RestArt method: innovative high-precision mechatronic-based procedure for fragmented stone statues restoration

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RestArt method: innovative high-precision mechatronic-based procedure for fragmented stone statues restoration

Pietro Nardelli[1], Martina Pavan[2], Giulia Pompa[2], Silvia Borghini[3], Vincenzo Fioriti[4], Angelo Tatì[4], Alessandro Colucci[4], Massimiliano Baldini[4], Alessandro Picca[4], Ivan Roselli[4*]

[1]Architect, Via G. Calderini 68, Rome, Italy
[2]Ma.Co.Re'. srl, Via G. Severano 35, Rome, Italy
[3]Museo Nazionale Romano, Laboratorio di Restauro Grandi Marmi, Via E. De Nicola 70, Rome, Italy
[4]ENEA, C.R. Casaccia, Via Anguillarese 301, Rome, Italy

[*]corresponding author, e-mail: ivan.roselli@enea.it

Abstract. The RestArt method is an innovative mechatronic-based procedure for high-precision reassembly of stone fragments intended to improve the restoration of ancient statues and architectural elements. The procedure comprises high-accuracy 3D laser scanning of two fragments positioned on the RestArt machine. After software simulated best-fitting of the two homologous fractured faces, the calculated roto-translation matrix is sent to the machine control system that moves one fragment to match the other one. The machine integrates a numeric-controlled moving drilling device for high-precision boring of the fractured surfaces at selected points for optimal rods insertion. This permits a very effective fixing of the fragments and allows multi-point fixing, which is practically impossible with conventional methods. Several stone specimens were experimentally recomposed through the RestArt and the traditional method. Then, they were compared in terms of mechanical resistance by shaking table tests, reproducing extreme strong-motion vibrations. The specimens recomposed through the RestArt method resulted less time-consuming and much more resistant to vibration excitation than the ones by traditional reassembly method. The RestArt method was applied to reassemble some original ancient statues currently exhibited at several Italian museums.

1. Introduction

In the field of ancient stone artefacts restoration the need of efficient methods for precise fragments reassembly is a very relevant issue. In fact, it is a quite common experience for archaeologists to find several stone fragments that belong to a certain statue or architectonic element, but it is not always easy to practically put the pieces together with accuracy in order to provide a more complete view of the archaeologic finding.

In recent years, technologic innovation and advances in 3D virtual reconstruction, visualization and computing permitted high-precision virtual reconstruction of fragmented objects [1-4], but practical reassembly of real parts remains a challenging task. Of course, virtual reconstruction is very helpful to guide the restorer in manual procedures [5]. Then, restorer's skills and experience may result in excellent manual reassembling and fixing of the real object. But this may become an even more challenging – or a quite unsolved – issue, when it comes to large stone statues, requiring big and powerful machines to lift and move heavy fragments reaching even tons of weight, which is not uncommon. In such circumstances, it is possible today to integrate the high-technological advances of 3D reconstruction, visualization and computing typical of virtualization projects with mechatronics, which permits to design and build a numeric-controlled robotic machine capable to reassemble large stone fragments with high-accuracy. Not less important than a proper machine itself, it is also essential to point out a smart procedure capable to integrate the several parts and containing all the optimized steps necessary to finalize the restoration work with successful results. This is the case of the RestArt procedure integrating the mechatronic-based machine with advanced 3D scanning and virtual fragments fitting. The machine and its accessories were invented and designed by P. Nardelli [6]. The RestArt method allows high precision and safety, with the utmost respect of the original material. However, the mechatronic nature of the method is not intended to replace the restorers, but to help them in their delicate and experienced job of reassembling the fragments.

The overall procedure was experimented on fractured stone specimens representative of fragmented marble statues and architectonic elements. Identical specimens were reassembled through the traditional method and were used as a benchmark.

The mechanical resistance of both reassembly methods was evaluated through vibration tests on shaking table [7]. Indeed, reassembled parts may fail when subjected to strong natural (earthquakes) or anthropic (transport) vibrations. Before, during and after the vibration tests a series of measurements were carried out to verify the specimens state of damage. In particular, the response of the tested specimens was assessed by analysing vibration data acquired by 3D motion capture markers [8-9] and conventional accelerometers. Besides, video footages were taken and processed by motion magnification algorithms [10]. Moreover, sonic tests [11] were also performed before and after the shaking table sessions, which confirmed the damage assessment obtained by vibration data.

2. The RestArt method

The RestArt procedure is based on the use of a mechatronic system integrating a specifically invented and designed high-precision robotic machine with advanced 3D scanning and computing instrumentation. In Fig. 1 the RestArt machine is shown.

