Life-Cycle of Structures and Infrastructure Systems

Editors

Fabio Biondini and Dan M. Frangopol

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LIFE-CYCLE OF STRUCTURES AND INFRASTRUCTURE SYSTEMS

Life-Cycle of Structures and Infrastructure Systems collects the lectures and papers presented at IALCCE 2023 - The Eighth International Symposium on Life-Cycle Civil Engineering held at Politecnico di Milano, Milan, Italy, 2-6 July, 2023. This Open Access Book contains the full papers of 514 contributions, including the Fazlur R. Khan Plenary Lecture, nine Keynote Lectures, and 504 technical papers from 45 countries.

The papers cover recent advances and cutting-edge research in the field of life-cycle civil engineering, including emerging concepts and innovative applications related to life-cycle design, assessment, inspection, monitoring, repair, maintenance, rehabilitation, and management of structures and infrastructure systems under uncertainty. Major topics covered include life-cycle safety, reliability, risk, resilience and sustainability, life-cycle damaging processes, life-cycle design and assessment, life-cycle inspection and monitoring, life-cycle maintenance and management, life-cycle performance of special structures, life-cycle cost of structures and infrastructure systems, and life-cycle-oriented computational tools, among others.

This Open Access Book provides both an up-to-date overview of the field of life-cycle civil engineering and significant contributions to the process of making more rational decisions to mitigate the life-cycle risk and improve the life-cycle reliability, resilience, and sustainability of structures and infrastructure systems exposed to multiple natural and human-made hazards in a changing climate. It will serve as a valuable reference to all concerned with life-cycle of civil engineering systems, including students, researchers, practitioners, consultants, contractors, decision makers, and representatives of managing bodies and public authorities from all branches of civil engineering.

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Life-Cycle of Structures and Infrastructure Systems – Biondini & Frangopol (Eds)

Interface experimental behavior between basalt-FRCMs and natural stones

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ABSTRACT: The issue of environmental sustainability is central to several areas of research; in fact, the reduction of polluting emissions and concentration of CO_2 in the atmosphere is a key objective for both private and public institutions. In structural engineering, the sustainability goal involves the design stage, the construction technologies and materials, the maintenance. Specifically referring to structural materials, the research effort is very relevant, as the production of many materials currently used is particularly energy intensive. In the last years, innovative materials have been developed by replacing some components with recycled ones or from industrial processing waste. For example, innovative geopolymer mortars are made with lightweight components, blast furnace or fly ashes (a residue from coal combustion in electricity generation) that replace traditional binder. This new kind of materials can be used as inorganic matrix in case of FRCM (Fiber Reinforced Cementitious Matrix) applications to restore and strengthen existing buildings. The object of the experimental campaign, whose results are reported in this paper, is to study the shear-bond behavior between basalt-FRCM reinforcement system and masonry varying the binder in the mortar: two traditional (cement and lime-based, both with short fibers inside) and an innovative geopolymer matrixes. Two different types of substrates representative of the historical and artistic heritage of Southern Italy are also used: a compact calcareous stone, called *Pietra Leccese,* and a porous calcareous stone, called *Calcarenite*. The results obtained evidenced that the mechanical properties of inorganic matrix always influence the shear bond behavior of the samples, similar conclusion cannot be drawn referring to the mechanical properties of substrates.

1 INTRODUCTION

The Kyoto Protocol was adopted in December 1997 by the Conference of Countries to the United Nations Convention on Climate Change and entered into force in February 2005, following its ratification by the 55 countries responsible for 55% of carbon dioxide emissions. It aims to reduce emissions of six gases (carbon dioxide, nitrous oxide, methane, hydrofluorocarbons, perfluorocarbons and sulphur nexafluoride) considered to be the main causes of climate change and promotes, with the same scope, the protection and expansion of forests to absorb carbon dioxide. Following the entry into force of the Protocol, different solutions have been sought in several areas, including electricity generation, transport, agriculture, waste management and productions of building materials. In fact, the manufacturing of materials like cement, bricks, ceramics, etc. is particularly energy intensive. In addition, with the advent of Environmental Criteria, building materials must have a variable percentage of recycled components and the reuse of materials must be encouraged. Taking all this into account, in the last years new materials have been developed replacing some components with waste from industrial processes. Longo et al (2020) developed a new *Geopolymer Matrix* (GPM) made of dry binders (fly ash and metakaolin), alkali activators and LWA (i.e., expanded glass aggregate). This innovative inorganic matrix therefore involves the use of recycled components (waste from the processing of a coal-fired power plant) and also has further energy benefits in

