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A simplified approach to evaluate retrofit effects on curved masonry structures

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ABSTRACT: Masonry vaulted structures are diffused all over the world, in many cases in historical and monumental buildings, often characterized by high seismic risk. For this reason their conservation should be investigated. Composite materials are usually used to retrofit different types of masonry and concrete buildings. The behaviour of masonry arches retrofitted at their intrados and/or extrados surfaces by means of externally bonded composite materials (FRP or FRCM) has been investigated. The load capacity estimate due to composite strengthening could be performed through finite element analyses. The numerical simulations provide important information about the mechanical behaviour of the masonry structures and on the composite-masonry interaction. However, such numerical analyses present often some drawbacks. For this reason it is useful to have simplified calculation methods to estimate capacity increase of masonry vaulted structures due to composite retrofit. Such simplified methods are the goal of this work and they consider linear and nonlinear behaviour of masonry. Validation of the proposed method is carried out by comparing predictions of the load capacity and failure mode with those obtained from shaking table experimental tests.

1 INTRODUCTION

Most of the international cultural heritage buildings are made of masonry. Often, a relevant part of these structures is located in high seismic risk areas and their safeguard is needed. The innovative retrofit techniques are certainly a valid tool to reduce the vulnerability of these structures. The knowledge of the innovative techniques and of seismic capacity assessment, following to retrofit of masonry structures, is the point of departure to protect cultural heritage buildings against the earthquake effects.

The use of Fibre Reinforced Polymers (FRP) laminates (or fabrics) for the structural retrofit of masonry buildings has turned out to be efficient. However, such retrofit technique has shown some critical aspects as well as disadvantages (Valluzzi et al. 2001).

The principal drawback in the traditional FRP systems applied to masonry elements is the epoxy resin matrix, and the lack of bond between resin and masonry substrate. Indeed the epoxy resin matrix has a low vapour permeability, which is not compatible with the physical-chemical characteristics of the masonry (Angelillo et al. 2014). Furthermore epoxy resin matrix has very low performances at high temperatures dissimilar to the masonry substrate. All these disadvantages can be overcome by means of alternative retrofit techniques based on inorganic matrices. An alternative technique uses Inorganic Matrix such as the Fiber Reinforced Cementitious Matrix (FRCM).

The key difference compared to the traditional FRP systems is that the inorganic matrix replaces the epoxy resin matrix. The physical and chemical compatibility of this matrix with the masonry guarantees the improvement of the bond between the retrofit system and the masonry substrate. Additional advantages of the FRCM system are the fast and simple installation and arrangement. Furthermore it can be easily removed being fully reversible (Lignola et al. 2009).

The FRCM retrofit system, due to its characteristics, is particularly appropriate for curved masonry elements such as arches and vaults. Masonry vaulted structures, which are much diffused in the heritage buildings, are a crucial structural element in the seismic behaviour of buildings and are often artistic valuable elements. Therefore, the effectiveness of these interventions is subordinated to have an analytical approach aimed to the assessment of the seismic behaviour of arches and vaults retrofitted through FRP or FRCM systems.

The seismic behaviour assessment of vaults and arches, through the Finite Element Method (FEM), can be analyzed. However, this numerical approach needs often specific calibrations which make them not easily extended to other cases.

The present work represents a first step towards the development of a simplified calculation approach for the seismic behaviour assessment of masonry vaulted structures retrofitted by innovative techniques. The aim is indeed to provide practical tools which do not require high computational efforts for its application.

The validation of the method has been conducted by experimental and numerical comparison. Indeed experimental results have been available through shaking table tests which are the starting point for the validation.

2 MASONRY VAULTS: BASIC ASSUMPTION

Masonry vaulted structures are generally spatial three-dimensional elements. In the case of barrel vaults, the structural behaviour can be studied as a two-dimensional problem. This allows to analyze the barrel vaults as a sequence of elementary arches neglecting the three-dimensional effects.

