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EXPERIMENTAL TESTS ON FRCM AND FE MODELLING FOR THE HERITAGE STRUCTURE'S REUSE

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Abstract. *This paper presents the first results of an ongoing research in partnership with Kimia S.p.A. company (Italy). In particular, experimental tests on masonry specimens reinforced with Fiber Reinforced Cementitious Matrix (FRCM) have been recently conducted by Kimia according to the up-to date guidelines: specifically the single-lap shear test. On the base of the experimental results, a finite element model has been developed in order to reproduce the actual behaviour of the specimens. The results, derived both by the experimental tests and the FE model calibration, constitute the basis for planning an experimental campaign on masonry walls strengthened by FRCM loaded in the plane. The constructive details of the experimental set-up, conceived in order to create a self-balanced system and to bring the specimens to failure, are described together with a preliminary numerical modeling based on the already done test.*

1 INTRODUCTION

It is well known that the level of knowledge and the in-depth investigations regarding ancient masonry buildings are the mandatory conditions on which to base reliable structural safety assessments. Those evaluations derive from an articulated and rather complex process including, in general, historical investigations gathered by direct surveys of the building, also by means of experimental campaigns. In order to assess the vulnerability condition of a structure, the correct interpretation of the seismic behaviour in its current state is essential, especially when dealing with historical constructions built with masonry elements often characterized by structural peculiarities. Possible interventions for structural strengthening derive from the knowledge of the constructive properties and the peculiarities of the buildings. The conceiving of such design actions must prevent the occurrence of damages related to the artifact's survival without jeopardize the role and the meaning they stood for during the centuries.

Nowadays new reinforcement methodologies are including the use of FRCM composite materials that allow to fulfill the strengthening of ancient masonry structures in compliance with the environmental, cultural and social context where the buildings are placed. The FRCM composite system offers multiple benefits with respect to other composites or traditional reinforced plasters:

- good mechanical properties;
- reduced thickness (minor than 3 cm);
- easy installation thanks to the lightness of the mesh and the building work modalities (e.g. FRP);
- reversibility of the intervention, being the inorganic mortar less aggressive than the epoxy resins used in other composite materials;
- good performance against fire (resulting in part from their inherent non-combustibility);
- possible recyclability of the natural origin nets in function of the characteristics of the matrix.

Even if some guidelines about the design rules have been proposed for the application of such composite [1], the definition of effective numerical strategies is still an open issue, due to the complexity of the interactions among fiber, matrix and masonry, requiring further studies with special attention peculiar applications. Some recent contribution can be found in literature about it based on numerical and/or analytical models [2, 3],

In a previous research, this new-gen. structural reinforcement has been proposed in relation to the structural strengthening of the Vanvitellian Palazzo Murena [4], actual headquarters of the University of Perugia. In this framework, indeed, the peculiar feature of the "*in falso*" bearing walls, masonry panels built without a direct load path to the ground and laying on the below vaults, has been highlighted as a recurrent circumstance in Italian Renaissance architecture and marked as a possible risk factor, Fig. 1.

Figure 1: Cross-section of Palazzo Murena, in red are highlighted some of the "*in falso*" walls

That occurrence, in case of seismic action, could trigger a sort of domino effect, due to possible collapse of the underlying masonry vaults, then compromising the safety of the entire structure. In the perspective of its strengthening, the design of interventions has been necessary to act in compliance with the valuable elements of the building such as marble floors and precious

stuccos, without further increasing the existing structures with the weight of additional non-canonical gears, if compared to the structural genesis of the building. In this context, the reinforcement of the masonry walls through FRCM appears an adequate solution.
This composite system proved many applications in relation to masonry structures and in literature there are several experimental studies [5- 8] carried out on elements reinforced with FRCM systems, as well as modeling strategies primarily based on the finite element methods [2, 3]. However, it should be noted that the investigation for the mechanical behaviour of the proposed application (*wall beam*) is not adequately investigated.