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terms of conductivity, as it results lower than that of a traditional mortar. Nonetheless, the proposed GPM has proper mechanical characteristics for being used in FRCM systems to restore existing building. FRCMs are composite materials made by inorganic matrix and dry fibers meshes. The composite is an externally bonded system, so its effectiveness is influenced by stress transfer mechanisms between fibre mesh and inorganic matrix and between composite and substrates. With the aim of investigating the parameters most influential on the shear bond behavior, Raoof et al (2016) analyzed different aspects: the bond length, the number of layers, the concrete surface preparation, the substrate compressive strength. Eighty shear bond concrete samples reinforced with carbon fibers different kinds of matrix were fabricated and tested under double-lap direct shear. The results evidenced that:

- increasing the bond length, the bond capacity increases in a non-proportional way for all the number of layers;
- increasing the number of layers for the same bond length, the bond capacity increases in a non-proportional way;
- the number of layers has a significant effect on the failure mode;
- different concrete surface preparation methods did not influence the bond characteristics between TRM and concrete; the use of lower concrete compressive strength marginally affected the bond strength of the TRM to concrete.

In Askouni et al (2019) et al the bond between (AR) glass FRCM and solid clay bricks was studied testing 37 specimens under double lap shear configuration. The matrix of the reinforcement was polypropylene fiber-reinforced cement-based mortar. The chosen variable parameters were bond length, bond width, number of layer and number of yarns. The results evidenced that the maximum axial stress increases almost linearly with the bond width because of the transversal yarns provide improved anchoring conditions for the longitudinal yarns and improved mechanical interlocking between mortar and meshes. Moreover, different textile configurations exhibit different shear bond behaviors.

The present work aims to investigate the stress transfer mechanism between Basalt FRCMs and masonry substrates typical of Southern Italy. Three different kind of mortar (two traditional, cementitious and lime-based, and the new GPM) and two types of substrates (Calcarenite – a calcareous porous stone - and Pietra Leccese – a calcareous compact stone) were considered.

2 EXPERIMENTAL PROGRAM AND SET-UP

The work is part of a research project, whose first results can be found in Bramato et al (2022). The experimental program discussed in the present paper is reported in Table 1 and included 18 samples divided into 6 series of 3 samples made by varying the type of substrate and matrix.

Table 1. Experimental program.

	#	Substrate	Matrix	Fibre
PL_B_R	3	Pietra Leccese	Lime-based	Basalt
PL_B_M	3		Cementitious	
PL_B_G	3		Geopolymer	
C_B_R	3	Calcarenite	Lime-based	
C_B_M	3		Cementitious	
C_B_G	3		Geopolymer	

The used nomenclature W_X_Y_Z indicated: W the type of substrate (C=Calcarenite, PL=Pietra Leccese), X the type of dry mesh (B=Basalt), Y the kind of inorganic matrix (R=lime-based, M=cementitious and G=Geopolymeric) and Z the progressive number of samples (i.e. 1 to 3). The mechanical properties of the constituent materials were reported in previous papers – Longo et al (2020) and Bramato et al (2022) - and the utilized geopolymer matrix was developed in Longo et al (2020). The experimental mechanical strength (compressive and flexural strength) for the traditional mortars (lime-based and cementitious) are those reported in manufacturer technical sheet Bramato et al (2022). In Longo et al (2020) the characteristics of the innovative GPM are reported in terms of energetic and mechanical properties. Comparing the GPM with an equivalent traditional NHL mortar, better performance in terms of conductivity but worse mechanical properties were found. The Geopolymeric matrix exhibited 73% lower values of conductivity if compared with a traditional NHL according to the experimental data reported in Longo et al (2022).

The substrate used is a calcareous compact stone called *Pietra Leccese,* and a calcareous porous stone called *Calcarenite*. The mechanical properties of the natural stones were evaluated according to the current guidelines in terms of flexural and compressive strength and discussed in Bramato et al (2022).

All the tests were performed in displacement control with a rate of 0.2 mm/min by using the same universal machine and test set-up (Figure 1) reported in Bramato et al (2022).

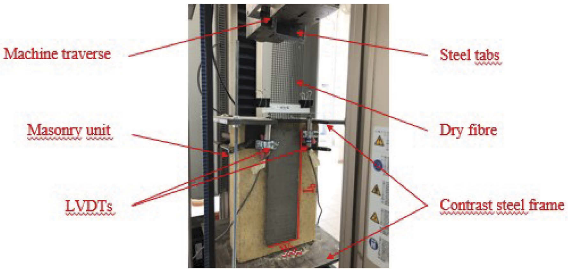


Figure 1. Test set-up.