Therefore, in plane stress conditions, the masonry arch analysis represents a firm base for the assessment of masonry vaults.

Masonry arches are structural elements made of blocks assembled with or without mortar joints. The equilibrium of each generic block and of the entire structure is achieved by means of the compressive stress distributions given between two adjacent blocks. On each side of the generic block the thrust is defined as the resultant of the compressive stress distribution. The envelope of all the points of application of the thrust is the theoretical curve named thrust line.

2.1 Assessment of behaviour of masonry vaults: classical approach

According to the limit analysis theorems reformulated by Heyman (1995), for a given load pattern, if the thrust line lies entirely within of the thicknesses arch, all the blocks are capable to withstand the load by means of internal stresses compatible with the characteristics of the material (Angelillo et al. 2004). According to the framework of the lower bound theorem, there is not only one thrust line which guarantees the stability of the curved element. Indeed, each possible thrust line that lies within the thicknesses of the arch, corresponds to an equilibrium configuration of the curved element without any tensile strength.

Therefore, the collapse of the curved element is strictly related to the configuration of the thrust line. In particular, the arch is expected to collapse if the thrust line does not entirely lie within the thickness of the arch.

The contact of the trust line to the arch boundary corresponds to a limit condition for which in this section a failure condition can be reached. Failure at section level does not correspond to the collapse of the masonry arch, if the structure has a certain degree of redundancy.

Variations in the thrust line configuration are mainly induced by variations in the acting load patterns. Such variations can result in the development of unexpected stress and strain states and also variations in the thrust line configuration.

Unexpected variations of either horizontal or vertical loads or of their combination are the key reasons of the collapse of this structures. The origins of such variations can be due to several reasons. The critical effects are to be regarded in the variations in the vertical and horizontal loads due to seismic events.

In particular, due to seismic loads tensile stresses could arise in the cross sections leading to the formation of cracks/hinges alternate at the extrados and intrados of the vault. The hinge formations take place at the locations in which the thrust line becomes tangent to the arch boundaries (i.e. where the "virtual" plastic hinge forms). The formation of a sufficient number of hinges yields to the vault collapse. Preventing the formation of the minimum number of hinges which activates the hinge mechanism prevents the vault from the collapse. In conclusion, the assumptions that are at the basis of the classical theory are:

- Infinite compressive strength: even a local crushing generally does not cause global effects and axial loads are usually low compared to the compressive axial strength;

- No brick/masonry sliding: it is an assumption that sometimes should be opportunely verified;

- No tensile strength: this is generally a conservative assumption.

Due to the no tensile strength assumption, the thrust line must be entirely contained in the geometrical boundaries of the structure. In fact it is possible to define the failure surface of the masonry. Due to the no tensile strength assumption the tensile failure surface has origin in zero (Figure 1a), and the eccentricity of the thrust line with respect to the structural axis is $e=M/N$, in such assumptions is the slope of the failure surface. The failure surface is linear (for one direction of the bending moment and starting from zero axial force) in linear elastic behaviour assumption, while it is almost nonlinear accounting for masonry plastic behaviour. However due to the typically reduced axial loads, in its first branch both surfaces are approximately linear.

Defined S the in-plane masonry thickness, the failure surface has a slope equal to S/6 in linear elastic assumption without cracking, while according to the plastic behaviour of the masonry material and allowing for cracking, the initial slope is S/2 and it can be assumed approximately to be almost constant, justified by the low values of the axial loads. Indeed, even in collapse conditions, the axial load values, reached in this type of structures, are very low.

