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Innovative experimental techniques in the service of restoration of stone monuments - Part I: The experimental set up

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Abstract

The mechanical response of marble epistyles interconnected to each other by means of metallic connectors when subjected to shear loading is studied experimentally. The study is motivated by the need of the scientific group of the Athenian Acropolis to substitute damaged ancient connections by new ones. In this direction "I"-shaped titanium connectors are placed in the grooves sculptured by ancient stonemasons in the marble blocks and the empty space is then filled by a suitable cement-based material. Guided by the experience gathered from the inspection of failed connections, which clearly indicates that failure starts at the interior of the "titanium-mortar-marble" complex, along the material interfaces, an experimental protocol was improvised, aiming at pumping data from the interior of the interconnected epistyles. For this to be accomplished innovative sensing techniques like pressure stimulated currents, digital image correlation and acoustic emission were used in conjunction with traditional ones. In the first part of this short two-paper series the experimental set-up, the materials and the specimens' geometry are described.

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1. Introduction

As it happens with most stone temples of classical antiquity, the monuments on the Acropolis of Athens are dry-stone constructions, the structural elements of which are marble blocks of various sizes. The epistyles of these temples are kept in place (e.g. in case of seismic loading) by joining them together by means of "I"-shaped metallic connectors (Fig.1a). These connectors were placed in properly sculptured grooves which were then filled with molten lead [1].

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During the passage of centuries, and as a result of the action of both corrosion and mechanical straining, the connections were damaged, leading the marble surrounding them to fracture (Fig.1b). Inevitably the restoration of damaged joints became one of the most serious problems that had to be confronted by the team of scientists working for the restoration/conservation of the monuments of the Acropolis of Athens [2,3] under the aegis of the "Committee for the Conservation of the Acropolis Monuments" (ESMA). Following the pioneering work of Angelides [4] and Skoulikidis [5] it was decided to substitute the steel connectors by new ones made of titanium, for a series of reasons covering the whole range of compatibility from chemical to physical and mechanical. The specific choice for the connectors' material prohibits the use of lead as filling material of the grooves since the "titanium-lead" pair of metals forms strong galvanic element. As a result it was decided that in new connections a special cement-based product should be used as filling material [5]. Therefore in the restored connections the "Steel-Lead-Marble" (SLM) complex of the ancient Greek stonemasons is substituted by the "Titanium-Mortar-Marble" (TMM) one.

The "I"-shaped connectors of the epistyles are under various complicated combinations of tensile and shear loads. Due to serious difficulties encountered during the laboratory reproduction of shear tests it is only the mechanical response of the connections under pure axial loads that has been studied experimentally until now. The pioneer work by Zambas [6] (scientist-in-charge of the Parthenon restoration project from 1984 until 1994) is perhaps the one that simulates in an optimum manner the axial loading of the ancient connections of the Parthenon's epistyles. The specimens used in that protocol were in-situ constructed by the technicians of the Parthenon worksite. They consisted of two identical marble blocks with two grooves (instead of one) sculptured in each marble block (Fig.2a) and two "I"-shaped steel connectors (Fig.2b) were placed in the grooves. Following the ancient technique molten lead was poured until the connectors were covered and the grooves were completely filled (Fig.2c). The tests were implemented with the aid of a specially designed and constructed loading frame (Fig.2d). In all tests only the connectors failed while the marble blocks remained intact. Dial gauges were used to measure the relative displacement of the interconnected marble blocks and estimate the elongation of both the connectors and the surrounding lead as a function of the load applied. Zambas' protocol was not repeated for blocks connected according to the technique adopted nowadays, however the specific topic was recently the subject of a number of numerical analyses [7].

Considering the above discussion and taking also into account the fact that unpredictable failures of restored connections (in the form of fractures of the epistyle body itself) have been reported in the meantime [3], it becomes evi-

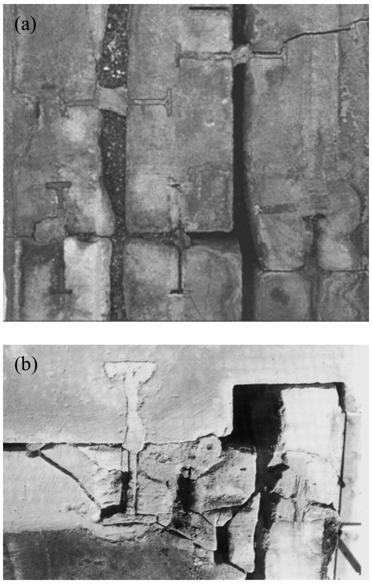

Fig. 1. (a) Typical "I"-shaped connectors; (b) fracture of the marble volume surrounding a typical connector.

