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Influence of three-dimensional (3D) fabric orientation on flexural properties of cement-based composites

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ABSTRACT

This research studied the flexural behavior of textile reinforced cement-based composites reinforced with 3D fabrics. Three different 3D fabrics were examined, each with a different orientation of the spacer yarns. This work focused on the influences involved in the two plane fabric directions, weft and warp. Plain 2D fabrics (not in cement) and within the cement were also examined for comparison. It was found that the warp direction of the plain fabric has higher tensile strength than the weft direction. On the contrary, when the fabric is in a composite, the weft direction presents improved behavior in flexure due to three mechanisms: the tightening of the warp bundles by the loops, the waviness of the warp yarns, and the angle of the yarns located along the composite thickness to the loading direction. In general, compared with 2D fabrics, 3D fabrics are highly beneficial reinforcements for cement-based composites due to their greater reinforcing efficiency via mechanical anchoring.

1. Introduction

In recent years, there has been considerable interest in TRC (textile-reinforced concrete) and its mechanical performance [1,2]. Superior tensile strength, toughness and ductility were reported with TRC [3–5]. These works were focused on two dimensional (2D) textile fabrics in which the reinforcing yarns composing the fabric are only located in the directions of the fabric planes (X, Y) and not in the direction orthogonal to the fabric planes. In order to achieve reinforcement by means of 2D fabrics throughout the composite thickness, laminated composites should be prepared with several layers of fabric. However, such laminated composites, that have poor shear and split resilience properties, may be sensitive to failure by delamination.

Modern textile technology enables the production of a wide variety of fabric structures, allowing for great flexibility in fabric design. It is also possible to produce three-dimensional (3D) fabrics, providing reinforcement in three orthogonal directions (X, Y, Z); this can limit failure by delamination and enhance the shear strength of the composite and is expected to improve the mechanical properties of cement-based composites. 3D fabrics can be manufactured by several methods, such as knitting, weaving, etc. Among the different 3D fabric production technologies, an attractive option for cement-based composites is double needle bar warp knitting, since it creates a fabric with an open structure, as required for cement-based composites. Warp knitting can create 3D fabric structures by joining two sets of independent 2D knitted fabrics together with a third set of yarns along the thickness of the fabric (Z). The Z yarns are referred to as 'spacer yarns', which serve two purposes - stabilization and reinforcement. 3D spacer fabrics were developed for use in cement–based products [6,7]. Several studies dealt with the behavior of TRC reinforced with 3D fabric, demonstrating the potential of using these types of fabrics in the cement field [8,9]. In 3D fabrics, the existence of the spacer yarns can influence the mechanical properties of the TRC component, depending on their material type, geometry and orientation.

The objective of this research was to study the flexural behavior of textile-reinforced cement-based composites reinforced with 3D fabrics. Three different 3D fabrics were examined, having different orientations of the spacer yarns. This work focused on the influences in the two plane fabric directions, weft and warp. In most cases, the fabrics were impregnated with epoxy in order to achieve improved reinforcing efficiency. 2D fabrics were also examined for comparison.

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2. Experimental program

2.1. Fabrics

For this work, 3D warp knitted fabrics were prepared, in which two sets of independent 2D knitted fabrics were stitched together in the Z direction of the fabric using a third set of yarns, defined as 'spacer yarns'. The warp (Y) and weft (X) yarns were stitched together by loops of fine multifilament polyester (PES), leaving square openings of 8 × 8 mm in the fabric planes, i.e., at both 3D fabric surfaces. The yarns used in this research, to prepare the fabric at its two surfaces, were multifilament alkali-resistant (AR) glass yarns, i.e., located along the weft and warp directions. The spacer (Z) yarns that connected the two AR glass fabrics to a 3D fabric structure were made from two different yarn types. The first one, mainly used for stabilization, was made from low-performance monofilament PES, while the second one was used to provide reinforcement, so it was made from high-performance multifilament aramid. All the fabrics were specifically produced for this research at the Institute of Textile at RWTH Aachen University (ITA).