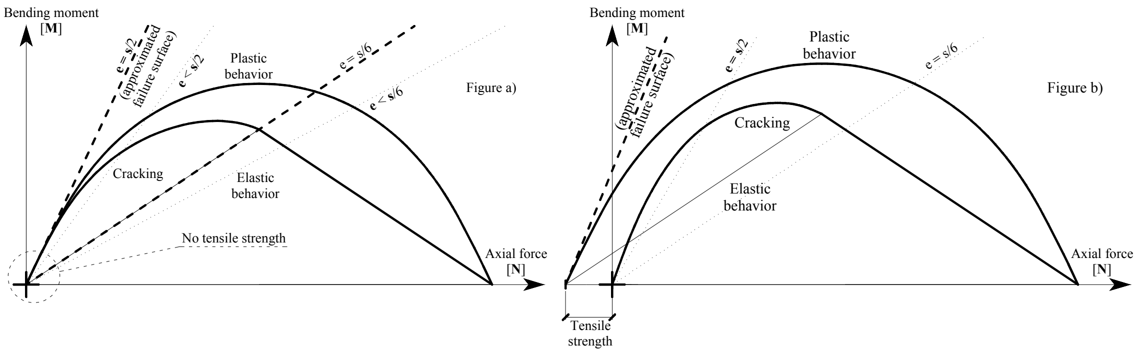

Figure 1. Unreinforced vault: bending moment-axial force failure surface with and without tensile strength.

2.2 *Assessment of behaviour of masonry vaults: effect of tensile strength*

The no tension assumptions could generate some problems for the slender vaulted structures with high aspect ratios even for static conditions. It may happen that the thrust line is not internal to geometric boundaries already for static conditions, making it impossible the equilibrium.

For this type of structures it is not possible to neglect the tensile strength of the material (Figure 1b). The failure surface hence moves to the tensile side due to the tensile strength and the slope of the surface is no longer the maximum eccentricity of the thrust line, and the ratio M/N in failure conditions is no longer constant, but it can be easily argued that eccentricity e is higher than before and it tends asymptotically to previous values (either S/6 or S/2 according to basic assumptions) however the surface is limited by the descending part representing the compressive failure conditions (never reached according to assumptions and typical loads on such structures). This means that eccentricity can be higher than S/2 and higher and higher as axial force reduces, (infinite at zero axial force and misses physical meaning if tractions occur, however, in practical applications the cases in which the brickwork is in tension are very rare). Hence thrust line could lie outside the arch geometric boundary, but inside a virtual, fictitious, thickness defined by an eccentricity e=M/N given by the failure surface (depending on actual axial force).

2.3 *Assessment of behaviour of masonry vaults: effect of tensile retrofit*

In order to prevent the collapse due to the hinge mechanism, the vault is retrofitted at the hinge formation locations or at least on a portion such as to prevent the formation of these hinges. According to the expected hinge arrangement, the FRCM reinforcement can be applied at the extrados, at the intrados or at both the intrados and the extrados of the curved element.

The tensile strength provided by the FRCM reinforcement allows higher loads to be reached. In this condition, as discussed before for masonry tensile strength, a thrust line could lie externally to the physical thickness of the arch without reaching the collapse. The masonry vaults retrofitted by means of FRCM, may have three main failure modes: crushing failure, grid rupture, sliding failure.

Crushing failure mode occurs when the compressive stress in the masonry becomes higher than the compressive strength. This failure mode has a low probability to be activated, since the crushing load is usually higher than the load which activates the hinge mechanism (Lignola et al., 2011).

Grid rupture occurs when the tensile stress in the reinforcement material becomes higher than its tensile strength. The high strength of these materials guarantees that grid rupture is rarely obtained in reinforced masonry vaults, however grid rupture leads to a very brittle failure of the curved element, hence it is a failure mode jeopardizing the plastic redistribution.

Sliding failure mode occurs when the shear stress at the interface surface reaches the shear strength (Drosopoulos et al. 2011). Sliding failure can be related to the angles between the thrust line and the structural axis. This failure mode is prevented if the angle is lower than the friction angle. Hence if sliding planes are orthogonal to the axis and the thrust line must be within geometric boundaries, this failure mode has clearly a low probability, however if the thrust line is allowed to move broader, this failure mode could become critical.

