Testing Procedures for the Uniaxial Tensile Characterization of Fabric Reinforced Cementitious Matrix (FRCM) Composites

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Abstract

Fabric Reinforced Cementitious Matrix (FRCM) composites made of dry-fiber fabric embedded in an inorganic matrix are advanced cement-based materials designed for retrofitting masonry or concrete structures. Characterization of the tensile behavior of FRCM composites provides the parameters needed for the design of the structural reinforcement and has given rise to numerous research studies on the aspects that influence its mechanical properties. In order to obtain the tensile behavior characteristics of this composite under different boundary conditions, two test set-ups were investigated. A *clevis grip* (pin action) was used to reproduce field boundary conditions from typical installation and used to obtain design parameters. A *clamping grip* was used to obtain a complete characterization of the composite by inducing a tensile failure of each constituent material. Several FRCM systems made with different fabrics were used for the investigation: polyparaphenylene benzobisoxazole (PBO), carbon (C), and glass (G), plus carbon and glass with a special protective coating. This paper offers a critical analysis of the

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experimental results and provides recommendations for the tensile characterization of FRCM materials.

Key words: Fabric reinforced cementitious matrix; Material behavior; Repair; Strengthening; Tensile characterization; Test procedure.

Introduction

Fabric Reinforced Cementitious Matrix (FRCM) composites consist of one or more layers of dry-fiber fabric reinforcement embedded in an inorganic matrix made of a cementitious or lime based mortar enriched with a low dosage of short fibers and additives. They can be considered as a subset of Textile Reinforced Concrete (TRC) composites that are intended specifically for repair and strengthening applications and in which the fabric must be composed of dry-fibers, meaning they are not completely impregnated by a resin. Both TRC and FRCM are part of a larger family of brittle matrix composites (ACI 549 2013) which among others include normal and high performing Fiber Reinforced Concrete (FRC) and Ferrocement (Arboleda 2014).

Given the increased interest in the utilization of FRCM composite systems for structural retrofitting applications, their specifications need to be available. System specifications include both material performance properties and installation instructions. While the manufacturer determines the installation instructions, research laboratories determine the material properties through experimental and analytical investigations. FRCM is a relatively new composite with unique and complex behavior, yet proven performance as a structural strengthening technique (Papanicolaou et al. 2008, D'Ambrisi et al. 2012, Ombres 2012, Babaeidarabad et al. 2014, Loreto et al. 2014). FRCM strengthening systems present some advantages when compared with Fiber Reinforced Polymer (FRP) materials, in particular when used for the reinforcement of historical buildings as the matrix, consisting of an inorganic mortar, provides a higher compatibility with the substrate and vapor permeability. The complexity of FRCM behavior has given rise to numerous research studies on the aspects that influence its mechanical properties. The aim of this paper is to provide a context and recommendations for the determination of the test method to be used to characterize the tensile behavior of FRCM composites based on the type of parameters sought.

Overview of Tensile Test Methods for FRCM

For structural reinforcement design, the values of the mechanical and bonding properties of the applied materials must be known. These values are determined through experimental tests. The apparent uniaxial tensile behavior of this type of composite is influenced by several factors including the load transfer mechanism (grip method), specimen geometry and fabrication, and strain measurement technique. Since none of these factors are yet standardized, various set-ups for FRCM tensile tests with different gripping methods and specimen geometries have been developed (Contamine et al. 2011, Zhu et al. 2011, Hartig et al. 2012, Arboleda et al. 2012). Figure 1 shows the main gripping methods used by different research groups. Hartig et al. (2010) identified two types of load application: “rigid load application” (Figure 1a and 1c) in which the transfer mechanism between the specimen and the grip is by adhesive tension and shear realized through metal plates glued to the specimen ends (in this study realized with “clevis grip”), and “soft clamping” (Figure 1d) which uses friction for load application realized by applying a compressive force normal to the plane of the specimen at its ends.

Molter (2005) proposed a waisted specimen in which the mortar is prevented from cracking within the supported range. Steel plates are glued or inserted inside the specimen, causing the load transfer mechanism between specimen and clamping through adhesive tension and shear, and no slip can occur between clamping and specimen (Figure 1a). The clamps adopted for bone-shaped specimens (Figure 1b) are articulated steel flanges located in the curved part of the specimens over a rubber sheet (Orlowsky and Raupach 2008). The ICC-Evaluation Service acceptance criteria (AC434 2013) recommends gripping the specimen through adhesive tension and shear method such as a clevis grip (Figure 1c). This includes two plates glued at each end of the specimen and connected with a transversal pin outside of the length of the specimen. This system is connected with a clevis joint to the testing frame.

