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EXPERIMENTAL AND NUMERICAL INVESTIGATION ON THE LONG-TERM BEHAVIOUR OF BOND BETWEEN FRP AND MASONRY SUBSTRATES

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EXTENDED ABSTRACT

Modern composite materials like fibre reinforced polymers (FRP), steel reinforced polymers (SRP) and natural fibres have been increasingly accepted as effective repairing or strengthening materials for masonry structures due to high mechanical properties and light weight. The efficacy and reliability of FRPs intrinsically depends on bond between the composite and the masonry substrate. Hence, investigation of long-term durability is a key issue since failures due to inaccurate characterization of bond performance may result in costly repair or premature component replacement [1-2].

Despite of the extensive research in designing of accelerated laboratory tests and developing theoretical models in the field of polymeric materials [1-3], much efforts are required to give insight into long-term performance of FRP-masonry specimens exposed to various ageing factors, including temperature, humidity, salts, etc. [4-6]. Investigation on long-term durability of bond between composites and masonry makes using accelerated aging tests necessary. Studies on bond behaviour of FRP-masonry specimens subjected to accelerated freeze-thaw tests can be found in [4] and [6]. Different exposure paths were used and a change in bond behaviour was experienced after exposure. Moreover, results showed the decrease in shear strength with increasing the number of cycles. As for moisture exposure, tests were usually performed by exposing the samples to wet-dry cycles or immersing them into water for different time spans ([4], [5]). The main outcomes pointed out that significant reduction of bond strength is expected after wet-dry exposure. Experimental research on the UV exposure effect on bond behaviour was carried out in [6]. The maximum reduction in shear bond strength was of about 40 %. Moreover, the bond strength decay was quantified and related to the number of cycles.

A review of experimental techniques for predicting durability of polymers and composites materials can be found in [8] and in [9-10], respectively. However, standardized accelerated ageing procedures to establish long-term performance of FRP-masonry components is still strongly required, as already recognized by the RILEM Technical Committee 223-MSC "Masonry strengthening with composite materials". Furthermore, while methods for evaluating fundamental responses of composite materials are fairly well established for specific degradation mechanisms acting alone, the potential for synergistic effects among mechanisms is not completely understood. In this case, statistical experimental approaches should be used to establish dependencies between the various degradation mechanisms, as well as reliable numerical models should be implemented for an accurate simulation of the experimental behaviour.

The ability to predict the interface time-dependent behaviour as a function of environmental changes over the structural components lifetime is a critical issue at design stage. The coupled effects on porous media due to e.g. heat, air, moisture is a very recent issue [11, 12]. Analytical studies for predicting the life expectancy of plastics and polymer composites able to take into account a plurality of degradation mechanisms demand further investigation [13-18]. The common approach to model the fundamental relationships among damage accumulation rates and structure and property metrics of such materials makes use of refined multi-scale modelling [19, 20].

The thesis deals with characterization of the long-term bond behaviour between composite materials and masonry supports through advanced laboratory-based tests and refined computational analysis. The aim of the study is to achieve insight into the effects of critical environmental conditions on FRP-masonry interface performance. A brief introduction of the main activities is presented in the following sections.

Experimental activities

The effects of freeze-thaw and salt conditions on the composite material-masonry interface will be studied through accelerated ageing tests. The accelerated ageing tests will be used and properly designed on the basis of (i) climatic data analysis of selected Mediterranean countries, (ii) durability guidelines available for building materials and (iii) the characterization of the basic materials.

The specimens will include stone and brick samples with a composite fabric applied on a single side, to be tested under shear bond, and wallets for pull-off tests. Accelerated freeze-thaw tests will be performed by varying the following parameters: the number of cycles per day, the exposure time, heating and cooling rates. Test parameters will also include unidirectional and omni-directional exposure, the number of cycles per day and the exposure time. Failure modes and their changes after exposure will be monitored. The outcomes of this task will provide the reference information for the numerical analysis.

A reliable database of properties of units, mortar and wallets under the synergistic action of moisture and temperature variations will be provided by performing the appropriate tests. Temperature and moisture profiles within the materials itself are of interest, along with progression of damage.

In particular, moisture exposure will be accompanied by temperature cycling. Particular attention will be paid to the following: (i) moisture absorption properties of the constituents after immersion in water; (ii) damage under low temperature during the freeze part of the cycle. Moisture absorption properties of resin will be deeply investigated with focus on the reversible and irreversible effects. Moreover, data on glass transition temperature of the resin will be gathered by using a differential scanning calorimetry (DSC). As for the FRP coupons, degradation mechanisms due to hygrotermal exposure will be studied at fibre level, focussing on fibre-matrix debonding and matrix micro-cracking in the composite. Moreover, exposure to temperature variations will allow analysis of thermo-mechanical properties of the FRP materials involved in this study.

The quantitative analysis of bond behaviour before and after ageing exposure (exposure will be carried out for different periods) will be carried out through direct shear tests and pull-off tests. These tests will allow us to develop a large dataset that will account for different test specimen configurations. Comparisons between exposed and unexposed specimens will provide fundamental understanding about degradation mechanisms, failure modes and bond-slip interface laws.

In shear bond tests, suitable monitoring systems will be used for complete characterization of the interface deformations and debonding phenomenon along the entire bond length, and therefore providing valuable information about the active mechanics along the interface. The result of these tests will provide interface law parameters (e.g. maximum transmissible shear, energy fracture) for the advanced numerical simulation of the bond behaviour of the tested specimens.

