*Fraying of the terminal part of the rope, and folding of the fibers on the stone ashlar, so as to form a species of the pin head, and subsequent sealing of frayed fibers on the block of travertine, with thixotropic mortar, modification: cut*

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# Basalt fibers: the green material of the XXI-century, for a sustainable restoration of historical buildings

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## ABSTRACT

In recent decades in the construction industry, the need to experience consolidation techniques with non-corroding materials is being developed. Studies and tests have been led about integration of basalt fibers in concrete structures: they have shown improvements both in terms of mechanical strength and in terms of intervention of consolidation durability (Ólafsson, Thorhallsson, 2009). The basalt rock can be used to produce not only basalt bars, but also fabrics, paddings, continuous filaments and basalt network. Some applications of these basalt-composites materials concern the consolidation of civil construction structures, thermal and acoustic insulation, security clothing, etc. Some years ago the Italian company ENEA (National Agency for New Technologies, Energy and Sustainable Economic Development) has signed an agreement with HG GBF (one of the world's leading companies in the production of basalt fibers), for the verification of possible applications of this material in the construction field but also in the nautical and automotive ones. The use of basalt fiber in construction could present a series of advantages: natural origin, a cycle of production to lower energy impact compared to other fibers, a high chemical inertia and thus a high degree of durability, low thermal conductivity, good mechanical and thermo-acoustic properties, high fire resistance, a competitive cost and, in general, more environmental compatibility and sustainability than other synthetic fibers.

## KEYWORDS

*basalt fiber, sustainable restoration, historic buildings*

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# 1. THE BASALT FIBER: PRODUCTION PROCESS, PRODUCTS AND PERFORMANCE CHARACTERISTICS

## 1.1 THE PRODUCTION PROCESS

Basalt is a kind of volcanic rock, mainly known for its high temperature resistance, strength and durability, widely spread throughout the world, composed of silicon dioxide (SiO2), and aluminum oxide (Al2 O3), oxide ferric (Fe2 O3), calcium oxide (CaO) and manganese oxide (MgO). For this reason, basalts are classified according to the alkaline SiO2 content (up to 42% SiO2), slightly acidic (from 43 to 46% SiO2) and acid basalts (more than 46% SiO2). Only acid basalts meet the conditions for the preparation of fibers.
The productive technology of basalt fiber is similar to the glass fiber's one, but it requires less energy. This aspect, together with a greater availability of the raw material, justifies the lower final cost of basalt fibers production compared to glass fibers'. Basalt fibers derive from a natural fusion process of the basalt rock, without application of any additives. The general scheme of the manufacturing process can be summarized as illustrated in figure 1[1]. Once removed from the quarry, the basalt is first crushed, then washed and, subsequently, transferred into gas furnaces, for melting at a temperature of 1.450 to 1.500 ° C. The molten basalt leaves the oven through a platinum-rhodium bushing with 200, 400, 800 or more holes, from which the fibers are extracted by means of hydrostatic pressure. In output, the surface of the fibers is impregnated with a primer, to give it cohesion, lubrication, and compatibility with the resin. Finally, the melt is wrapped in large spools of continuous filament basalt. Some characteristics of the production process, as the oven temperature levels, are considerably important for the final mechanical properties of the material. For example, in presence of an equal chemical composition, an increase in the fiber drawing temperature of 160 °C (from 1,220 °C to 1,380 °C) increases their resistance from 1.3 to 2.23 GPa and the elasticity modulus from 78 to 90GPa.

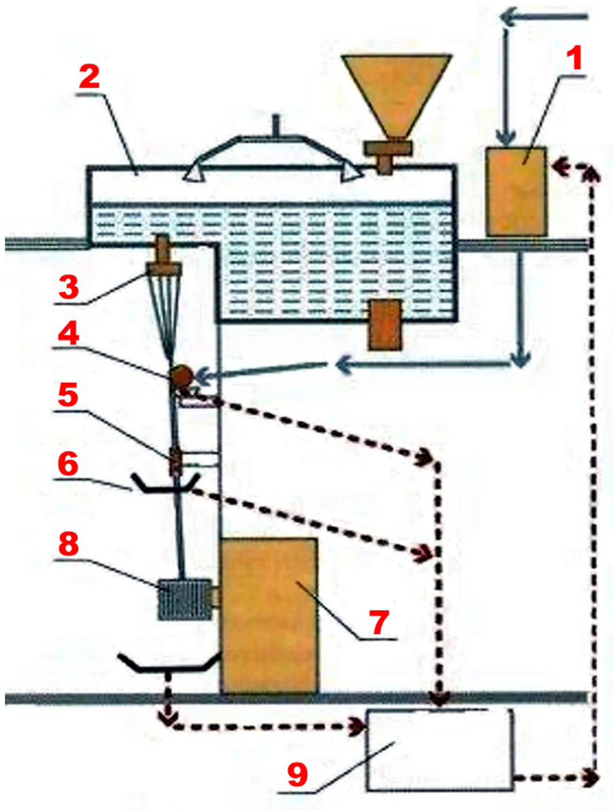


Figure 1.

