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FLEXURAL BEHAVIOR OF CEMENT BASED ELEMENT REINFORCED WITH 3D FABRIC

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Abstract: This research studied the flexural behavior of concrete elements reinforced with 3D fabrics. The influences of the yarns along the Z direction were studied, focusing on four parameters: (i) Z yarns properties, high performance aramid vs. low performance polyester, (ii) content of aramid Z yarns, 50% and 100%, (iii) epoxy impregnated fabrics to increase stiffness and reinforcing efficiency and (iv) 2D fabric vs. 3D fabric composites. Improved performance was found for the 3D fabric as compared with 2D fabric composites. High properties yarns along the Z direction found to highly improve the strength and toughness of the cement-based composite, with more significant improvement of epoxy impregnated fabrics. It can be concluded that 3D fabrics can be beneficial as reinforcements for cement-based composites although the Z yarns are not along the applied loads, as they hold the whole fabric together providing stiff and tight single unit, leading to improved mechanical anchoring and properties, mainly when impregnated in epoxy.

1 INTRODUCTION

In recent years there has been considerable interest in FRC/TRC (fiber/fabric/textile reinforced cement/concrete) composites and ways to improve their mechanical performance [1-2]. Addition of fibers/fabrics as reinforcement for the brittle cement matrix can greatly improve its tensile strength, elongation to failure and energy consumption. Most high performance fibers are in the form of multifilament bundles (rovings) with a wide range of properties. These bundles can be assembled into technical fabrics, which can be tailored for high performance cementitious composites with controlled two- and three-dimensional geometry. Superior tensile strength, toughness, ductility and energy absorption were reported with TRC [3-6]. Two dimensional (2D) fabrics reinforce the composite along the directions of the fabric plane, but not in the direction orthogonal to the fabric plane. To achieve reinforcement throughout the composite thickness, laminated fabrics are required, resulting in sensitivity to failure by delamination. Due to these characteristics, TRC elements reinforced with 2D fabrics is limited, resulting poor shear and split resilience properties under static, dynamic or impact loads.

Modern textile technology enables wide variety of fabric structures which allows great flexibility in fabric design. It is also possible to produce three-dimensional (3D) fabrics, providing reinforcement in the plane normal to the panel. 3D fabrics having reinforcement in three orthogonal directions can limit failure by delamination and enhance shear strength of the composite and therefore expected to improve the mechanical properties of cement composites. 3D fabrics can be produced by several methods such as knitting, weaving, braiding, etc. Among the different 3D fabric production technologies, an attractive option for cement-based composites is double needle bar warp knitting, as it is allows open structure. Warp knitting can create 3D fabric structures by connecting two sets of independent 2D knitted fabrics together with a third set of yarns along the thickness of the fabric. The connecting yarns are referred to as spacer yarns. Spacer yarns serve two purposes, stabilization and reinforcement. Recently 3D spacer fabrics were developed for use in cement–based products [7]. Several studies dealt with the behavior of cement-based composites with 3D fabric as reinforcement demonstrating the potential of using these types of reinforcement in the cement field [8-10]. These studies mainly focused on 3D fabrics where the yarns along the thickness (Z direction) of the fabric were used for stabilization purposes only, having low modulus.

The objective of this research was to study the flexural behavior of concrete elements reinforced with 3D fabrics. The fabrics were all with AR (alkali resistance) glass yarns along the X (width) and Y (length) direction, only the influences of the yarns along the Z direction were studied. Four parameters were studied: (i) the properties of the yarns along the Z direction, high performance of aramid vs. low performance of polyester, refer here as reference (REF), (ii) the content of the high performance aramid yarns along the Z direction, 50% and 100%, (iii) impregnation of the yarns made the fabric in epoxy to increase fabric stiffness and reinforcing efficiency, and (iv) 2D fabric were compared with the 3D fabric composite, made of the exact same AR glass X, Y yarns.

2 EPERIMENTAL PROGRAM

2.1 Preparation of specimens

2.1.1 Fabrics

3D warp knitted fabric structures were used for this work, in which two sets of independent 2D knitted fabrics (Fig. 1a) were connected together with a third set of yarns along the thickness, the Z direction, of the fabric (Fig. 1b) to produce the 3D fabric (Fig. 1c). The warp and weft yarns (the yarns along the X and Y directions) were connected together by stitches (loops) to provide square opening of 0.8x0.8 cm (Fig. 1a). Fine multifilament polyester (PES) used to create the loops.