2.1 *Experimental results*

The experimental results are reported in Table 2 in terms of peak axial force, exploitation rate and global displacement average values. The exploitation rate was calculated as the ratio between the peak axial stress obtained by the shear bond test and the tensile strength of the dry mesh, while the global displacement was set equal to the relative shift of the universal machine transverses, in the following called “global displacement”. The peak axial stress (σ_{max}), was calculated according to the following equations.

$$\sigma_{peak} = F_{peak} / \left(A_y * n \right) \tag{1}$$

where:

σ_{peak} = Peak axial stress [*MPa*];

F_{peak} = Peak axial load [*N*]

A_{sy} = Single yarn section area [equal to 0.23 mm^2, according to data sheet provided by the supplier]

n = Number of yarns [equal to 15]

Table 2. Average experimental results.

Label	F_{peak} [kN]	σ_{max}/ f_{tf} [%]	s [mm]	Label	F_{peak} [kN]	σ_{max}/ f_{tf} [%]	s [mm]
C_B_R	3269.85	72.24	10.98	*PL_B_R*	2897.04	64.00	7.78
C.o.V.	5.48%	5.48%	6.58%	*C.o.V.*	20.74%	20.74	20.20%
C_B_M	4167.35	92.07	9.79	*PL_B_M*	4738.64	104.69	10.16
C.o.V.	11.69%	11.69%	11.55%	*C.o.V.*	7.77%	7.77	10.20%
C_B_G	1037.63	22.92	4.67	*PL_B_G*	1513.54	53.68	2.65
C.o.V.	11.66%	11.6%	25.22%	*C.o.V.*	-	-	-

Three different kinds of failure mode were observed and reported in Figure 2:

- FM type "C": debonding at the matrix-fibre interface;
- FM type "F": widespread tensile failure of the dry fibre at the unbonded zone of the reinforcement;
- FM type "F*": tensile failure of the dry fibre at the fibre-reinforcement interface.

In case of samples reinforced with lime-based mortar, about 83% of the specimens failed for debonding at the matrix-fiber interface, while half of the samples reinforced with cementitious matrix failed for debonding at the matrix-fibre interface, the other half failed because of a diffuse tensile failure at the unbonded zone of the reinforcement. All samples reinforced with geopolymer matrix were characterized by a tensile rupture at the dry fibre-reinforcement interface.

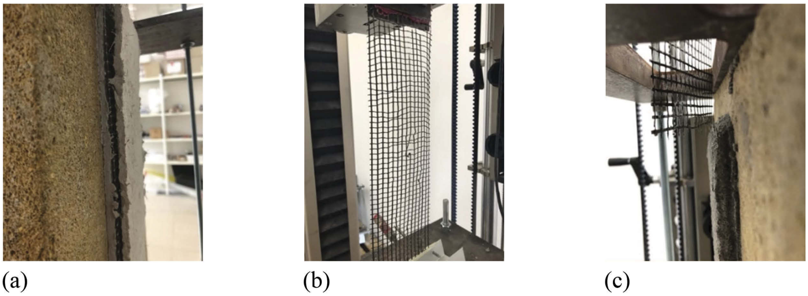
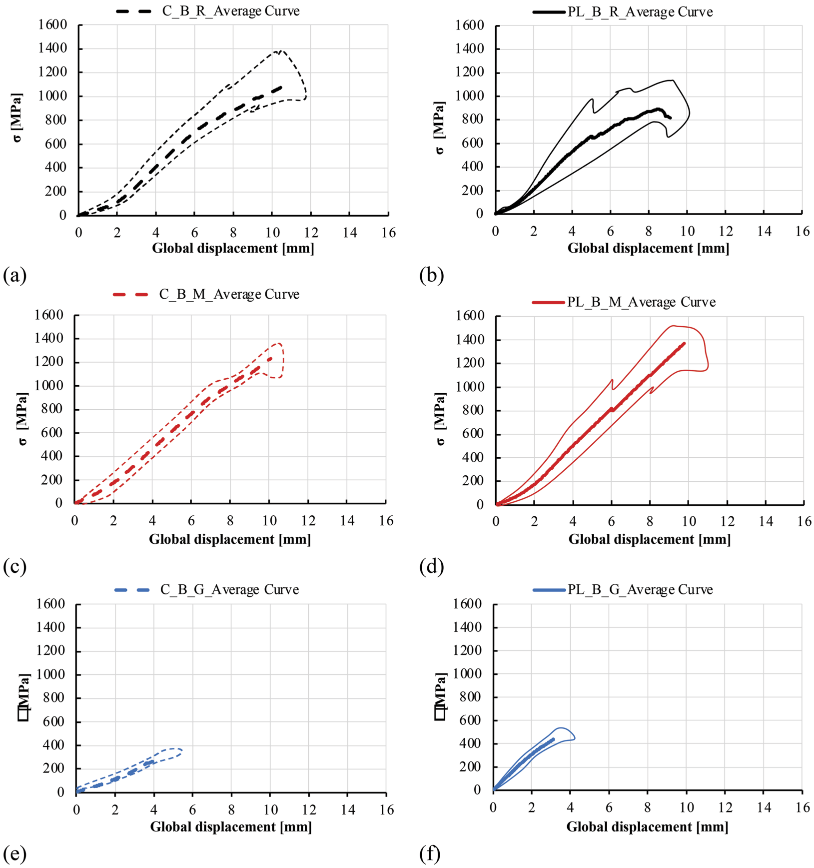