2.4 Assessment behaviour of reinforced masonry vaults: proposed approach

According to the expected hinge arrangement, the FRCM reinforcement can be applied at the extrados, at the intrados or at both the intrados and the extrados of the vault.

If FRCM retrofit is applied at the intrados or extrados only of the curved element, the failure surface becomes not symmetrical as shown in Figure 2. Conversely, if the FRCM is applied at both the intrados and extrados of the masonry vault the failure surface assumes a symmetrical shape.

Due to the low values of axial force that characterize these structures, the first part of the failure surface is usually involved from gravitational conditions up to incipient collapse under horizontal loads.

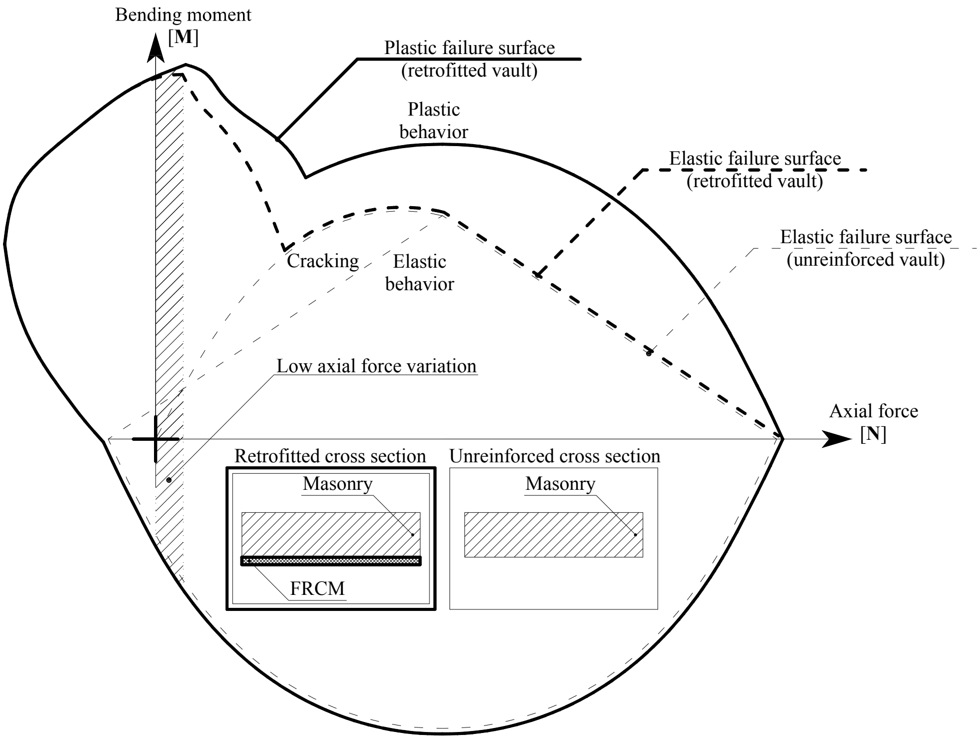

Figure 2. Retrofitted vault: bending moment-axial force failure surface.

Furthermore at low axial loads only the effects of retrofit are evident, in fact at higher axial forces the FRCM becomes compressed and, as well known, due to its slenderness, its contribution vanishes and failure surface drops to the failure conditions of masonry without retrofit. At low axial force values, the elastic or plastic assumptions for material behaviour lead to similar failure surfaces as shown in Figure 2.

Due to FRCM the eccentricity of the thrust line can increase further (Figure 3). The eccentricity value is dependent on the axial force value and it is higher at lower axial forces.