In order to improve the knowledge about such a technology and its application, an experimental campaign, has been started in partnership with Kimia S.p.a.to evaluate the effectiveness of the applications of FRCM to masonry walls regarding the prevention of in-plane collapse.

2 EXPERIMENTAL INVESTIGATIONS

The research program consists in experimental tests to assess the mechanical characteristics of the materials and the composite, and the development of numerical strategies able to reproduce the behaviour of the structural system. In this chapter are partially reported the first tests recently conducted by Kimia S.p.a. company for the preliminary characterization of such composite materials at the mesoscale level. The results have been used to calibrate a numerical model described in the following.

2.1 Single-lap shear test

According to the specific guidelines provided by the Reluis [9] *single-lap shear tests* have been conducted on rectangular walls samples reinforced with FRCM, which geometrical characteristics are reported in Tab. 1. Concerning the composite materials, the fiber net *Kimitech BS ST 200* and the matrix *MALTA M15/F* have been used; the nominal mechanical properties are reported for the net in Tab. 2, and in Tab. 3 for the masonry. The test method (also called *bond test*) consists in applying increasing shear forces between the composite and the support in order to assess the quality of the bonding and of the interaction between the fiber and the matrix.
The sample's preparation required:

- the cleaning of the surface of the masonries substrate and its saturation and wetting (condition s.s.a.);
- application of a first layer of mortar *Basic MALTA M15/F*;
- positioning of the fiber net *Kimitech BS ST 200*;
- application of a second layer of mortar *Basic MALTA M15/F*. After the curing period (at least 28 days) the traction device installation procedures were carried out, Fig. 2;
- the specimen is positioned vertically in a steel support, with a free portion of the fiber net, of a length in the range between *221* and *245 mm*, facing downwards and secured in a vice;
- a mechanic vice keeps the mesh tab stationary, while the crossbar of the test machine goes up, and therefore the reinforced wall, pulling the fiber and engaging the reinforcement with a shear actions.

Table 1: Geometric features of the reinforcemnt net samples: *B [mm]* the witdh*, L [mm]* the total length*, L_e [mm]* the effective length*, L_f [mm]* the free length*, T [mm] the thichness, M [mm x mm] the network sizes, L_t [mm]* the reiforcement net witdh, *N* the number of yarns

Fiber	B	L_f	L_e	Lf	T	M	L_t	N
B_01	153,3	305,0	300,0	254,0	10,00	20x20	135,0	7
B_01	156,6	308,0	302,0	220,6	10,00	20x20	135,0	7
B_03	154,0	307,0	304,0	245,3	10,00	20x20	135,0	7

(a) (b)

Figure 2: Sample's preparation: a) Application of the fiber net on the first layer of matrix, b) Fulfilment of the implementation with the second mortar layer according to a reference thickness

Table 2: Mechanical properties of the basaltic fiber: T_e [mm] the equivalent thichness, *Q [N/mm]* tensile breaking load of the warp, *E [GPa]* elastic modulus, *ε* strain, *G [kg/m²]* grammage, D [kg/m³] density, *σ_u [MPa]* ultimate tensile strength

Fiber	Texture	T_e	Q	E	ε	G	D	σ_u
B	bidir.	0,035	78	89 ±2	<8	0,24	2670	3100

Table 3: Mechanical properties of the matrix

Element	Material	Particle size distribution	Compression strength [MPa]	Bending strength [MPa]	Shear strength [MPa]	E [MPa]
Mortar - Matrix	Lime inorganic mortar M15/F	maximum 1,20 mm	at 7 dd >9 at 14 dd >12 at 28 dd >15	at 7 dd >3,8 at 14 dd >3,9 at 28 dd >4	0,15 (with masonries - EN 711)	9600

(a) (b) (c)