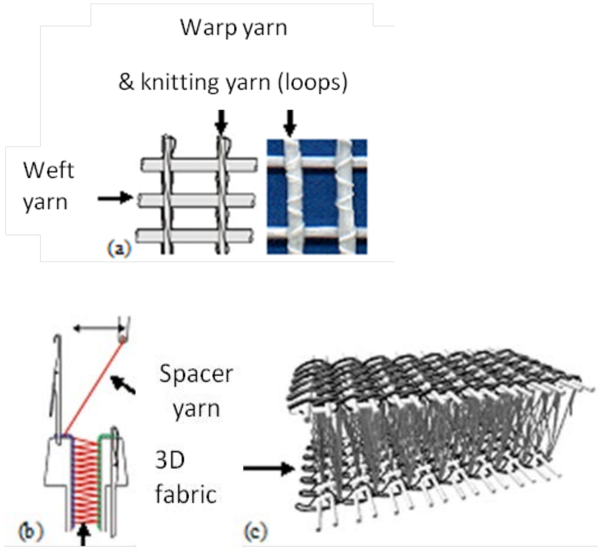
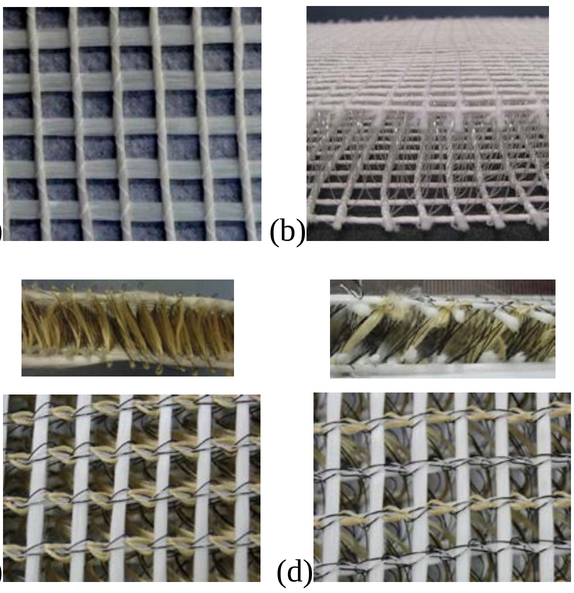


Figure 1: (a) 2D warp knitted fabric at both faces of the 3D fabric, (b) schematic description of the 3D fabric production, and (c) simulated 3D fabric.

The 3D fabrics used in this research were all made with multifilament alkali resistance (AR) glass yarns (Cem-FIL© grade) along the X (weft) and Y (warp) directions. The spacer yarns in Z direction were made from two different yarn types. The first was monofilament polyester (PES) used mainly for stabilization. The second spacer yarn type was for reinforcing purposes, using high performance yarn of aramid. The AR glass was with a modulus of elasticity of 72 GPa, tensile strength of 1700, and tex of 2400. The aramid was with modulus of elasticity of 55 GPa, tensile strength of 2367, and tex of 1670. The PES was with tex of 66.4.

The glass and aramid yarns were in a multifilament form and the PES yarn was with a monofilament form.

Four different fabrics were prepared: i) 2D fabric – made with AR glass along the weft and warp directions exactly as the 3D but without the yarns along the Z direction, will refer here as 2D (Fig. 2a). (ii) 3D Reference - in which the spacer yarns were made of PES only, i.e., without high performance reinforcing spacer yarns. Will refer here as 3D REF (Fig. 2b). iii) 3D Aramid 100% - In which high performance reinforcing aramid yarns were located along the Z direction, in such a manner that all yarns were close together without any gap. In this fabric the content of the spacer aramid yarns was the maximum possible, providing 100% reinforcing aramid yarns along the Z direction. This fabric will refer here as 3D Ar100 (Fig. 2c). iv) 3D Aramid 50%- In which aramid yarns were located along the Z direction with a formation of arranged in "one in one out", i.e., here the spacer aramid yarns are in such a manner that there is one yarn and then a gap with the size of one yarn diameter, providing 50% reinforcing aramid yarns along the Z direction. Will refer here as 3D Ar50 (Fig 2d).