A preliminary feasibility study based on the fragments state of conservation and conditions is carried out by expert personnel. The procedure is intended for two fragments at a time. After fixing each fragment to the two machine cribs the procedure starts with high-accuracy 3D laser scanning of the fragments. Through software simulated best-fitting of the two homologous fractured faces, the roto-translation matrix is calculated and sent to the machine control system that moves one fragment to match the other one.

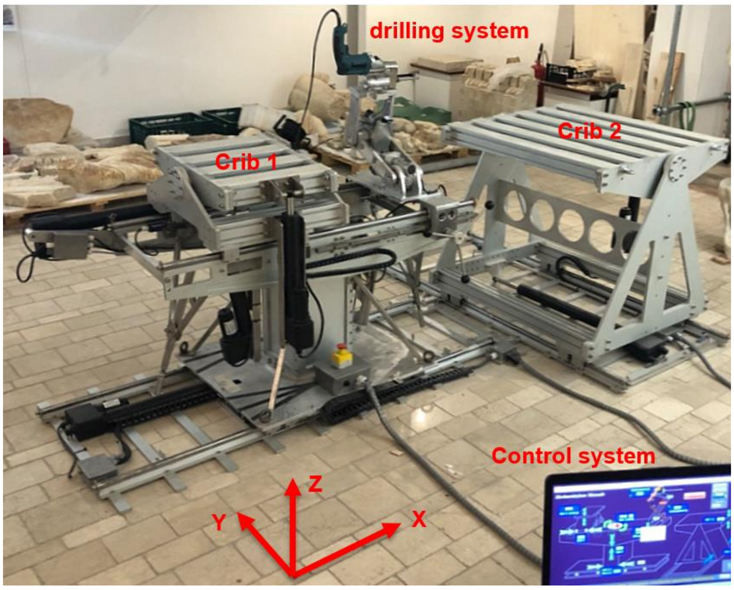

Figure 1. RestArt high-precision robotic machine.

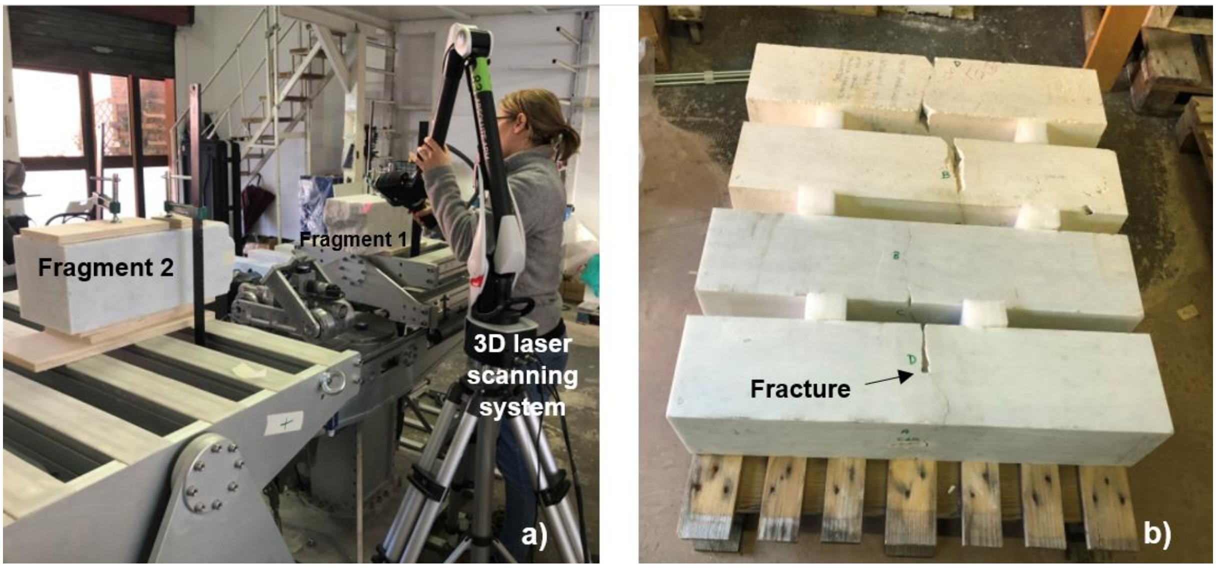

Figure 2. Scanning of the specimen's fragments laid on the cribs of the RestArt machine (a). Reassembled specimens ready for vibration tests (b).

The following step is to move away the fragment on crib 1 in order to permit the moving drilling system to bore each fragments surface at a proper point selected by the restorers. All motions are numeric-controlled in the order of 0.01 mm to perform high-precision boring of the fractured surfaces at selected points for optimal rods insertion with minimal original material extraction. Machine positions can be memorized and repeated with high precision. This permits a very effective fixing of the fragments with a very small amount of glue or similar products needed to fill up the holes exceeding the rod volume. Moreover, controlled drilling allows perfectly coaxial bores paving the way to easy multi-point fixing, which is practically impossible with conventional methods.

