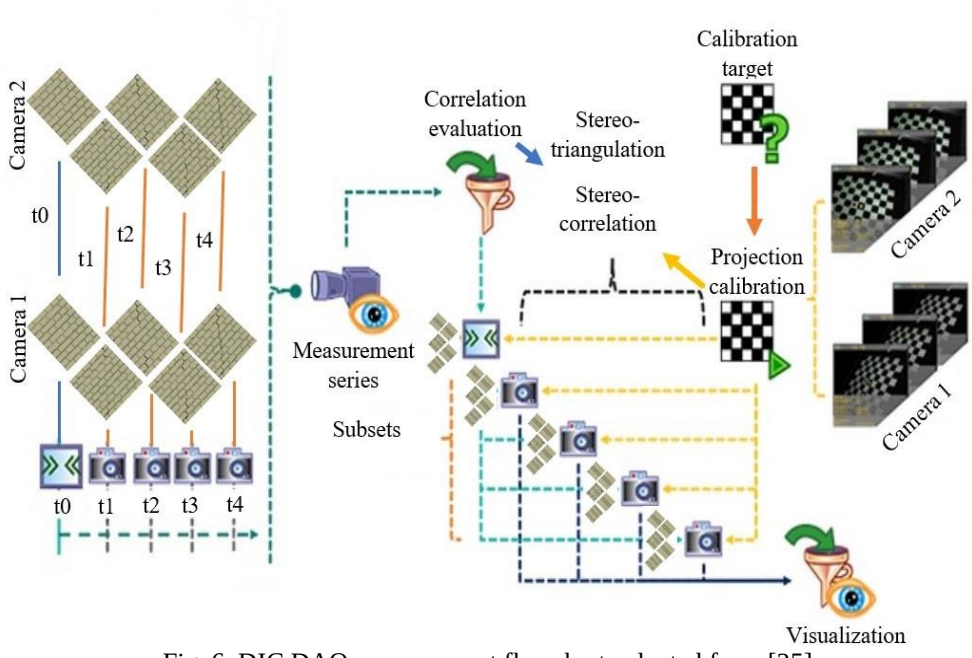

Fig. 6. DIC DAQ measurement flowchart, adapted from [25]

By using a projection calibration, the 2d panel surface is then reconstructed into a 3D perspective. This process is referred to as the stereo-triangulation or stereo-correlation. The intersections of the rays (lines) from each camera are considered as material points (figure 7). By using an independent calibration model, the material points are grouped into a test area volume [25]. Thus, the variation in displacements, shape and strains can be evaluated in relation to the entire 3D geometry of the stone masonry panel.

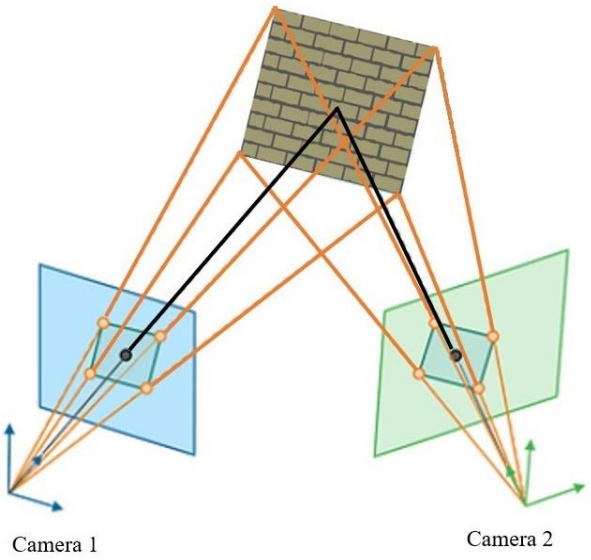

Fig. 7. The stereo-triangulation of the DIC DAQ, adapted from [25]

6. CONCLUSIONS

This paper presents the experimental set-up of a study aiming to evaluate the in-plane shear performance of strengthened stone masonry panels using a prototype hemp-based TRM system. The preparation and instrumentation of the stone masonry panels were extensively detailed. In order to draw reliable and predictable conclusions, the experimental study was designed to account for the influence of various strengthening variables on the shear overall capacity of the stone masonry walls. These variables included the type of the hemp reinforcing net, the mortar mixture, the geometry and the number of the hemp through-wall connectors. Based on the results of this experimental program, analytical and numerical models can be stated and assessed and, if needed, corrections may be applied to the already existing ones. Also, after the comparative evaluation between the numerical and the experimental results, a complete and new solution for the rehabilitation of stone masonry walls can be proposed. The latter consists in an analytical/numerical model design to evaluate the stress-strain state, materials used for the hem-based TRM system and a guide to apply the system with minimum environmental impact.

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