Other research groups (Carozzi et al. 2015, De Santis et al. 2015) proposed an alternative system in which the two extremes of the specimens are fixed into the grips of a standard testing machine but the lower grip allows for torsional rotation. In this case the clamps produce compressive stresses at the end of the specimens where fiber reinforced tabs are applied using epoxy resin in order to facilitate a more homogeneous stress distribution and avoid local damage in the matrix.

In reference to specimen geometry, rectangular shaped FRCM coupons are generally easier to implement and fabricate than waisted ones such as the dumbbell (Hegger et al. 2006), for which the specimen section is gradually increased at its ends and a perforated metal plate is placed at mid-thickness to ensure the transmission of force. A variation of the dumbbell was used by Papantoniou and Papanicolaou (2012) in which the specimen's end sections are thicker than the rest of the specimen. Other types of waisted specimens include bone-shaped specimens (Raupach et al. 2006), which require expensive molds and particular care in implementation. Rectangular shaped specimens are often cut from larger panels which tend to provide more control of production, but can also be made from single molds requiring more careful manufacture to ensure proper alignment of the fabric. The rectangular shape is recommended as it ensures the integrity of the rectangular geometry of the fabric.

Different procedures to measure the deformation are available. Roth (2007) used strain gauges that provide locally accurate information, but are inadequate in case of multi-cracking behavior. Clip-on and laser extensometers are reliable techniques which also allow for the determination of possible misalignment of the specimen due to out-of-plane bending. Photogrammetry and digital image analysis are other refined methods that provide a complete overview of the crack formation in the specimen. These would be adequate systems of measurement but are sensitive to loss of focus due to specimen curvature (Arboleda et al. 2013) and can become burdensome for large series of tests due to extensive data analysis. AC434 (2013) suggests the use of "*an extensometer with a minimum gauge length of 50 mm that shall be adequate to include at least one significant crack*".

Overview of Tensile Behavior

Typical stress-strain behavior of FRCM under tensile test (Figure 2b) is idealized as a tri-linear curve (Jesse et al. 2008). The first linear phase represents the uncracked state of the composite controlled by the matrix properties which are enhanced by the presence of fibers. The second phase corresponds to the formation and propagation of cracks. In this state there is a significant decrease of the stiffness and relatively fine cracks form. The length and slope of this portion of the curve depend on the quality of the bond between fabric and matrix and on the volume proportion of the fibers activated for load transfer (Butler et al. 2010).

The third phase is the crack-widening region, where the existing cracks become wider up to the final failure caused either by reaching the tensile strength of the fabric, or by slippage of the fabric from the matrix, or a combination of both. This phase is defined by a number of factors including end boundary conditions and fabric properties such as volume percent, geometry, and whether the yarns are fully impregnated by resin or dry, meaning only partially impregnated by the cementitious matrix or yarn partially coated by resin thus having a dry fiber core held in place only by frictional forces. In this phase only the fabric resists the load and, therefore, the slope of the curve often reflects the elastic modulus of the dry fibers. In certain conditions a tension stiffening effect is observed where the modulus in this phase runs parallel, but at a slightly elevated stress compared to the fabric (Figure 2b). This is attributed to a contribution of the uncracked matrix between the cracks. In conditions where the matrix strength is very low or the dry fibers slip, the modulus of the third phase can be undistinguishable from the second phase and a bi-linear behavior is obtained instead (Figure 2c).

The transition points T_1 and T_2 are defined at the change in slope of the stress-strain curve and are determined by the intersection of the linear portion representing the modulus of elasticity of each phase. Furthermore, cementitious composites with insufficient fabric volume will behave as FRC with strain softening and are not considered FRCM composites.

Fiber to Matrix Bonding

When yarns are fully impregnated with resin they behave as internal FRP and increase the organic content of the composite. By definition, FRCM is composed of “dry-fiber fabric”, meaning that the yarns are not fully impregnated with resin. When the fabric is completely dry, the mortar partially impregnates the outer fibers in the yarn bundle. When the fabric has a protective coating applied on the exterior of the yarn the mortar does not impregnate the bundle. In either case, however, there is a core of dry fibers. Therefore dry fiber yarns can be modeled as having a sleeve and a core. It is important to investigate the adhesive bond between the external fibers of the yarn and the mortar and also the frictional bond among the internal fibers within the yarn.

