STRAIN HARDENING BEHAVIOR OF TEXTILE REINFORCED CONCRETE (TRC)

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Abstract

The current paper discusses several parameters that affect strain hardening behavior of Textile Reinforced Concrete (TRC) systems: fabric geometry, yarn nature (multifilament), and processing methods with relation to bonding mechanisms. When considering fabric geometry to reinforce TRC systems, the unique structure of the fabric can control bonding of by mechanical anchoring and therefore improving the overall mechanical behavior of the composite. Yarn nature in most fabrics for TRC applications is in a multifilament form, in such reinforcements, cement penetrability is a controlling factor to obtain high performance and strain hardening behavior. Controlling of cement penetrability in TRC systems can be in numerous ways, for example: by proper design of fabric geometry to govern loops or stitches size connecting the multifilament yarns into a fabric form; or by inserting fillers in between the filaments of the bundle prior to composite production, as well as processing methods such as using the pultrusion technique. These approaches can lead to improve bonding and therefore strain hardening behavior of the composite even when low modulus yarns are used such as PE or PP. However on the other hand, lack of cement penetrability can lead to significant low reinforcing efficiency of extremely high modulus fabrics such as carbon.

1. INTRODUCTION

Textile reinforced concrete (TRC) has emerged in recent years as an attractive cement composite which can provide numerous advantages for developing new types of thin sheet components for a variety of building systems [1-2]. Modern textile technology offers a wide flexibility in fabric production methods which enable controlling of fabric geometry, yarn geometry and orientation of yarns in the fabric in various directions, yarns material combinations as well as three-dimensional fabrics, providing reinforcement in the plane normal to the panel. These numerous options create a useful opportunity to tailor the fabric design to the specific needs of different cement-based composite products.

In many cases the basic unit of the textile fabric is usually a yarn, which is composed of an assembly of several hundred to several thousands of filaments with each having a diameter of up to several tens of microns. As the cement is composed of grains ranging in size from several microns to tens of microns these particles cannot easily penetrate in between the filaments of the strand. The potential penetrability of the cement particles into the bundle
spaces can also be affected by tightening effects induced by the junction points of the fabric. Therefore matrix penetration into multifilament yarns is a critical factor in TRC systems.

Researchers were reported that textiles could significantly improve the mechanical behavior of cement matrices under static and dynamic conditions [1-7]. In addition to the improved strength, these textile-reinforced concrete (TRC) can exhibit superior strain-hardening behavior [4]. Such improvement can be achieved with many types of yarn and even with low modulus of elasticity yarns [3].

Strain hardening behavior of TRC systems can be obtained and controlled by fabric geometry, yarn geometry, yarn nature, yarn materials, and the related bonding developed between matrix and fabric. In the current paper several of such parameters are discussed.

2. FABRIC GEOMETRY

Tensile behavior of cement-based composite reinforced with AR (Alkali Resistance) glass fabric (Textile Reinforced Concrete – TRC) compared with conventional GFRC (Glass Fiber Reinforced Concrete) containing short glass fibers produced by the spray process is presented in Fig.1 [8]. Compared with the conventional GFRC, superior tensile behavior in both strength and toughness is seen for the TRC system. This improvement in tensile behavior is about 1.5 folds, indicating the advantage of using continuous fibers in the form of fabrics (textiles) to obtain strain hardening behavior of cement-based elements. The structure of the fabric can improve bonding by mechanical anchoring of the fabric within the cement matrix due to penetrability of the matrix in between the opening of the fabric. Note that the GFRC are commercial samples and used for comparison with the fabric-composite prepared for this study.

The range of yarn types that can be used to produce fabrics for cement reinforcement is relatively high. In general, a high-strength, high-modulus fiber, such as glass, carbon, aramid and high density polyethylene (HDPE – Dynima, Spectra), will usually increase the strength and toughness of the cement composite, providing strain-hardening behavior. In low-modulus fiber, such as polypropylene (PP) and polyethylene (PE), the reinforcement enhances mainly the ductility of the cement composite, but not its strength, resulting in a strain softening or elastic-plastic behavior as presented in Fig.2 [3]. However with proper design of fabric geometry it is also possible to obtain strain hardening behavior when low modulus fabrics,
such as PE, are used to reinforce the TRC composite. Fig. 3a compares between the flexural behaviors of TRC systems and cement-based composite reinforced with continuous yarns, all made of low modulus, ~ 2 GPa, PE yarns in a form of monofilament. Positive effect induced by the fabric structure in the woven and the short weft knit PE fabrics is clearly observed, showing strain hardening behavior of the PE TRCs compared to the strain softening behavior of the composite with the straight PE yarns not in a fabric form. The improved performance is considerably high at large deflections. Note the difference in the yarn volume content at each composite system, 5.7% in the woven and the straight yarn compares to only 2% in the short weft knit fabric. The high performance with the strain hardening behavior of the TRCs compared to the low and strain softening behavior of the straight yarns can be accounted for by differences in geometrical characteristics of the reinforcing yarns: the yarns are in crimp geometry in the woven fabric, in relatively complex geometry, “zigzag” in the short weft knit fabric and straight in the continuous yarns composite. These differences in yarn geometry, affect the bond, especially mechanical anchoring, and as a result the overall flexural performance. Moreover, when short weft knitted fabrics are used; the reinforcing yarns are held tightly by the fabric structure, which apparently induces extremely strong anchoring effects. This enhanced bonding can result in the improved performance of the composite with the short weft knit fabric, leading to a strain hardening behavior with only 2% volume of low modulus fabric reinforcement.

