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Research Paper

EXPERIMENTAL STUDY OF MASONRY VAULTS REINFORCED WITH COMPOSITE MATERIALS

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This paper discusses problems associated with masonry rehabilitation techniques, as well as the use of composite materials in sewage-system infrastructure. The goal of the experimental design presented in this paper is to study the effect of Fibre Reinforced Mortar lining, which was strengthened with composite materials of modest thickness, during the restructuring of ovoid masonry works. To this end, failure tests on reinforced and non-reinforced masonry vaults were conducted. The implementation of a mortar lining reinforced with composite materials (i.e., carbon-fibre strips and fabric) increased the tensile strength and delayed the onset of cracks. The primary advantage of this type of lining in comparison with conventional reinforcement, such as reinforced shotcrete lining, includes considerable gains in rehabilitation durability and the preservation of the structure's hydraulic capacity.

Keywords: Sewerage systems, Composites materials, Masonry, Rehabilitation

INTRODUCTION

Parisian sewers date back to the 16th century. Numerous descriptive and historical studies have been written on the construction and evolution of the sewage system in Paris. An important change took place under Belgrand (1887), which led to the current sewage network. Sewage drains may be subject to various types of loading. One can distinguish among the stress produced by the weight of the sewer structure itself, the loads relative to the weight of the soil (i.e., vertical or lateral loads) and overloads from the surface (e.g., buildings or road construction). These loads may lead to various types of damage such that reinforcement materials and repairs may be necessary to re-establish performance and avoid structural rupture. At present, masonry sewage infrastructures constitute the majority of works needing rehabilitation, due to their deteriorated structural conditions. These structures consist of a vault, abutments and an invert (see Figure 1).

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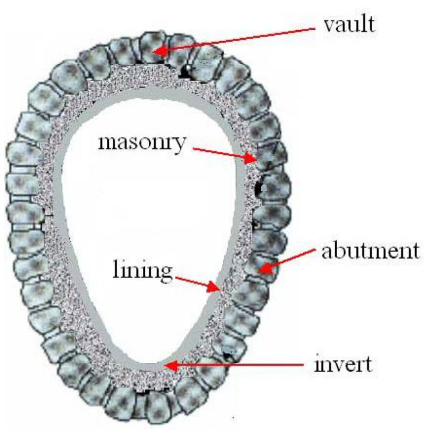
Figure 1: Ovoid in Masonry



The search for reconstruction procedures that reduce repair costs has led engineers to consider punctual rehabilitation methods. Since the 1990s, partial reconstruction has been used by the French construction industry. This technique consists of rehabilitation by gluing composite plates or fabrics composed of carbon fibres.

This technique is not directly applicable to masonry works, due to the irregularity of support. For masonry works, it is necessary first to apply a fine lining to regularise the support. This lining also allows for the stress to be transmitted from the masonry to the composite materials. The coating usually selected for the lining is a fibre-reinforced mortar currently used in works for resurfacing and form reconstitution. This coating is also used to repair surface cracks and address problems connected with sealing. The goal of this study is to reduce rehabilitation costs, improve the durability of repairs (without rebar) and to reduce the on-site intervention time. To address these demands, the RESAME project (Restructuration par chemisage mince sans réduction de section hydraulique et Sans Armatures MEtalliques, or reconstruction through fine lining without reduction of hydraulic capacity and without rebar) was initiated by French companies.

This paper first presents the problems and repair techniques associated with sewage infrastructure, depending on whether these structures are accessible. Next, this paper reports on efforts towards characterizing the various materials used in these repairs (millstone, bonding mortar and high performance, fibre-reinforced mortar). Due to the complexity of the geometry of millstone ovoids, trials at scale 1, were conducted on non-lined millstone vaults, vaults with 2 cm linings with fibre reinforced mortar and vaults with 2 cm linings reinforced with composite materials. The behavior of these vaults is compared to the behavior of vaults reinforced with shotcrete to show the usefulness of a fine lining in rehabilitating these drains.

PROBLEMS WITH SEWAGE SYSTEMS IN MASONRY

Before undertaking repair work, it is important to be able to identify problems, as well as their underlying causes. The causes of these problems are usually explained based on visual, geometric or mechanical factors. Most mechanical trials involve the application of interior pressure to cause the ovate deformation of the tested structure to measure the global rigidity of the drain, which is used to determine Young's modulus.

There are numerous problems pertaining to sewage drains in masonry or concrete (reinforced or non-reinforced) works (Gerad, 1991). These anomalies consist typically of longitudinal cracks at the level of the abutments and the vault. These defects are often accompanied by transverse cracks. The defects can be the consequence of various deteriorating factors, such as overloading, chemical attack and antiquated structures (Gerad, 1991).