Some innovative integrated features that improve the efficacy of restoration method are: a customized air cooling system; a special stone dust suction system; controlled recognition of fragments faces and drilling positioning through high-precision 3D laser scanning. The innovative air cooling system for the special drill bits is specifically designed to avoid the overheating of the mechanical parts without using a water-based system, which would be more time consuming, complex and inappropriate for water-sensitive and polychromatic objects that could be damaged.

3. Experimentation

The experimentation was conducted on six stone specimens. All specimens had dimensions (HxLxW) 800x180x180 mm. Four specimens were in Carrara marble and two were in Roman Travertine. The Carrara marble was intended to represent a typical stone statue material, while the Roman Travertine represented a typical material for ancient architectural elements. All specimens were fractured in the middle, as shown in Fig. 2b, simulating a random fracture as it may occur in real archeologic artefacts in consequence of natural or anthropic damaging events during their centuries-old life. Then, the specimens were reassembled by Ma.Co.Re'. at its own laboratory with the collaboration of P. Nardelli and the *Museo Nazionale Romano* according to the following program:

- T2R: Roman Travertine specimen reassembled by RestArt method with 1-point fixing;
- T3T: Roman Travertine specimen reassembled by traditional method with 1-point fixing;
- C1R and C3R: Carrara marble specimens reassembled by RestArt method with 1-point fixing;
- C4T: Carrara marble specimen reassembled by traditional method with 1-point fixing;
- C2R: Carrara marble specimen reassembled by RestArt method with 3-point fixing (Fig. 3).

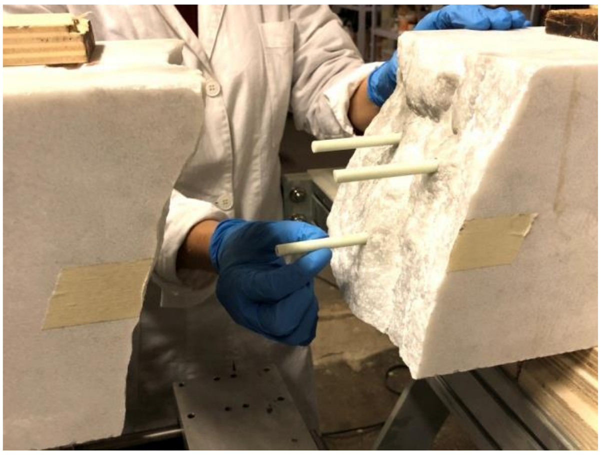

Figure 3. Specimen reassembly with 3-point fixing.

During the reassembling of the specimens the main advantages of the RestArt method in comparison to the traditional method stood out:

- the preparation and the handling of the heavy fragments (around 40 kg) were much easier and less time-consuming;
- the handling of the fragments was operated in safer conditions both for the fragment itself and for the restorers, as each motion speed can be regulated and proximity checks and automatic brakes can be set;
- the high-precision numeric-controlled positions can be memorized so that motions were perfectly repeatable;
- eventual manual positioning corrections and adjustments can be made on discretion of restorers;
- the use of a 3D laser scanning system integrated with a best-fitting software allows to reduce the time for homologous and optimal drilling points.

After reassembly all specimens were tested by non-destructive sonic tests in order to verify their compactness and state of integrity. Such sonic speed values were compared with same measurements carried out after transport by truck from Ma.Co.Re'. laboratory to the ENEA Casaccia Research Centre shaking table laboratory (distance of around 40 km on combined urban and extra-urban roads) in order to identify any possible damage. Changes in sonic speed values were negligible so it could be revealed no damage. Then, the above specimens were subjected to vibration tests according to the testing program as follows:

- Session 1: T2R and T3T were excited with Amatrice earthquake record with peak acceleration scaling factors (FS) from 0.2 to 2.0;
- Session 2: C4T and C3R were excited with vibration recorded on a 100-km/h-speed wheeled vehicle (truck) on pot-holed road with peak acceleration scaling factors (FS) from 0.1 to 1.0;
- Session 3: C1R and C2R were excited with 7-20-Hz 30-s-duration synthetic earthquakes with peak ground acceleration (PGA) from 0.2 g to 4.5 g.

Five markers were located on each specimen to capture 3D motions and relative displacements of the fragments under vibration tests (Fig. 4) with accuracy of 0.1 mm. Also, two triaxial accelerometers were installed at the base and on top of each specimen (Fig. 4). Acceleration data were processed by Experimental Modal Analysis (EMA) in order to extract a global Damage Index D based on the reduction in the specimen fundamental frequency after each test. A series of sonic tests were performed before and after each testing session. Video footages were also processed by motion magnification (MM) algorithms to enhance differences in the dynamic behaviour of the specimens.

