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Fabric-reinforced cementitious matrix behavior at high-temperature: Experimental and numerical results

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ABSTRACT

The use of externally applied composite systems to upgrade, strengthen or rehabilitate masonry or concrete structures is well established. However, structural strengthening with organic type composites, such as fiber-reinforced polymer (FRP) systems, may be impractical when the element is exposed to high-temperature service conditions, due to significant degradation of the organic resin. Instead, the use of an inorganic matrix, as in the case of fabric-reinforced cementitious matrix (FRCM) composites, may overcome this problem.

The purpose of this study is to evaluate the mechanical behavior under high-temperature conditions of FRCM systems. Different FRCM composites are evaluated and include carbon fabrics ranging from dry to highly-impregnated with an organic resin. The experimental spectrum is comprised of uniaxial tensile and double-shear bond tests performed under temperatures ranging from 20 to 120 °C to determine the influence of temperature over the FRCM mechanical properties. Furthermore, SEM analysis was used to study the damage processes at the fiber-matrix interface post tensile testing. Experimental results show variations in the FRCM mechanical properties if tested at high temperature conditions (caused by the deterioration of the resin coating at the interface fiber-matrix) while residual performance after exposure to elevated temperatures remains unchanged. FRCM reinforced with dry fabrics has proven not to be affected by temperatures up to 120 °C.

A numerical model using a fracture variational approach, based on incremental energy minimization, was also developed to simulate the FRCM behavior in double shear tests under different temperatures exposition.

1. Introduction

The use of fiber-reinforced polymer (FRP) systems to reinforce masonry or concrete structures may be impractical when the element is exposed to high-temperature service conditions. FRP mechanical properties can be drastically reduced if the temperature exceeds the glass transition temperature (T_g) of the organic resin used for fiber impregnation and bond to the substrate. Experimental studies showed a severe reduction of FRP tensile strength, stiffness and bond properties to the substrate when exposed to elevated temperatures due to a rapid deterioration of the FRP-substrate adhesion when the temperature exceeds the T_g of the resin (typically around 60–80 °C), resulting in delamination of the composite and loss of efficacy of the reinforcement [1–5].

Studies conducted by Bisby and co-workers [6] on the mechanical characterization of FRP materials at high temperature showed that half of the tensile strength of the FRP was lost when tested near the T_g of the epoxy matrix. Lap-splice tests showed that the FRP-to-FRP bond strength was affected even more by temperature exposure near T_g with 90% loss in lap-splice strength.

Al-Salloum and co-workers [7] suggested to not exceed the FRP T_g in order to avoid serious consequences. In case temperature is allowed to reach up to 200 °C (thus greatly higher than T_g), the ultimate capacity of FRP-strengthened members should be kept at less than 25% of its corresponding value at room temperature.

For this reason, the use FRP composites in construction, where

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Nomenclature

Geometrical parameters

A	sectional area of the yarn
b_1	thickness of the 1st layer of mortar
b_2	thickness of the yarn in numerical simulation
b_3	width of the FRCM in numerical simulations
h	FRCM anchorage length in double shear tests
l_1	mean length of the internal isostatic lines
l_2	mean length of the external isostatic lines
l_m	internal length of the damage surface
β	geometrical ratio
Ω_f	yarn domain
Ω_m	matrix domain
Λ	interface domain

Variables

α	damage parameter
$\mathbf{u}$	displacement field

Displacements and strains

s	fabric total displacement
δ	yarn displacement in numerical simulations
ε_2	FRCM ultimate tensile strain

Materials parameters

G	fracture toughness
B	size of the process zone
q	exponent of the interface damage energy
E_m	elastic modulus of the mortar
E_2	FRCM elastic modulus in the cracked phase
E_f	tensile elastic modulus of the yarn
μ, λ	Lamé's coefficients
k	elastic coefficient of interface springs

Forces and stresses

f_{max}	peak load in double shear tests
σ	tensile normal stress in the yarn
τ_e	maximum shear stress at the interface
τ_r	residual shear stress at the interface
σ_e	tensile strength of the mortar
σ_u	FRCM ultimate tensile strength
τ_1	shear stresses along the internal isostatic lines
τ_2	shear stresses along the ext. isostatic lines
f	longitudinal force in the yarn

high temperature exposure is critical, may be limited and additional information is needed when selecting strengthening solutions. For example, the use of insulation to maintain the temperature on the FRP surface below T_g is possible, although not always practicable [8,9]. Hence, alternative solutions need to be explored and evaluated.