However, certain problems are unique to millstone drains. An investigation (Structure and Rehabilitation) based on approximately, thirty diagnostic and recommendations studies, covering a ten-year span, listed the most usual problems for millstone structures. The principal deteriorations are numerous and include stone defects and separation of the masonry (Figure 2).

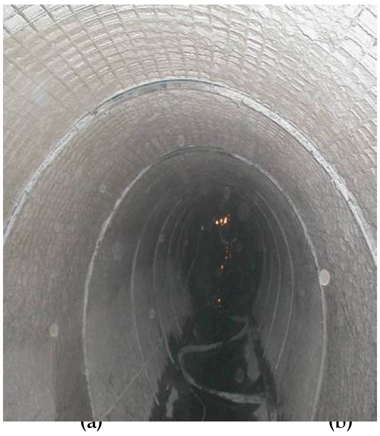
Figure 2: (a) Stone Defects (b) Separation of the Masonry [3]

(a) (b)

CONTEMPORARY REPARATION TECHNIQUES

Structural deterioration (from ageing, aggressive environment, new stresses and the decompression of soils) generates the need for restructuring. The most widespread technique consists in carrying out a reinforced shotcrete lining of 6 to 8 cm in thickness on an entire section of the drain (Figure 3) or using rigid or flexible prefabricated elements to fill the annular space.

Figure 3: Construction Reinforced with Shotcrete [4]



The major drawbacks for these techniques include the reduction of the hydraulic section, the corrosion of rebars and steel buckling. To address these issues, it is necessarily to explore new reinforcement techniques.

Following advances made in the construction industry and public works, Kesteloot (2006) carried out a study on the reinforcement of concrete ovoids reinforced with the aid of composite materials. A load gain of 50% was noted in comparison with ovoids with nonreinforced concrete. The results of this study demonstrated the adaptability and advantages offered by the application of this new procedure to accessible, ovoid reinforced concrete drains. This procedure was applied at a site in Saint Maur (94) in France in 2005. Since this procedure was employed, no deterioration has been observed (see Figure 4).

Figure 4: Construction Reinforced With Composites Matérials [6]

To our knowledge, no study has been conducted on sewage infrastructure reinforcement in masonry (millstone). By contrast, numerous trials have been conducted on clay brick masonry vaults in Italy in an effort to protect cultural landmarks against seismic risk (CNR-DT, 2004).

Bati Bricolli and Rovero (2000) and Aiello *et al*. (2000) implemented experimental studies on the reinforcement of masonry arches. These studies indicated that the application of Carbon Fibre Reinforced Polymer (CFRP) increases the resistance of the structure and modifies both the failure mechanism and the breaking load.

Valluzi *et al*. (2001) presented results from trials on brick masonry vaults, which were reinforced by carbon fibre or glass fabrics on the extrados or the intrados. The breaking load was the same for the two types of reinforcement, but the failure mechanism was different.

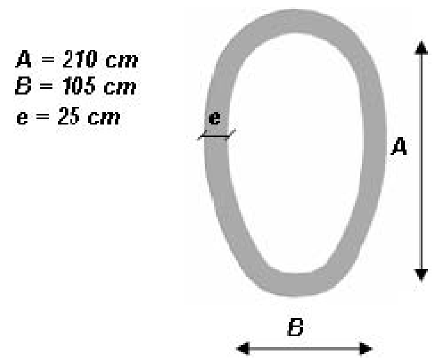
Luciano *et al*. (2002) demonstrated the effectiveness of carbon strip reinforcement on masonry arches. These researchers developed numerical calculations that reproduce the same behavior as the vaults tested.

These studies have shown that the application of composite materials modifies the classical breaking mechanism of the arch and improves the capacity of the breaking load.

DIMENSIONING OF THE TEST BODY

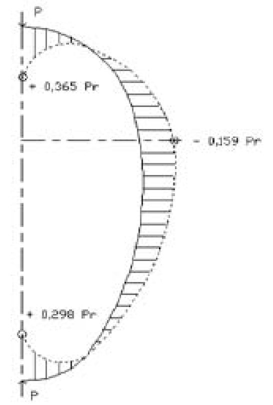
Due to the complexity of the material and its geometry, a geometry suitable for laboratory testing must be achieved. The test bodies chosen for our study were vaults. These bodies should correspond to the upper part of the ovoid (Figure 5) between the start of the arch curvature, where the abutment and arch connect.

