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OPTIMIZATION OF DESIGN FOR FLOORS, ROOFS AND VAULTS

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ABSTRACT

Typical horizontal elements in historic buildings are represented by timber floors and roofs and masonry vaults. All these components have a crucial role in seismic area, as they are required to resist under lateral loads, to improve the global behaviour through effective connections and to distribute forces, with proper in-plane stiffness, to the shear walls. Niker project, by the Work Package 5 (WP5) "Optimization of design for floors, roofs and vaults", gave the opportunity to compare various strengthening solutions applied to representative components present in existing buildings, taking into account the variety of types on a regional scale, and considering as priority the selection and use of compatible techniques and materials and/or minimum interventions. These solutions are intended to preserve the existing horizontal elements by improving their mechanical performance, as needed to keep their structural contribution on the overall behaviour, thus avoiding generalized substitutions. The validation of strengthening techniques applicable to existing buildings was carried out by means of comprehensive laboratory experimental campaigns, the results of which were used to calibrate numerical models. Materials characterization and on-site investigations provided additional data to increase knowledge and calibrate models. On the basis of these results, parametric studies were performed, to support the design and assessment of strengthening components. In the paper, the main results obtained on strengthened horizontal components are described.

Keywords: *Floors, Roofs, Vaults, Strengthening, Calibration, Modelling*

1. INTRODUCTION

The seismic response of existing buildings is strongly influenced by the in-plane stiffness of horizontal components and their connections to the bearing walls. As a matter of fact, floors and roofs play a relevant role in the activation of the overall behaviour of buildings, thus avoiding the triggering of brittle out-of-plane mechanisms involving partial or more extended overturning. Besides structural regularity, the way how horizontal components can distribute seismic actions to the shear walls characterizes the vulnerability level of existing buildings in seismic area [1, 2]. This involves the efficiency of boundary conditions at each floor level, as well as the typical features of components

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(typologies and materials) used traditionally in historic buildings (Fig. 1). Both these aspects need to be carefully checked to define possible improvement solutions, according to the main preservation criteria [3].
The last seismic experiences in Italy (i.e., the 1997 Umbria-Marche earthquake and the 2009 L'Aquila earthquake), showed and confirmed very clearly that generalized substitutions of horizontal components with heavy slabs and the use of materials (such as concrete) not compatible with the original ones, induce a hybrid behaviour and consequently expose the structure to brittle collapses (Fig. 2) [4, 5].

Fig. 1 Out-of-plane deformation due to lack of connection at intermediate floor level (left) and brittle collapse of corner (right), showing inadequate floor and roof (from 1997 Umbria-Marche earthquake, Italy) [6]

Fig. 2 Effect of use of concrete for roof (left) and floors (right), involving the collapse of vaults (from 2009 L'Aquila earthquake, Italy)

Therefore, the identification of strengthening techniques able to improve the safety level of the existing structures without changing their main structural function, constitutes one of the bases of the current research. On one hand, this involves the understanding of the behaviour of the historical components, as well as the knowledge of their constitutive materials and constructive details, in the frame of the various types detectable at regional scale. On the other hand, the research of a proper balance between traditional and modern materials or techniques is nowadays unavoidable, taking into account the number of solutions proposed in the restoration field.
To harmonize past with modern innovation, is then fundamental to refer to the attainment of at least some of the known preservation criteria, as compatibility, minimum intervention, durability, removability, etc.
In this connection, Niker project dealt with single components, sub-structures, connections, up to global behaviour of buildings. In its frame, WP5 concerned the optimization of design for floors, roof and vaults, considered as single elements, not connected to the other structural parts of a buildings. As a matter of fact, WP5 was aimed at:

- defining adequate and feasible intervention technologies for horizontal structural elements, related to specific requirements included in a comprehensive catalogue (produced within the project);
- defining and improving laboratory procedures for evaluating the intervention technologies and specifications for laboratory specimens;
- carrying out the necessary tests to characterize the experimental behaviour of original and strengthened wooden floors and roofs and masonry vaults, in order to obtain information on the system performance and the main constitutive laws relevant for modelling;
- numerically simulating the experimental behaviour to perform parametric assessment and seek for structural limitations or define optimized design procedures.