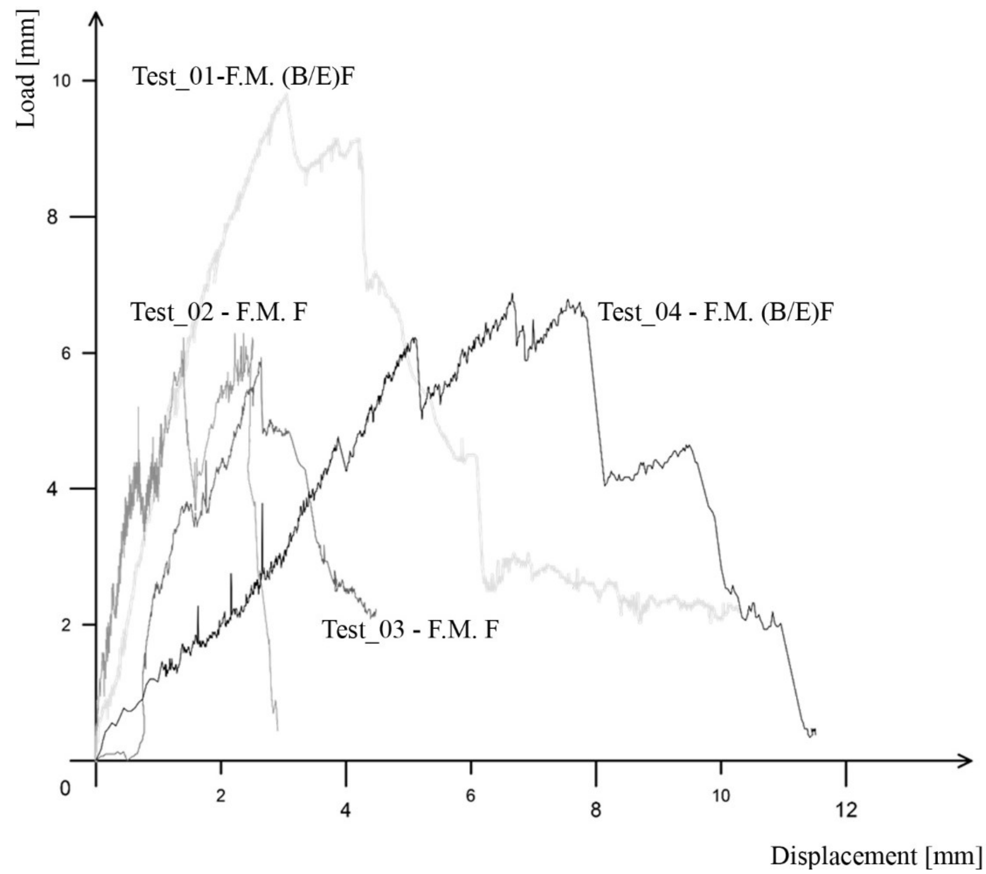
Figure 3: Experimental set-up: a) Testing machine, b) Detail of the pulling vice with the location of one LVDT sensor on the net, c) Cracks' appearance on the external layer of the matrix of one of the samples

Fig. 3 illustrates the experimental set-up carried out through a universal testing machine, on which the installation of LVDTs allowed to obtain the displacement describing the progressive shear failure of the composite. In the present paper the data related to a sensor located at the lower side of the sample are reported, in particular the one attached to the net (Fig. 3 b), with respect to three tests (Tab. 4).

Two tests (Test 01 and Test 02, Fig. 4) have been characterized by the breaking of the fiber while the sample (Test 03, Fig. 4) failed according to a mixed collapse mode. For all the tests the maximum resistance corresponds to the breaking of the fiber within the reinforcement (Failure Mode - FM F – Fig. 4) and with specific reference to third test this condition is preceded by a matrix-substrate detachment to which subsequently followed a break of the fabric on the free scrap; indeed, the matrix-substrate detachment is the cause of the observed ductility (Failure Mode – FM (B/E) F – Fig. 4b). The elaboration of the data gathered by the experimental observation permitted to create a load-displacement diagram for FRCM with basaltic fibers in relation the failure modes reported by the guidelines [9], Fig. 4.