Fig. 2. (a) One of the two marble volumes; (b) typical iron connector; (c) the procedure of in-situ filling the groove with molten lead; (d) the loading frame and the dial gauges used during the tensile tests [6].

dent that it is imperative to study the response of the connection type used today under shear load, in order for definite conclusions to be drawn about its performance against mechanical excitations. In this context an experimental protocol was designed the main target of which (besides the macroscopic description of the connections' response) was to pump data from the interior of the TMM complex when it is subjected to pure shear. This is because indications exist [7] that failure mechanisms leading to fracture are firstly activated along the material interfaces (marble-to-mortar and mortar-to-titanium) created due to the forced co-existence of three materials, which are in fact completely different from the point of view of their constitutive behaviour. The specimens of the protocol were designed in close collaboration with the scientists-in-charge for the restoration project in progress of the Parthenon Temple and were in-situ prepared by highly qualified and experienced technicians of the Parthenon's work-site.

For the targets of the protocol to be achieved both traditional and innovative experimental techniques were employed as it will be analytically described in Section 3. The innovative sensing techniques used were the Acoustic Emission (AE), the Pressure Stimulated Current (PSC) and the Digital Image Correlation (DIC) ones. Their outcomes, properly assessed against the respective ones of traditional clip-gauges, are found to be in excellent mutual correlation. Taking advantage of the data gathered from the combined use of all the sensing techniques used interesting conclusions are drawn (as it will be analytically described in the accompanying Part II paper [8]) indicating the need to carefully reconsider the design of the connections primarily in the direction of reducing their stiffness.

2. Materials

2.1. Dionysos marble

Almost all temples of the Athenian Acropolis were built by ancient Greeks using Pentelic marble, an extremely durable material of almost perfectly white colour. Unfortunately, the access to the ancient quarries is nowadays prohibited for environmental and historic reasons. As a result the needs of the restoration project in progress are covered using marble quarried from Mountain Dionysos very close to Mountain Pentelicus. Dionysos marble is the material used, also, for the preparation of the specimens of the present experimental protocol. Both its physicochemical and mechanical properties are remarkably close to the respective ones of the authentic material of the temples [9,10].

The physicochemical properties of Dionysos marble have been described thoroughly by Tassogiannopoulos [9]. Concerning its mechanical properties, the data published vary within broad limits [10,11] probably due to different quarrying depth and location of the blocks used for the preparation of the specimens used in the tests and also due to the anisotropic nature of the specific marble. Indeed Dionysos marble is an orthotropic material, however it can be modelled with sufficient accuracy as transversely isotropic [11,12], the constitutive behaviour of which is adequately described using five elastic constants. Moreover it is slightly non-linear both in the tension and in the compression regime and slightly bimodular, which means that its elastic modulus in compression exceeds that in tension by about 15%. The values of the mechanical properties are recapitulated in Table 1 [11].

Table 1. The mechanical properties of Dionysos marble.

	Young's modulus *(GPa)*	σ_{max} *(MPa)*	ν *(-)*
Tension	75	9.1	0.23
Compression	84	78.4	

2.2. Titanium

For the construction of the connectors, ancient Greeks used a variety of steel consisting of successive layers of "soft" pure iron and "hard" steel of increased carbon content [13]. Testing specimens obtained from already fractured ancient connectors of the Parthenon Temple under uniaxial tension tests Zambas [6] determined the mechanical characteristics of the ancient iron. The values obtained from this series of tests are recapitulated in Table 2.

Based on arguments related to optimum resistance to corrosion, suitable mechanical strength and coefficient of thermal expansion similar to the respective one of marble, Angelides [4] and Skoulikidis [5] suggested pure titanium as the best choice for the construction of the restored connections. Pure titanium has approximately the same Poisson's ratio and thermal expansion coefficient as Dionysos and Pentelic marbles. Therefore the restored structural members

Table 2. The mechanical characteristics of ancient iron.