(a) (b) (c) (d)

Figure 2: Different fabrics: (a) 2D, (b) 3D REF, (c) 3D Ar100 top and side view, and (d) 3D Ar50 top and side view

All fabrics were produced by ITA, RWTH Aachen. One set of each fabric type was coated with epoxy. The epoxy was applied by coating the yarns with a brush leaving the fabric openings free of epoxy to allow cement matrix penetrability. A low-viscosity high-strength Sikadur® 52 epoxy was used for this purpose. In this set the yarns in all directions were coated with the epoxy, providing greater stiffness of the fabric and improved reinforcing efficiency, as the loads will be carried by one single bundle unit and not separately by the individual filaments of the bundle.

2.1.2 Composites

Eight composite systems were prepared from the four different fabric types discussed above with and without epoxy. In all, the matrix was of cement paste (water and cement only) with 0.4 water/cement ratio using CEM II 42.5 N/B-V. The specimens were prepared by casting a thin layer of cement paste at the bottom of the mold then placing the 3D fabric in the mold on top of this layer, following by casting the matrix into the 3D fabric until complete filling and coverage of the fabric. In the case of the 2D fabric, first casting a thin layer of cement paste at the bottom of the mold and placing one layer of the 2D fabric on top of this thin layer, then casting a cement paste almost up to the top of the mold, placing a second fabric layer in the mold and cover it with a cement paste up to the top of the mold. This provides a two fabric layer composite similar to the 3D fabric composite but without the connecting yarns along the thickness of the composite (Z direction). In all composites the warp yarns (see Fig. 1a) of the fabric were located along the reinforcing direction.

During the cement paste casting, a vibration procedure was applied using a strong vibration table, in order to allow good penetrability of the matrix in between the opening of the fabric. The composites were left to harden for 24 hours after casting, demolded, and then were cut to slices providing specimens with a 320x40x26 mm of length, width and thickness, respectively. The specimens cured in 100% relative humidity for 12 days and then another 2 days at room environment until testing, at 15 days from casting.

2.2 Test procedure - 4 point bending

All the composite systems were tested by 4 point bending having a support span of 300 mm and loading span of 100mm. The crosshead velocity was fixed to 0.5 mm/min. The test was executed with Instron tensile machine, having closed loop operation and load cell capacity of 100 kN. A linear variable differential transformer (LVDT) with a range of ±15 mm was connected to the bottom surface of the specimen for measuring the deflection. A camera was placed in front of the specimen capturing its side view during the bending tests, in order to record crack pattern and mode of failure. The test was stopped at 12 mm and those with epoxy of about 18 mm.

In all composites, the AR glass yarns were located along the specimen length relative to the load direction of the crosshead, where the Z yarns were located through the thickness of the composite from top to bottom.

For each system four specimens were tested and load vs. deflection curves were recorded. The stresses and toughness (as the area under stress – deflection curves) were calculated including their standard deviations. A typical curve was chosen for each system for comparison.

3 RESULTS

3.1 Flexural behavior

The flexural stress vs. deflection curves of composites reinforced with 2D fabric, 3D fabrics with the aramid yarns along the Z direction and the reference without the aramid Z yarns are compared in Fig. 3, with and without epoxy impregnation. The benefit of the 3D fabric composites as compared to the 2D fabric composite is clear, exhibiting greater flexural responses than the composite reinforced with the 2D fabric. This is the case for both systems with and without the epoxy.

For the system with the epoxy (Fig. 3a) the improvement in flexural performance is in flexural strength as well as deflection at peak and toughness of the 3D fabric composites as compared with the 2D fabric composite. Note that here the test was ended at 18 mm deflection. The improvement in flexural strength of the 3D vs. 2D fabric systems is twice as much for the 3D REF composite and three folds for the 3D Ar100 composites, with values of 9 MPa, ~18 MPa and ~27 MPa for the 2D, 3D REF and 3D Ar100 composites respectively. When comparing the two 3D fabric composite systems, the one with the aramid yarns along the Z direction of the fabric exhibits the best performance. Note that the only difference between the two 3D fabric systems is the presence of the high modulus aramid yarns along the thickness of the composite. Therefor these results clearly show the advantage of using high performance yarns along the Z direction of the fabric to the overall flexural behavior of the composite; this is although these yarns are not in the direct direction of the applied loads.