Table 4: Experimental tests' data

	Fiber resistant area [mm^2]	Maximum Load [kN]	Maximum stress [MPa]	Failure Mode FM	Age of testing [dd]
Test 01	5,37	6,48	1207,45	F	74
Test 02	5,48	5,93	1081,46	F	81
Test 03	5,39	6,79	1259,74	(B/E) F	129



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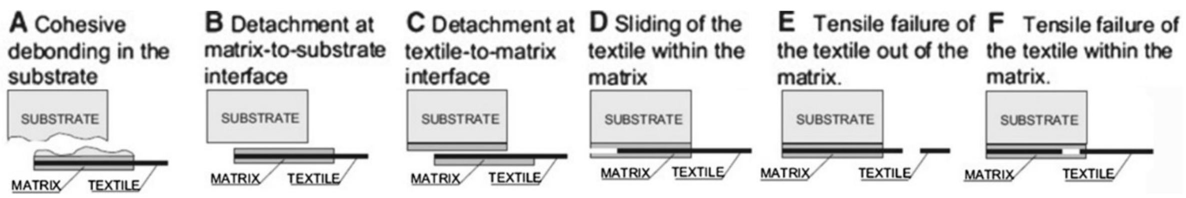

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Figure 4: Experimental outcomes: a) Load-displacement diagram for FRCM with basaltic fibers, b) FRCM failure modes (FM) for single-lap shear tests [1]

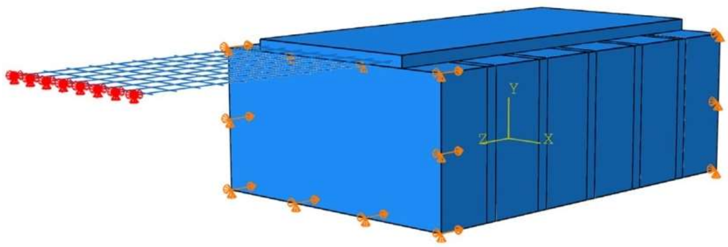
3 NUMERICAL MODELLING OF THE SINGLE-LAP SHEAR TEST

In order to describe the mechanical behaviour of the FRCM strengthening system, a preliminary FE numerical modelling has been developed aiming at reproducing the experimental tests.

The elements that make up the specimens have been modeled as follows:

- bricks, mortar *M10* (masonry joints) and mortar *M15* (matrix) with 8-node solid elements:
- the fiber basaltic net (*20x20 mm* mesh) with 2-nodes linear elements.

Internal constraints have been applied between the mortar joints and bricks, and between the wallet and matrix, preventing any relative displacement. In this way, the interaction between the matrix and the support has been condensed in the nonlinear behaviour of the matrix itself. Similar kinematic constraints have been applied for the interaction between the matrix and the fiber, which lies embedded into the matrix layers. In relation to the external constraint, in order to reproduce the test modalities, the end portion of net free from matrix has been completely constrained while to one of the terminal surfaces of the masonry wallet incremental displacements has been imposed, Fig. 5.



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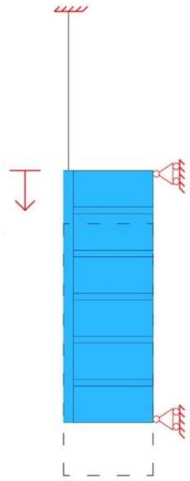