(a) (b) (c)

Figure 2. Typical Failure Modes observed: (a) Type "C"; (b) Type "F"; (c) Type "F*".

For samples reinforced with geopolymeric mortar, the exploitation rate is very low even if a fibre rupture was observed. It seems that there is a possible compatibility problem between the basalt mesh utilized and the innovative geopolymer matrix. With the aim to understand these experimental results, a deep microscopic analysis of the tested specimens has been performed, that evidenced the absence of fibre damage or matrix cracking. Moreover, the lower values of coefficient of variation of both series confirmed the absence of possible experimental error. However, further tests are suggested for validating the data obtained and deepen the problem of the fibre-geopolymeric matrix compatibility. In fact, different studies evidenced that basalt fibers have good chemical stability, chemical resistance, corrosion resistance and water resistance [6-10], however studies devoted to the compatibility between Basalt fibers and geopolymeric matrix are still limited.

Figure 3 shows the average curves axial stress-displacement and the variability range for each of the six series of tested specimens. It can be observed that the variability range is very small as confirmed by the values of the coefficient of variation reported in Table 2. All the average curves show a similar trend and almost the same slope of the first phase (except for C_B_G series), even if the average peak axial stress obtained by samples reinforced with the innovative geopolymer mortar is lower with respect to that obtained in case of traditional mortar. The comparison between the experimental average curves, shown in the Figure 4, evidences and confirms that the mechanical properties of the inorganic matrix influenced the results in terms of peak axial force for both type of substrates (i.e. PL and C stone). In fact, based on this experimental data, increasing the compressive strength of inorganic matrix the maximum axial stress increases as well. In particular, comparing data obtained in case of cementitious and based-lime mortar an increase of 27% and 63% has been registered in case of *Calcarenite* and *Pietra* Leccese samples, respectively.

Figure 5 evidences the effect of substrate on the experimental results. The average curves and the relative scatter areas of series reinforced with lime-based (a), cementitious (b) and geopolymer (c) mortar are drawn. It can be observed that experimental results in terms of average peak axial stress of samples reinforced with lime-based mortar are influenced by the kind of substrates. In this case, the mortar and both the substrates have similar mechanical properties. Contrariwise, in case of cementitious samples, the influence of substrates seems negligible,

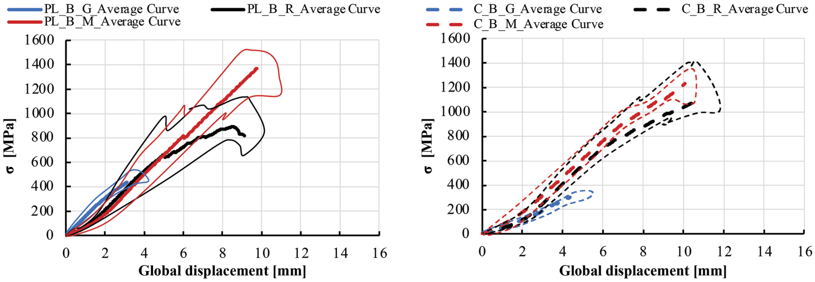


(a) (b)

(c) (d)

(e) (f)

