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Experimental study on reinforced stone beams

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ABSTRACT

Stone structures such as bridges, civil and worship buildings or monuments represent the largest part of the construction heritage in the world. They are indeed remarkably durable and earthquake resistant if they were correctly designed. Beside they also have very interesting environmental properties, notably in terms of life cycle analysis, so that stone has a good potential as building materials for modern architecture. The understanding of their mechanical behaviour is hence necessary to develop proper design methods for the prediction of displacements, crack opening or plastic failure in the sense of Eurocode or other modern design recommendations.

The proposed article is dedicated to the study of an innovative system of reinforced stone beam in which the reinforcement is not used as a simple tie that overtakes the structure thrust but rather works with the stone together to build a system that resists vertical forces by bending. The study consists in an experimental program carried out on three beams made of dimension stones tested under four points bending. The beams are subjected to a small number of loading–unloading cycles to evidence hysteresis effects. Typical load–displacement curves are produced from data recorded by load cells, extensometers and strain gages measuring characteristic displacements, crack opening and strain in the reinforcement. Then a simple analytical model based on existing models for reinforced concrete is used to interpret the experimental results and by reverse analysis to identify some characteristics of the beams. Finally a short conclusion closes the paper on the potential of these structures for modern architecture and gives some perspectives of further investigations.

1. Introduction

Natural stone is one of the oldest construction materials used by humans [1]. It became a key material in construction and contributed to the evolution of human well-being and it is the preferred building material for many reasons that include accessibility, beauty, durability, hardness, strength and sustainability [2]. Symbolic pieces of art such as bridges, civil and worship buildings or monuments have been made of stone throughout human history [3]. These structures represent the largest part of the construction heritage in the world. They are remarkably durable, widespread and earthquake resistant if they were correctly designed. They resist fire, water, and insect damage [4]. They have very interesting environmental properties, notably in terms of life cycle analysis especially if the stone is produced locally [5–7]. In term of durability, stone structures have the ability to endure and maintain their characteristics of strength, resistance to decay or appearance and the methods for the identification of these characteristics through time in relation to a specific environment are well established [8–10]. There seems hence to be no reason why stone do not have a good potential as building materials for modern architecture [11].

From a mechanical point of view, the main characteristics of stone structures are a high compressive strength and an almost null tensile strength due to the joints. Therefore, in historical structures, the use of stone is mostly restricted to members mainly working in compression (piers, arches, walls and vaults). The inverted catenary effect, in particular, is used to cover horizontal spans by vaults and arches. In any case, a bending resistance appears whenever the structural section can be partly stressed. In the limit of such bending resistance, an opening of joints is observed which can be modelled as the outcome of a sort of plastic hinge [12]. To enhance the bending resistance, recent researches investigated innovative systems by playing with the geometry of joints [13,14] or the arrangement of stones [15], but the most current solution which is often used in restoration of historical buildings is the reinforcement of the stones by steel bars or rings and/or composite materials [16–18] especially in seismic area [19,20].

In most classical applications, as well as in the present current practice, steel is integrated into stone structures as a tie (with uniform tensile stress) like for example in some recent remarkable

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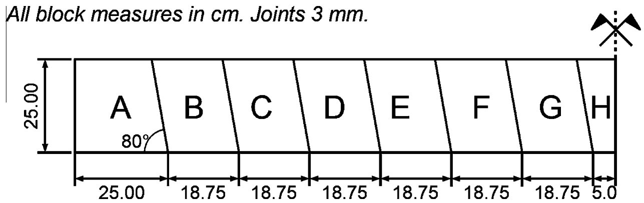

Fig. 1. Scheme of the reinforced freestone beams.

Fig. 2. Dry assembling of the beam and reinforcement.

achievements by Peter Rice for the Pavilion of the future in Seville (1992) and, at least intentionally, by Renzo Piano in San Giovanni Rotondo for the church of Padre Pio (2004). Though, at the end of the XIX century, E. Violet Le Duc, the well-known French architect, had already thought of a system to build an arch where steel and stone are coupled in a way very similar to reinforced concrete: a steel rod is posed at the intrados of an arch (or beam) and connected with stirrups to the compressed part of the stone structure through the joints (examples of such structures have recently be built for experimental purposes by authors of this paper [14]). As a consequence, in these structures, the steel is non-uniformly stressed, as that in reinforced concrete beam, and the stone-stirrups system withstands shear forces, hence generating a bending resistance. For these solutions to come out of confidentiality and for their application not to remain limited to a few extraordinary works, it is necessary to have a good understanding of their mechanical behaviour to develop proper design methods for the prediction of displacements, crack openings or plastic failure in the sense of Eurocode or other modern design standards.