*Production cycle of the continuous basalt yarn: 1.Tank for sizing; 2.Furnace; 3.Bushing; 4.Sizing applicator; 5.gathering shoe; 6.Tray for used sizing collection; 7.Winder; 8.Cake; 9.Tank for used sizing*

## 1.2 PRODUCTS

Basalt is a kind of volcanic rock, mainly known for its high temperature resistance, strength and durability, widely spread throughout the world, Once produced, basalt fibers are processed into various textures and warping, depending on the uses. Some of which are:

- continuous fiber (Figure 2.a), constituted by a bundle of parallel strands, without twist; the thickness of a fiber usually ranges from 7 to 24 microns. It is the base material, directly produced by the process of fusion of volcanic rock, from which it is then possible to obtain other products with different manufacturing methods;
- fabric for structural consolidation by confinement (Erlendsson et al., 2013), as well as for fire retardant and electrical insulation - Figure 2.b (Landucci et al., 2009);
- mesh for reinforcing wall elements- Figure 2.c
- self-supporting panels for fire retardant, thermal and acoustic insulation - Figure 2.d (Burattia et al. 2015);
- bars of composite fibers (Figure 2.e) for reinforcement of cement-concrete (BFRC), replacing the steel bars (Erlendsson et al. 2009); a particularly suitable solution for structures exposed in corrodible environments and for the consolidation of stone structures (Monni et al., 2014);
- broken fibers (Figure 2.f), produced by the cutting of continuous basalt fiber, used to reinforce concrete and mortars (Ramesh Kumar et al., 2015);
- unidirectional basalt fiber connector for structural reinforcements (Figure 2.g).

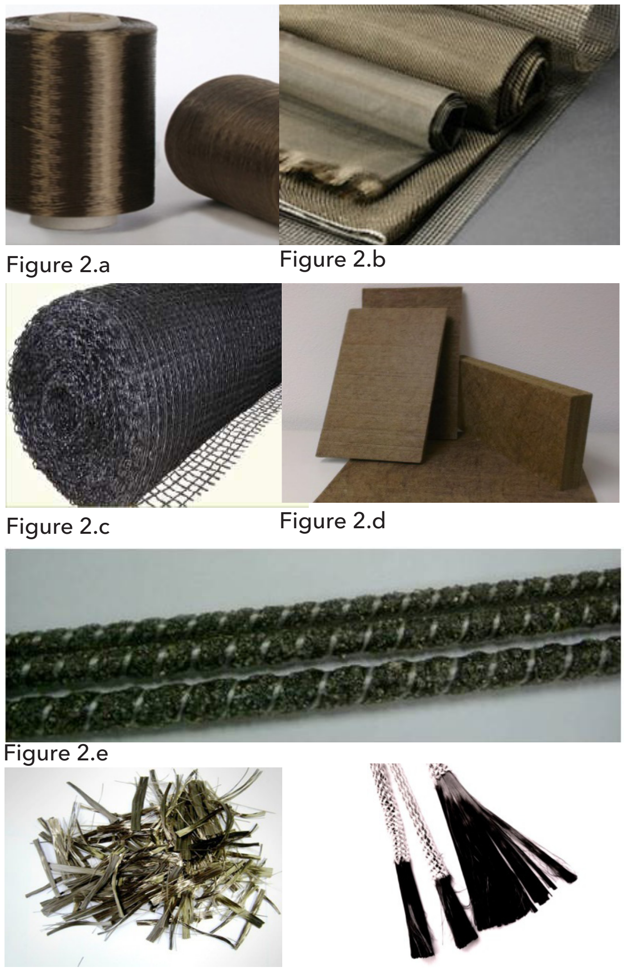

Figure 2.a Figure 2.b Figure 2.c Figure 2.d Figure 2.e Figure 2.f Figure 2.g

Figure 2.