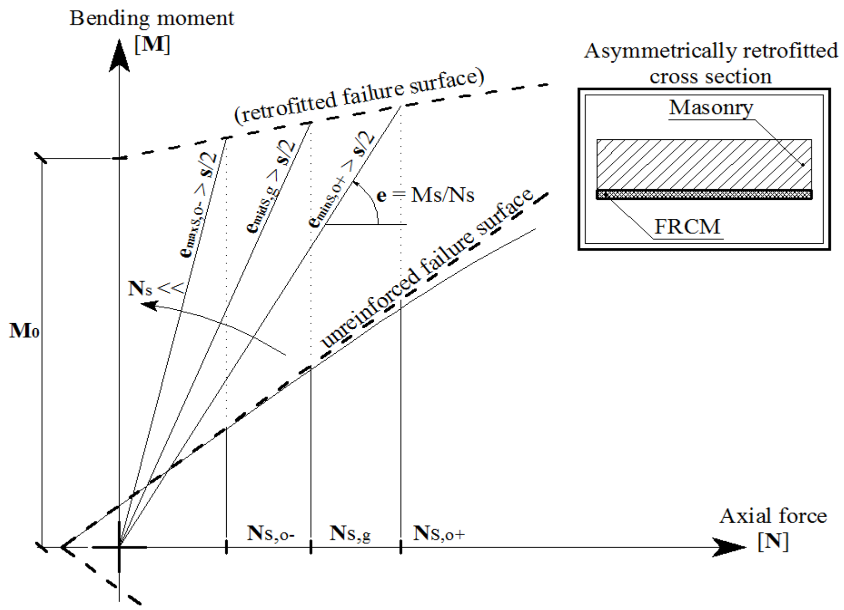

Figure 3. FRCM retrofit effect on the thrust line eccentricity e.

The FRP or FRCM retrofit allows to have a thrust line outside the geometric boundaries. The maximum eccentricity can be calculated according to the failure surface and the maximum eccentricity changes according to the axial force variations.

Figure 3 shows how the retrofit effects can be considered through a fictitious thickness. The thickness evolution defines the boundary within which the line of thrust must be contained. Unlike of the gravitational conditions, the eccentricity is variable during the horizontal load increments (or acceleration increments).

In conclusion, for a generic load step it is possible to define a new fictitious geometric boundary within which the line of thrust must be contained. Due to aforementioned brittle failure of FRCM retrofitted masonry, a first safe estimate stops to the first plastic hinge formation. However if the thrust line is tangent to the unreinforced side of the fictitious boundary, hence no brittle failure is expected, hence the classical limit analysis concepts could be extended to retrofitted masonry structures.

3 MASONRY VAULT: NUMERICAL AND EXPERIMENTAL COMPARISON

The masonry curved elements are usually prone to the flexural failure by means of hinge mechanisms rather than sliding failure that is often neglected. The experimental tests of masonry vaults are often carried out by means of load actuator systems that generate localized effects. Indeed when the point load is applied, the loading jacks could either restrain the retrofit of the vault or prematurely damage it.

Such issues could lead to an improper interpretation of the seismic performances of the reinforcement system and to invalidate the total results.

In the study of the seismic performances of a composite retrofit system, an accurate simulation of the actual load conditions is critical. Therefore the shaking table systems are able to simulate realistically the earthquake ground motions. The shaking table tests can be considered as a reliable seismic testing method, allowing a direct and actual evaluation of the seismic performances.

A study conducted at the University of Naples Federico II, aimed to the assessment of the structural performances of FRCM reinforcement system, consists of several shaking table tests on a masonry vault, before and after the FRCM retrofit application. This study has allowed to validate the proposed approach applied to both the unreinforced and retrofitted specimen.

3.1 *Geometrical and mechanical characteristics: masonry and FRCM retrofit*

The tested curved element was a real scale masonry vault. This structure was made of solid facing clay bricks (0.25x 0.55x 0.12 m^3) and pozzolan-based mortar joints (10 mm thickness). The geometry of the specimen is representative of the vaulted roofs commonly adopted in the historical buildings, without backfill. The in-plane geometry of the vault is characterized by a segmental arch profile.

