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Bond behavior of carbon fabric reinforced cementitious matrix (FRCM) composites considering matrix impregnation

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Abstract

This paper presents an investigation on the bond behavior of the carbon fabric-cementitious matrix interface within the fabric reinforced cementitious matrix (FRCM) composite. The embedded carbon yarn shows a complicated bond behavior due to stochastic and incomplete impregnation of the matrix and can be subdivided into the outer (impregnated) and inner (non-impregnated) parts. Pullout tests were carried out on the carbon FRCM composite aiming at examining the effect of matrix impregnation on the bond behavior between fabric and matrix. The test results show that pullout specimens with a 30 mm embedded length failed due to pure slippage of the carbon yarn, while the failure became the slippage and partial rupture of the carbon yarn for the specimens with longer
lengths. The impregnated filaments are estimated as about 30% of the total filaments within an embedded carbon yarn according to image processing and analysis results. Different bond slip relationships were assumed and evaluated for the outer and inner parts within an embedded carbon yarn based on pullout test results. The accuracy of the evaluated bond slip relationships was validated through a good agreement between experimental results and finite element modeling.

**Keywords:** Carbon fabric, Fiber/matrix bond, FRCM composite, Matrix impregnation, Bond behavior, Bond slip relationship.

**1. Introduction**

Fabric reinforced cementitious matrix (FRCM) composites, also termed as textile reinforced concrete (TRC) and textile reinforced mortar (TRM), have emerged as a promising and alternative option for constructing lightweight thin-walled structures and strengthening masonry or concrete structures [1]. The composites normally comprise one or more layers of dry fabric or textile embedded in a cementitious matrix. The fabric is made of fibers, such as glass, carbon, basalt, aramid and PBO fibers, while the cementitious matrix mainly refers to the finely-grained mortar that contains fine aggregate with a maximum size of about 1 mm. The dry fabric has a heterogeneous structure as there are hundreds or thousands of filaments in each yarn, where the term *dry* means that the yarn is not impregnated by resin. In comparison to conventional fiber reinforced polymer (FRP), the FRCM composites perform better in compatibility with substrate concrete, vapor permeability, ease in installation and performance at elevated temperature.

In comparison to the cementitious matrix, the FRCM composite normally shows improved tensile strength and ductility, which is influenced by the bond behavior between the fabric and matrix. The composite is normally employed to strengthen masonry or concrete structures. Potential applications involve flexural [2–7] and shear [6,8–11] strengthening of reinforced concrete (RC) beams,
confinement of RC column [12,13] and so on. One of the most common failure modes in strengthening systems with FRCM composites is associated with the fabric/matrix interface and featured by the slippage of the fabric through the matrix within the composite [14–18]. Hence, it is necessary to characterize the bond behavior at the fabric/matrix interface, which helps to understand the mechanical behavior of the composite and the corresponding strengthening systems.

To characterize the bond behavior between the fabric and matrix, shear bond tests [14–20] and pullout tests [21–33] have been carried out. The studies with performing shear bond tests involve a wide range of factors, including different types of the fabric and matrix, bond lengths of the fabric, the number of the fabric plies, compressive strength of substrate concrete, surface treatment of substrate concrete, substrate materials (masonry or concrete), test setups and so on. Besides, these studies also involve different aspects in the bond between the fabric and the matrix and the bond between the composite and the concrete in terms of the failure mode, the strain distribution in the fabric, the load-carrying capacity, the effective anchorage length, and the bond slip relationship [14–20]. The bond slip relationship can be obtained for the fabric/matrix interface based on test results from shear bond tests in which an FRCM composite is applied onto the substrate. Such a relationship somehow reproduced the global mechanical behavior of the shear bond joints, while the relationship that represented as a result of multiple mechanisms, such as bond behavior at the matrix/substrate interface and among different filaments as well as possible matrix cracking, did not distinguish individual affecting mechanisms. Another type of test method called pullout tests, in which fabric was gradually pulled out of the matrix, was also conducted with a focus on characterizing the bond behavior between fabric and matrix within the FRCM composite. The bond slip relationship could be extracted from pullout test results, while the multifilament fabric, at the same time, was idealized as a monolithic reinforcing bar [21,23,25–29,31–33]. Such a relationship is mainly dependent on the bond behavior between carbon fabric and the matrix. However, each yarn in the fabric itself exhibits heterogeneous
bond characteristics because of non-uniform and incomplete matrix impregnation, i.e., the filaments in each carbon yarn show variations in their bond behavior. Filaments in the outer layer of the yarn embedded in the matrix can receive matrix impregnation, leading to strong adhesion between filaments and matrix, while the core filaments are in no contact with the matrix and only friction exists among them. Consequently, there is a non-uniform normal stress profile within the cross-section of an embedded yarn and a particular failure mode called telescopic failure when pulling the fabric out of the matrix [22]. The telescopic failure means that the filaments within a yarn fail in a progressive manner with the failure propagating from the outermost to the core. Thus, taking the multifilament fabric as a monolithic bar can neither capture the telescopic failure mode nor account for variations in the bond behavior of different filaments with a yarn.

To address the varying bond behavior, some studies postulated that cement hydration products that discretely settled down on the surface of filaments should be responsible for the bond mechanism between the fabric and matrix and attempted to conceptualize these hydration products as cross-linkages [34,35]. A cross-linkage model was thereafter developed assuming that the number of cross-linkages gradually reduced from the outmost filaments to the core filaments within an embedded yarn. Furthermore, these discrete cross-linkages were lumped together and different free lengths were formed to denote varying bond behavior for different filaments [34,35]. Although the global pullout behavior and the non-uniform normal stress distribution can be simulated, the number of cross-linkages and different free lengths should be first assumed, and no interfacial slip could occur between filaments and matrix. In order to consider varying bond behavior within a yarn, the yarn was subdivided into multiple layers, and in some cases, each layer was further subdivided into several segments [36]. Although refined subdivision reflects the heterogeneous bond behavior of the yarn and allows to capture the telescopic failure, a higher amount of computational efforts is needed and difficulties in practical applications arise. To determine the respective bond slip relationship for each
layer or segment also constitutes a challenging task. Besides, it is difficult to determine the percentage of the impregnated filaments within a yarn, especially for the fabric with small filaments, such as carbon fabric.