Property (as obtained from direct tension)	Yield stress *(MPa)*	Fracture stress *(MPa)*	Ductility *(%)*
Minimum value	218	335	3.5
Maximum value	356	538	22.5

of the monument are protected from fracture due to differential lateral shrinkage and differential thermal expansion, respectively. In addition, the type of titanium used for the restoration project has a high modulus of elasticity combined with increased ductility enabling the joins to absorb a significant amount of energy and bear high deformations before fracture. The values of the mechanical properties of the titanium used in the present experimental protocol, as they were obtained from a series of preliminary direct tension tests with cylindrical bars of various diameters (covering the whole range of diameters used in the Acropolis work-sites), are summarized in Table 3.

Table 3. The mechanical properties of titanium used in the experimental protocol.

	Young's modulus *(GPa)*	Yield stress *(MPa)*	Elongation at max stress *(%)*	Ductility *(%)*	σ_{max} *(MPa)*	ν *(-)*
Minimum value	105.8	369.6	11.2	32.5	462.3	0.33
Maximum value	113.1	401.5	13.6	45.2	498.2	0.34

2.3. Filling material

Taking into account that lead, used by ancient Greeks for filling the groove (after placing the connector in it), is incompatible to titanium, alternative solutions were sought already from early seventies. Skoulikidis [5] studied the pair of materials used by Balanos for the restoration of the Erechtheion temple (a cement-based filling material and the marble which was in contact with it) and found no mechanical or chemical decay at all. Based on this observation he proposed a mix of one part white cement and three parts silica sand as the most suitable filling material for the new restoration projects [5]. The mechanical properties of this material were quantified by Marinelli et al. [14] and Kourkoulis and Pasiou [15] and their results are recapitulated in Table 4.

Table 4. The mechanical properties of mortar [15].

Young's modulus *(GPa)*	Tension strength *(MPa)*	Compression strength *(MPa)*	ν *(-)*
10.5	2.1	23.8	0.18

3. The experimental techniques used in the protocol

Based both on naked-eye observations of in-situ (i.e. that were never removed from their original place) epistyles of the Parthenon Temple [3] and also on previous laboratory experimental studies [7] it is definitely concluded that failure mechanisms leading to the fracture of the epistyles connections are first activated along the two material interfaces (marble-to-mortar and mortar-to-titanium) at the interior of the structural members. The traditional experimental techniques (e.g. strain gauges, clip gauges, photo-elasticity etc.) usually employed in laboratory tests are unable to detect the internal events (local failures, micro-fractures etc.) preceding the macroscopic observable ones on the specimens' surface. To cure this problem modern sensing techniques, which can collect data from the interior of the specimens, are nowadays available. Some of these techniques are at mature application stage and are already commercially available while some of them are still at pilot stage and their application is limited at a laboratory scale.

In the present study one technique from each group was used for gathering data from the specimen's bulk: From the commercially available ones the Acoustic Emission technique was favoured while from the ones at pilot stage the Pressure Stimulated Current technique was chosen. Taking into account that the data obtained from these techniques are qualitative rather than quantitative it is crucial for their outcomes to be properly calibrated against quantitative ones obtained from other "more mature" sensing techniques. For this purpose the Digital Image Correlation (DIC) technique was used in the present protocol to determine and record the overall 3D displacement field, while traditional clip gauges were also used mainly for comparison reasons. The main features of the PSC, the AE and the DIC techniques used are very shortly described in next sections together with the respective devices and accessories.

3.1. Electric emissions or Pressure Stimulated Currents (PSC) technique

Electrical signals have been detected during experiments with brittle materials like marble [16], amphibolite [17] and cement-based materials [18] when they were subjected to either tension or compression. The electrical signals are recorded as a weak electric current with the aid of extremely sensitive electrometers. The sensor used to collect these recordings is usually a pair of gold plated electrodes. The construction of such sensors is relatively simple and their cost is extremely low compared to that of other strain-sensing sensors. It is here mentioned that weak electric currents have been detected also in tests with beams under three-point bending [19]. In this case however electrodes must be attached at both the compressive and the tensile zones of the specimens.