In the following, the general structure and organization of WP5 is reported, and the main results derived from the experimental testing, modelling and parametric analyses are shortly discussed.
These results, in their different forms, are connected with the requirements and objectives of several other WPs, that will receive contributions until the end of the project, namely to: (i) feed the catalogue in WP3, with experimental test results and parameters derived from analyses; (ii) suggest interventions and provide parameters for design and assessment in the study of substructures and overall constructions (WP6, WP7, WP8, WP9); (iii) provide indications for guidelines (WP10).

2. WP5 RESEARCH PROGRAM

Table 1 Research work carried out on floors

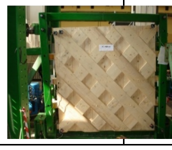
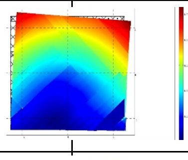
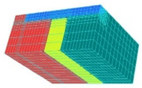
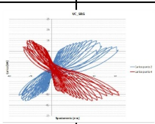
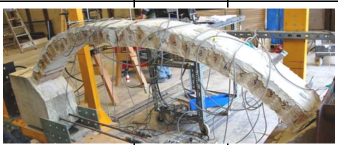
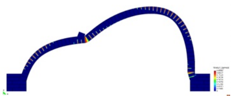
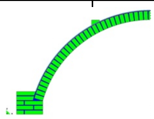
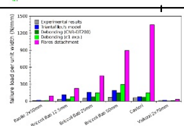
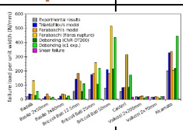
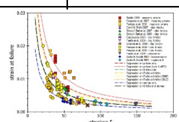
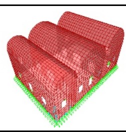
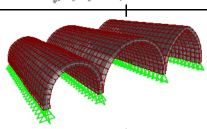
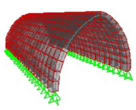
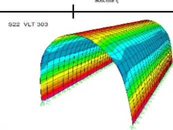
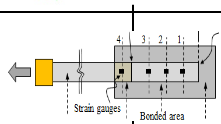
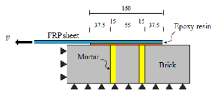
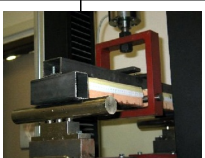
FLOORS								
Level of investigation	Partner	Testing	Modeling			Parametric analysis		
		Experimental tests	Analytical modeling	FEM Linear	FEM Non Linear	Analytical modeling	FEM Linear	FEM Non Linear
Element	UNIPD BOZZA	Monotonic and cyclic tests on strengthened timber floors	Identification of in-plane stiffness and energy dissipation parameters	Calibration of global behaviour (in-plane strength and deformability)				
	ITAM	Experimental in-plane cyclic tests on authentic floor segments	Identification of in-plane stiffness and energy dissipation parameters	Calibration of global behaviour (in-plane strength and deformability)		Influence of planking orientation on the floor stiffness		
Local	UNIPD BOZZA			Characterization and calibration of behaviour of connections		Influence of connections on the global behaviour of floors		

Table 2 Research work carried out on vaults

VAULTS								
Level of investigation	Partner	Testing	Modeling			Parametric analysis		
		Experimental tests	Analytical modeling	FEM Linear	FEM Non Linear	Analytical modeling	FEM Linear	FEM Non Linear
Element	UNIPD	Monotonic and cyclic tests on barrel vaults						
	UBATH	Pseudo-dynamic and cyclic tests on arches						
	UPC				Modelling of strengthened vaults			Simulation of strengthening and failure modes
	UNIPD					Calibration of design parameters for shear bond		
	GUNI					Interaction of parallel vaults with boundary conditions		
Local	UMINHO	Shear bond of composites to brick units			Shear bond behaviour between bricks and composites			3D modelling of bond behaviour on prisms
	UNIPD	Bond of composites (pull-off, shear loads, dowel effect) to bricks	Analytical formulation of local mechanisms in strengthened conditions			Influence of local effects on load capacity. Calibration of pull-off bond		

Nine partners were involved in the research on horizontal components; they belong to the following institutions: University of Padova (UNIPD, Italy), Bozza Legnami srl (BOZZA, Italy), Institute of

Theoretical and Applied Mechanics (ITAM, Czech Republic), University of Bath (UBATH, United Kingdom), Universitat Politecnica de Catalunya (UPC, Spain), Universitade do Minho (UMINHO, Portugal), Ecole Nationale d'Architecture (ENA, Morocco), Gazi University (GUNI, Turkey), Politecnico di Milano (POLIMI, Italy).