Figure 5: T210 Ovoid



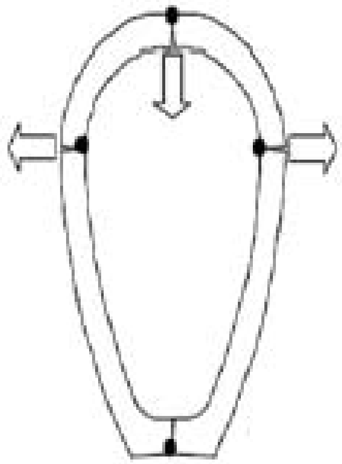
Based on the calculations carried out by Kentie (1968), the failure mechanism can be derived from the moment diagram. Tense areas represent areas of cracked material; cracks occurred because the stress limits of traction were exceeded. Figure 6 shows the

Figure 6: Moment Diagram During Vertical Overload



distribution of moments along the contour of an ovate structure. The maximum moment occurs at the keystone of the vault. Vertical loading denotes the vertical pressure of soils, as well as pressures due to dynamic loads such as rolling loads, permanent roads and surface construction sites. The most common failure mechanisms associated with vertical loading include a sagging vault and abutment divergence, as shown in Figure 7.

Figure 7: Failure Mechanisms in an Ovoid



Finite element modelling was conducted by Khoufache (2008) to determine boundary conditions to ensure that the test body would be representative of an ovoid vault in real conditions. The laws of behavior which are used for masonry and coating correspond to exponential distribution (Figure 8). The loading block follows a linear elasticity model. The characteristics of the materials are given in detail in Table 1, according to the results which were obtained from tests on a building site.

Figure 8: Exponential Distribution Law

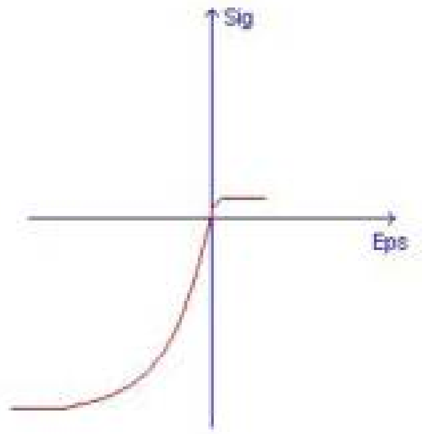
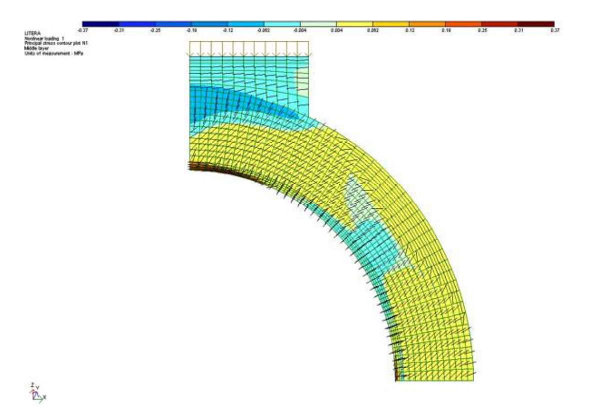


Table 1: Materials Characteristics

	Masonary	Coating	Loading Block
Young's modulus (MPa)	5000	24000	200
Poisson's ratio (σ)	0,2	0,15	0,3
Compressive Strength (MPa)	5	30	19
Tensile strength	Various	0,5	/

The pre-modelling shows, as far as tensile strength is concerned, a distribution which is identical to the behavior met in theory for an ovoid which is subjected to a vertical load. Indeed, the tensile strengths are weak; the cracks thus appear in the tight areas. Figure 9 represents the tensile strengths and consequently the cracked areas. These tight areas, obtained by our models, correspond to the cracked areas in theory.

Figure 9 : Main Stresses and Main Associated Directions

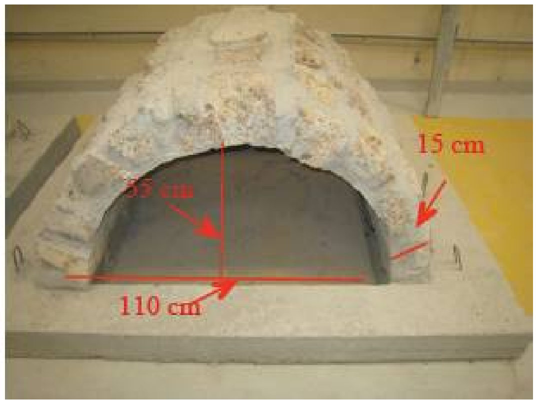


The results thus obtained show a correlation between the numerical calculations and theory. Moreover, the stresses and the displacements correspond to those of an ovoid. Tests (Kesteloot, 2005) will be conducted on vaults instead of ovoids. The dimensions of the vault used in our Finite Element Method (FEM), will be used again for the experimental campaign, with a diameter of 1.00 m and a thickness of 0.15 m.