Fig. 2: Flexural behavior of TRCs reinforced with high modulus (HDPE) and low modulus (PE) fabrics

As mentioned most of yarns used to produce fabrics for cement reinforcement are made of multifilament bundle. In such multifilament reinforcements the situation is relatively complex as the cement matrix consists of relatively large particles (~10 µm) that cannot easily penetrate the spaces between the bundle filaments, leading to reduced bonding and the overall behavior of the composite. When the reinforcing bundles are part of a knit fabric structure, the penetrability of the matrix is even lower than that of individual bundles, due to the presence of the bulky stitches themselves, as well as the tightening effect of the stitches, which strongly hold the filaments in the bundle and prevent spaces from being opened between them, reducing the bond. Such influences on composite flexural behavior are presented in Fig. 3b, which compares TRC reinforced with knit fabric made of multifilament high modulus PE (HDPE) yarns, of ~ 55 GPa, with a similar composite made of individual continuous HDPE yarns (not in a fabric form) [3]. The HDPE knit fabric shows a poor performance relative to the superior properties of its yarn (not in a fabric form). Moreover, when comparing the flexural behavior of the high modulus PE TRC (Fig. 3b) with the low modulus PE TRCs
(woven and short weft knit fabrics, Fig 3a), the composite with the HDPE fabric does not perform much better than the PE composites, in spite of the fact that the latter fabrics are made of low modulus yarns. Furthermore, in spite of the relatively low content of the reinforcing yarns, 2%, of the knitted short weft fabric, the flexural performance of this composite is quite similar to that of the HDPE fabric composite. This is completely different than the trend observed for the composite with the straight yarns of similar systems HDPE and PE (Fig.3b compared to Fig.3a).

Fig. 3:  Flexural behavior of composites reinforced with (a) monofilament low modulus (PE) with different geometry, woven and short weft fabrics compared to straight PE yarns not in a fabric form, (b) high modulus PE (HDPE) multifilament yarns, in a knit fabric form and as individual straight yarns.

When considering fabrics made of multifilament yarn as reinforcements for cement-based composites, cement penetrability is a controlling factor to obtain high performance and strain hardening behavior, therefore there is a need to improve cement penetrability in between the filaments of the bundle.

3. PENETRABILITY

Several ways can be considered in order to improve cement penetrability in TRC systems. One way can be by controlling the loops or stitches size connecting the yarns of the fabric. As mentioned the stitches can strongly hold and tight the filaments in the bundle and prevent spaces from being opened between them. Fig.4 compares the tensile behavior of TRCs made of similar the HDPE fabrics discussed above made with 2 mm or 4 mm loop size. The
influences by loop size are clear in this figure. The comparison shows significant higher strength of more than 20% for the 4 mm loop size fabric than that of the 2 mm loop size composite. This improvement in behavior is mainly at large strains providing significant strain hardening behavior. The improvement of composite performance with the larger bundle size is due to improve cement penetrability in between the reinforcing filaments [5].

Another way to improve the mechanical performance of multifilament TRC systems is to insert fillers in between the filaments of the bundle prior to composite production. These fillers can fill the empty spaces between the filaments of the bundle leading to better bonding (better stress transfer between inner filaments and cement matrix) and the overall behavior of the composite. Tensile behavior of TRCs reinforced with AR glass fabrics, with two different fillers: silica fume and polystyrene polymer, which remains in particle form at room temperature ($T_R$ is higher than room temperature, 100 °C), both with 200nm particle size is shown in Fig.5 [9]. The results are compared to a reference AR glass TRC system without any filler. The filler-treated composites showed improvement in tensile strength compared to the reference composite, due to better transfer of stresses from the matrix to the inner filaments, which improving the overall efficiency of the bundle and the mechanical performance of the composite.

Figure 4: Tensile behavior of composites reinforced with knitted fabrics having two loop sizes, 4 mm and 2 mm, made of high modulus HDPE multifilament yarns.

Figure 5: Tensile behavior of AR glass TRCs with silica fume and polymer fillers compared to similar TRC without fillers
4. PROCESSING

Penetrability of the cement matrix in between the bundle filaments can be influenced and controlled by production methods and processing of the composite. Two examples are presented here: one is improvement of cement penetrability and bonding by the pultrusion process [Fig.6] [6], and the second is by pressure applied on top of the TRC element at its fresh stage [Fig.7] [8].