WP5 concerned two main activities:

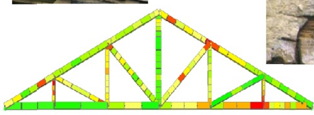
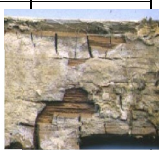
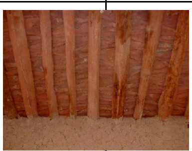
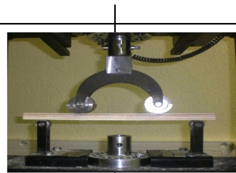
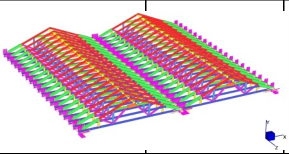
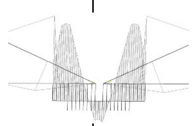
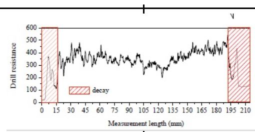
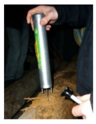
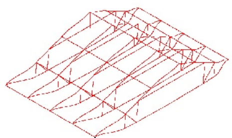
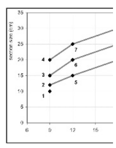
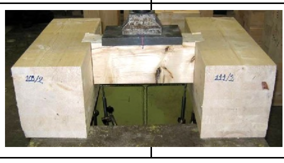
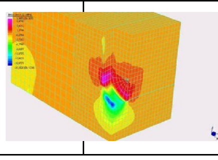
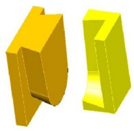
– WP5.1: experimental characterization of single elements (floors, roof, arches and vaults), supported by laboratory and in-situ testing;
– WP5.2: design optimization, supported by analytical and numerical modelling and parametric studies.

The contribution given by partners concerned various levels of investigation and analysis (basic materials, structural component, whole element, series of elements), as described and illustrated in Table 1, 2 and 3 for floors, vaults and roofs, respectively. As it can be seen, this WP included a number of different aspects concerning several problems and various approaches, that may be difficult to synthetize in a proper comprehensive way.

Therefore, in the following, an example of the approach applied to the various horizontal structures included is given more in detail for some categories.

In particular, the aspect of strengthening is pointed out, thus roofs and vaults are mainly described. Experimental work and calibration of modelling are discussed, aimed at characterizing the mechanical behaviour of those structural components, verifying the interventions efficiency, and contributing to the definition of design rules supported by simulations in various conditions.

Table 3 Research work carried out on roofs

ROOFS								
Level of investigation	Partner	Testing	Modeling			Parametric analysis		
		Experimental tests	Analytical modeling	FEM Linear	FEM Non Linear	Analytical modeling	FEM Linear	FEM Non Linear
Element	UMINHO	Vertical loading on wooden trusses rescued from existing building and deterioration investigation on connections				 		
	ENA	Physical and mechanical characterization of wooden materials in timber elements	Verification of wooden floors and joists based on design criteria					
	UNIPD			Modelling of series of trusses				Influence of corbel length on behaviour of serial trusses
	UMINHO			Modelling the load-carrying tests performed in full-scale timber trusses		Reliability assessment of timber trusses from NDT data		
	POLIMI			Dynamic response of roof structures			Influence of geometric parameters in seismic vulnerability of timber trusses	
Local	UNIPD BOZZA			Calibration of mortise-tenon joint behaviour				