In the present study, a pair of electrodes (Fig.3a) was attached on the front surface of the specimen very close to the region where marble's fracture is expected according to previous preliminary tests [7] and in-situ observations [2]. The measuring system employed consisted of a very sensitive programmable electrometer (Keithley, 6517A), Fig.3b, capable of resolving currents as low as 0.1 fA, and as high as 20 mA in 11 ranges. The data output from the electrometer were stored in a computer using a GPIB interface.

3.2. Acoustic Emission (AE) technique

The AE technique detects acoustic events taking place within the material during mechanical loading. It is dated back to 1933 where the process of shock occurrence in a wood specimen under bending was studied by F. Kishinoue [20] with the aid of a phonograph pick-up and a steel needle. The first studies concerning the acoustic emission in geomaterials were carried out in 1938 by Obert [21]. One of the advantages of this technique is that it monitors internal failure processes during the whole loading procedure of either a specimen or a structure by just attaching a number of sensors on it. In addition, taking into account that acoustic emissions depend mainly on irreversible deformations, it becomes evident that the AE technique could be very useful for structural health monitoring. Further applications include the quantification of the fracture process zone by means of the source location of the acoustic emissions in concrete and other structural materials as well as in-situ inspection of vessels, leak detection etc.

For the needs of the present protocol eight R15α acoustic emission sensors (Fig.3c) with 150 kHz resonant (Physical Acoustics) were attached on the specimen with the aid of silicone. Preamplifiers with 40 dB gain were used. The specimens tested consist of three different materials however a uniform wave velocity vector was considered. This velocity was determined equal to about 1000 m/s and 500 m/s along the connector's axis (x-axis) and normal to it in the xy plane (y-axis) (Fig.4b), respectively, according to the results of a series of preliminary breakings of a pencil lead pressed against the specimen. The equipment and the software used were by Mistras Group, Inc.

3.3. Digital Image Correlation (DIC) technique

DIC is an optical-computational method which was theoretically founded and experimentally applied almost 30 years ago [22]. It is a contactless technique the application of which necessitates a random pattern of dots on the specimen's surface which is captured successively by two cameras during the experiment. The basic principle behind DIC is the correlation of each dot's position in the undeformed specimen's state to the respective position in the deformed one. DIC is successfully used for full-field representation of displacement/strain fields, monitoring crack propagation, estimating crack-tip-opening displacement and determination of stress intensity factors.

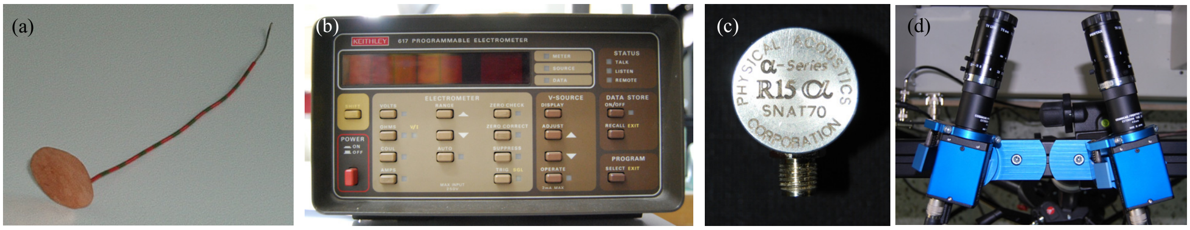

Fig. 3. (a) Typical electrode and (b) electrometer Keithley, 6517A used for the PSC technique; (c) typical R15α acoustic emission sensor; (d) the two cameras of the digital image correlation technique.

A novel three dimensional DIC system (LIMESS Messtechnik & Software GmbH, Germany) was used in the present study (Fig.3d). The resolution of the cameras is equal to 1624x1234 pixels with an accuracy for displacements equal to 0.01 pixel. Since the full field displacement field on the front surface of the specimen was to be determined the 3D DIC active field was a rectangle of dimensions 53.0x37.5 cm^2 and the size of the pattern's dots was calculated equal to about 1 mm. The sampling rate was set equal to 1 photo per 6 s.