The objective of this study is to investigate the bond behavior of carbon FRCM composites at the interface between carbon fabric and matrix considering the influence of matrix impregnation. Pullout tests were carried out on the composite specimens with various embedded lengths. The carbon yarns that were pulled out of the matrix after pullout tests were epoxy-impregnated and processed for obtaining clear sectional images from microscopic observations. An image processing and analysis technique was utilized on sectional images to evaluate the number of pullout filaments, which can be used to inversely evaluate the percentage of the impregnated part within an embedded carbon yarn.

To capture the effect of the matrix impregnation and consider the variations in the bond characteristics of the embedded carbon yarn, the yarn was subdivided into two parts, the outer part where the filaments were impregnated with matrix and the inner part in which the filaments were bare of the matrix. Consequently, two types of interfaces with different bond slip relationships were introduced, including the outer interface between the matrix and outer part and the inner interface between the outer and inner part. Bond parameters required to define these two different bond slip relationships were evaluated based on the experimental results obtained from the pullout tests. Finite element modeling was carried out to simulate pullout tests to examine force transfer mechanisms and the global pullout response of the carbon FRCM composites. Numerical results were then compared with experimental results to verify the accuracy of the evaluated bond slip relationships for different interfaces. In addition, the effects of key parameters on the pullout behavior were investigated by a parametric study using finite element modeling.
2. Experimental investigation

2.1. Raw materials

A bidirectional carbon fabric and a cementitious matrix were used to make the carbon FRCM composite in this study. The fabric comprised carbon yarns disposed in two orthogonal directions with all the warp yarns passing over one side of the weft yarns, as shown in Fig. 1. Each carbon yarn in both directions had 12000 filaments, and each filament had a diameter of 7 μm, according to the data given by the manufacturer. The carbon fabric had a mesh size of 6.49 mm × 5.00 mm, and the widths of the warp and weft yarns were 3.29 mm and 2.30 mm, respectively. There was no strong interlocking at the connection joints between warp and weft yarns as the warp yarns can be easily pulled away from the weft ones. As per GB/T 3362-2005[37], six tensile coupons made of carbon yarns in the warp direction were prepared and tested to obtain the tensile properties. The tensile strength and elastic modulus of the warp carbon yarns were 2077 MPa and 181 GPa, respectively.

The effect of matrix type on the carbon yarn-cementitious matrix has been studied. It was found that the pullout response curve was similar for all the pullout specimens despite the various matrices, indicating similar bond behavior of the carbon yarn in various cementitious matrices. In this study, therefore, a cementitious matrix with a water to cement ratio of 0.40 was chosen as an example. The quartz sand was used as aggregate with different sizes, including fine sand (0~0.5 mm) and medium sand (0.5~1.0 mm). The sand to cement ratio by weight was 1.0, while the weight ratio of the fine sand to the medium sand was 0.5. The aggregate had a maximum size of 1.0 mm, which helps better penetration of the matrix through the mesh of carbon fabric. Three matrix prisms with a dimension of 40 mm × 40 mm × 160 mm were cast and tested to determine the flexural and compressive strengths. As per ISO 679:2009 [38], three-point bending tests and compression tests were carried out on these prisms after 28 days’ curing. The obtained flexural and compressive strengths of the matrix are 6.3 MPa and 74.1 MPa, respectively.
Carbon FRCM composites comprised a layer of carbon fabric embedded in the cementitious matrix. A timber formwork of 500 mm × 300 mm × 10 mm was designed and made to cast the carbon FRCM composite panels of which the thickness can be controlled as 10 mm. The panels were manufactured in the following procedure. A first 5-mm thick layer of the fresh matrix was placed and leveled on the bottom timber plate. Then, a layer of carbon fabric was placed and slightly stretched on the first matrix layer. Finally, another cover layer of 5 mm thick matrix was applied on top of the fabric and leveled by a metallic trowel. Plastic wrap was applied to the top of the panels. The panels were demolded one day after casting and then cured in a moist chamber (100% relative humidity and a temperature of 20 °C). Before testing, the panels were taken out and processed to prepare relevant specimens for pullout tests.

2.2. Specimen preparation and test implementation

Up to now, there is no available standardized test method for characterizing the bond behavior of the FRCM composite. Two types of pullout tests can be found in the existing literature, including one-sided and double-sided pullout tests. In the case of one-sided pullout tests [22,23,26,28,31,32], a yarn was embedded in the matrix on one end, while the other end bare of the matrix was impregnated with epoxy resin for clamping. The axial load was applied to the yarn and transferred to the matrix through the interface between the yarn and matrix. As for the double-sided tests that were developed in [21,25,27], both sides of the fabric were symmetrically or unsymmetrically embedded in the matrix, and the load was transferred to the fabric from the matrix through the interface between the fabric and matrix. The advantage of the unsymmetrical configuration is that a longer embedment length can provide sufficiently strong anchorage while a short embedment is being investigated. The double-sided tests were herein employed to characterize the bond behavior between the carbon fabric and matrix.
Fig. 2 shows the specimen configuration for double-sided tests. The prismatic pullout specimens (200 mm × 30 mm × 10 mm) comprised one layer of carbon fabric. Three carbon yarns were included in each pullout specimen along the warp direction. The unsymmetrical configuration as shown in Fig. 2(a) was used in this study, which was accomplished by an upper cut that intercepted the middle carbon yarn to be examined and a pair of cuts that only kept the middle carbon yarn intact. Each specimen comprised two matrix blocks connected by the examined middle carbon yarn. The upper block was termed as the bond block with a shorter embedded length ($L_b$), while the lower block as the anchoring block with a longer anchoring length ($L_a$) that provides sufficiently strong anchorage. Thus, failure is expected to first occur in the bond block. Three embedded lengths of 30, 50 and 70 mm were considered, and the corresponding anchoring lengths were 170, 150 and 130 mm, respectively. These embedded lengths were chosen so that different failure modes can be observed for the pullout specimens, which will be illustrated in section 2.3. The specimens were labeled according to the embedded length. For instance, L30 means the specimens have a 30 mm long embedded length.