3. STRENGTHENING OF TIMBER FLOORS

Existing wooden floors are typically made with simply supported beams covered by nailed timber planking. Their extensive application in both old and current buildings is due to their satisfactory flexural and comfort performances, and easy production and workmanship. However, the study of the influence of traditional wooden floors on the seismic behaviour of existing masonry buildings has not been sufficiently investigated, both at experimental and numerical scale [7-9], especially if considering the effect of flexible diaphragms on the global response [10, 11]. Within this context, the research program aimed at evaluating the in-plane behaviour of original and strengthened timber floors by comparing traditional and modern techniques and materials: simple or double planking and dry wood-to-wood techniques; Fibre Reinforced Polymer (FRP), Steel Reinforced Polymer (SRP) or Natural Fibre Reinforced Polymer (NFRP) for bracing the floors diagonally or as a grid, trodden earth, etc. The challenge relies on the ability of increasing the mechanical performances by avoiding excessive alteration of masses, static function, and cultural/architectural value.

3.1. Experimental tests on simple slab warping wooden floors

The experimental program on wooden floors carried out by UNIPD&BOZZA took into account two types of wooden floors (common raw finished or tongue and groove joint planking), strengthened by means of eleven different solutions belonging to three main categories: additional planking, diagonal strips, and diagonal nets (Fig. 3). Specimens were made of spruce wood, and original boarding is simply nailed to the five beams. In detail, the following techniques were applied, all of them only to tongue and groove original floors: single and double planking with an orientation of ±45° and different thicknesses; Oriented Strand Board (OSB) or similar wooden panels types; steel, Carbon FRP (CFRP), SRP or wooden diagonals applied with dry hard wood pins; hemp NFRP nets applied with resin or vinyl glue, and wooden nets applied with hardwood pins and screws. Specimens had dimensions of approximately 2.2 × 2.2 m^2 and were tested under monotonic (14 floors, of which 2 unreinforced) and cyclic (15 floors, 1 unreinforced) shear loading, for an overall number of 29 tests.

Shear deformations were measured through LVDTs placed on the two main sides of the floor. For cyclic tests, the amplitude of the cycles is referred to the yielding displacement, V_y, recorded at the correspondent yielding load (Fig. 5).

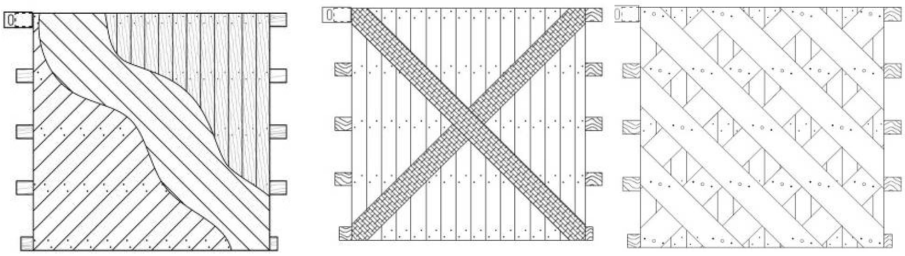


Fig. 3 Some strengthening techniques applied to original floors: double planking (left), SRP diagonals (center), wooden net (right)

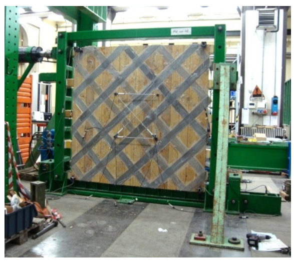


Fig. 4 Laboratory setup (hemp net specimen)