THE TEST BODIES

Derived from the modelling procedures described above, the test bodies are vaults with the geometric characteristics given in Figure 10.

Figure 10: Geometric Characteristics of a Vault



Nine vaults were constructed in accordance with the construction techniques used during the Baron Haussmann period (i.e., the mid-19th century) (Hervieu, 1897). The same mortar composition was used for all the vaults. The mechanical resistance of the mortar was monitored during vault construction. Each millstone block was unique, with different resistance and dimensions being observed.

Wooden half-cylinder form works were designed (see Figure 11). The height of the arches was 55 cm. The arches were made up

Figure 11: Wooden Formwork

of two juxtaposed parts, with each corresponding to a half-vault. This arrangement facilitated the removal of the formwork after construction was completed. Millstone blocks of various shapes were arranged on the arches to create a mesh. The blocks were cut and trimmed by stonecutting specialists. The vaults were subsequently hand-built, as shown in Figure 12.

Figure 12: Construction of the Vaults

The millstone blocks used for vault construction originated in a quarry located approximately 100 km from Paris. This stone exhibits good cohesion with the connecting mortar. Various characterization trials were performed on the millstone (Khoufache, 2008). All of the results obtained during the characterization trials show that the millstone is a material that has strong disparities in its characteristics. The mortar used in the construction of sewage networks was procured in the laboratory. The composition was identified based on bibliographic research. At the time of Baron Haussmann, the binder used for millstone masonry structures was a mix of 3/5 cement and 2/5 hydraulic lime. This mortar, known as "bastard", was prepared by mixing the various constituents in the following proportions (by weight): 2 kg of cement, 1.34 kg lime, 32.7 kg sand and 5.4 L water. Table 2 shows the mechanical characteristics of the millstone and the mortar.

Table 2: Mechanical Characteristics of Millstone and Mortar

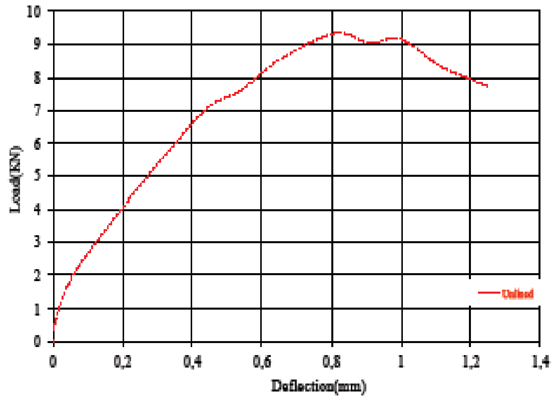
Characteristics	Millstone	Mortar
Modulus of elasticity [MPa]	2500	5931
Average compression strength [MPa]	12 to 26	0.9
Average tensile strength by pullout test [MPa]	1.47	-
Bending strength [MPa]	-	0.5

EXPERIMENTAL PROCEDURE

The trials were performed with a single vertical loading on the vault. The horizontal resultant for soil movement was not taken into account to highlight the zone that was the most stressed, that is, the keystone with respect to the tensile stress present in the keystone. This loading is thus the least favorable loading. To obtain a load that is uniformly distributed on the upper part of the keystone, a metallic profile (0.20 m x 1.20 m) was placed on the keystone. Load application was performed uniformly without slippage on the keystone. The actuator has a capacity of 250 kN. The test setup was directed remotely at a speed of 0.01 mm/s. During the trials, instrumentation included a displacement sensor and a force sensor to measure the load. An inductive displacement sensor was located at the level of the keystone on the intrados (i.e., vertical displacement). The range was 100 mm (see Figure 13).

Figure 13: Experimental Device

Figure 14: Load variation as a Function of Deflection for the Test Vault



The trial results provided insight on vault deformation with successive appearance of cracks, the behavior of the vaults in the course of loading and the breaking load.

The vaults tested are listed below:

- Two unlined vaults, which are called control vaults.
- Two vaults with a 2-cm fibre reinforced mortar lining.
- Two vaults with a 2-cm fibre reinforced mortar lining reinforced by carbon-fibre strips.
- Two vaults with a 2-cm fibre reinforced mortar lining reinforced by carbon-fibre fabric.
- One vault reinforced by 6 cm of steel-reinforced concrete.

In the case where two vaults were tested, the results are given for a single vault given the good reproducibility of the trials.