FRCM systems use inorganic matrices, which are less susceptible to high temperature and may result cost effective compared to FRPs [10–15]. However, the bond between fibers and inorganic matrix is a critical issue in FRCM composites and is strongly influenced by the ability of the cementitious matrix to saturate dry fiber yarns; also affected is the bond between internal and external fibers within the yarns and between external fibers and matrix in case of dry fabrics and possibly between coating and matrix in case of coated fabrics. FRCM for structural strengthening applications is a relatively new material and durability is an important aspect to be considered. Factors affecting the durability of FRCM composite systems must consider the environmental performance of each of its components and their interfaces: the cementitious matrix, the fabric reinforcement, the fabric-matrix interface and the matrix-substrate interface are the different elements that need to be considered in relation to the service environments in which they are expected to perform [16]. FRCM is expected to overcome some of the issues that are typically found in FRP because of the better performance of the cementitious matrix to high temperatures. However, limited experimental and analytical studies have been conducted to evaluate the behavior of FRCM under high temperatures and the residual performances after exposure to elevated temperatures.

An experimental study on the effect of high temperature on the performance of carbon fiber-reinforced polymer (CFRP) and FRCM confined concrete element was conducted by Trapko [17], using concrete cylinders reinforced with CFRP sheets and FRCM mesh and exposed to temperature ranging from 40 to 80 °C. In the case of polymer jackets, 40 °C increase in temperature resulted in 20% decrease of the load-bearing capacity. The compressive strain of specimens tested in 80 °C was approximately half of the strain in specimens tested at 40 and 60 °C. Load-bearing capacity decrease by 5–10% was observed for FRCM confined elements upon temperature increase from 40 to 80 °C. Also, compressive strain decrease by approximately 11% was observed upon temperature increase from 40 to 60 and 80 °C.

FRCM performances at high temperature exposure may change when fabrics are pre-impregnated with polymeric resins. Experimental studies showed that the use of a polymer coating applied on carbon fabric may significantly increase the mechanical capacity of FRCM systems for both tensile and shear bond strengths when applied to masonry or concrete supports [18–20]. However, when the textile reinforcement is coated with a polymer, the bond performance between fibers and matrix is strongly affected by temperature [21].

Recent studies by Silva and co-workers [22] using FRCM reinforced with carbon fibers showed a polymer interlocking mechanism between filaments and matrix when heating the polymer coated fibers up to 150 °C. This mechanism results in significant increases in the maximum pullout load. Krüger and Reinhardt [23] performed fire tests on four different I-shaped mortar beams reinforced with AR-glass and carbon textiles. The investigation was focused on the load bearing capacity of the composite during a fire test under constant load. In one of the cases a SBR (Butadien-Styrol) thermoplastic resin was used as coating in the fiber. The results showed to be very dependent on the fire behavior of the used fibers. Due to the softening of the SBR coating (around 90 °C) the fiber–matrix interface rapidly deteriorated, resulting in fiber pullout and, subsequent, failure.

Michels and Motovalli [24] presented experimental results of the tensile strength decrease of coated carbon fiber yarns after high temperature exposure up to 1000 °C. The investigation was performed at room temperature on carbon fiber yarns after having been thermally subjected to constant temperature of 300, 500, 700 and 1000 °C in a tube furnace for 30 min. It was observed that an exposure at 300 °C for 30 min does not affect the mechanical properties of the analyzed reinforcement. However, a further increase in temperature results in significant damage to the material performance at 500 °C and no residual strength at 700 °C. Tests on a