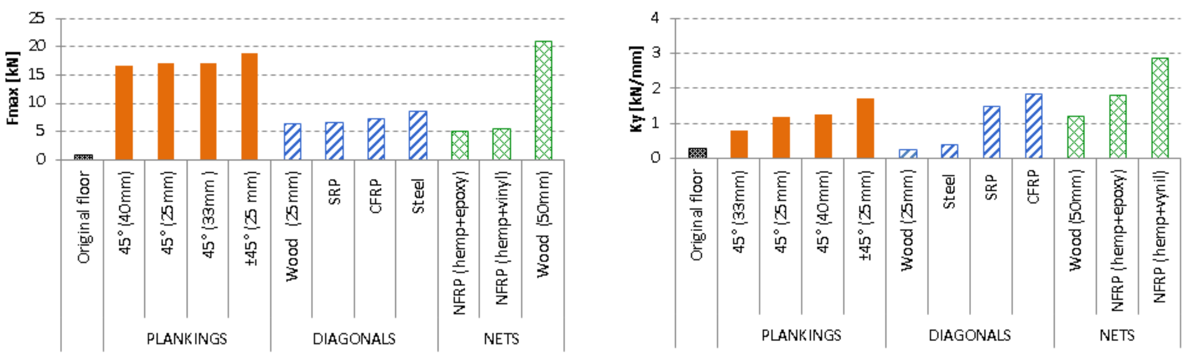


Fig. 6 Comparison of maximum lateral force (left, from cyclic tests) and stiffness in elastic phase (right, from monotonic tests) among some strengthened specimens

Results showed the high performance of double planking and wood net (Fig. 6). The thickness of the simple boarding does not influence significantly the performance of the floor in comparison with the

double planking, even when in this last case the minimum thickness (25 mm) is adopted. NFRP nets are able to achieve performance similar to diagonal reinforcements (steel or CFRP), although in the case of hemp, almost half of the equivalent quantity of composite is applied.
Stiffness (K_y) in elastic phase showed high values for fibres glued to the original boarding. Nevertheless, these specimens have a sliding Vy very low, in some cases even lower than for unstrengthened floors. This validates the ductility of mechanical connections (nails, screws, pins) used for double planking, wooden diagonals and wooden nets, thus confirming also the better optimization for strengthening wooden elements by using the same parent material.

3.2. Modelling on timber ceilings

ITAM performed experimental tests on specimens also built with some material taken from old buildings (timber, planking); results were used to calibrate non-linear FE models and parametric analysis. Laboratory experiments concerned in-plane cyclic tests on five timber ceilings under original and strengthened conditions: one as bare wood and another including a trodden earth floor; the others are joist ceilings including a single planking at 90°, with simple boarding or with tongue and groove one (25 mm thick), and a diagonal double planking (45°, 20 mm) (Fig. 7).
The specimens are made of spruce wood and have dimension of 2.5 × 2.4 m^2. Horizontal displacements were measured by LVDT at the bottom and top of the ceilings.

Fig. 7 Wooden ceiling with trodden earth floor (left), joist ceiling with double planking (right)

Maximum lateral capacity and deformations were measured. Best results in terms of strength were achieved by the double planking (45°) application (Fig. 8).

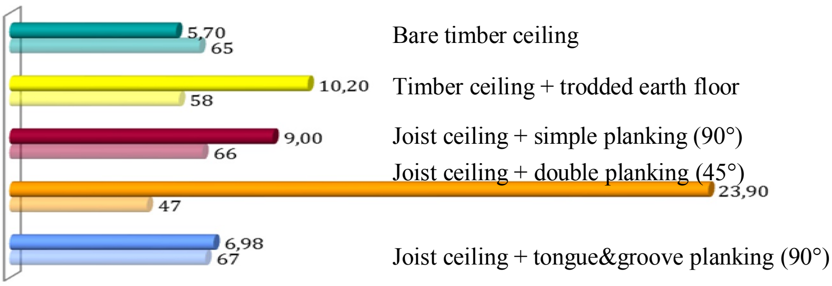


Fig. 8 Comparison of maximum load (kN, upper bars) and displacement (mm, lower bars) for tested floors