As shown in Fig. 2, the specimen was clamped on both the top end above the upper cut and the bottom end of the anchoring block. Both ends of the specimens were reinforced by gluing CFRP (carbon fiber reinforced polymer) sheets to both sides of the matrix to prevent local damage caused by clamping. The pullout tests were carried out under displacement control by a 10 kN universal electronic testing machine, and the loading rate was 0.2 mm/min. The applied force was measured by a loading cell with an accuracy of 1 N, while the opening displacement between the bond block and the anchorage block, also called the pullout displacement, was measured by configuring two clip-on extensometers with a gauge length of 50 mm and an accuracy of 0.001 mm. The pullout displacement was taken as the average of the measured displacements by two extensometers. The position at the opening was defined as the loaded end of the embedded length and anchorage length. The pullout
displacement was equal to the sum of the slips at the loaded end of the embedded and anchoring lengths.

2.3. Test results

It is beneficial to clarify the heterogeneous features existed in the carbon yarn-matrix interface prior to interpreting failure modes observed in pullout tests. The fabric used in FRCM composite is normally in the dry state, which means no impregnation of epoxy is applied to the fabric. As a well-known fact, the fabric comprising many filaments cannot be fully impregnated by the inorganic matrix, like the cementitious matrix, due to smaller spacing between filaments compared to the grain size of the matrix. As a result, all filaments within a single carbon yarn have different bond properties, depending on their location in the cross-section. For filaments in the outer part of the yarn, they are fully embedded in the matrix, and the load is transferred due to the adhesion between filaments and matrix. As for filaments in the inner part, no contact with the matrix is gained and thus the load transfer is due to friction among filaments. Fig. 3 shows an SEM (Scanning Electronic Microscope) image and the idealized cross-section of an embedded carbon yarn. Filaments that show decreased bond property starting from the extremity towards the core of the carbon yarn and, for simplicity, can be grouped into either the outer or the inner parts. For brevity, the interfaces between the outer part and matrix and between the inner part and the outer part are termed as the outer interface and the inner interface, respectively.

Fig. 4 shows the failure mode observed in the pullout tests with 30 mm embedded length. In general, all the specimens exhibited a similar failure mode which is the slippage of the carbon yarn through the matrix at first sight. By performing a careful observation, a pronounced difference can be found in the failure mode for specimens with different embedded lengths. Fig. 5 presents a schematic illustration of different failure modes observed in the pullout tests, including pure slippage of the carbon yarn and slippage and partial rupture of the carbon yarn. The specimens with a 30 mm
embedment length failed by pure slippage of the carbon yarn through the matrix. As for the longer lengths (50 mm and 70 mm), the failure was characterized by slippage of the inner part and tensile rupture of the outer part within a single carbon yarn. This is because filaments in the outer part show a strong adhesion with the matrix, leading to higher normal tensile stress compared to the inner filaments and thus the occurrence of tensile failure of the outer part.

Fig. 6 presents the applied force ($P$) versus the pullout displacement ($u$) curves (hereafter called pullout curves or $P$–$u$ curves) obtained from pullout tests. As can be seen, a similar overall tendency is exhibited in these curves, characterized by an ascending portion up to the peak and a post-peak softening behavior followed by a slowly descending portion. The slope of the ascending portion is similar among all specimens with different embedment lengths, as it is mainly related to the bond activated on the outer interface. However, although the post-peak softening behavior and the horizontal portion are similar for various embedment lengths, the underlying mechanisms are quite different. In the case of 30 mm embedded length, the reduction in the applied force after the peak is caused by the degradation in the bond of the outer interface. Whilst the post-peak decreasing portion is due to the progressive rupture of filaments in the outer part of the carbon yarn for longer embedded lengths (50 mm and 70 mm). As for the slowly descending portion in $P$–$u$ curves, it is due to the presence of friction on the outer interface for 30 mm embedded length, while for the longer embedded lengths the reason becomes the friction on the inner interface after breakage of the outer part. The effect of the friction between matrix and fiber on the maximum force has been discussed [39], indicating that the friction contributes to an increase in the maximum force above the debonding force. While in the carbon fabric-matrix system, there are two different interfaces on which the friction can occur, and the effects of the friction on the peak force are complex, which will be explained below. Besides, the peak force rises with increasing embedded length. The peak force increases rapidly for embedded length increasing from 30 mm to 50 mm, while a smaller increase in the peak force is
found for a further increment in embedded length. When pullout specimens show the failure by the slippage of the whole carbon yarn, the peak pullout force is related to the bond behavior of the outer interface and increases significantly with longer embedded length. As for specimens exhibited the slippage of the carbon yarn with partial rupture, the peak pullout force is related to the tensile capacity of the outer part and the force transferred through the inner interface. The force transferred is less effective through the inner interface than the outer interface, so the peak force goes up at a decreasing rate for a further increment in the embedded length.

3. Discussions

3.1. Estimation of the outer part cross-sectional area within an embedded carbon yarn

As previously described, filaments within a single yarn can be grouped into the outer and inner parts due to incomplete impregnation of the matrix. A problem arises from the estimation of the cross-sectional area of the outer part within a single embedded carbon yarn, which means how much percentage is the impregnated filaments by the matrix compared to the total number of the filaments. According to the SEM image shown in Fig. 3, it is hard to accurately differentiate the filaments between the outer and inner parts. Thus, an approach was proposed to estimate the number of the filaments pulled out from the matrix, which was equal to the total number of filaments subtracted by the number of the filaments remained in the matrix after pullout tests.

The examined carbon yarn was pulled out from the matrix after pullout tests, followed by impregnating using a two-component epoxy resin. Samples were prepared for microscopic observation by cutting the impregnated carbon yarn into pieces at the free end which is close to the upper cut in the pullout specimens. To investigate the variations in the number of the pullout filaments along the embedded length, the examined carbon yarn collected from one specimen with a 70 mm embedded length was processed, and two samples were collected at the free end and the loaded end
of the embedded length. The cross-section of the samples was carefully ground and polished to remove the possible scratches and help acquire high-quality images. Afterward, the samples were observed by an optical microscope, and the cross-sectional images were acquired. As the viewing field of the microscope is limited, the cross-section of each sample should be subdivided into several areas. Afterward, image processing was carried out with the NIT ImageJ software to analyze the number of the filaments pulled out of the matrix. Fig. 7 illustrates the image processing procedure involving original image, contrast enhancement, binarization and counting. As can be seen in Fig. 7(d), black spots represent the filaments, of which the number can be analyzed.