CONTROL VAULT TRIAL

Figure 14 represents load variation as a function of deflection for the control vault. In the

Figure 15: Cracks in the Mortar Joints at the Level of the Spandrels on the Extrados

curve, we can distinguish two phases. In the first phase, load values did not lead to significant cracking in either the binding mortar or in the millstone. The first crack appeared in the mortar joints at the level of the spandrels on the extrados and subsequently at the keystone on the intrados for a load of 7 kN. In the second phase of the trial, the load values produced cracking in the binding mortar across the entire length of the vault. The breaking load was 9.32 kN for a displacement of 0.77 mm. The cracks appeared in the same way for the two vaults (Figure 15).

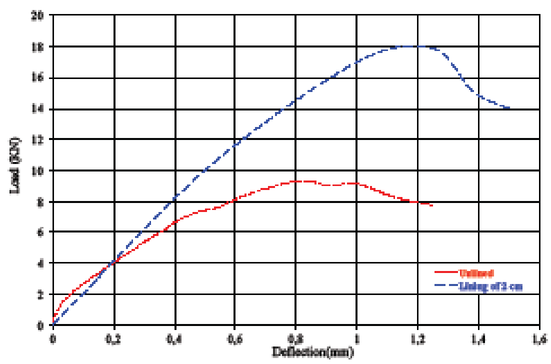
Vault reinforcement using fibre reinforced mortar The lining used for repairs is a fibre reinforced mortar. It is used for resurfacing and form reconstruction. Table 3 presents the mechanical characteristics of the lining.

Table 3: Mechanical Characteristics of the lining

Lining	Characteristics
Water content (%)	12
Bending strength [MPa]	7.79
Compression strength [MPa]	52.53
Bonding strength [MPa]	2.2
Splitting tensile strength [MPa]	4.31
Young's Modulus [MPa]	27308

Twenty-eight days after the construction of the vaults, a fibre-reinforced mortar lining was manually applied to the vaults in two layers of 1 cm each with the aid of a trowel, a float and a ruler. Before and after the application of the two layers of lining, the vaults were covered with a tarp, and a humidifier was placed underneath the vault to maintain a relative humidity of 90% and a temperature of 20°C. This method replicated the environmental conditions of sewage infrastructure. The humidity was monitored with the aid of a hygrometer. Figure 16 shows load as a function of the vertical displacement of the vault for both the lined vault and the control vault.

Figure 16: Load Deflection Curve For Control And Lined Vaults



The behavior of the vault exhibits two phases, as with the control vault. The breaking load for the reinforced vault was 18 kN. The displacement of the vault was 1.3 mm. This displacement corresponds to a gain of approximately 114% for the load at first crack and 93% for the breaking load. The addition of a lining helped increase the breaking load. Meanwhile, the first crack appeared at the keystone on the intrados at 15 kN (i.e., the first phase of the curve). Next, cracks appeared at the level of the spandrels on the extrados and were propagated in the joints of the masonry across the entire length of the vault until breakage occurred on a single side (see Figures 17 and 18).

Figure 17: Cracking at the Keystone Of the Vault Lined On The Intrados

Figure 18: Cracking In The Mortar Joints at the Level Of The Spandrels On The Extrados

The two lined vaults exhibited the same failure mechanism.

VAULT REINFORCEMENT USING CARBON STRIPS

The vaults were later reinforced with carbon strips. This procedure was intended to repair and reinforce the structures. The strips are composite plates composed of carbon fibres embedded in a polymer matrix. The mechanical characteristics of the strips are given in Table 4.

Table 4: Characteristics of Carbon-fiber Strips

Designation	Strips
Modulus of elasticity in tension[GPa]	>165
Tensile strength [MPa]	>20
Elongation at failure [0/00]	>17

The interior surface of the lined vaults was lightly planed to remove all defects in the lining as well as any laitance. The reinforcements were glued along the entire vault on the intrados. To apply the reinforcements, a special adhesive composed of an epoxy was used. The adhesive is notably important because it allows for the stress in the structure to be transmitted to the composite materials. The mechanical characteristics of the strip adhesive are shown in Table 5.

Table 5: Characteristics of Strip Adhesive

Designation	Characteristics
Modulus of elasticity	12 800 MPa
Bending strength	≥30 MPa at 2 days at 20°C
Adherence to the concrete support)	≥4 MPa (breakage in the

The addition of the carbon-fibre strip was achieved by double gluing. A fine layer of adhesive was applied on the support and on the strip (Figure 19). This double gluing allows for uniform dispersion of the adhesive. Then, the surplus adhesive was scraped with a roller.