*Main products based on basalt fiber: (a) continuous fiber; (b) textiles; (c) mesh; (d) Panel; (e) bars composite; (f) chopper wires; (g) connectors- Source: HG GBF*

## 1.3 PERFORMANCE AND SUSTAINABILITY

As known, steel tends to corrode if not properly protected. There are different systems to limit its oxidation, among which increasing the concrete layer that covers the armature or using stainless steel (more expensive solution) or bars of glass fiber. The latter solution is limited due to the lower resistance in alkaline environment, associated to the concrete, in addition to having a different coefficient of thermal expansion, compared to the latter. The bars in the basalt fibers are more resistant than glass fiber (Deák et al., 2009), in an alkaline environment. Their use, therefore, gives the final solution multiple advantages, compared to a conventional structure in concrete/steel, as for example: a lighter structure, both for the lower armature weight (1/3 the weight, compared to steel, to equal the strength characteristics), and for the reduction of the external concrete thickness, necessary to protect the steel from oxidation. Basalt properties, in addition, make it preferable to steel in reinforced concrete (Ramakrishnan et al., 2005) for greater resistance to aggressive environments (both alkaline and acidic environments) and, therefore, higher corrosion resistance. While the steel of classic armors can corrode through cracks, which may occur when the structural element is subjected to bending and water, oxygen, chlorides, carbon dioxide transport phenomena, basalt ensures good durability both because it's resistant to cementitious environment, and because it is not subject to corrosion phenomena by contaminants. The basalt fiber is also a sustainable material (Quattrociocchi et al., 2015), since its production cycle needs a lower use of primary energy. For each kilo of basalt fiber used instead of the corresponding amount of steel, you can obtain an energy saving of over 9 kWh of primary energy. Moreover, the basalt fiber's thermal and acoustic insulation, heat stability, durability and resistance to vibration properties, are substantially higher than both the steel and all known reinforced plastics. The basalt fiber is a biocompatible material: it has no recycling problems when it is disposed of, since it is a natural element which reduces the wrapper weight, and requires a smaller amount of energy for its processing compared to the one which normally serves for steel. This material's echo-compatibility, thus, enables it to be completely recycled together with the concrete; the basalt fiber reinforcements, unlike steel, does not require a preliminary separation of the structural part from the cement before disposal to landfill. Then, savings and cost effectiveness lie in the fact that separation facilities designated to the spin-off of concrete from steel for the material recovery wouldn't be necessary anymore, but everything could be intended for a single treatment with no further disposal processes. From these considerations we can understand how the use of basalt in construction could be beneficial. If we assumed it to replace the steel already with only 5% of the steel currently used within a year - equivalent to 25 million tons a year - we would save as much energy as the one used in a plant producing 500 MW, being active for 8000 hours per year (with savings of about 4,000,000 MWh/year). In addition, the reduction in overall energy consumption corresponds to a reduction of CO2 emissions equivalent to 700,000 tons per year, which would bring us closer to the objectives of the climate package - EU energy (De Fazio, 2011).

## 1.4 CHEMICAL AND MECHANICAL PROPERTIES

Basalt fibers are characterized by a good resistance to both low and high temperatures and have better performances, compared to other fibers, in terms of thermal stability, acoustic insulation, vibration resistance and durability. From the point of view of performance, the basalt fiber stands between the carbon fiber and the glass fiber, even if, among others, it has a great advantage: it has an excellent compatibility with the carbon fiber. This feature allows the creation of a high-efficiency hybrid material by adding small amounts of carbon fibers to basalt ones (Czigány, 2005). The wire obtained, which has an insignificant difference in terms of costs (because of the small content of carbon fiber, more expensive), shows considerably better elastic properties than the 'only fiber' basalt (note that the elastic modulus of the basalt fiber is about 11,000 kg/mm2, while the carbon fiber is 22.000-56.000 kg/mm2). However, the glass fiber (Wallenberger et. al., 2001), for its shape and chemical composition, can be considered as a reference material for a better understanding of basalt fibers' properties. Both of them are inorganic but they are produced by different processes. Glass fibers are produced by molten charge, composed of quartz sand, soda, lime, fluxing agents, etc. Basalt fibers are obtained, as already mentioned, by melting basalt rocks without additives. Table 1[2] shows the comparison between the average values of some main indicators of basalt fiber and glass fiber.
From Table 1 we can observe that:

- the elasticity modulus of basalt fibers is higher (at least 18%) than glass fibers', in particular E-glass fibers and, as known from the literature, it very closely approximates the modulus of elasticity and the high resistance of magnesium fibers - aluminosilicate glass (S-glass);
- application temperatures of basalt fibers' products are markedly higher (from -260°C to 700°C) with respect to the glass (-60°C to 250°C);
- the vibration resistance of the basalt fiber is much higher than the glass fiber's one. This is why the BF is widely used in a large range of structures, subjected to strong vibrations and acoustic loads: transport, engineering, etc. Furthermore, basalt fiber products are used as an effective sound-proofing system, being resistant to the acoustic vibration effect, being so suitable for isolation applications in the aircrafts.