Fig. 8 shows the number of pullout filaments for different embedment lengths and the different locations within one embedded carbon yarn. For comparison purposes, the number of filaments in one as-received carbon yarn (i.e. 12000) is also plotted in Fig. 8. For specimens with a 30 mm embedded length, the number of pullout filaments is close to that of the as-received yarn, indicating almost all the filaments were pulled out from the matrix after pullout tests. As for longer embedded lengths, the number of pullout filaments is almost equal, which means the equal number of filaments left in the matrix due to the partial rupture of the carbon yarn. No significant difference is found in the number of pullout filaments at different locations according to Fig. 8(b). The image processing and analysis results are consistent with the observed failure modes in the pullout tests. As the remained filaments in the matrix reflect the strong bond between the filaments and matrix, these filaments belong to the outer part within an embedded carbon yarn. The number of remained filaments is equal for embedded lengths of 50 mm and 70 mm, which means the number of filaments subjected to tensile failure equals, and thus this number can be used to indicate the number of filaments within the outer part. Based on the result obtained from image processing and analysis, the number of filaments in the outer part can be estimated at around 3600, which accounts for 30% of the total cross-sectional area of one carbon yarn. In other words, the percentage of impregnated filaments is about
30% of all filaments within an embedded carbon yarn. It should be noted that the adopted procedure of determining the number of the impregnated filaments pertains to the case in which the embedded length is sufficiently long so that all the filaments within the outer part are broken and left in the matrix after pullout tests.

### 3.2. Evaluation of the bond slip relationship for the outer and inner interface

#### 3.2.1. Description of the interfacial issue of an embedded carbon yarn

As each carbon yarn has many filaments, accurate modeling of the bond behavior of the whole carbon yarn in the matrix should take into account the different bond behavior of each filament and the interaction among them. It may cause much computational effort and become extremely difficult in practical use, such as modeling the mechanical behavior of FRCM strengthening systems. Besides, to accurately determine the bond behavior of each filament remains a challenging task. Since the difference in the bond behavior of the filaments is mainly associated with matrix impregnation, an embedded carbon yarn can be at least subdivided into two parts. According to an idealized cross-section of the embedded carbon yarn as shown in Fig. 3(b), the carbon yarn was simplified as the outer and inner parts, and two types of interfaces were introduced. By doing this, the computational effort in modeling the overall bond behavior of the whole yarn can be reduced, and the different bond behavior caused by the matrix impregnation can be captured. Furthermore, it is also more practical to evaluate the bond behavior of different parts within the yarn rather than that of each filament.

As shown in Fig. 3(b), the inner part is located in the core of the cross-section of the carbon yarn and connected to the outer parts through the inner interface, while the outer parts encompass the inner part and are connected to the matrix through the outer interface. The cross-section of the embedded carbon yarn is assumed as a rectangular shape. The cross-sectional area of the outer part and the inner
part can be estimated based on the image processing and analysis results. Fig. 9 shows a diagram of the force equilibrium of a small segment dx of an embedded carbon yarn in the matrix.

As there are two types of interfaces, the bond behavior of the embedded carbon yarn can be represented by a set of two interfacial governing equations. According to Fig. 9, this set of equations can be established as,

\[
\frac{dP_{\text{out}}}{dx} = 2(\tau_{\text{out}} - \tau_{\text{in}})c \tag{1a}
\]

\[
\frac{dP_{\text{in}}}{dx} = 2\tau_{\text{in}}c \tag{1b}
\]

where \(P_{\text{out}}\) and \(P_{\text{in}}\) denote the tensile force carried by the outer part and the inner part, respectively; \(\tau_{\text{out}}\) and \(\tau_{\text{in}}\) indicate the bond stress at the outer interface and the inner interface, respectively; \(c\) is the width of the carbon yarn.

With substituting the linear tensile behavior of the carbon yarn and geometric equations, Eq.1 can be re-written as follows.

\[
\frac{d^2s_{\text{out}}}{dx^2} - \frac{2(\tau_{\text{out}} - \tau_{\text{in}})c}{EA_{\text{out}}} = 0 \tag{2a}
\]

\[
\frac{d^2s_{\text{in}}}{dx^2} - \frac{2\tau_{\text{in}}c}{EA_{\text{in}}} = 0 \tag{2b}
\]

where \(s_{\text{out}}\) is the slip of the outer part relative to the matrix and \(s_{\text{in}}\) is the slip of the inner part relative to the outer part; \(E\) denotes Young’s modulus of the carbon yarn; \(A_{\text{out}}\) and \(A_{\text{in}}\) are the cross-sectional area of the outer part and the inner part, respectively.
As can be seen in Fig. 9, the boundary conditions can be represented by the strain at the free and loaded end of the carbon yarn. The strain of the carbon yarn at the free end is identically equal to zero for the embedded and anchorage lengths, whilst the loaded end strain of the embedded length equals the loaded end strain of the anchoring length.

To solve the interfacial governing equations, bond slip relationships of the outer and inner interfaces are required. When determining the bond slip relationship, different bond mechanisms should be considered for different interfaces. The filaments in the outer part are stressed due to the adhesion at the interface between the filaments and matrix. According to the previous study [33], a trilinear bond slip relationship can be used to represent the interface between the yarn and matrix. Fig. 10(a) shows the trilinear bond slip relationship for the outer interface, which includes an ascending branch and a descending branch followed by a horizontal branch. These three branches indicate the elastic, debonding and friction states, respectively.

As for the filaments in the inner part, the bond is due to the presence of friction. It is commonly known that friction is the force that resists the relative sliding of two objects in contact. The static friction occurs when these objects are kept stationary, and the dynamic friction develops if one object is sliding over another. The static friction force is marginally higher than the dynamic friction force. Considering the presence of friction, constant bond stress can be assumed for the bond slip relationship of the inner interface. During the pullout process, however, the inner part becomes more compact due to the Poisson effect of carbon filaments and the contraction of free space between the filaments, and the exiting pressure normal to the inner interface is reduced. Thus, bond slip relationship featured by a descending behavior, as shown in Fig. 10(b) can be assumed for the inner interface between outer and inner parts.
3.2.2. Evaluation of the bond parameters for the outer interface

After choosing different bond slip relationships for different interfaces, a problem arises from how to determine the necessary bond parameters involved in these relationships. In pullout tests with a small embedded length (30 mm), specimens failed by pure slippage of the whole carbon yarn, which indicates the overall pullout behavior of the specimens was controlled by the interfacial bond between the outer part and the matrix. The test results obtained from pullout tests with 30 mm embedded length can be used to evaluate the bond parameters in the trilinear bond slip relationship for the outer interface. As it is not easy to solve the interfacial problem involving multiple interfaces, the inner interface was neglected when evaluating the outer interface. Afterward, the bond behavior of the carbon yarn can be simplified as one governing equation with respect to the outer interface, as expressed by Eq. (3).

\[ \frac{d^2 s_{\text{out}}}{dx^2} - \frac{2\tau_{\text{out}}C}{EA} = 0 \]

where \( A \) is the cross-sectional area of the whole carbon yarn.