The evolution of the load as a function of the deflection, shown in Figure 25, exhibits linear behavior for the first phase of the curve. Cracks first appeared at 70 kN. An increase in load progressively led to cracking. Cracks

Figure 19: Lined Vault Reinforced by Carbon Strips

appeared both in the mortar joints at the level of the spandrels on the extrados and in the middle of the abutments on the extrados (Figures 20-22). After the breaking load of 85.85 kN, the load diminishes rapidly as the strips at the keystone on the intrados became unglued (Figure 21). The tensile strength gain is about 788% that of the unlined vault and approximately 377% that of the lined vault. The vault behavior exhibited an elastic zone followed by fragile failure.

Figure 20: Mode of Failure for the Lined Vault Reinforced With Carbon Strips

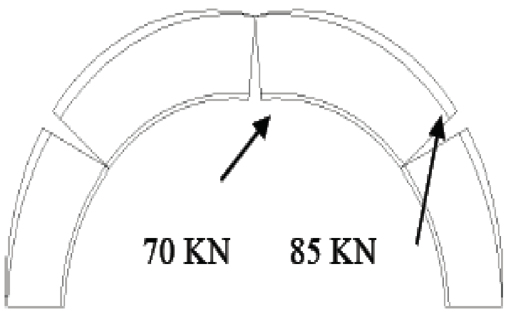


Figure 21: Strip Ungluing

Figure 22: Cracks at the Level of the Spandrels on the Extrados

The cracks were continuous across the entire length of the vault. The vaults reinforced by strips did not undergo sagging (see Figure 23).

VAULT REINFORCEMENT USING CARBONFIBRE FABRIC

The carbon-fibre fabric is unidirectional, and its mechanical characteristics are shown in Table 6.

The mechanical characteristics of the adhesive are given in Table 7.

Figure 23: Vault Reinforced with Carbon-fibre Strips

Table 6: Characteristics of carbon-fiber fabric

Designation	Carbonfibre Fabrics
Modulus of elasticity in tension [GPa]	>230
Tensile strength [MPa]	>3500
Elongation at failure [0/00]	>15

Table 7: Characteristics of Fabric Adhesive

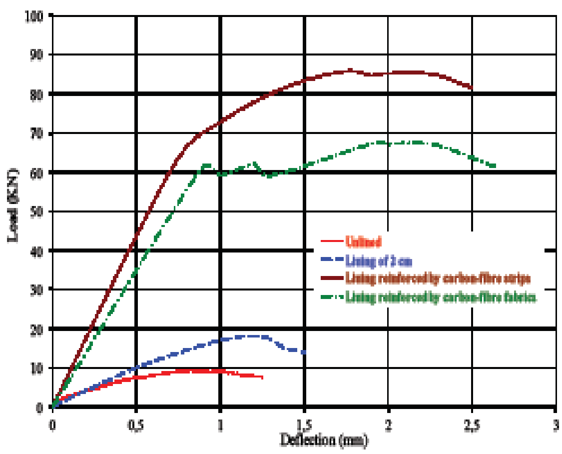
Designation	Characteristics
Modulus of elasticity in bending	3 800 MPa at 7 days and 23°C
Compressive strength	≥55 MPa at 2 days and 20°C
Tensile strength	≥30 MPa at 2 days and 20°C
Adherence on sand blasted concrete	Superior to the cohesion of the support (after 24 h)

The interior vault surface was prepared in the same way as the vaults reinforced by carbon strips. The addition of the carbon fibre fabrics was achieved by simple gluing. A fine layer of adhesive was applied on the support. Next, the fabric was arranged on the intrados of the vaults with the assistance of a PVC spatula. As with the strips, a roller was used to remove any surplus adhesive (see Figure 24).

Figure 25 shows the load variation as a function of deflection. The vault behavior was identical to the vault reinforced by carbon-fibre strips. Specifically, the vault behavior exhibited an elastic phase up until 63 kN with a deflection

Figure 24: Lined Vault Reinforced With Carbonfibre Fabric

Figure 25: Evolution of Load as a Function of Deflection for the Vaults Tested



of 0.9 mm and subsequently a plastic plateau corresponding to a load of 64 kN until a deflection of 1.5 mm. Next, the load increased slightly until 67.76 kN, which was the point of vault failure. In the course of the trial, the carbon-fibre fabric became unglued at 63 kN on the intrados at the keystone. At the plateau, additional ungluing subsequently occurred at various spots on the intrados (see Figure 26). The stress was transmitted to the carbon-fibre fabric. The tensile strength gain was approximately 600% that of the unlined vault and 276% that of the lined vault. In contrast, the tensile strength gain was reduced by 21% compared to the vault reinforced with carbon-fibre strips. The failure mechanism is identical for the two vaults tested. Cracks appeared in the mortar joints at the level of the spandrels on a single side (see Figure 27).