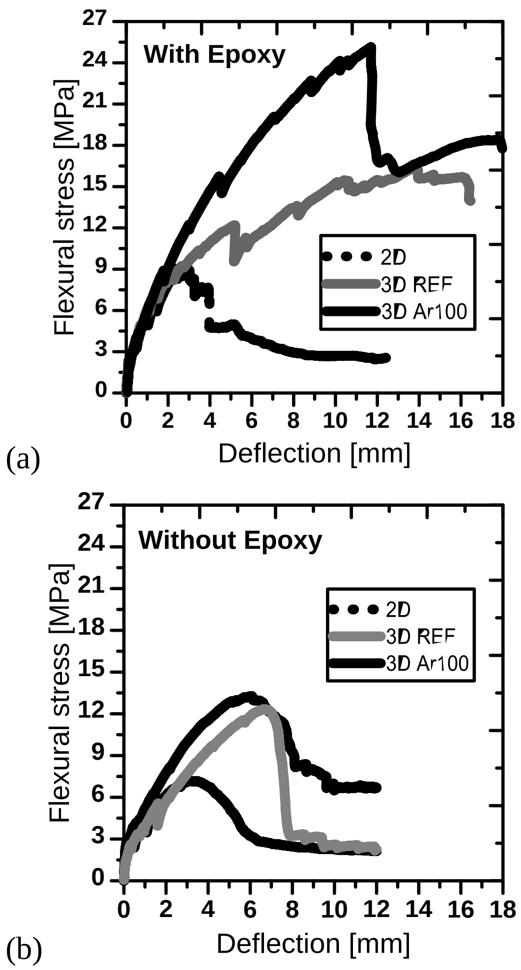


Figure 3: Flexural behavior of the composites with the 2D fabric, and 3D fabrics with and without (REF) aramid yarns: (a) with epoxy, (b) without epoxy.

When comparing the three composite systems, 2D, 3D Ar100, and 3D REF without the epoxy impregnation (Fig. 3b), the 3D composite performs better than the 2D fabric composite, but the improvement of the 3D fabrics composites over the 2D fabric composite is much smaller than that with the epoxy in all terms, strength, deflection at peak and toughness. Moreover no significant difference is observed between the 3D fabric composites Ar100 and REF, both showing similar flexural behavior. This suggests that the 3D fabric are beneficial as reinforcements for cement-based elements however this is mainly when the fabrics are first impregnated in epoxy.

In addition, the epoxy impregnation mainly influences the flexural behavior of the 3D fabric composites and much less the 2D fabric composite. When comparing the bending responses of the two 2D fabric composites with and without the epoxy (Figs. 3a with 3b) their behavior is quite similar with only small benefit for the epoxy impregnated system. A significant different in flexural behavior of the 3D fabric composites with and without the epoxy is observed, exhibiting much greater performance for the epoxy impregnated systems. For the 3D Ar100 composite, the impregnation in epoxy results in increase of strength in about 30%, from 12 MPa to ~16 MPa, but even more pronounce is the improvement in ductility. The deflection at peak is 6 mm for the non-epoxy composite and as high as 11 mm for the epoxy impregnated system composite. For the 3D REF (without aramid yarns), the difference due to epoxy impregnation is even greater, exhibiting increase in strength from 14 MPa up to 26 MPa, which is almost twice as much. The improvement in ductility is also very large from 6 mm to 12 mm deflection at peak. However for the 2D fabric composites the epoxy does not lead to a major difference in flexural performance, with flexural strength values of ~8 MPa and ~9 MPa for the non-epoxy and epoxy impregnated system, respectively. This indicates the importance of using a 3D fabric unit as one unit reinforcement for cement-based elements.

3.2 Influence of Z yarns content

Two different yarn contents along the Z direction of the fabric were studied: Ar100 and Ar50 (Figs. 2c, 2d). Fig. 4 presents the composite flexural strengths and toughness values vs. aramid yarn content along the Z direction of the fabric. The values presented for the 0 content are of the 3D REF composite without aramid yarns. Four values of each tested specimen are given for each composite type. The flexural strengths are given per the reinforcing yarns, as the number of yarns along the applied load direction was not always the same for all specimens, due to the cutting process mentioned above. The results are presented for the epoxy and non-epoxy impregnated systems.