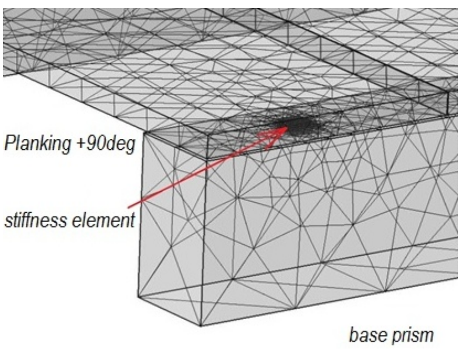


Fig. 9 Detail of joist ceiling modelling

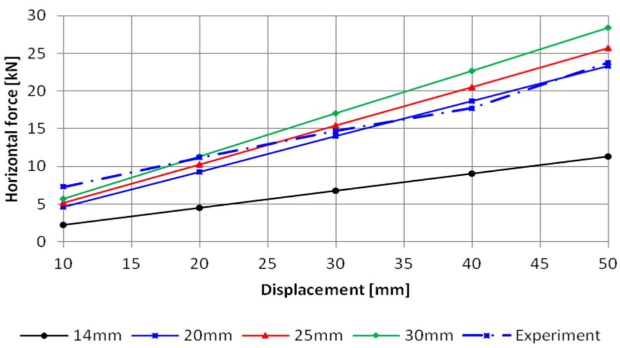


Fig. 10 Influence of planking thickness

The model of timber and joist ceilings was created in COMSOL environment, taking into account the elasto-dynamic behavior and, thanks to a specific combined method, the contact between timbers, with and without friction (Fig. 9). Parametric analysis aimed at evaluating the influence of four values of boarding thickness (from 14 to 30 mm), representative of strengthening, both in single (90°) and double (45°) planking condition. The final model allowed calculating the local stresses relevant for the analysis of connections and design of retrofitting. Results showed that horizontal capacity and stiffness increase with planking thickness, especially for 30 mm, both for double and single (Fig. 10) planking.

4. STRENGHTENING OF MASONRY VAULTS

Arches and vaults deserve particular attention in preservation of CH assets, as they constitute peculiar elements in constructions, for both structural and aesthetic functions. They are particularly vulnerable in seismic region, therefore the investigation of behaviour under dynamic actions (often simulated by cyclic loads) is essential for the definition of proper interventions. To prevent the brittle failure of unreinforced arches and vaults, composites materials (FRP, SRP/G), are largely applied for strengthening, due to high feasibility and structural performance. Strips of reinforcing materials carry tensile stresses and therefore prevent hinges formation related to instability failure mode [12]. Experimental research and modelling analyses in this field are increasing [13-15]; nevertheless, aspects related to the proper design of intervention, or masonry transpirability and strengthening removability (e.g., use of Textile Reinforced Mortar – TRM, instead of FRP), are still under study.

4.1. Experimental tests on voussoir arches

At UBATH, three voussoir arches [16] and three double-ring arches [17] were tested respectively in monotonic regime and for fatigue. SRP were applied at the intrados or the extrados on the whole width (22,5 cm). Clear span was 200 cm, rise at the crown 50 cm. Monotonic load was applied with sand bags simulating the fill; one abutment was free to move from the other; formation of cracks and failure mode were monitored. Fatigue tests aimed at quantifying degradation of masonry under cyclic loading; load was increased at regular steps after a number of cycles until failure occurred.

Fig. 11 Debonding of SRP applied at intrados (left) and arch reinforced at extrados (rigth) [16]

In monotonic tests, the use of strengthening resulted in different failure modes in respect to the brittle failure of unreinforced arches: for SRP intrados strengthening failure occurred by debonding after a load capacity increase of 93%; whereas in SRP extrados reinforced arches hinges did not appear until failure, which occurred after a displacement capacity increase of 100% (Fig. 11). Fatigue tests on unreinforced arches highlighted variable degradation, this being measured as permanent deformation, depending on the amount of fatigue experienced by the arch, as well as the importance of mortar on the global response.

4.2. Modelling of masonry vaults

UPC modelled masonry vaults in strengthened and unstrengthened conditions tested at UNIPD. The experimental program consisted in two monotonic tests (unreinforced and reinforced with SRG) and five cyclic tests (CFRP, SRP, SRG, BTRM), aimed at characterizing the performance of strengthening systems alternative to the use of epoxy resins as matrix for composites. Barrel vaults had a span of 300 cm and the rise at the crown of 114 cm; SRP/G and CFRP were applied in two strips (around 12 cm wide each), whereas basalt net was applied on the whole width of the vault (77 cm). An inorganic mortar (hydraulic lime based) was selected. Spikes were used to anchor the composites to the base of the vaults. Load was applied at ¼ of the span for monotonic tests, and at ¼ and ¾ for cyclic ones.
Results among composites systems are compared in Table 4 and failure modes are shown in Fig. 12.