Figure 26: Detachment of Carbon-fibre Fabrics

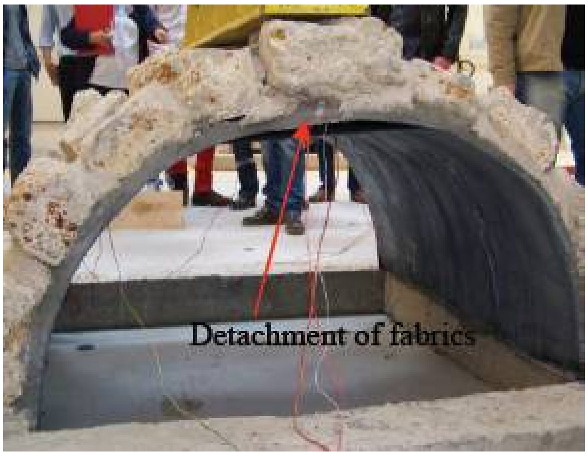
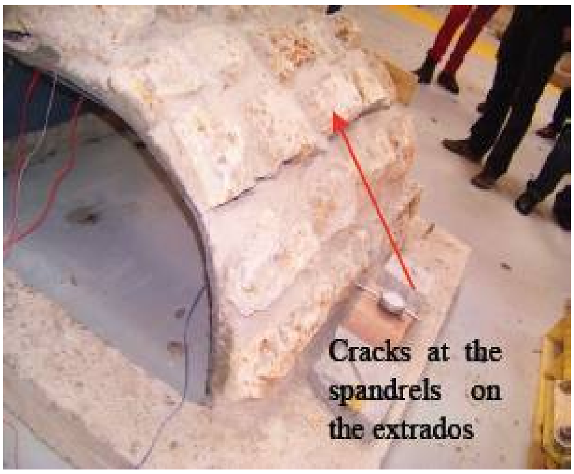


Figure 27: Cracks at the Spandrels on the Extrados



The cracks are continuous across the entire length of the vault. The vaults reinforced by carbon-fibre fabric collapsed (see Figure 28).

Figure 28: Collapse of a Vault Reinforced by Carbon-fibre Fabric

Vault Reinforcement Using Shotcrete

The use of shotcrete for repairs is quite old. The first applications date back to 1907 in the United States. In France, this technique was used for the first time during work on the railway tunnel in Puymorens in 1921.

Currently, two methods of projection are commonly used: dry and wet spraying:

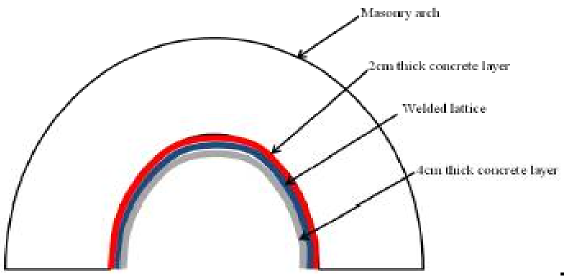
- Dry spraying is used for open-air work.
- Wet spraying is used for work in very confined spaces (i.e., sewage drains and networks).

The thickness of the concrete layer varies between 6 and 8 cm. For this study, dry spraying was used to create a 6-cm concrete lining on the entire interior surface of the vault (see Figure 28). The reinforcement was a welded lattice with a 0.9-mm diameter and a mesh of 50 x 50 0.9 mm². The distance between the lattice and the underside of the arch was 2 cm (Figure 29).

The various stages of reinforcement were

- Spraying of 2-cm thick concrete;
- Installation of a welded lattice;
- Spraying of 3-cm thick concrete; and
- Spraying of a final layer of 1-cm thick concrete.

Figure 29: Vault Reinforced with Reinforced Shotcrete



The concrete is prepared by mixing the following components:

- 350 kg of grey cement CEM I 52,5 N CE PMES CP2 NF “HRC (high resistance cement)” (conforming to French and European standards NF EN 197-1) and
- 1 m³ of dry sand (conforming to the French standard XP P 18-540).

Measurements of shotcrete resistance (see Figure 30) were obtained by carrying out compression trials (see Figure 32) on previously cored 6 x 12 cm² samples of sprayed shotcrete (Figure 31). The average resistance was 36.7 MPa (Table 8).