Increase of the high modulus aramid yarns content results in greater composite properties of both, flexural strength and toughness. This trend is observed for both systems with and without epoxy. A linear relation is observed between the composite properties and Z yarn content. The improvement by Z yarn content is more significant for the epoxy impregnated composites for both, flexural strength and toughness. Also here the advantage of impregnating the 3D fabric with epoxy is obvious, exhibiting much greater properties for the epoxy impregnated composite system. Indicating again the benefit of the 3D fabric mainly when apply as single whole unit.

It is also appears that the obtained values are relatively uniform showing fairly small deviation between the four tested specimens of the same composite set in all cases. This uniformity of the 3D fabric composite properties indicates the ability of producing 3D fabric TRC systems with repeatable properties, which important for application purposes.

These trends clearly show the reinforcing benefit of the yarns located at the Z direction of the fabric, when these yarns are of high modulus.

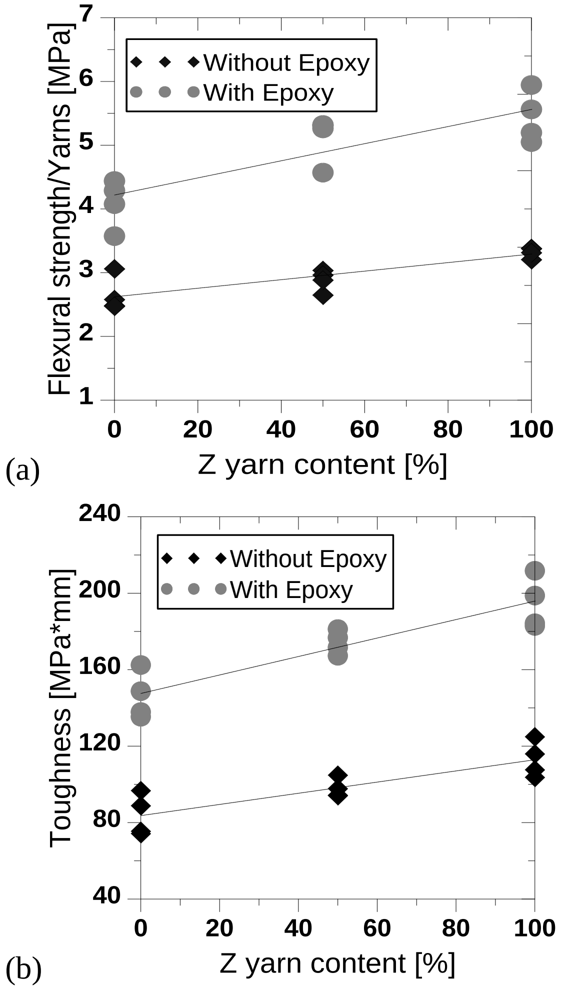


Figure 4: Flexural proprties vs. aramid Z yarn conten (a) flexural strength, (b) toughness, with and without epoxy

3.3 Main mechanisms

The improved mechanical performance of the composites with the 3D fabrics can be explained based on mechanical anchoring of the fabric within the cement matrix. Such mechanical anchoring can be developed by the penetration of the cement matrix into the opening of the fabric as presented in Figs. 5a, 5b. These images clearly show the penetrability of the cement matrix into the fabric opening and the strong embedment of the fabric in the matrix. Additionally the cement matrix can also penetrate in between the loops of the knitted fabric as observed in Fig. 5c, which provides stronger anchoring of the fabric in the cement matrix. This is the case in all fabric structures reinforced cement-based elements including 2D fabrics [1,3,4], however the presence of yarns along the Z direction can provide three dimensional anchoring, developing much stronger mechanical anchoring as compared with 2D fabric composite. This leads to the improved mechanical performance of the 3D fabric composites obtained here (Fig. 3).