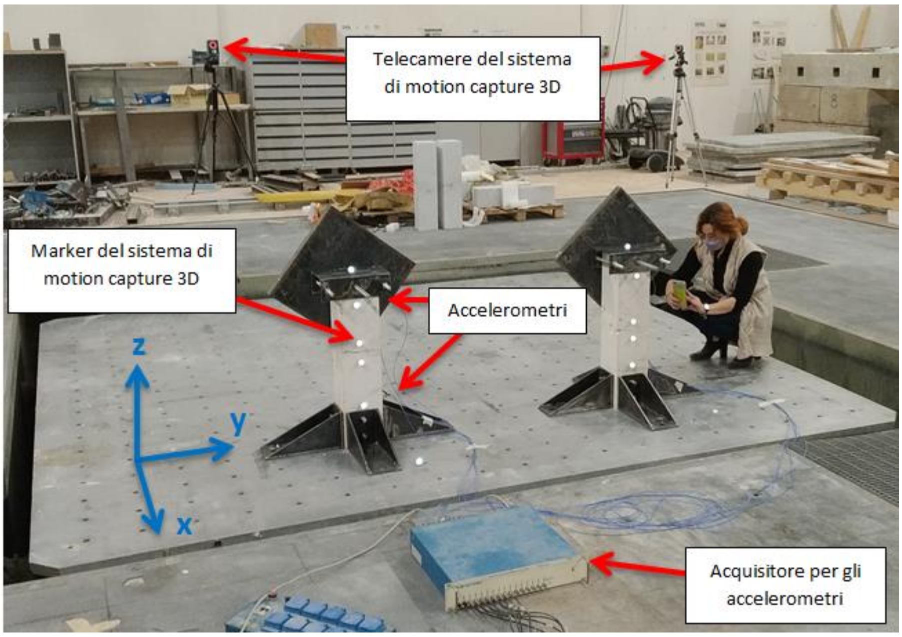

Figure 4. Shaking table set-up of Session 1 comparing the traditional T3T (left) and RestArt T2R (right) specimens.

4. Results

The results of vibration Session 1 are depicted in Fig. 5. The RestArt specimen T2R remained substantially undamaged throughout all the testing session up to FS equal to 2.0. On the contrary, in the traditional specimen T3T a significant damage started arise at FS equal to 1.4 and increased rapidly in the following tests reaching 80% at the end of the session. Similarly, in Session 2 the RestArt specimen C3R showed only negligible damage up to the last test, in which D reached 37%, while C4T appeared more damaged since FS of 0.35 and ended up with almost 70% of D.

Finally, in Session 3 the 3-point fixed specimen C2R did not show relevant damage until the final sudden failure occurred only at 4.5 g of PGA, while C1R showed significant damage since PGA of 1 g and failed at 2.5 g. Sonic tests and MM analysis confirmed the damages indicated by D values.

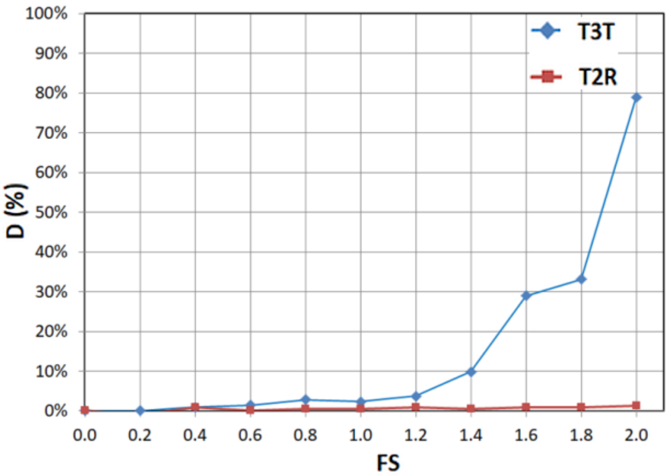

Figure 5. Damage index D for traditional (T3T) and RestArt (T2R) specimens after shaking table tests with Amatrice earthquake at intensity scaling factor FS.

5. Conclusions

An innovative mechatronic-based method for high-precision reassembly of stone fragments was developed to improve the restoration of ancient statues and architectural elements. The experimentation carried out on reassembled stone specimens proved that the RestArt method is very effective. It permitted a very resistant fixing of the parts, even in case of extremely strong vibrations, much stronger than traditional reassembled specimens could withstand. Moreover, the overall procedure resulted much less time consuming and also easier for restorers than the traditional method.

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