Figure 30: Spraying of Shotcrete

Figure 31: Coring of the 6 x 12 cm² Samples

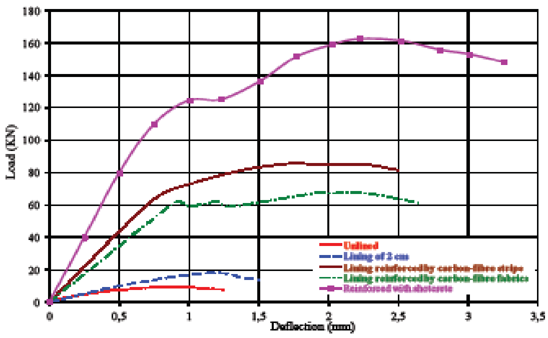
Table 8: Mechanical Resistance of Shotcrete

Samples	Rc_{28} [MPa]
1	39.85
2	35.00
3	35.32

Figure 32: Compression Trial

The vaults were later subjected to a load test up to failure to study the effect of the reinforcement. Figure 33 shows load variation as a function of the vault displacement.

Figure 33: Load Variation as a Function of the Vault Displacement for the Reinforced and Control Vaults

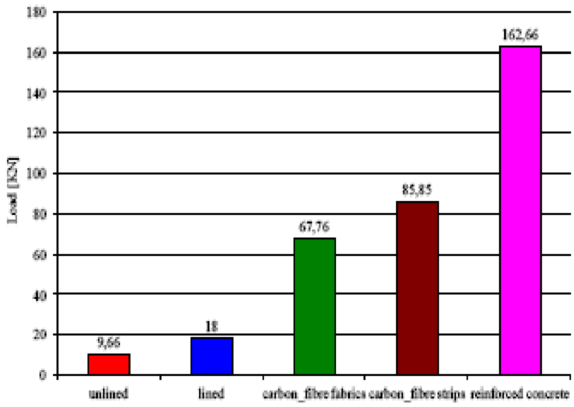


The curve shows three zones. An elastic zone is followed by a plateau up to 125 kN, which corresponds to a deflection of 1 mm. Beginning with a displacement of 1.25 mm, the behavior of the vault reinforced with shotcrete is elastic. The breaking load is 162.66 kN with a displacement of 2.25 mm. The first crack appeared at the keystone on the intrados at 110 kN (Figure 34) and continued until failure.

Figure 34: Breaking Mechanism

This method of reinforcement yielded the best results. Figure 34 compares all methods of reinforcement studied. The tensile strength gain was approximately 1583% that of the unlined vault, 803% that of the lined vault, 140% that of the lined vault reinforced by carbon-fibre fabric and 90% that of the lined vault reinforced by carbon-fibre strips (Figure 35).

Figure 35: Breaking load for each type of Reinforcement



The reinforcement method using shotcrete yielded the best results for breaking load, but it has several disadvantages:

- Very high cost of rehabilitation;
- Very complicated implementation;

- Reduction in hydraulic section; and
- The use of rebars.

This method does not fulfil the requirements of the RESAME project. In fact, reinforcement with carbon-fibre strips and fabric yielded good results with respect to cracking delay and breaking load increase. Furthermore, this method is easy to implement (i.e., it results in reduced labor costs), and it is responsive to the demands of specific projects.

However the realization of the projected concrete has been achieved within the intrados of the vault, but also on the existing. The concrete should have been only projected on the vault itself.

CONCLUSION

Various procedures to reinforce millstone masonry vaults have been presented. This study aimed to compare the breaking load, failure mechanism and tensile strength gain in reinforced vaults as compared nonreinforced vaults. Based on the results, the following conclusions were reached:

- Each method of reinforcement (i.e., fibre-reinforced mortar, carbon-fibre strips, carbon-fibre fabric and shotcrete) has its own failure mechanism.
- The presence of composite materials (i.e., carbon-fibre strips and fabric) delayed cracking, and therefore the results suggest that steel is not necessary in reinforcement materials.
- The hydraulic section was better maintained compared to the shotcrete method.
- Increased durability was achieved by avoiding the use of steel and other corrosive materials.
- From a financial point of view, fabric application is easier and thus more rapid in comparison to the other techniques. Furthermore, it is simpler to create multiple layers of fabric to increase the bearing capacity of the structure.
- Breaking load increased 8-fold for carbon-fibre strips and fabric and 16-fold for reinforced concrete compared to unlined vaults. Various parameters may affect this increase, including the thickness of the reinforced layer and the application time.
- A review of the literature (Aiello, 2000; Valuzzi, 2001; Lucianno, 2002) confirmed that gain in tensile strength can be achieved by applying composite strips to the intrados of vault-type masonry structures.

Concerning the durability, a collage *in situ* has been achieved in 2005. After several inspections, no detoriation has been miticed so far.

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