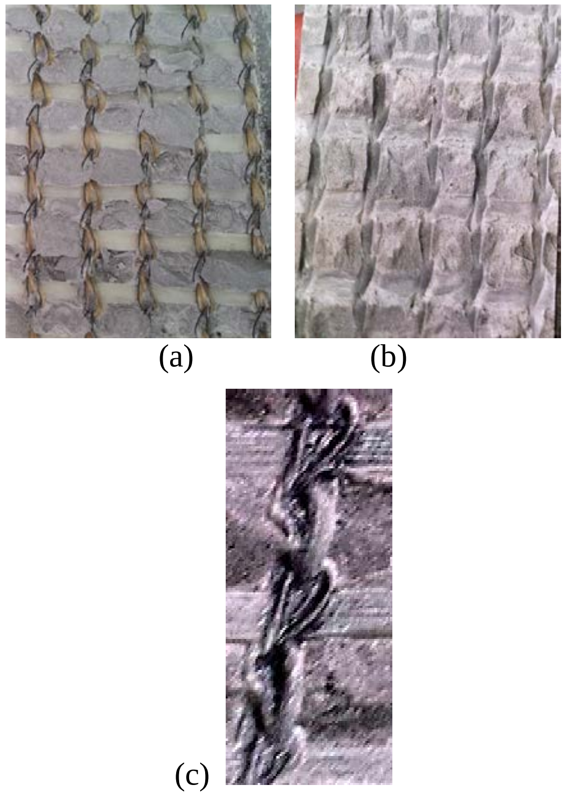


Figure 5: (a, b) Anchoring of the fabric within the cement matrix, a. the fabric itself, b. print of the fabric structure within the matrix, (c) anchoring of the loops in the matrix.

In knitted fabrics including the one used for this work, the yarns are connected together to produce the fabric structure by loops which provides strong connecting points at the fabric junctions; however such connection cannot completely hold all yarns, and therefor they can slide at list partly within the fabric structure. This is even more pronounce when the yarns are made of multifilament, as with such yarn form the filaments can freely slide against each other, especially those located at the core of the bundle far from the connecting loop. This situation of bundle and filament sliding, can also occur within the composite due to the difficulty of the cement particles to penetrate into the bundle filaments [1,4,5], this is more sever when the bundles are tightly hold by the loops of the knitted fabric [3]. However, if the yarns within the 3D fabric are impregnated with epoxy, such sliding of the individual filaments is impossible and the 3D fabric becomes one single unit, acting together. This can lead to extremely strong anchoring mechanism and significantly improvement in composite mechanical behavior as obtained here (Figs. 3a. 4).

3.4 Crack pattern and failure

The crack pattern of the 2D, 3D REF and 3D Ar100 composites with and without epoxy impregnation are presented in Figs 6-7.

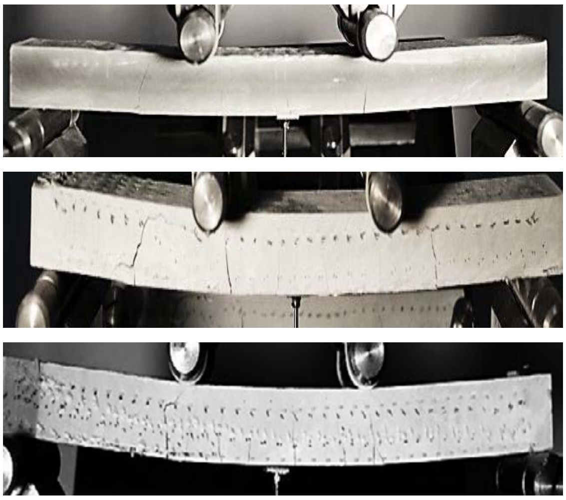

(a) (b) (c)

Figure 6: (a) 2D, (b) 3D REF and (c) 3D Ar100 composites without epoxy

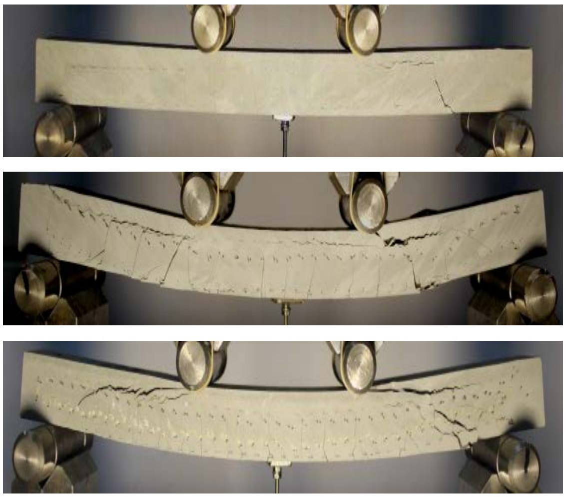

(a) (b) (c)