Span of the vault is 2.98 m, whereas rise and depth are 1.14 m and 2.20 m respectively. For further details about the specimen and the experimental characteristics please refer to the specific literature (Giamundo et al. 2015).

The specimen has been retrofitted according to the damage exhibited after the first part of the experimental tests, by means of FRCM system. The intervention through FRCM system was aimed to improve the seismic behaviour of the vault. This reinforcement system has been installed at the extrados of the vault. A mortar layer (10 mm thick) incorporates an alkali-resistant primed basalt fibre grid. The mechanical characteristics of the masonry and reinforcement materials used are shown in table 1.

Table 1. Masonry and FRCM reinforcement mechanical properties

Masonry Property	Brick	Mortar	FRCM Property	Grid	Mortar
Compressive strength (MPa)	19.8	10.1	Compressive strength (MPa)	-	≥15
Flexural strength (MPa)	3.7	-	Tensile strength (kN/50mm)	≥3	-
Splitting tensile strength (MPa)	2.5	-	Initial shear strength (MPa)	-	≥0.15
Tensile strength (MPa)	-	2.4	Elastic modulus (GPa)	89	8
Elastic modulus (MPa)	5756	1452	Weight (g/m^2)	250	-

3.2 *Preliminary numerical analysis and experimental comparison: unreinforced specimen*

Preliminary theoretical calculations have been carried out in order to assess the structural behaviour. A simplified incremental analysis of the vault has been performed to the purpose to evaluate its seismic capacity.

The vault has been modelled as a fixed base arch and both constant gravity acceleration (first) and uniform monotonically increasing horizontal accelerations (after) have been considered acting on the whole curved element. Through these assumptions the horizontal load pattern is proportional to the masses of the structure.

For the unreinforced vault an incremental non-linear analysis has been developed. For this structure starting from a gravitational configuration load, a distribution of the inertia forces has been considered. This assumption is equivalent to considering a distribution of constant accelerations (proportional to the masses). The horizontal load grew up to the maximum horizontal acceleration imposed to the vault experimentally (the test was deliberately stopped before reaching collapse to perform a retrofit and re-test).

According to the experimental test (Giamundo et al. 2015), at an acceleration of about 0.48g, the formation of 3 hinges occurred (see figure 4: hinges A, B and C, where the thrust line is tangent to the fictitious boundaries or the NM points make contact with the failure surface), without of the collapse mechanism activation. According to proposed approach an acceleration of 0.54g would yield to the activation of the fourth hinge, hence of the collapse mechanism.

However a further validation is given by the analysis of the experimentally tested retrofitted vault.

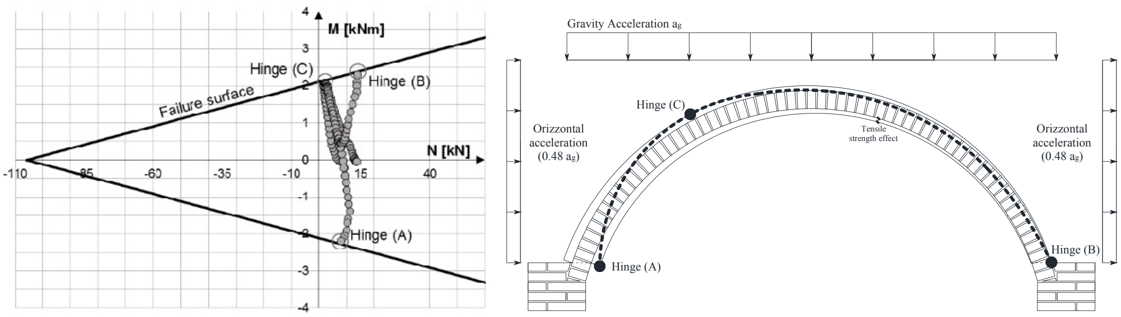

Figure 4. Unreinforced vault: thrust line and NM points at 0.48g load condition on failure surface.