## 2. THE ITALIAN RESEARCH: THE SEAMS OF BASALT FIBERS FOR THE CONSOLIDATION OF ANCIENT MASONRY WALLS

Due to the seismic activity, the masonry buildings don't show a clear overall structural behaviour; therefore, a "macroelements" analysis results more realistic, ie portions of masonry which in size and shape autonomously react to stresses (such as seismic), identified and categorized on the basis of past experiences. This approach, proposed by various authors (Giuffrè, 1991; Doglioni, 1994), is also well established within the legal framework that regulates the interventions on the existing masonry constructions in general. So, old brick buildings' answer to earthquakes is the one offered by their macroelements, whose motion defines the so-called "kinematic collapse activatable". Through analysis of these mechanisms you can check the safety with respect to seismic action expected and, therefore, design and size appropriate safeguards to prevent their activation. An essential hypothesis, at the base of the theory of discretization of the building in macro-

| | Basalt fiber | Glass Fiber |
|---|---|---|
| Thermo-phisical properties | | |
| working temperature (C°) | -260°C ~ 700°C | -60°C ~ 250°C |
| Thermal con-ductivity | 1100°C | 600°C |
| Phisical properties | | |
| Flament diameter (μm) | 7~15 | 6~17 |
| 3) | 2560 | 2500 ~2600 |
| 2) | 10000 ~ 11000 | Up to 7200 |
| Tensile strenght MPa | 4150~4800 | 4150~4800 |
| Residual Tensile strength under heat treatment (%) | 20ª 100 | 20ª 100 |
| | 200ª 95 | 200ª 92 |
| | 400ª 82 | 400ª 52 |
| | 600ª 76 | 600ª caking |
| Chemical resistance | 2NHC1 2.2 | 2N Hc1 38.9 |
| | 2N NaOH 6.0 | 2N NaOH |
| (loss of weight) (%) | H2O 0.2 | H2O 0.2 |
| Water absorption for 24 hours(%) | 0.02 | 107 |
| Vibro resistance (loss of weight) (%) | | |
| At temperature 200°C | 0 | 12 |
| 450°C | 0.01 | 41 |
| 900°C | 0.35 | 100 |
| Acoustic characteristics | | |
| sound absorption coefficient | 0.95~0.99 | 0.8~0.92 |

Table 1.

*Comparative features of basalt fiber and glass fiber.*

| Fiber type | Tensile strenght, MÇPa | Moduls, MPa | Cost,$/kg |
|---|---|---|---|
| OCF 450Yield Type 30 E-glass | 2586 | 74.4 | 1.5 |
| BFC 15-2500 KV12 Basalt fiber | 3100 | 89 | 3.2 |
| Graft 34-700 12K Carbon fiber | 4881 | 231 | 28 |

Table 2.

*Comparative economic-technical analysis*[3]

elements, is to be able to consider these parts in the building as monolithic and, therefore, that the masonry that composes them have a "good quality". The "quality" level of the historic building work is subject to essential characteristics that denote its "workmanlike" execution: the presence of diatones (ie cross-cutting elements, arranged at right angles to the wall structure, whose function is the two faces' clamping), regular horizontal rows, staggered vertical joints, the use of squared elements, linked with good quality mortar. In many cases, these features are completely absent: that's the case of walls made of erratic pebbles and irregular stones arranged disorderly and chaotically, with low-strength mortar, or the so-called "bag" walls, with two independent (external and internal) facings and an inconsistent inner core. Therefore, in these cases, before proceeding with a structural analysis we need to confer the missing monolithicity to the bearing wall panels. From this assumption it has been developed the idea of perfecting a consolidation technique capable of making monolithic a masonry which hasn't been perfectly done. This approach is clearly in line with the principles governing the interventions on historical buildings, namely: minimal intervention trend, compatibility investigation, intervention reversibility, respect of authenticity, preservation of the original material, visual impact control and interventions recognition. These criteria are not always respected if we act with traditional consolidation techniques (reinforced plaster, reinforced perforations, injections of binder, etc.) and only partially with the most innovative ones (bandages with fiber-reinforcing composites).