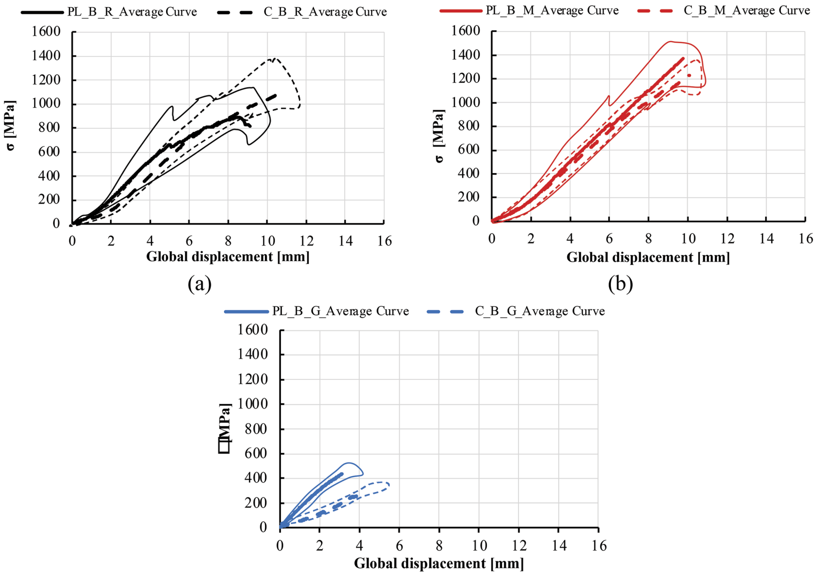
Figure 3. Shear bond specimens global displacement-stress curves: a) C_B_R series; b) PL_B_R series; c) C_B_M series; d) PL_B_M series; e) C_B_G series; f) PL_B_G series.



(a) (b)

Figure 4. Shear bond specimens global displacement-stress curves: a) *Pietra Leccese* substrates; b) *Calcarenite* substrates.

probably because, the mortar has flexural and compressive strength higher than both the substrates. The analysis is still in progress to understand if the recorded percentage difference could be also attributed to the physical properties of the substrates. In case of samples reinforced with geopolymer matrix, a reduction of the slope of the curve was observed passing from *Pietra Leccese* to *Calcarenite*. A reduction in average peak axial force was also recorded. However, this data are still under investigation.



(a) (b)

(c)

Figure 5. Shear bond specimens global displacement-stress curves: a) C_B_R series; b) PL_B_R series; c) C_B_M series; d) PL_B_M series; e) C_B_G series; f) PL_B_G series.

Billotta et al (2017) tested 10 clay bricks prisms with mechanical properties similar to natural stone used in the reported investigation and reinforced with almost the same Basalt open grid dry mesh and matrix. In detail, a natural hydraulic lime mortar with short fibers inside was used. In this case, an average peak axial force equal to 4.6 kN was recorded, a value 41% and 58% higher than in case of C_B_R and PL_B_R series, respectively. Two different failure mode were observed: tensile failure at unbonded zone of the reinforcement and a mix of tensile failure at unbonded zone of the reinforcement and slippage between fibre and matrix without matrix cracking.

Lignola et al (2017) carried out a large experimental campaign in order to investigate the performance of Basalt FRCMs in retrofitting applications by making single lap shear bond test. Some samples made had geometry and mechanical properties of fibre, substrate and matrix similar to those reports in this paper. In detail, 16 coupons were realized with clay bricks prisms with compressive strength equal to 14.6 MPa reinforced with lime-based mortar with 15 MPa compressive strength and almost the same open grid dry mesh. The results obtained was average peak axial force equal to 3.75 kN, a value 15% and 29% higher than in case of C_B_R and PL_B_R series, respectively. Moreover, Lignola et al recorded two different types of Failure Mode: type “E” – slippage between fibre and matrix with mortar cracking; type “F” – tensile failure of fibre at unbonded zone of the reinforcement.

The diversity of the results obtained in terms of axial peak strength and failure mode highlights the need to further deepen the experimental and theoretical investigation.

3 CONCLUSION

The present paper reports the main experimental results of shear bond tests on masonry samples reinforced with different Basalt-FRCM systems. In detail, three different mortars (lime-based, cementitious and an innovative geopolymer mortar) were used with the same Basalt open mesh grid. Two different substrates typical of Southern Italy were considered. The following conclusions can be drawn:

- The types of substrates influence the experimental results when their mechanical properties are similar to those of inorganic matrix;
- The mechanical properties of inorganic matrix strongly influenced the experimental results. In fact, increasing the mortar strength, a higher experimental peak stress was found;
- A possible compatibility problem between the basalt mesh and the innovative geopolymer matrix utilized in the reported investigation was observed. The progress of the research aims to deepen this issue.

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