4. The specimens and the experimental procedure

4.1. Geometry and construction of the specimens

The specimens used in the present study were prepared by the technicians of the Parthenon work-site on the Acropolis of Athens. They consisted of two parallelepiped marble blocks of dimensions equal to 25x26x20 cm^3 and 25x33x20 cm^3 (Fig.4a), one "I"-shaped titanium connector (Fig.4b) and suitable (cement-based) filling material. The construction of the specimens was realized according to the following procedure:

- A groove (mortise) of depth equal to 7 cm was sculptured in the blocks (Fig.4a)
- The connector was placed in the groove
- The cement-based material was prepared
- The groove was saturated with water, in order for the cement-based material not to lose water
- The filling material was poured in the volume between the connector and the marble blocks
- Two holes were drilled on the one marble volume for exerting the shear force. The holes were drilled on the block which is larger in its vertical dimension (along y-axis) compared to the other block. This asymmetry was considered necessary in order to avoid undesirable parasitic marble's fracture, around the holes during loading. In other words attention was paid for the distance between the holes and the block's upper surface to satisfy the requirement of a minimum distance from the free surface.

Before the tests the specimens were cured for 28 days in order for the filling material to attain its maximum strength.

4.2. Gripping and loading fixtures

The laboratory reproduction of pure shear tests is in general a difficult task. Sophisticated devices are required for the application of the load and the measure of displacements and strains. The most important problem, hard to overcome, is related to the application of the load in such a way that the generation of parasitic stresses to be avoided.

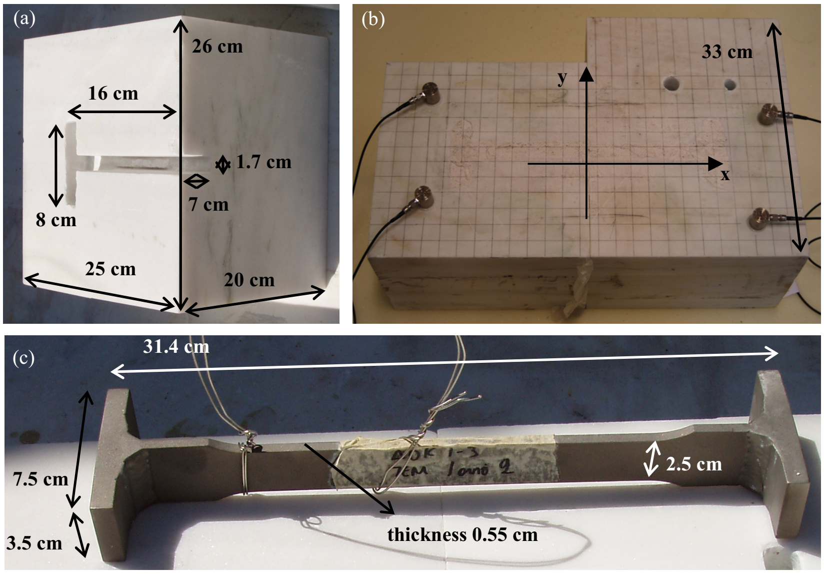

Fig. 4. (a) One of the two marble blocks and its dimensions; (b) typical specimen; (c) "I"-shaped connector.

Fig. 5. Custom-made metallic devices.

Various solutions are mentioned in the literature, mainly for concrete and soils [23], however the studies related to the shear of marble structural elements joined together with metallic connectors are very rare if they exist at all.

The additional difficulty in the present study is that besides the parasitic bending moments (appearing almost inevitably in shear tests) torsional ones are expected, due to an inherent asymmetry of the specific specimens. This asymmetry is imposed by the fact that the metallic connector is placed relatively close to the surface rather than at the center of the specimens. Restricting these moments by means of complementary constraints is not advised since it could seriously influence the failure mode and therefore it was avoided. Finally, the nature of the specimens' material (Dionysos marble) induces additional difficulties since it is very brittle and anisotropic.

For the minimization of the above parasitic phenomena non-commercial gripping and loading fixtures had to be designed and constructed. The solution favoured consisted of (Fig.5): (i) A rectangular rigid holding plate and two "Γ"-shaped metallic elements restricting the motion of the one volume of the specimens with the aid of six rigid threaded metallic bars (or tie rods). (ii) A "Γ"-shaped loading platen designed in such a way that the load to be exerted at the level of the metallic connector in an effort to reduce torsional moments. (iii) Two "Π"-shaped metallic elements keeping the loading platen in contact with the loaded volume of the specimen. (iv)Two titanium bars.