3.3 Preliminary numerical analysis and experimental comparison: retrofitted specimen

A similar approach for the retrofitted masonry vault has been adopted and the proposed method was applied.

The FRCM was applied to the vault's extrados only, excluding the wall cross section to simulate real applications. Therefore, the base sections were considered not retrofitted because there is not sufficient anchorage length.

The numerical analysis was considered up to an horizontal acceleration 1,19g, according to experimental test. Figure 5 shows the formation of 2 hinges (hinges D and E, where the thrust line is tangent to the fictitious boundaries or the NM points make contact with the failure surface), obviously without any collapse mechanism activation. In the experimental test it was possible to verify that the masonry vault did not present obvious damage at that shaking level, despite its high intensity. It is noted that the formation of the hinges along the curved element is not easily visible in the specimen due to the opening and closing mechanism of cracks.

Figure 5 shows that the thrust line is internal to the new fictitious geometric boundaries of the retrofitted vault. Only at the supports it is possible to observe that the thrust line is tangent to the fictitious boundaries and the supports are supposed not retrofitted due to the absence of anchorage of fibres beyond the curved portion. This condition is also remarked in the NM diagram looking at the failure surface and NM stress points (intersecting the unreinforced failure surface only). It is noted that if retrofit system would be effective since base sections, hinge D would not have formed.

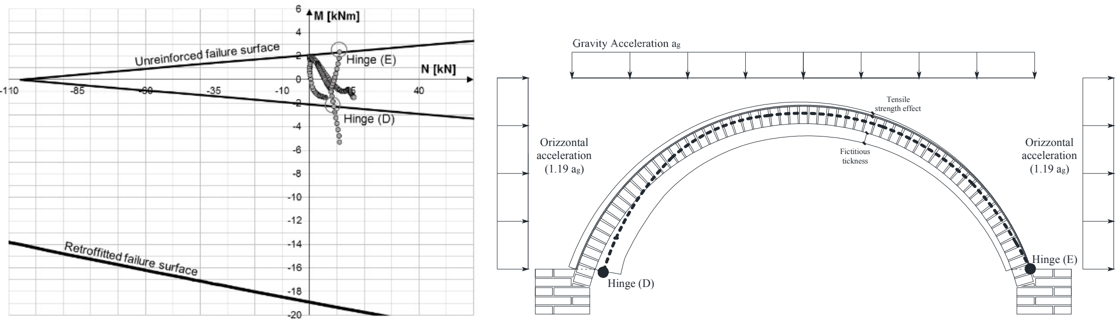

Figure 5 Reinforced vault: thrust line and NM points at 1.19g load condition on failure surface.

Through the numerical analysis it is possible to assess the activation of further hinges. The acceleration for the third hinge activation is close to the experimental maximum acceleration value, and it is 1.22g (and crack opens at the intrados). Obviously a third hinge is not able to activate the failure mechanism. For the FRCM o FRP system it is important to take into account that the hinge behaviour depends on the sign of bending moment. When the hinge relies on masonry crack opening on unreinforced side the hinge develops. However when the hinge formation includes the brittle failure of the composite, the analysis should be stopped since the plastic hinge does not activate. This means that the NM stress points intersect the failure surface on the retrofit side or from a graphical point of view; the thrust line is tangent to the boundary opposed to the retrofit side. In this case the analysis should be stopped at the formation of such a hinge.

4 CONCLUSIONS

In conclusion, through the numerical and experimental comparison, it is possible to validate the proposed simplified method and it can be applied directly as a graphical method too, eventually assuming a constant safe value of axial force (having an impact on fictitious thickness of arch). This approach allows to simply verifying that the FRP or FRCM retrofit system is able to increase the load carrying capacity of the vaults because the failure surface moves away from unreinforced failure condition and higher loads can be carried by the masonry structure. The effect of the reinforcement can be seen also form a cinematic point of view. The fibres prevent the hinges to form and cracks to open, hence prevent the activation of a number of hinges to allow the mechanism is prevented.

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