## 2.1 TICORAPSIMO® SYSTEM

The Ticorapsimo system[4] (from greek, literally "sewing with stone"), is a project made by teachers S.Lenci and E.Quagliarini (Quagliarini, Bondioli et al., 2016), from Polytechnic University of Marche. It moves from the need to restore the masonry monolithic characteristics, through a clever weft and warp game in which flexible elements (plot) in basalt stone hold together the various segments (warp). The proposed technique (tested through laboratory testing, in situ and subsequent numerical analysis) aims to consolidate the wallboards, using confinement, and at the same time by connecting the two sides through continuous flexible seams. In practice, a 'wire' that continuously surrounds the masonry on both sides after traversing its thickness in several points, as a real "seam." The main advantages of this system, compared to the known techniques and the ones used up to now, can be briefly summarized as follows:

- reversibility: the intervention can be performed "dry"; the basalt ropes are manually inserted through the through holes and do not require anchorages with resins or other sealants (Quagliarini, Scalbi et al., 2016);
- material preservation: it complements, but does not replace or transform the original material;
- bio-compatibility and sustainability: the intervention does not involve the use of toxic or harmful substances for health, it does not require special precautions for the residues disposal after processing or for dumping at the end of its

life cycle. It is therefore at the forefront both for its environmental sustainability and for workers safety;
- compatibility with the masonry support: an element made of stone material (the basalt string) sews stone structures;
- non-invasiveness (criterion of minimum intervention): the intervention can also be localized in the mortar joints (without damaging the stone blocks); it is feasible, therefore, also on masonry with a "face-to-view" parameter;
- cost-effectiveness: even if applied on uneven walls, it expects reduced processing steps and application times compared to alternative techniques;
- durability: some features of basalt fiber (such as high resistance to fire) guarantee a greater duration of the intervention compared to dressings made of FRP in which the resin is the weak point against high temperatures (Landucci et al., 2009).

More in detail, the operating sequence is defined by the following operations:

- Realization of through holes of a small diameter, on the masonry to be consolidated. The holes' location is established after careful examination of the wall structure;
- The 'wire' of continuous reinforcement (basalt fiber rope) is passed on the two faces and in the thickness of the wall panel, as a real "seam." The application is performed with a minimum pre-tension, exerted by hand by the operator;
- The operation can also be repeated in several directions, always using the same holes, with the result of confining the masonry with a continuous wire mesh, without interruptions.

If necessary, the reinforcement can be hidden from view, inside the mortar joints, for preserving its original aspect. The system can also be employed to restore the continuity of a masonry in the presence of lesions, to strengthen the connection among not well clamped masonry parts or for improving the structural connections among walls, floors and roofs. Moreover,

Figure 3.

*Application phases of TICORAPSIMO® system* thanks to its speed and versatility, it can also be used for a possible safety implementation in emergency cases, as an emergency coverage to avert local collapses or the evolution of wall portions' collapse mechanisms.

## 2.2 CONSOLIDATION OF CAMORCANNA'S VAULTS

The Italian monumental historical building is characterized by churches, theaters, noble palaces etc, which have light vaults, called in "camorcanna" or false vaults (Figure 5), made of reeds and plaster mats hung to wooden ribs. To their soffit they often have cycles of paintings and decorations of great artistic value. This system, already known in Roman times for plastering walls and ceilings of bathrooms with predominantly gypsum mortars, was designed as a lightweight and economical formwork, disposable, consisting of a corrugated surface on which mortar being applied; a surface also able to prevent shrinkage cracks or detachment of any disconnected parts (Fabbri, 2010).
In 2006, the Molise Region approved the protocol for interventions on Private Estate Planning for Post-Earthquake Reconstruction (Lemme et al., 2006), a document that analyzes the main intervention techniques deemed invasive by current seismic regulations and possible alternative solutions. In several cases, the intervention cards provide the use of products based on basalt fibers: for the consolidation of the masonry structures, vaults, etc.
In this seat we'll analyze, in particular, the intervention to camorcanna vaults. The camorcanna vaults are composed of a wooden beam frame and on its intrados straws immersed in a layer of lime mortar are placed. This kind of vaults is particularly sensitive to the time action: rust in the nails, plucking the wattle from the rafters, mold and cracks in the wooden beams. These defects cause deformations, detachment and cracking of various orientation. The intervention includes the consolidation of the entire surface in cannucciato (juxtaposed bamboo canes) structures by laying a reinforcement system made entirely of natural and bio-compatible materials and modules and mechanical strength similar to those of the existing structure.
Extrados reinforcement (Figure 5) takes place through balanced entirely natural nets in flax-fiber, impregnated with inorganic natural hydraulic lime matrix, and linked to the existing vaulted system using basalt fiber micro-connectors.
The proposed intervention is summarized in the following processes:

- antibiotic treatment of all wooden surfaces;
- removal of loose parts;
- consolidation of the surface to be treated by application of a coat of ready product based on ethyl silicate;
- construction and installation of "Ω" Basalt fiber connectors, enveloping the purlin section, with drawing up a layer of two-component epoxy resin;
- construction and installation of double bowed basalt fiber micro-connectors made of a rigid resin potted part and a double bowed part to be connected to the support with natural hydraulic lime mortar; the goal consists of linking the reinforcement system in linen and mortar network in the intrados to the vault's bearing structure, so to be integrated with the connection system currently present;

Figure 4.

*Camorcanna topsail barrel vault*

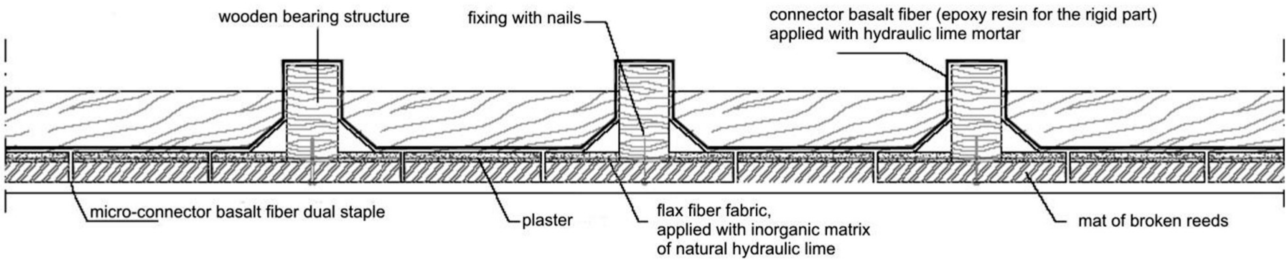


Figure 5.

*Consolidation intervention of camorcanna vault*

- realization of a first layer of ready 5 mm thick mortar;
- cool drafting of damp linen fiber network;
- drafting of the final layer of structural mortar in the package closure with the purpose of binding the linen and mortar network reinforcement system to the bearing structure.

## 3. THE INTERVENTION OF RESTORATION OF THE COLOSSEUM (ROME)

The Colosseum, originally known as Amphitheatrum Flavium, is the largest amphitheater in the world. Located in the city center of Rome, it was able to hold up to 50,000 spectators. Since 1980 it is considered a UNESCO World Heritage. In 2007 its complex was also included among the New Seven Wonders of the World, following a competition organized by New Open World Corporation (NOWC). In 2015 the Colosseum was found to be, with more than 6.5 million visitors, the second most visited archaeological site in the world, behind only the Great Wall of China.
The amphitheater was built on an area on the eastern edge of the Roman Forum. Its construction was begun by Vespasian in 72 A.D. and was inaugurated by Titus in 80, with further changes made during Domitian’s reign. No longer in use after the sixth century, its huge structure has been reused in various ways for centuries, also like a material quarry. Its name "Colosseum", deriving from the nearby statue of the Colossus of Nero, was spread only in the Middle Ages.
Soon the building became a symbol of the imperial city, expression of an ideology in which the celebration will define models for the people’s entertainment[5].
In recent decades, the monument has been object of interest and numerous scientific studies, with special emphasis on knowledge of construction techniques and organization of the construction site in Roman times (Manieri Elia, 2002).
Before restoration work, this monument presented biological encrustations, smog films (which had blackened most of its facades), delamination and cracking due to seismic events, plundering operations, unsuitable consolidation techniques.
In reference to the damage found, the goals of the restoration were:

- eliminating the deterioration causes present on Prospectus, in order to safeguard its integrity and improving its transmissibility to the future, taking into account the variety and types of materials, the history of the construction and restoration interventions;
- adopting of measures that respect the guiding principles of modern restoration, namely: "reversibility", "compatibility with the original matter", the policy of 'minimum intervention' (or 'non-invasiveness'), the 'recognition' (or the "expressive authenticity") of the new additions

Figures 6.