4.3. Experimental procedure

The tests were carried out with the aid of an INSTRON (Model 1126) servohydraulic loading frame of capacity 250 kN. The frame was selected due to the fact that it is equipped with an extremely rigid working table permitting stable fixing of the specimens on it. Both *displacement-* and *load-control* tests can be realized. Before the tests the load cell was calibrated using certified weights for the lower scales and certified load-rings for the high ones. It was concluded that the maximum load error was well below 0.15%. In addition the displacement of the traverse of the frame was checked using a suitable certified micrometer and the error determined was insignificant.

The target of the experimental procedure was to impose parallel sliding of the one marble block with respect to the other, normally to the longitudinal axis of the titanium connector. In this context the specimens were placed on the table of the frame and one of its two constituent parts (marble blocks) was rigidly clamped with the aid of the rigid holding platen, the two "Γ"-shaped parts and six rigid threaded metallic bars (Fig.6). The loading platen was fixed on the other marble block with the aid of the "Π"-shaped parts paying attention to perfectly align the load axis with the axis of symmetry of the metallic connector and the interface of the two marble blocks.

The tests were realized under displacement-control conditions at a rate of 0.2 mm/min (quasi-static conditions).

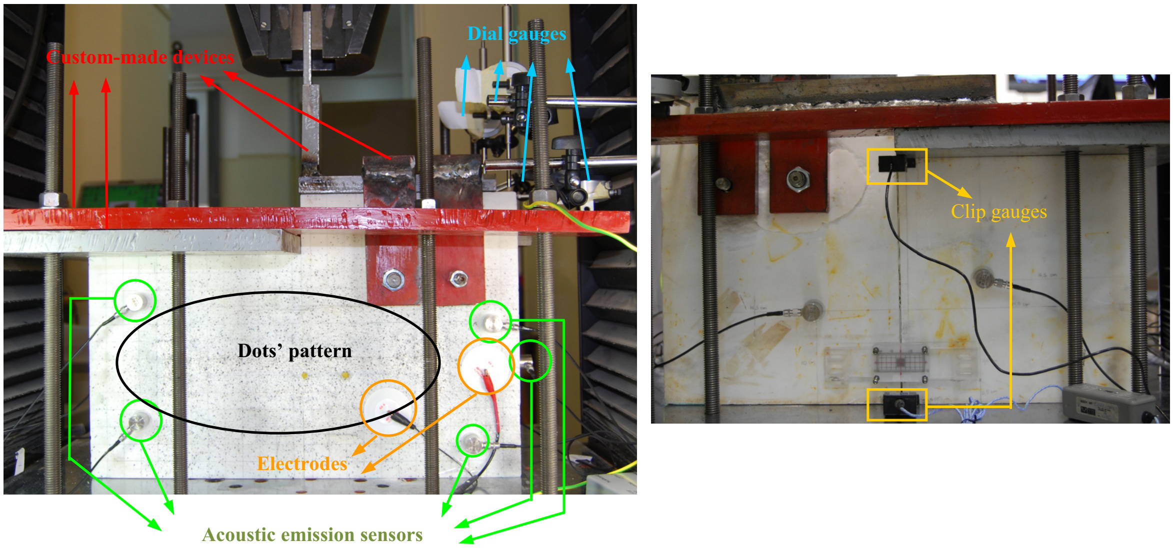

Fig. 6. The front side of a typical specimen on which the AE sensors, the electrodes and the dots' pattern can be seen (left); the back side of a typical specimen and the positions of the clip gauges (right).

5. Concluding remarks

An experimental protocol aiming at the study of the response of interconnected marble epistyles under shear load was described. Its main advantage is that the strain sensing system improvised is capable to provide data from the interior of the specimens. Concerning the procedure followed for the complete restriction of all degrees of freedom of the one marble volume of the specimens it could be anticipated that it might influence the stress fields developed. On the other hand the gripping of the second marble volume was realized in such a way that, at least the regions of interest (Fig.6, left photo) (i.e. these around the flange of the connector) can be considered as insensitive to the external restrictions. For comparison reasons and in order to check possible parasitic effects the relative displacement of the two marble volumes were recorded also by two traditional clip gauges properly attached at each volume (Fig.6, right photo). In this direction preliminary tests [7] were implemented indicating that the set-up described balances in a quite satisfactory manner between the need to eliminate parasitic moments and the demand to avoid interference with the failure mode. The results of the main experimental protocol are described in the accompanying Part II [8].

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