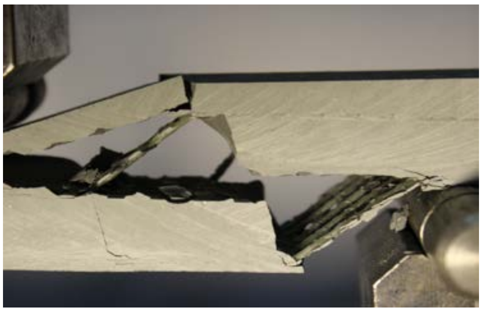
Figure 7: (a) 2D, (b) 3D REF and (c) 3D Ar100 composites with epoxy

Multiple cracking is clearly observed for the 3D fabric composites in both cases, with and without epoxy. However for the 2D fabric composite not such clear multiple cracking is seen. This suggests much better bonding, i.e., stronger mechanical anchoring, for the 3D fabric systems compared with the 2D fabric composite, leading to their improved mechanical properties. When comparing the systems with and without epoxy the crack development and pattern is somewhat different. For the composite without the epoxy (Fig. 6) in both 3D fabric cases with and without the aramid yarns, i.e., the 3D REF and 3D Ar100 composites, the cracks are developed from bottom to top at relatively straight path. This may suggest more likely bending type of failure for the 3D fabric composites without the epoxy. However when looking at the epoxy impregnated composites (Fig. 7), cracks are developed diagonally from bottom to the top surface up to the points of the applied loads, suggesting more likely shear failure mechanism. These observations suggest that different mechanisms are taking place depending on the stiffness and reinforcing efficiency of the 3D fabric. When the fabric is pre-impregnated with epoxy it behaves as one whole single unit within the composite. However for the non-impregnated epoxy 3D fabrics the bundles as well as filaments act, at least partly, separately, leading to low reinforcing efficiency and low load bearing capacity.

Fig. 8 presents the cracked composites at the end of testing with the 2D fabric and 3D Ar100 fabric impregnated with epoxy. The complete failure with a single wide crack is clearly observed for the 2D fabric composite. Also clear separation of the fabric from the matrix. i.e., delamination, is observed for this 2D fabric composite. This indicates low reinforcing efficiency of this fabric, and poor bonding between fabric and matrix. Contrary, for the 3D Ar100 composite with the aramid yarns along the thickness of the composite, multiple cracking is observed with damage at the bottom (tensile) zone of the composite. Not as sever separation and delamination between the 3D fabric and matrix is occurred at this case, as compared with the behavior of the 2D fabric composite. Note that in the case of the 3D fabric a deflection of about 18 mm was reached at the end of testing. Such failure behaviors indicating better reinforcing unit of the 3D fabric, i.e., better bonding and mechanical anchoring of the

3D fabric within the cement matrix. These failure mechanisms correlate well with the overall flexural behavior of the composites.

(a)



(b)

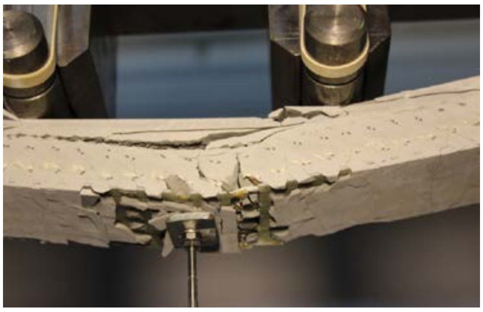


Figure 8: Failure mechanism of (a) 2D fabric composite and (b) 3D Ar100 composite at the end of testing.

4 CONCLUSIONS

This work studied cement-based composites reinforced with 3D fabric, mainly the influences involved with the yarns along the Z direction of the fabric, i.e., the thickness of the composite.

It was found that 3D fabrics are beneficial as reinforcement for cement-based composites compared with 2D fabrics. Low properties and delemination were obtained with the 2D fabric composites.

When the yarns along the Z direction are of high properties, such as aramid, they highly improve the strength and toughness of the cement-based composite. This improvement is more significant when the fabric was impregnated in epoxy, i.e., for stiff fabric.

The content of the high performance yarns along the Z direction was found to influence the properties of the composite, greater content leads to better performance. This influence was more pronounce when the fabric was first impregnated in epoxy.

It can be concluded that 3D fabrics can be beneficial as reinforcements for cement-based composites although the Z yarns are not along the direction of the applied loads. The Z yarns hold the whole fabric together leading to good mechanical anchoring. The mechanical anchoring can be improved when the bundles within the fabric are filled and glued with epoxy leading a reinforcement component that act as a single unit and therefore improved mechanical performance of the composite.

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