*Phases of surface cleaning*

Figure 7.

*Phases of mechanical treatment for the removal of deposits*

and expansions compared to the oldest;
- contributing to the knowledge of the monument, complementing the existing take-over and mapping the state of affairs, systematizing gradually obtained data and information in the course of the work, in order to contribute to the reconstruction of a more comprehensive framework of knowledge possible.

The restoration project has been managed in a scientific way, using all knowledge tools, from historical and archaeological analysis to metric survey, from technologies and constructive techniques history to chemical and physical insights about the nature of materials, from degradation problems to disruption ones, in a professional competition and skills offered by designers. The same care and attention, the same methods and correctness in the scientific approach have been taken in the design phase as well as in the execution one. The technical team[6] has used, both in the planning stage and in the management one, innovative technologies for the management of the construction site security, such as a mobile arm, installed at critical points, suitably identified in relation to the building history in order to detect the state of consistency, orientation and exposure, interferences among different activities going on various parts of the monument. The technique used for the cleaning of facades (Figure 6-9) turned out to be very innovative: for the cleaning of the outer face (blackened by atmospheric pollution for decades) no chemical agent was used, but a web of tubes has been installed to fuel hundreds of spray nozzles with adjustable intensity, each with its own tap. It has been a totally natural process, structured in the following phases:

- at a first stage atomized water was sprayed to dissolve the degradation film;
- at a later stage the film has been removed by the use of sponges and soft bristled brushes;
- in the final stage, by the use of mortar made of hydraulic lime, chipped travertine grouting and consolidation of stone elements were performed.

The pressure of the water jet was adjusted with extreme care, in order to dissolve all impurities but not spoil or scratch the stone surface.

## 3.1 PROJECT MANAGEMENT: WORK BREAKDOWN STRUCTURE

Another innovative aspect is the design process management, through a project management strategy, work breakdown structure (Norman et al., 2008), an integrated management of design, execution, and management and organization of the construction site. In fact, the final design has been drawn up as

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Figure 8.a

Figure 9.a

Figure 8.b

Figure 9.b

Figure 8.

*Cleaning of a fornix: initial state (a), and the final effect of an arch (b)*

Figure 9.

*Cleaning the frame of the third order: initial state (a), and the final effect (b)*

an organized system of logically and chronologically related activities, and since its inception has been implemented WBS elements' hierarchical and ordered structuring, meant according to technical and operational logic. WBS has acquired, structured and managed the following elements: activities, performance requirements of the interventions, costs. In this way a structured model of management and planning of all resources (including the economic ones) has been defined; it allowed to conduct, according to a unitary logic, the detailed engineering and, later, will handle the works execution and activating the appropriate control processes. The construction sequence has been defined: in it the individual processes are related to WBS' technical-operational elements in terms of their logical and chronological order (WP - work program). The machining cycles have been characterized on the basis of responsibilities and duties, and specific instructions have been defined to be given to technicians and operators according to the hierarchical corporate structure - OBS - organizational breakdown structure (Kerzner, 2005). In the validation or the execution phase of the work a methodology was adopted, consisting in setting and progressive updating of a website, with a dedicated FTP connection, accessible by password, with appropriate levels of protection depending on the specific skills.

## 3.2 THE INTERVENTION WITH STRINGS OF BASALT FIBERS

The restoration has availed itself of a special patent: the use of basalt rope[7], for Basalt compatibility with all the stones such as travertine, as well as ensuring minimal impact and more operating time. In particular, connectors basalt rope were adopted (Figure 2.g) to consolidate the corbels of the cornice of the third order, when presenting detachment injuries, with a danger of collapse. The consolidation intervention has provided the use of very small diameter basalt fibers strings (3 - 4 mm). The intervention techniques used in the past, for seaming cantilever or flaking elements, involved the use of elements such as pins, nails, etc., generally made of iron. The different thermal expansion of materials (travertine and iron) and the oxidation of iron, has involved ejection phenomena of sewn items occurred (Figure 10.a-10.b). In the specific case, the basalt fiber rope was prepared the day before intervention, by immersion in epoxy resin, in order to make the portion that is stuck inside the stone to be consolidated rigid. The fibers of the rope's terminal part are frayed to be able to be folded and glued to the external side, as a kind of anchor plate, with a thixotropic mortar. The rope's resistance is comparable to a S235 steel bar (according to the European standard EN 10025-2). Therefore, limited-diameter but highly resistant elements have allowed to limit the invasiveness, and made very small holes.
The consolidation intervention with basalt fibers ropes is divided into several phases:

- the recognition of the lying crack, so to achieve a perpendicular hole to the lying plane;
- realization of the hole, after depth calculation;
- injecting the thixotropic grout;
- inserting the basalt rope, for the entire length of the rigid part;
- fraying of the terminal part of the rope, and folding the fibers on the stone ashlar, so as to form a species of pin head;
- sealing the frayed fibers on the travertine block, with thixotropic mortar;
- protection of the sealing means of travertine powder pack, recovered from the initial drilling. This operation, while ensuring the recognizability of the intervention, it camouflages, an overall view of the monument[8].

Figure 10.a

Figure 10.b

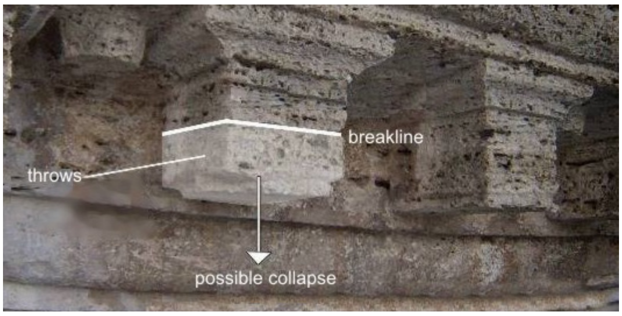


Figure 10.c

Figure 10.d

Figure 10.g

Figure 10.e

Figure 10.h

Figure 10.f

Figure 10.

*Consolidation intervention of the corbels, at the third order cornice*
*(a) (b) metal rivets, heads of detachments and injuries*
*(c) identification of the lying posture of the crack (crack), so as to achieve a hole perpendicular to the plane in the same plane*
*(d) drilling the hole, after the calculation of depth*
*(e) injection of thixotropic grout*
*(f) insertion of the basalt rope, for the entire length of the rigid part*
*(g) fraying of the terminal part of the rope, and folding of the fibers on the stone ashlar, so as to form a species of the pin head, and subsequent sealing of frayed fibers on the block of travertine, with thixotropic mortar*
*(h) of the sealing mortar protection, through the implementation of a travertine powder compress, partly recovered from the initial drilling. This operation, while ensuring the recognizability of the intervention, it camouflages, an overall view of the monument, reducing the impact*

## 4. CONCLUSIONS

The basalt fiber, by its nature, characteristics and properties, can be realistically considered as the material of our future, for a green and sustainable development. If we consider the environmental impact of the technological processes necessary to obtain basalt fibers (in its life cycle), the 'environmental cost' of the basalt fiber is much less than the one of glass, carbon or mineral fiber material in general. In recent years, a growing number of researchers has been dedicating to the development of the basalt fiber industry and of this material's possible applications, in particular on historic building. An indicator of this particular situation may be the growing number of articles published about basalt fibers, in particular since 2004. These articles mainly deal with an overview of the basic properties of basalt fiber and its manufacture, but the development of concrete applications of basalt fiber is steadily increasing. Beyond this material's intrinsic characteristics, and consequently the type of product used, the basalt fiber, in the light of literature and experiments carried out, is particularly suitable in restoring monuments, for its compatibility with stone materials and its non-susceptibility to corrosion that result in a greater durability of the intervention.

## NOTES

1. http://www.b-composites.net/210.html
2. http://www.enea.it/it/pubblicazioni/pdf-eai/maggio-giugno-2011/sr-basaltfibra.pdf/view
3. http://www.b-composites.net/228.html
4. Domanda di brevetto italiano per invenzione industriale "Metodo per rinforzare opere edili ed opere rinforzate così ottenute" depositata in data 07 giugno 2011 al n. BO2011A000327
5. http://restaurocolosseo.it/
6. team: Capponi G. (Construction manager); Conti C. (Director of surface restoration); Podestà S. (Director for the structural aspects); contracting companies: ATI Gherardi-RECO-B5srl (Roma) / Aspera SpA (Genova)
7. http://www.hg-gbfbasalt.com/it/news.htm
8. http://video.repubblica.it/edizione/roma/roma-colosseo-la-corda-di-basalto-il-segreto-del-restauro/227550/226841

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