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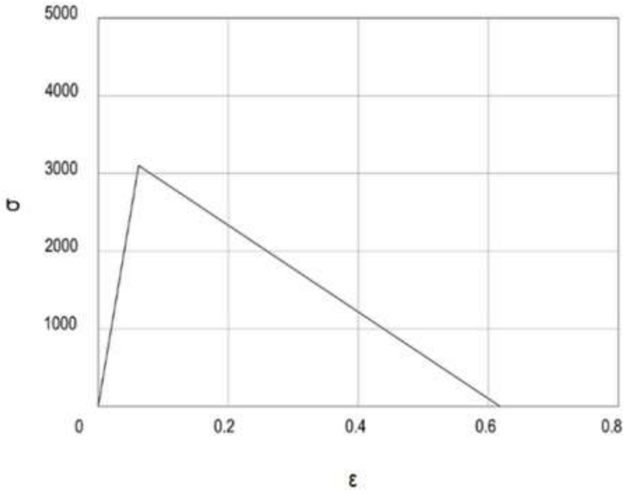
Figure 5: a) External constraints; b) Modeling hypothesis

In order to better reproduce the response of the composite (Fig. 6) different models for all the materials composing the sample have been calibrated, especially in the post-peak behaviour, being some mechanical properties known in their nominal values, provided by the Kimia company. Following the approach proposed by [2] an elastic-plastic model with softening has been used for the fiber net, while a concrete model for bricks, mortar joints and the matrix. For the matrix also a tension damage model has been used to describe the evolution of damage observed during the test.

In addition, with the aim of evaluating the effect of each parameter on the structural response, a sensitivity analysis has been carried out by varying the mechanical parameters which significantly affect the response of the specific problem analyzed. Two analyses (FEM_Test_01 and FEM_Test_02) have been conducted in order to simulate the structural behaviour of Test 01 and Test 02; the first has been calibrated in total agreement with the nominal mechanical values and integrated with literature parameters, while the second with reduced stiffness values compared to the nominal ones, Tab. 5-6.

With the aim of further describe the damage behaviour, expressed contextually to Test 03, the damage for mortar matrix has been introduced according to the literature data [8] and the observations gathered by the experimental tests. Also in this case a sensitivity analysis has been carried out, in order to evaluate the influence of the nonlinear and damage parameter on the numerical response. Two models have been considered, FEM_Test_03 and FEM_Test_04 which differ in the mechanical properties according the values reported in Tabs. 7-8.



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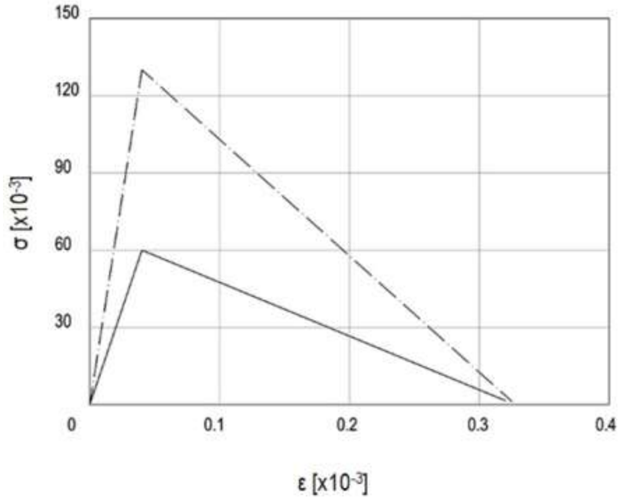

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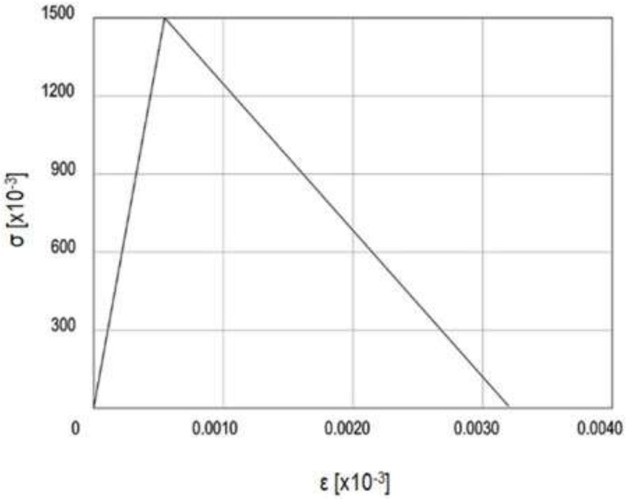