By introducing the boundary conditions and the trilinear bond slip relationship into Eq. (3), it is possible to derive the analytical solution of Eq. (3) and thus the overall pullout curve. The compatibility condition that the loaded end strain is equal for the embedded and anchorage lengths was employed in analytical derivation.

As the trilinear bond slip relationship is a piecewise function, it has different formulations depending on the magnitude of the slip. The trilinear relationship was used in some studies [26,28,32,33] with respect to one-sided pullout tests, and the corresponding overall pullout behavior has been derived based on the possible interfacial bond stress distributions, namely interfacial stress states. Similarly, the analytical expressions of the \( P-u \) curve can be obtained for the double-sided tests when using the
trilinear bond slip relationship, based on the possible interfacial states along the embedded and anchoring lengths. The analytical expressions of the $P-u$ curve for double-sided pullout tests can be referred to in Appendix A.

The bond parameters of the trilinear bond slip relationship can be evaluated by comparing the above analytical solution to the experimental $P-u$ curve. The evaluated bond parameters of the trilinear bond slip relationship for the outer interface are $k_1 = 24.96$ N/mm$^3$, $k_2 = 1.55$ N/mm$^3$, $\tau_{\text{max}} = 1.38$ MPa and $\tau_0 = 0.23$ MPa, respectively.

### 3.2.3. Evaluation of the bond parameters for the inner interface

As for the inner interface, two bond parameters, $\tau_{\text{in,\,max}}$ and $k_{\text{in}}$ are required to determine the corresponding bond slip relationship. As previously described, the pullout specimens failed due to slippage and partial rupture of the carbon yarn for embedded lengths of 50 mm and 70 mm. After the breakage of the outer part, the applied force was carried by the inner part through the bond between the outer and inner parts. Thus, the experimental results of these specimens were used to evaluate the bond parameters for the inner interface.

The interfacial governing equation of the inner interface is expressed by Eq. (2b). With inserting the bond slip relationship of the inner interface, the relationship between the pullout force and the slip at the loaded end can be derived respectively. The analytical expressions of the $P-u$ curve for the inner part can be referred to in Appendix B.

The pullout displacement after breakage of the outer part can be treated as the sum of the loaded end slip of both the embedded length and the anchoring lengths. Combining Eq. (B.1) with Eq. (B.2), the $P-u$ curve after the breakage of the outer part can be established and then compared with the experimental results in order to evaluate the bond parameters. Based on the test result obtained with
50 mm and 70 mm embedded length, the evaluated bond parameters of the bond slip relationship for
the inner interface are $k_{in} = 0.12 \text{ N/mm}^3$ and $\tau_{in,max} = 0.60 \text{ MPa}$, respectively.

3.3. Numerical modeling of pullout tests

3.3.1. Finite element model

In order to reproduce the pullout behavior of carbon fabric in the cementitious matrix and verify the
accuracy of the bond slip relationships evaluated for the outer and inner interfaces, a nonlinear finite
element (FE) analysis was carried out with a commercial Diana 10.3 package. The numerical
modeling results were then compared to the experimental results obtained from pullout tests.

FE models of pullout specimens were developed using the principle of symmetry. The model included
exclusively the examined middle carbon yarn that connected the bond block and anchoring block,
while the other longitudinal and transverse carbon yarns were neglected. The examined carbon yarn
was divided into the outer and inner parts, and the respective cross-sectional area can be obtained
from the image processing and analysis. The outer and inner interfaces were modeling using zero-
thickness interface elements. Besides, a zero-thickness layer of interface elements was defined
between the matrix at the opening of pullout specimens in order to connect the bond and anchorage
blocks. The numerical model had the embedded and anchorage lengths that equal those of the pullout
specimens. Based on the adopted test setup, the clamped side of the anchoring block was fixed in two
perpendicular directions. A displacement-controlled analysis was carried out by applying the
prescribed displacement to the end of the matrix of the bond block.

The plane stress hypothesis was applied assuming that the stress condition across the specimen width
is uniform. Four-node quadratic plane stress elements were used to model the cementitious matrix
and the outer and inner parts of the carbon yarn. The material behavior of the matrix in tension was
assumed linearly elastic, as the tensile stress in the matrix was under the tensile strength and no tensile
cracks occurred. As can be seen from tensile tests performed on the plain carbon yarns, these yarns
show a linearly elastic behavior until the brittle failure featured by a full reduction in tensile stress after the ultimate tensile strength. However, while the carbon yarn is embedded in the matrix, non-uniform distribution in the tensile stress can be developed, as filaments within the yarn show various bond characteristics. Consequently, the filaments would fail progressively due to the non-uniform distribution of the tensile stress, as shown in Fig. 11(a), which is grouped as the outer part of the carbon yarn. The tensile strength of the embedded carbon yarn should be lower than that of the plain carbon yarn, as the progressive failure cannot mobilize all filaments of the yarn simultaneously. The effective tensile strength of the embedded yarn is defined as $f_e$, while it is $f_u$ for the plain yarn. A strength factor, $\beta$, defined as the ratio of $f_e$ to $f_u$ is used to consider the reduced strength of the embedded yarn. The effective tensile strength of the embedded carbon yarn can be estimated by the difference between the peak pullout force and the residual force after progressive failure. Based on the test results of specimens with 50 mm and 70 mm embedded length, a value factor of 0.7 is suggested for $\beta$. To represent the progressive failure, a tension softening behavior can be defined for the embedded carbon yarn, in which the post-peak tensile stress declines gradually, as shown in Fig. 11(b). Such a softening behavior can also be assumed for the fiber reinforced polymer that exhibits the progressive failure [40,41]. As can be seen in Fig. 11(b), the tension softening behavior can be described by fracture energy, $G_f$, that is defined as the area under the softening part of the stress-strain curve. Different fracture energies in the range of 0 to 1000 N/mm were used in FE modeling in order to investigate the effects on the pullout behavior. When $G_f$ is zero, the carbon yarn is reduced to be a pure brittle material.