Finite Element Analysis

The results obtained from the experimental tests will serve as the basis for simulation of the degradation mechanisms of the interface behaviour through advanced numerical modelling. Analysis of long-term behaviour of materials, as well the strengthened specimens is a complex non-linear problem that needs the use of numerical approaches, typically the Finite Element Method (FEM), and the appropriate definition of the material models. The task has been divided in the following three subtasks:

1. Development of a novel numerical model for the simulation of the experimental shear bond behaviour between composite materials and masonry substrates subjected to freeze-thaw or hygrotermal exposure. The model will be based on numerical models available in literature and also the experimental results obtained in this study.
2. Parametric investigation will be performed by varying the FRP materials and layouts, the number of cycles per day, the exposure time, heating and cooling rates, unidirectional and omni-directional exposure, single and combined degradation agents.
3. Assessment of the proposed numerical model by comparisons with results obtained from experimental accelerated freeze-thaw and hygrotermal tests. Attention will be focused on bond degradation mechanisms and failure modes of the specimens.

Recommendations for practical purposes

In this section, reliability of standard codes and guideline provisions related to the design of FRP strengthening systems bonded to masonry structures will be investigated. Moreover, comparison of detailed numerical simulations with available methods presented in codes of practice will be carried out, in order to provide useful insights towards applicability of advanced simulation procedures for safety assessment of historical structures strengthened with composite materials. Practical recommendations on accelerated ageing test methods for the assessment of the long-term bond behaviour will be also provided.

REFERENCES

[1] Karbhari, V.M., (2007). "Durability of composites for civil structural applications", V.M. Karbhari. (Ed.), Washington, DC: CRC Press.

[2] Holloway, L.C., (2010). "A review of the present and future utilisation of FRP composites in the civil infrastructure with reference to their important in-service properties", Construction and Building Materials, 24(12): p. 2419-2445.

[3] Karbhari, V.M., Chin, J.W., Hunston, D., Benmokrane, B., Juska, T., Morgan, R., Lesko, J.J.M, Sorathia, U., Reynaud, D. (2003). "Durability gap analysis for Fiber-Reinforced Polymer composites in Civil infrastructure", ASCE Journal of Composites for Construction, 7(3): 238-247.

[4] Briccoli Bati, S., Rotunno, T., (2001). "Environmental durability of the bond between the CFRP composite materials and masonry structures", Proc. Historical

Constructions, P.B. Lourenço, P. Roca (Eds.), Guimarães, Portugal.

[5] Aiello, M.A., Sciolti, M.S., (2004). "Influence of environmental agents on bond between FRP reinforcement and calcarenite ashlars", Proc. 4th Int. Seminar on Structural Analysis of Historical constructions, Modena, Lourenço & Roca (*Eds.*), Vol. 2, Padova, Italy.

[6] Desiderio, P., Feo, L. (2005). "Durability evaluation of EBR CFRP strengthened masonry structures", Proc. Int. Symp. on Bond Behaviour of FRP in Structures, Chen and Teng (*Eds.*), Hong-Kong, China.

[7] ASTM E632 (1998). "Standard practice for developing accelerated tests to aid prediction of service life of building component and materials", ASTM: Philadelphia.

[8] Maxwell, A.S., Broughton, W.R., Dean, G., Sims, G.D., (2005). "Review of accelerated aging methods and lifetime prediction techniques for polymeric materials", NPL report: DEPC 016.

[9] Jedidi, J., Jacquemin, F., Vautrin, A., (2005). "Design of accelerated hygrothermal cycles on polymer matrix composites in the case of a supersonic aircracft", Composite structures, 68(4): p. 429-37.

[10] Youssef, Z., Jacquemin, F., Gloaguen, D., Gullien, R., (2008). "A multi-scale analysis of composite structures: Application to the design of accelerated hygrothermal cycles", Composite structures, 82(2): p. 302-309.

[11] Khoshbakht, M., Lin, M.W., C.A. Feickert, (2009). "A finite element model for hygrothermal analysis of masonry walls with FRP reinforcement", Finite Elements in Analysis and Design, 46(10): p. 783-791.

[12] Tariku, F., Kumaran, K., Fazio, P., (2010). "Transient model for coupled heat, air and moisture transfer through multilayered porous media", International Journal of Heat and Mass Transfer, 2010. 53(15-16): p. 3035-3044.

[13] Karbhari V.M., (2007). "Durability of composites for civil structural applications", Karbhari V.M. (Ed.), Woodhead Publishing Limited, Abington Cambridge, England.

[14] Martin, J.W., Ryntz, R.A., Chin, J., (2009). "Service life prediction of polymeric Materials: Global Perspectives", Martin, J.W., Ryntz, R.A., Chin, J., Dickie, R.A. (Edts), Springer.

[15] Daniotti, B. Cecconi, F.R., "Test Methods for service life prediction", CIB Report 331 - State of the art report on accelerated laboratory test procedures and correlation between laboratory tests and service life data - Politecnico di Milano, Italy.

[16] Masters, L.W., (1987). "Service life prediction", Building Research & Information, 15(1): p. 292-296.

[17] Clifton, J.R., (1993). "Predicting the service life of concrete", ACI Mater. J., 90(6): p. 611-617.

[18] Purnell, P., Cain, J., van Itterbeeck, P., Lesko, J., (2008). "Service life modelling of fibre composites: A unified approach", Compos Science and Technology, 68: p. 3330-3336.

[19] Maekawa, K., Multi-scale modelling of structural concrete. 2009: Taylor & Francis Edts.

[20] Maekawa, K., Ishida, T., Kishi, T., (2003). "Multi-scale modelling of concrete performance- Integrated material and structural mechanics", Journal of Advanced Concrete Technology, 1(2): p. 91-126.

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