(c)

Figure 6: Constitutive laws in tension used for the constituent materials in terms of σ (stress) [*kN/m*^{2}] and ε (strain): a) Basaltic fiber, b) Dash-dotted line bricks, straight-mortar *M10*; c) inorganic matrix *M15*

Table 5: Mechanical properties for the FE modelling: *ρ [t/m³]* the mass density, *E [KN/m²]* the Young's modulus, ν the poisson's ratio, *θ [°]* the dilatation angle, *e [KN/m²]* the eccentricity, f_{b0}/f_{c0} the ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress; *k* the ratio of the second stress invariant on the tensile meridian to that on the compressive meridian

Material	ρ	E	ν	θ	e	f_{b0}/f_{c0}	K
Brick	1,7	$8x10^6$	0,1	10	0,1	1,16	0,667
Mortar M10	1,85	$1,06x10^7$	0,2	10	0,1	1,16	0,667
Matrix M15	1,9	$1,06x10^7$	0,2	10	0,1	1,16	0,667
Basaltic net	2,67	$8,9x10^7$	0,26	-	-	-	-

Table 6: Mechanical properties used in FEM_Test_01 and FEM_Test_02 regarding the nonlinear characteristics of the concrete model. The Yield stress and the Displecemtent are reported respectively in [*kN/m²*] and in [*m*]. Between brackets are indicated the values used in FEM_Test_02

	Compression hardening		Tension stiffening	
Material	Yield stress	Cracking strain	Yield stress	Strain or *Displ.
Brick	1000	0	350	0
	10	0,0085	1,3	0,000325
Mortar M10	6000	0	50 (20)	0
	60	0,017	1,6	0,00064
Matrix M15	9000	0	50 (20)	*0
	15000	0,0067	1,6	*0,00224 (0.0005)
	20000	0,0026		
	12600	0,01185		
	90	0,017		

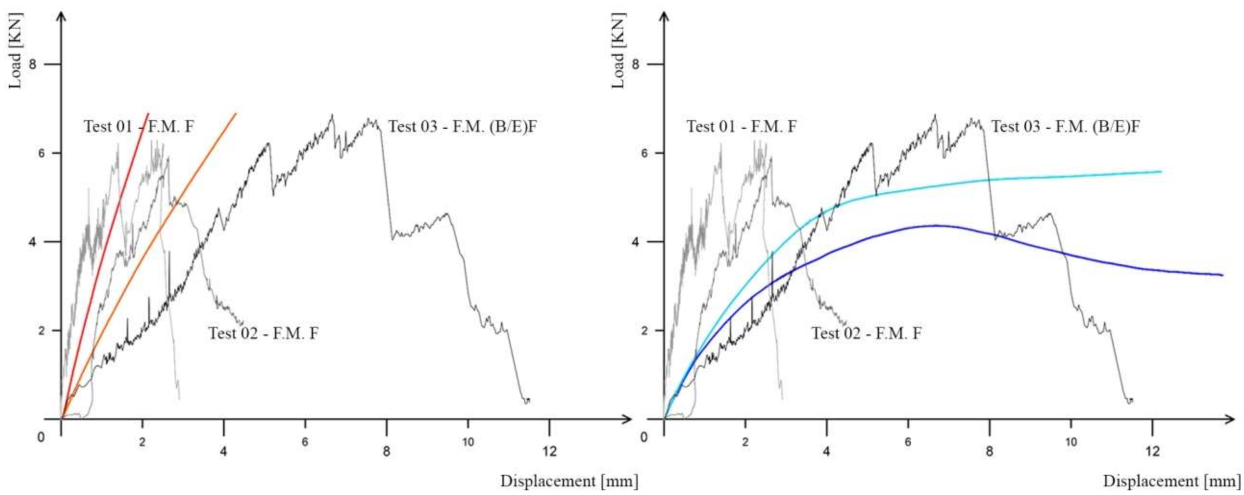
The outcomes (Fig. 7) revealed to be promising and quite consistent to the conducted experimental tests, also with respect to the collapse modes observed during the third one; anyway a better description of the progressive damage of such composite can be obtained through the characterization of the interfaces between the matrix and support.