The framework of the present research is hence the study of this simple but innovative system of reinforced stone beams. Our final purpose is the calibration of numerical models and the development of design recommendations for such structures. To simplify matters, in this first exploratory study, stirrups have been replaced by simply gluing the steel rod at the intrados of the beam. The present article consists thus in the presentation of experimental tests on three beams under four point bending tested in the laboratory. Typical load–displacement curves have been produced from recorded data, together with sliding between blocks at supports, joints opening and strains in the reinforcement. Then a discussion of experimental results is proposed based on standard reinforced concrete models. Finally a short conclusion closes the paper on the potential of these structures for modern architecture and give some perspectives of further investigations.

2. Experimental study

2.1. Description of the beams

Three reinforced stone beams with the dimensions of 20.0 cm width, 25.0 cm height, 18.75 cm length and an inclination of the contact surfaces of 10° have been manufactured according to the sketch of Fig. 1. These beams have been made of 15 stone blocks assembled using hydraulic lime mortar joints and reinforced with a steel re-bar with ribs (14 mm diameter) glued with epoxy to the underside of each beam in a deep groove of a half diameter. The average length of the beams was 289.2 cm with joints approximately 5 mm thick. The manufacturing process consists in aligning the 15 stones on a flat board with 5 mm distance between blocks to inject the limestone mortar. After the mortar hardening, the beams area overturned with a kind of formwork and then the digging of the groove for the reinforcement was carried out with a traditional hand tool for stone-hewers. The preparation of the beams was finally completed by a bonding of the steel bar using epoxy resin to ensure good adhesion between the steel and stone (see dry assembling in Fig. 2).

2.2. Material properties

Experimental measures have been carried out to determine the physical properties of the stone according French standard for rock mechanics. Core sampling operations were first made on some stone blocks to have cylindrical specimens with the diameter of 40 mm. The porosity and dry mass were then determined using a vacuum saturation apparatus on 10 specimen that are dried at 100 ± 5 °C until constant weight and then filled with water until saturation. Sound velocity was also measured on the dry specimen. Afterward, compression and split tensile tests were conducted using universal testing machine. Every test was done five times to get average and standard deviation of values. Measures of Young's modulus and Poisson's ratio have concluded these tests. All the results of these tests were summarized in Table 1.

No measures were made for the reinforcement: the diameter of the reinforcing bars was designed by limit analysis, so that the bars remains elastic until the stone breaks in compression. Concerning the mortar, mechanical tests were not found relevant given the stress conditions in the real structure and so, as it is a key parameter of the structures stiffness, it was expected to identify it *a posteriori* by reverse analysis.

2.3. Testing procedure

Four-points bending test was performed on each beam until failure by using the experimental setup shown in Fig. 3. The beams were placed on rollers located in the middle of each end-block which gives a clear span of about 2642 mm. The translation of one roller was fixed so that the beam is isostatic. Two other rollers were positioned in atop the beam to apply the load at 1071 mm from the edge; so that the distance between these two loading cylinders is about 750 mm. Steel plates were set between the blocks and the cylinders to avoid stress concentration and cracking of the stone.

The load was applied with a hydraulic jack with a capacity of 1000 kN and distributed with a stiff metallic box girder (weighting approximately 360 kg). Recording of data was started before the girder is set, so that the load induced by the girder is taken into account. Then the structure was submitted to a loading program that consists on three sets of three cycles with amplitude of 3 kN each (see Fig. 4). Each cycle history had a triangular shape with constant load amplitude. These cycles were focused on increasing load levels (from 1 to 4 kN, 4 to 7 kN and 7 to 10 kN) which should allow the identification of hysteresis effects due to nonlinear behaviour of joints and of their sensitivity to the load level. The tests which end with a progressive increase of the load until failure, were displacement controlled with a speed of 1 mm in 2 min.

The instrumentation was set up to measure the local and global deflection of the beam and the deformation of the reinforcing bar (see Fig. 3). The deflections of the specimens at mid-spans and at