In addition to the matrix and carbon yarn, the material behavior should be defined for different interfaces involved. The interfacial discrete cracking law with null tensile strength was defined at the interface elements connecting the bond and anchoring blocks. Two sets of interface elements were employed to model the interfacial bond at the outer and inner interfaces, respectively. The evaluated
bond slip relationships for different interfaces according to Section 3.2 were assigned to these interface elements.

3.3.2. Comparison between experimental and numerical results

Numerical results obtained from FE modeling were compared with the experimental results. Fig. 12 compares the $P-u$ curves obtained from experiments and FE modeling for specimens with a 30 mm embedded length. As for 30 mm embedded length, specimens exhibit a failure mode characterized by the slippage of the carbon yarn, and thus the maximum pullout force is due to the transferred force that the outer interface can bear. Hence, the pullout behavior of the specimens is governed by the bond behavior of the outer interface. Since there is no tensile failure observed for all filaments within the embedded carbon yarn, the pullout behavior would not be affected by the fracture energy defined for the yarn. As can be seen in Fig. 12, a good agreement can be achieved between experimental and numerical results, suggesting that the evaluated bond slip relationship for the outer interface is appropriate.

As for longer embedded lengths ($\geq 50$ mm), the specimens show a similar failure mode, i.e. slippage and partial rupture of the embedded carbon yarn. The fracture energy of the carbon yarn can influence the pullout behavior, which is illustrated by a comparison between experimental and numerical results for different fracture energies. Fig. 13 compares the $P-u$ curves obtained from experiments and FE modeling for specimens with 70 mm embedded length. Various values of fracture energy in defining the tensile softening behavior of carbon fabric were considered, as shown in Fig. 13. There are some discrepancies in the post-peak branch of simulated $P-u$ curves. The discrepancies were caused by the different fracture energies used in the FE modeling. Once the tensile strength is reached for filaments in the outer part of the carbon yarn, these filaments start to fail in a progressive manner. According to the defined tension softening behavior of carbon yarn, if $G_f$ is higher, the tensile stress descends more slowly, which means the progressive failure phenomenon is more pronounced. Therefore, the
simulated $P-u$ curve shows a milder descending behavior after the peak for higher fracture energy. The fracture energy mainly affects the post-peak descending branch of the $P-u$ curve, while the pre-peak ascending branch and the last slowly descending branch are dependent on the interfacial behavior of the outer and inner interfaces, respectively. It is indicated that the fracture energy of 600 N/mm for the embedded carbon yarn can provide the best simulation of the whole experimental $P-u$ curves. Except for the post-peak descending branch of the simulated curves, a reasonable agreement can be seen between experimental and numerical results, indicating the accuracy of the evaluated bond slip relationships for outer and inner interfaces.

As FE modeling with $G_f = 600$ N/mm can provide the best prediction of the $P-u$ curve, the corresponding results were extracted to illustrate variations in the tensile force carried in the outer and inner part and the bond stress distribution along different interfaces during the pullout process. Fig. 14 shows the tensile forces at the loaded end of the outer and inner parts of the carbon yarn. The tensile force of the outer part is equal to the difference in the forces transferred through the outer interface and inner interface, while the tensile force of the inner part equals the force transferred solely through the inner interface. In the case of small pullout displacements, the tensile force at the loaded end of the inner part is higher than that of the outer part. According to the defined material behavior of the inner interface, the maximum bond stress can be reached once the non-zero slip occurs. Hence, a part of the force transferred from the outer interface can be effectively transferred to the inner interface for small pullout displacements. When the maximum force that the inner interface can bear is reached, the force carried by the inner part starts to decrease. With increasing pullout displacement, the tensile force of the outer part becomes higher until the tensile capacity is reached. Afterward, progressive failure appears for the outer part, and thus the tensile force of the outer part experiences a gradual reduction. After the tensile failure of the outer part, the pullout behavior of the specimen is
controlled by the inner interface and the inner part, indicated by the overlap of the $P-u$ curves of the whole carbon yarn and the inner part.

Fig. 15 shows the simulated bond stress distribution at the outer and inner interfaces for the embedded carbon yarn. For the outer interface, debonding initiates from the loaded end and propagates towards the free end for the anchorage and embedded length of the carbon yarn. As the anchorage length is sufficiently long, the bond stress at the free end is equal to zero due to the null slip, and two interface stress states (elastic and elastic-debonding states) appear during the pullout process of the carbon yarn. While for the embedded length, the multiple interface stress states can be developed with increasing pullout displacement, including the elastic, elastic-debonding, debonding, debonding-friction and friction states. The maximum pullout force is reached when the outer interface on the embedded length side is in the debonding state. As for the inner interface, the maximum bond stress occurs firstly at the loaded end of the embedded length and shifts to the free end. Afterward, a quasi-uniform distribution is developed along the inner interface on the embedded length side. This is due to the defined material behavior for the inner interface, in which the bond stress descends slightly with increasing the slip after the origin.

3.3.3. Parametric study on the effects of matrix impregnation and embedded length

Based on the developed FE model, a parametric study was conducted to investigate the effects of matrix impregnation and embedded length on the pullout behavior of the carbon fabric within the FRCM composite. The degree of matrix impregnation was denoted by $\beta_m$, which is equal to the ratio of outer part cross-sectional area to total cross-sectional area in percentage. It is possible to achieve high $\beta_m$ by using the matrix containing fine filling particles, such as micro- and nano-silica fume as well as nano-clay [42,43]. Besides, it is also practical to increase $\beta_m$ by changing the size of the yarn and the type of filament. Provided that the physical impregnation depth is the same, $\beta_m$ can be increased with decreasing the size of the yarn. If the size of the yarn keeps the same, the less the
filament prevents matrix impregnation, the larger the outer part becomes. It is worth mentioning that if the carbon yarn is very thin or contains only a few filaments, then the uniform full matrix impregnation can be achieved for the yarn, and thus the whole yarn can fulfill the tensile strength of all the filaments.