Table 7: Mechanical properties used in the FEM_Test_03 and FEM_Test_04 (same units of measure of Tab. 5) regarding the elastoplastic behaviour for the numerical models with damage parameter matrix. Between brackets are indicated the values used in FEM_Test_03

Material	ρ	E	ν	θ	e	f_{b0}/f_{c0}	K
Brick	1,7	$1.5x10^6$	0,1	10	0,1	1,16	0,667
Mortar M10	1,85	$(1,06x10^7)$ $1,5x10^7$	0,2	10	0,1	1,16	0,667
Matrix M15	1,9	$(1,06x10^7)$ $1,5x10^7$	0,2	10	0,1	1,16	0,667
Basaltic net	2,67	$8,9x10^7$	0,26	-	-	-	-

Table 8: Mechanical propertiesused in the FEM_Test_03 and FEM_Test_04 (same units of measure of Tab. 6) regarding the concrete damage model. Between brackets are indicated the values used in FEM_Test_03

	Compression hardening		Tension stiffening		Tension damage	
Material	Yield stress	Cracking strain	Yeld stress	Displ.	Damage parameter	Strain or *Displ.
Brick	1000	0	40	0		
	10	0,0085	1,3	0,000325		
Mortar M10	3000	0	60	0		
	30	0,0017	1,6	0,00032		
Matrix M15	3000	0	(80) 60	0	0	*0
	5000	0,0067	1,6	(0,001) 0,00024	0,8	(*0,001) 0,00024
	4200	0,01185				
	30	0,017				



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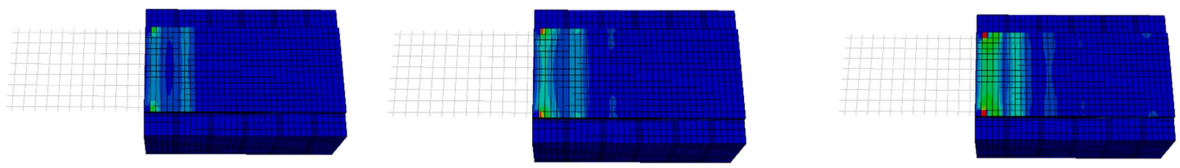

(c)

Figure 7: Comparisons between experimental and numerical outcomes. a) Models without damage parameters; respectively in red and orange lines FEM_Test 01 and FEM_Test 02 with respect to Tabs. 5-6; b) Models with tension damage model in the matrix, respectively in light-blue and blue lines FEM_Test 03 and FEM_Test 04 with respect to Tabs. 7-8; c) Progressive increasing of the damage pattern in the inorganic matrix (in red the most damaged areas)