Table 4 Results on vault tests: load and displacement capa city

Specimen	Loading	F_{max} [kN]	d_{max} [mm]	$F_{max}/F_{max,UM}$	$d_{max}/d_{max,UM}$
UM	monotonic	1,40	16,79	–	–
SRG-M	monotonic	13,55	50,12	9,70	2,99
SRG-C	cyclic	15,45	70,06	11,06	4,17
BTRM-C	cyclic	12,08	24,14	8,65	1,44
SRP-C	cyclic	24,82	26,87	17,78	1,60
CFRP-C	cyclic	12,93	30,22	9,26	1,80

Fig. 12 Strengthened vaults at end of test: SRG-C (left), BTRM-C (center), SRP-C (right)

All composites improved the load and displacement capacity of the vaults, lowest values being referred to BTRM, and highest ones to SRP and SRG. However, mortar matrix resulted in greater displacements than epoxy; a significant role of the mechanical anchoring was observed, as in all cases spikes prevented the shear sliding at the base of the vaults.
To model the tested vaults, both a macro- and micro-modelling approach [18-20] were adopted, by using the FE program COMET. The model was calibrated on the basis of the experimental results obtained from the UM and the SRG cases, then parametric analyses were performed. Models were able to reproduce the mechanism of failure (position of hinges) and the maximum load with a good approximation (Fig. 13). In particular, micro-modelling can represent correctly the effect of reinforcement. The compressive strength of the mortar is more influent than the compressive strength of the bricks on the arch capacity, although high-strength mortars are not recommended to be used, as they may lead to a reduced displacement capacity in the nonlinear range. Finally, the amount of the reinforcement affects significantly the capacity of the arch: the sensitivity analysis has shown that a half or a fourth of the experimental amount of steel fibre reinforcement can provide sufficient strengthening to the structure (Fig. 14).

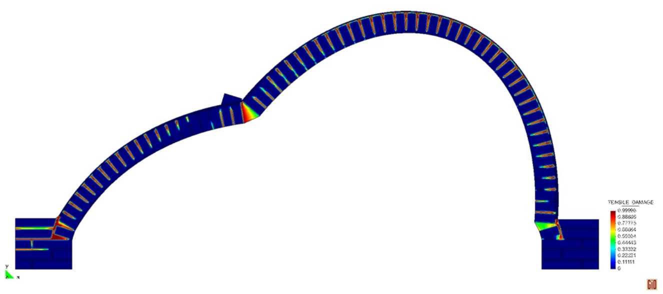


Fig. 13 Model of the strengthened arch at failure

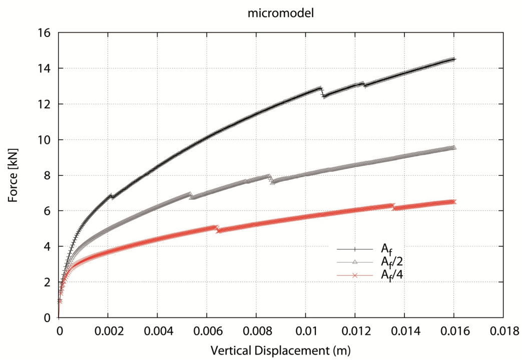


Fig. 14 Influence of external reinforcement

5. CONCLUSIONS

The optimization of horizontal components as floors, vaults and roofs in existing construction pursues a proper balance of technological advancement and preservation requirements. Traditional intervention solutions and materials need to be revaluated as they still show high performance also in comparison with modern/innovative materials, as composites (FRP, SRP, etc.). This is particularly relevant for the strengthening of floors, where double planking resulting in the best improvement of in-plane stiffness and displacement capacity of floors. As for vaults, composite strips have a definite advantage due to their high versatility and easy application; nevertheless, the use of selected mortar as matrix would guarantee more compatibility, durability and removability than epoxy resins, still improving both load and displacement capacity properly for a historical construction.

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