Provided there is a non-uniform matrix impregnation within the outer part of the carbon yarn, the filaments within the outer part are supposed to exhibit varying bond property due to non-uniform matrix impregnation. Therefore, the outer part shows a variant normal stress distribution during loading and starts to fail once the highest stress exceeds the strength of the filament. A simplified linear distribution is assumed for the tensile stress of the carbon yarn at the beginning of the breakage of the outer part as shown in Fig. 16. \( \beta_t \) is the ratio of the effective tensile strength of the outer part to the tensile strength of the plain carbon yarn. The actual area of the carbon yarn is normalized as 1.0, and the outer and inner part has a normalized area of \( \beta_m \) and 1-\( \beta_m \), respectively. In the present modeling strategy, the linear stress distribution within the outer part is approximated by constant equivalent stress, while the effective tensile strength \( f_e \) is defined as the strength corresponding to the beginning of the breakage of the outer part. Thus, \( \beta_t \) can be calculated by Eq. (4).

\[
\beta_t = \frac{f_e}{f_u} = \frac{f_u + \sigma_u}{2f_u} = \frac{1}{2} + \frac{\sigma_u}{2f_u} \geq 0.5
\] (4)

where \( \sigma_u \) is the tensile stress of the filament with no matrix impregnation when the outermost filament of the outer part reaches its tensile strength, \( f_u \). Therefore, \( \beta_t \) reflects the uniformity of the tensile stress distributed in the outer part. It seems that \( \beta_t \) is always larger than 0.5. In the present study, \( \beta_m \) can be taken as 0.3 based on the image processing and analysis results, while \( \beta_t \) equals 0.7.

FE modeling was performed to investigate the effects of \( \beta_m \) and \( \beta_t \) on the pullout behavior of the FRCM composite. \( \beta_m \) is fixed when analyzing \( \beta_t \), and vice versa. Fig. 17 shows the effect of \( \beta_m \) on the \( P-u \) curve of pullout specimens with an embedded length of 70 mm. The results show that the
maximum pullout force increases for $\beta_m$ increasing from 0.3 to 0.5, while a further increment does not increase the maximum pullout force. Besides, with increasing $\beta_m$ above 0.5, the failure mode changes from the slippage and partial rupture of the carbon yarn to the slippage of the whole carbon yarn.

Fig. 18 shows the effect of $\beta_t$ on the $P-u$ curve of pullout specimens with an embedded length of 70 mm. The results show that there is an increase in the maximum pullout force as $\beta_t$ is increased. The specimen behavior shows a more ductile behavior before the peak force for a larger $\beta_t$, though the same failure featured by the slippage and partial rupture of the carbon yarn takes place. This is due to that the $P-u$ curve before the peak is dominated by the outer interface. The higher the transferred force at the outer interface, the more ductile behavior (smaller increase in $P$ with a larger increase in $u$) is. Higher $\beta_t$ which means a larger tensile capacity of the outer part allows the force transferred at the outer interface to achieve a higher level and thus the more ductile pullout behavior is caused.

When analyzing the effect of the embedded length, the actual conditions of $\beta_t$ and $\beta_m$ were adopted in FE modeling, i.e. $\beta_t = 0.7$ and $\beta_m = 0.3$. Fig. 19 shows the effect of the embedded length on the $P-u$ curves. There is a pronounced increase in the maximum pullout force for the embedded length increasing from 70 mm to 100 mm, while no increase is seen for a further increment of 50 mm in the embedded length. In addition, the ductility of the specimen is improved with increasing the embedded length. Note that for 150 mm long embedded length, the applied force increases up the peak with displacement and then decreases, which is due to the rupture of the outer part; then the force increases again until another peak, which is due to the fact that after breakage of the outer part, the inner interface can still transfer the force to the inner part.

4. Conclusions

This paper presents an investigation on the bond behavior between fabric and matrix within the carbon FRCM composites with an aim at clarifying the effects of matrix impregnation. Double-sided pullout tests were performed on the embedded carbon fabric in the cementitious matrix. The degree of matrix
Impregnation was thereafter evaluated by analyzing the number of pullout filaments through the matrix after pullout tests. Furthermore, the respective assumed bond slip relationship for the outer and inner interface was determined based on the pullout test results. FE modeling was carried out with the obtained bond slip relationships to simulate pullout tests. Based on the test results and analyses, the following conclusions can be drawn.

The pullout specimens exhibit different failure modes, depending on the embedded length. As for 30 mm embedded length, all specimens experience a failure mode featured by the slippage of the whole carbon yarn through the matrix. As for longer embedded lengths (\(\geq 50\) mm), the specimens fail by the slippage and partial rupture of the carbon yarn. The peak pullout force increases rapidly as embedded length increases from 30 mm to 50 mm, and a small increase in the peak pullout force was found for a further increment of the embedded length after 50 mm.

The number of filaments pulled out from the matrix after pullout tests was evaluated through carrying out image processing and analysis. The results show that the number of pullout filaments for pullout tests with 30 mm embedded length is nearly equal to that of the as-received sample, indicating the slippage of the whole carbon yarn, while for longer embedded lengths, the number of the pullout filaments accounts for 70% of the total number, which means that 30% of filaments within a carbon yarn are left in the matrix after rupture. The percentage of impregnated filaments to the total number of filaments within a carbon yarn can be estimated as 30%.

The embedded carbon yarn can be subdivided into two parts considering the matrix impregnation - the outer part and inner part. Two types of interfaces were introduced with different bond slip relationships corresponding to different bond mechanisms. A trilinear bond slip relationship was assumed for the outer interface between the outer part and matrix, while a linear descending relationship for the inner interface between the outer and inner parts. These two bond slip
relationships were evaluated in an analytical manner using the experimental results. A FE analysis incorporating these two interfaces was conducted to simulate pullout tests. The results show that the predicted force versus pullout displacement curves agree well with the experimental results, suggesting the accuracy of the bond slip relationships evaluated for the outer and inner interfaces.

A parametric study was carried out to provide an understanding of the effects of the degree of matrix impregnation ($\beta_m$) and the strength factor ($\beta_t$) as well as embedded length on the pullout behavior of the FRCM composites. It can be found that as $\beta_m$ is increased, the maximum pullout force increases and then remains at a constant level, and the failure mode changes from the slippage and partial rupture of the carbon yarn to the slippage of the whole carbon yarn. While increasing $\beta_t$ and embedded length results in an increase in the maximum pullout force as well as a more ductile pullout behavior.