4 DESIGN AND PROCEDURE FOR THE EXPERIMENTAL CAMPAIGN ON MASONRY WALLS

The final aim of the experimental campaign planned in partnership with Kimia S.p.a. is to evaluate the incidence of the application of those new-gen composite materials regarding the prevention of the dangerous in plane wall's collapse. On this, a specific set-up has been designed in order to engage life-sized unreinforced and reinforced masonry walls with action similar to the ones ascribed to the condition of *"in falso"* walls. The tests will be conducted on three rectangular walls samples characterized by the same start traits about geometry features, masonry texture and material's mechanical properties: the first one in unreinforced masonry, the second enhanced by a widespread application of the composite material and the last presenting a FRCM strips of in order to configures as a truss beam. Also the experimental setup in terms of loads' application and constraint modalities were equal. With the aim of bringing the specimens to failure, a steel contrast system has been designed to make a self-balanced assembly and the respective breaking loads were applied by mean of a hydraulic flat jack. Furthermore, a monitoring system has been to record the increasing of the applied load and the structures' deformations in relation to the duration of the tests which had as a final moment the complete breaking of the masonry panels, Fig. 8. In addition, the breaking load will be also evaluated in relation to increasing of cracking pattern, (given the presence of the plaster) surveyed thanks to the use of a thermal camera combined with a previously implemented post-processing algorithm aimed at the wall texture damage analysis [10, 11].

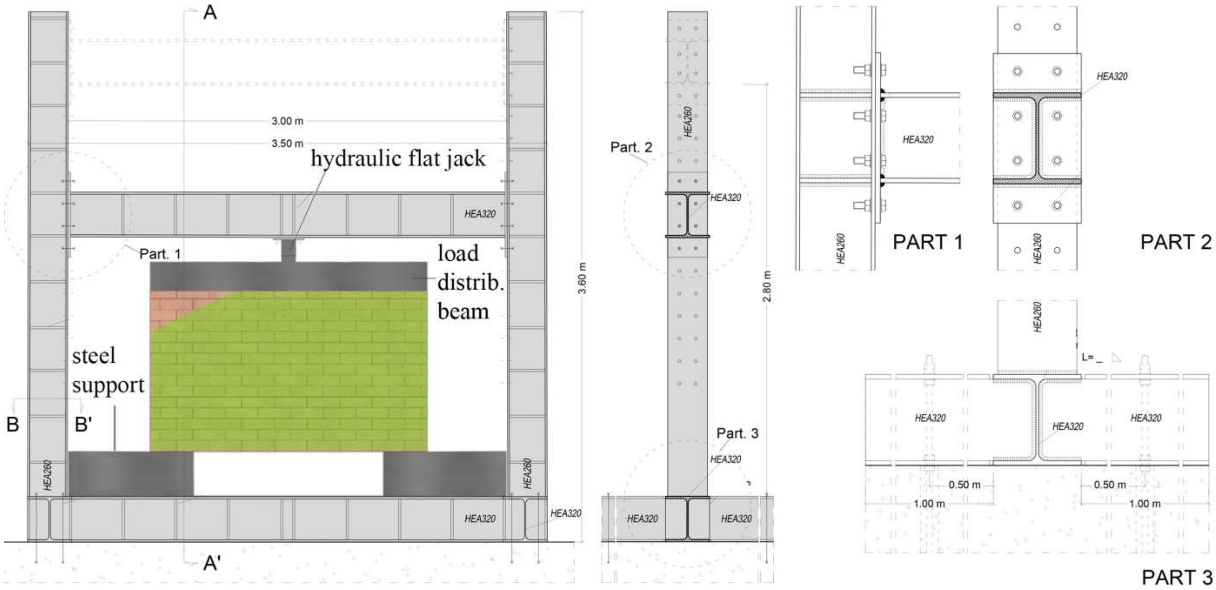

Figure 8: Design details of the steel contrast frame conceived for the near-future experimental campaign

5 CONCLUSIONS

- The results have clarified the experimental behaviour of the FRCM systems, in good compliance with the one of this preliminary numerical modeling referred to the nominal mechanical characteristics of two different materials composing such composite;

- The topic of this ongoing research is to create a model inclusive of the interface between net and matrix in order to replicate the complex failure modes;
- The just planned experimental campaign will be useful to correlate the in-work implementation, time and the skills required for their fulfillment, to the mechanic behaviour of such composite material with respect to the strengthening of masonry walls; subsequently the collected data will be used for a more in deep calibration of a numerical model.

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