![Diagram](image)

Figure 6: (a) Tensile response of TRC produced by the pultrusion and cast methods including crack opening during testing, (b and c) optical microscopy images of pultruded and cast composites, respectively.

Fig.6a compares the tensile behavior of two laminated TRCs one produced by the pultrusion method, in which the fabric impregnated and pass through a cement bath and the second produced by the cast method, in which the fabrics were hand laid up within the cement matrix. Both are reinforced with the same polypropylene (PP) fabrics made of multifilament yarns. Superior tensile behavior in both strength and toughness is seen for the PP fabric pultruded specimens compared with much poorer response of the cast specimens. The tensile strength of the PP pultruded composite is more than twice that of the cast composite. The improved cement penetrability in between the bundle filaments for the pultruded composite (Fig.6b) as compared to poorer penetrability in the case of the cast (Fig.6c) composite is clearly observed. Results of crack width vs. strains for the cast and the pultruded PP systems are also presented in Fig.6a. The width of the crack through the entire loading is significant larger for the cast system as compared with the pultruded system. These results and observations confirm the improved bonding of the PP fabric with the pultrusion process leading to tough and strong composite with strain hardening behavior.

Fig.7 compares pultruded laminated composites reinforced with multifilament AR glass fabrics, which exposed to two levels of pressure applied on top of the laminates at the fresh stage up to hardening of the composite. The figure clearly shows that the intensity of the pressure significantly influences the tensile response of the composite. When the processing pressure increases from 100 N (1.7 kPa) to 900 N (15 kPa) the tensile strength of the composite is improved by about 40%. However, the ductility of the low pressure composite (100 N) is much greater than that of the high pressure composite (900 N). Higher pressure leads to better bonding and cement penetrability in between the filaments of the bundle, resulting in enhanced tensile strength of the increased pressure composite, however less filaments are pulling out during loading offering lower ductility.
Based on the above results it can be concluded that improved bonding and cement penetrability in between the bundle filaments can lead to superior tensile response and strain hardening behavior even for low modulus fabric such as PP as observed in Fig.8a. The composite reinforced with low modulus PP fabric (~5 GPa) performed better than composite made of relatively high modulus (~70 GPa) due to improved cement penetrability and bonding by the pultrusion process. However on the other hand, low cement penetrability can lead to significant low reinforcing efficiency of extremely high modulus fabrics such as carbon as clearly observed in Fig.8b [7]. This figure presents the tensile behavior (under high speed condition) of TRC made of multifilament carbon fabric compared with the tensile response of the fabric itself not in cement matrix. Superior low performance is observed for the TRC as compared with the behavior of the fabric itself, due low penetrability of the cement matrix in between the carbon bundle (Fig.8c).

5. CONCLUSIONS AND SUMMARY

Bond in textile reinforced concrete composites is dependent on numerous mechanisms associated with the bonding of individual yarns as well as with the reinforcing fabric, both which can either lead to enhancement in bond due to anchoring effects, or reduction in bond
resulting from limitation in the penetration of the matrix into the fabric itself or into the spaces within the multifilament yarns. Several of these parameters that affect strain hardening behavior of Textile Reinforced Concrete (TRC) systems were discussed: fabric geometry, cement penetrability and processing methods.

The unique geometry of the fabric used to reinforce TRC systems can control the bonding of the composite by mechanical anchoring and therefore improves the overall mechanical behavior of the composite. Such mechanical anchoring can be due to special geometry of the yarn made up the fabric as well as fabric junction points, leading to strain hardening behavior even when low modulus yarns are used.

Most of fabrics for TRC applications are made of multifilament yarn, in such reinforcements, cement penetrability is a controlling factor to obtain high performance and strain hardening behavior. Several ways can be considered in order to improve cement penetrability in TRC systems, for example by enhancing the loops or stitches size connecting the multifilament yarns to a fabric form or by insert fillers in between the filaments of the bundle prior to composite production. Both ways improve bonding and stress transfer between filaments and matrix, leading to improvement in composite mechanical performance.

Two examples were presented here for influences induced by composite processing: one is improvement of cement penetrability by impregnation of fabrics in a cement bath using the pultrusion process and the second is improved bonding by a pressure applied on the TRC element at its fresh stage up to hardening. Both were affecting bonding and TRC mechanical behavior, leading to strain hardening behavior even when low modulus yarns were used.

In can be concluded that strong bonding either by fabric structure providing anchoring effects or by good cement penetrability can increase mechanical behavior of TRC systems, which can results in strain hardening behavior of the composite even when low modulus yarns are used such as PE or PP. However, low bonding and poor cement penetrability can lead to significant low reinforcing efficiency of extremely high modulus fabrics such as carbon.

REFERENCES