## Appendices

### Appendix A

Table A.1 Analytical expressions of the $P\sim u$ curve for double-sided pullout tests

<table>
<thead>
<tr>
<th>Interfacial stress state</th>
<th>Analytical expressions for $P\sim u$ curve</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /> (a) Elastic state</td>
<td>$P = EA\lambda \frac{\tanh(\lambda L_a)\tanh(\lambda L_b)}{\tanh(\lambda L_a) + \tanh(\lambda L_b)} u$</td>
</tr>
<tr>
<td><img src="image2.png" alt="Image" /> (b) Elastic-debonding state (I)</td>
<td>$P = \frac{\omega^2 \lambda EA \tanh(\lambda L_a)}{\lambda \tan(\varphi) \tanh(\lambda L_a) + \omega^2 \left( u - \frac{k_1 + k_2}{k_1 k_2} \tau_{max} \right)}$</td>
</tr>
</tbody>
</table>

$$\lambda = \sqrt{\frac{2ck_1}{EA}}$$

$$\omega = \sqrt{\frac{2ck_2}{EA}}$$
\[ \varphi = \omega l_b - \arctan \left( \frac{\lambda}{\omega \tanh(\lambda L_b - \lambda l_b)} \right) \]

(c) Elastic-debonding state (II)

\[ P = \frac{\omega E A}{\tan(\varphi) + \tan(\varphi_a)} \left( u - \frac{k_1 + k_2}{k_1 k_2} \tau_{\max} \right) \]

\[ \varphi_a = \omega l_a - \arctan \left( \frac{\lambda}{\omega \tanh(\lambda L_a - \lambda l_a)} \right) \]

(d) Debonding state

\[ P = \frac{E A \lambda \omega \tanh(\lambda L_u) \tanh(\lambda L_b)}{\omega \tanh(\lambda L_b) - \lambda \tanh(\lambda L_a)} \left( u - \frac{k_1 + k_2}{k_1 k_2} \tau_{\max} \right) \]

(e) Friction-debonding state

\[ P = \frac{2E A \lambda \tanh(\lambda L_u) \left( \tanh(\omega L_b - \omega d) + \omega d \right)}{\lambda \omega L_b^2 \tanh(\lambda L_u) + 2 \tanh(\omega L_b - \omega d) + 2 \omega d} \left( u - \frac{k_1 + k_2}{k_1 k_2} \tau_{\max} \right) \]

(f) Friction state

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**Appendix B**

As the anchorage length is much longer than the embedded length, the slip and the strain at the free end of the anchorage can be assumed to be null, the corresponding relationship between the pullout force and the slip at the loaded end can be derived as,

\[ P = 2 \sqrt{E A c \left( \tau_{in,\max} u_a - 0.5 k_{in} u_a^2 \right)} \] (B.1)
where $u_a$ is the slip at the loaded end of the anchorage length of the inner part.

For the embedded length, the strain at the free end of the inner part is always zero, while non-zero slip can occur. The relationship between the pullout force and the slip at the loaded end of the embedded length can be expressed by Eq. (B.2) and (B.3),

$$P = EA_{in} \lambda_{in} \tan \left( \lambda_{in} L_b \right) \left( \frac{\tau_{in,max}}{k_{in}} - u_b \right)$$  \hspace{1cm} (B.2)

$$\lambda_{in} = \sqrt{\frac{2ck_{in}}{EA_{in}}}$$  \hspace{1cm} (B.3)

Where $u_b$ is the slip at the loaded end of the embedded length of the inner part.

**Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Acknowledgment**

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**Data availability**

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.
References


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Figure captions

Fig. 1. Geometries of the carbon fabric (unit: mm)

Fig. 2. Specimen configuration (a) and a side view of the test setup (b) for double-sided pullout tests

Fig. 3. SEM image (a) and the schematic cross section diagram (b) of an embedded carbon yarn

Fig. 4. Failure mode observed in pullout tests with 30 mm embedded length

Fig. 5. Schematic illustration of different failure modes in pullout tests, (a) pure slippage of the carbon yarn and (b) slippage and partial rupture of the carbon yarn

Fig. 6. The applied force versus pullout displacement curves obtained from pullout tests

Fig. 7. Image processing procedure involving (a) original image, (b) contrast enhancement, (c) binarization and (d) counting

Fig. 8. The number of pullout filaments for (a) different embedded lengths and (b) different locations within one carbon yarn.

Fig. 9. Diagram of the force equilibrium for a small segment of an embedded carbon yarn

Fig. 10. Bond slip relationship for the outer interface (a) and the inner interface (b) of the embedded carbon yarn

Fig. 11. Schematic illustration of (a) progressive failure of the filaments in the outer part and (b) tensile behavior of the outer part

Fig. 12. Comparison of the $P-u$ curves obtained from experiments and FE modelling for pullout specimens with 30 mm embedded length

Fig. 13. Comparison of the $P-u$ curves obtained from experiments and FE modelling for pullout specimens with 70 mm embedded length

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Fig. 16. Simplified tensile stress distribution of the carbon yarn at the beginning of breakage of the outer part

Fig. 17. The effect of $\beta_m$ on $P~u$ curves

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\[
\frac{1}{2} P_{\text{out}} \rightarrow \tau_{\text{out}}(s_{\text{out}}) \rightarrow \frac{1}{2} (P_{\text{out}} + dP_{\text{out}}) \\

P_{\text{in}} \rightarrow \tau_{\text{in}}(s_{\text{in}}) \rightarrow P_{\text{in}} + dP_{\text{in}} \\

\frac{1}{2} P_{\text{out}} \rightarrow \tau_{\text{out}}(s_{\text{out}}) \rightarrow \frac{1}{2} (P_{\text{out}} + dP_{\text{out}}) \\

\]

Fig. 10. Bond slip relationship for the outer interface (a) and the inner interface (b) of the embedded carbon yarn

\[
\begin{align*}
\tau_{\text{out}} & \sim s_{\text{out}}^k \\
\tau_{\text{in}} & \sim s_{\text{in}}^k \\
\end{align*}
\]
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