Three different fabric types were prepared

1. *2D fabric* – made with AR glass yarns in the weft and warp directions (without any yarns in the Z direction, Fig. 1a);
2. *3D Ar100 fabric* – made of two plies of 2D fabrics, exactly the same as the 2D described above, but with spacer yarns in the Z direction comprised of monofilament PES and multifilament aramid (Fig. 1b–c). This fabric has different yarn geometries in the warp and weft directions as follows:
   (i) A difference in the angles of the spacer yarns in the two fabric directions, warp and weft, is clearly observed in Fig. 2, where the average angle of the spacer yarns in the warp direction is 79.6° (Fig. 2a) and 52.7° in the weft direction (Fig. 2b).
   (ii) Additional loops – the spacer yarns create loops around the warp yarns in order to connect the two 2D fabrics to a 3D fabric structure; these loops are in addition to the fine PES loops connecting the weft and warp yarns to form the initial 2D fabrics. These extra loops are clearly observed in Fig. 1b–c, along the warp, while only a fine loop structure is visible in the 2D fabrics (Fig. 1a). These extra spacer yarn loops strongly tighten the warp filaments together, which can lead to reduction in the penetration of the cement matrix in between the filaments composing the warp yarns, thus expecting to decrease composite performance. Meanwhile, the weft yarns are free and open, since the loops are located only around the warp yarns (as seen in Fig. 1).
3. 3D Ar100 with diagonal spacer yarns (big/small X) – these 3D fabrics were also made of two 2D fabric plies connected by spacer yarns comprised of monofilament PES and multifilament aramid, but here the spacer yarns are oriented in two cross directions, providing an X shape (diagonals that tilt to both sides), as presented in Fig. 3. The X shape is expected to improve the shear resilience of the composite. Two fabrics were prepared with two different diagonal angles of the spacer yarns: henceforth, 45° is referred to as the 'big X' (BX) (Fig. 3a) and 70° is referred to as the 'small X' (SX) (Fig. 3b). Note that in these fabrics the cross of the spacer yarns was on the weft side only, while along the warp side the spacer yarn orientation was similar to that observed in Fig. 2a. Additionally, the AR glass yarns in these fabrics are of 1200 tex, unlike the other fabrics (2D, 3D Ar100, Figs. 1–2) which are of 2400 tex. Therefore, a comparison was made between those two composite systems only, BX and SX, to evaluate the influence of the cross angles.

In total, four different fabrics were examined: 2D, 3D Ar100, 3D SX and 3D BX following the discussion above. Some fabrics were impregnated with epoxy in order to achieve improved reinforcing efficiency, thus all the constituent filaments in the impregnated yarns carry the load together, the entire fabric behaving as a single unit. Epoxy impregnation was done by coating all the yarns in all the directions using a brush, applying enough epoxy to penetrate the yarn bundle spaces, but without filling and closing the gaps between the yarns in the fabric, providing ~40% epoxy relative to the total weight of the textile Keeping these gaps free of epoxy maximized the penetration of the matrix into the fabric openings. A low-viscosity high-strength epoxy (a Sikadur® 52) was used to get good filling of the spaces between the filaments.

2.2. Composite preparation

All the composites were made with a matrix of cement paste (water and cement only) with a 0.4 water/cement ratio using CEM II 42.5 N/B-LL, in order to eliminate influences other than those related to the fabric structures. The 3D fabric specimens were prepared by filling the bottom portion of the mold with a thin layer of cement paste above which the 3D fabric was placed; the rest of the mold was then filled until the fabric was completely covered. For the 2D fabric specimens, a sandwich-type of composite was prepared, in which the two layers of 2D fabrics were located at the top and bottom of the composite, separated by a layer of cement paste. To situate the 2D fabric layers within the matrix, a thin layer of cement paste was first cast in the bottom of the mold; then the first 2D layer was laid down on that. More cement was added on top of the first fabric layer before the second 2D layer was positioned and then covered in cement to fill up the mold to the top. This method provided a two-ply fabric composite similar to the 3D fabric composite, but without spacer yarns along the composite thickness. During casting, a vibration procedure was applied, using a strong vibration table to ensure good penetration of the matrix between the gaps of the fabric and bundle filaments. After casting, the composites were left to harden for 24 h, demolded and then cut

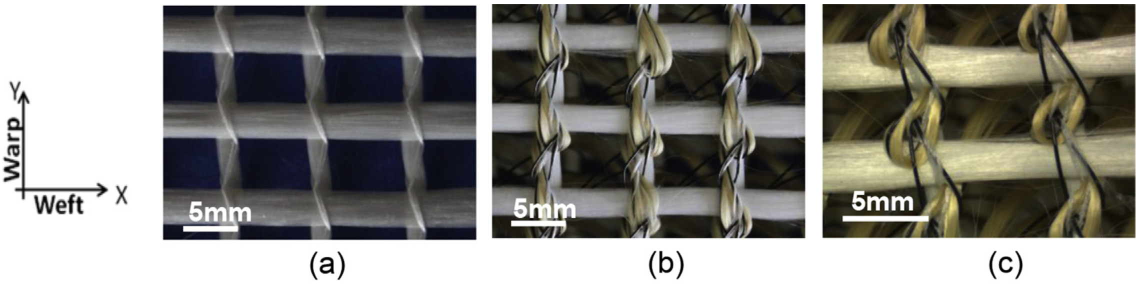

Fig. 1. Top view of the different tested fabrics: (a) 2D; (b) 3D Ar100; (c) close-up of 3D Ar100.