Two types of slippage can occur: between fibers and mortar or within fibers in the dry core of the yarn. Slippage between fibers and mortar is due to incomplete impregnation of the fibers, debonding, or to chemical incompatibility, and can be localized at the end of the specimen or in each crack region. Slippage appears between the fibers in the yarn due to a telescopic failure mode. It is known that a cement matrix is not ideal to impregnate fibers. The external fibers in a yarn are either in direct contact with the matrix or indirect contact with the matrix through the partial protective coating and are thus tightly bonded, while the internal fibers in the core of the yarn are not and can slip more easily because of the low friction between the fibers.

Peled (2008), Soranakom and Mobasher (2009) and Andic-Cakir (et al. 2014) presented a model to simulate the yarn as a cylindrical structure comprised of concentric rings composed of several fibers. The failure mode of the fibers in the sleeve is by fracture while the internal fibers slip due to the pull-out force. The telescopic mode pull-out (Banholzer et al. 2006) is influenced by cement penetrability, the geometry of the reinforcement, the presence of a coating, and the level of friction between the fibers in each yarn.

Experimental Program

Rectangular coupons of various FRCM systems were tested using two different test setups. The main difference between the set ups was the gripping method used to transfer the load. Since grip terminology is not standardized, in this paper “clevis grip” is the term used for load application through metal tabs glued on the specimen ends (Figure 1c) and "clamping grip" is the term used for load application through compressive stress normal to the specimen's plane (Figure 1d). The main difference between the two methods is the stress state generated by the grips. In the first case, only shear stresses are transferred. In this type of test the full strength of the fabric is never reached because the failure mode is by slippage of the fabric. In the second case, the clamping grips generate compression and shear in the specimen to limit slippage between fabric and matrix at the grip.

The tests performed with clamping grips allow a complete mechanical behavior characterization of the composite with a tensile failure of each constituent material, however, in field applications of FRCM the ends are not anchored and failure is often by slippage of the fibers. Thus the tests performed with clevis grips intend to reproduce the as-installed FRCM behavior.

FRCM composites used during the investigation

Five different FRCM systems were used during this study having these types of fabrics:

- polyparaphenylene benzobisoxazole (PBO fiber), composed of dry fibers only (Figure 3a);
- two types of carbon ("C fiber" and "cC fiber"), one composed of dry fibers only (Figure 3b), the second one having a protective coating over the dry fibers;
- two types of glass fabric ("G fiber" and "cG fiber"), the first one composed of dry fibers only, the second one having a protective coating of Styrene Butadiene over the dry fibers.

Each type of fabric was matched with the mortar that is specifically designed for it by the FRCM system manufacturer. The corresponding systems are denominated "x-FRCM", where "x" represents the name of the fabric (e.g.: "PBO-FRCM").

Fabric reinforcement

Figure 4 shows the geometry of the different fabrics involved in the experimental study. Fabric parameters shown include spacing between yarns and yarn nominal width. For unbalanced fabrics (different fiber volume in each direction) the warp (main or load carrying) direction is shown up/down and the weft direction is shown left/right. Another important parameter is the equivalent thickness, which is used to determine the nominal cross sectional area of the fabric when multiplied times its length.

The "PBO" fiber unbalanced fabric has equivalent thickness in the warp and weft directions of 0.046 mm and 0.011 mm respectively. The carbon fiber ("C fiber") is a balanced fabric with equivalent thickness is 0.047 mm in both directions. The coated carbon fiber (“cC fiber”) is an unbalanced fabric with equivalent thickness of the dry fibers in the warp direction of 0.175 mm. The glass fiber (“G fiber”) balanced fabric has an equivalent thickness of 0.036 mm per direction and the coated glass fiber (“cG fiber”) unbalanced fabric has an equivalent thickness of 0.05 mm and a dry yarn net cross sectional area of 0.9 mm^2.

Tensile tests of single yarns and of fabric strips of width 40 and 50 mm (containing 3 to 4 yarns as indicated in Table 1) in the warp direction were performed according to EN ISO 10618/2005 (2005). Tests were carried out using different testing machines with maximum load capacities of 2 kN and 100 kN and an extensometer with base length equal to 50 mm. In order to avoid local damage during the tensile tests, special tabs of glass fiber reinforced polymer (GFRP) were bonded using epoxy resin at the ends of the coupons. The tabs presented a width equal to the coupon and a length equal to 60 mm.

The failure mode shows a rupture of some fibers without a complete failure of the yarn for PBO and carbon fibers, in contrast a complete cut is evident in glass fibers. The failures occurred on the length of the specimens, not close to the grips. Due to the difficulties of bonding all the internal filaments in the tabs, it is very difficult to guarantee an homogeneous stress distribution in the filaments of the yarn. For this reason all filaments don’t fail simultaneously. The experimental results are summarized in Table 1.

Inorganic matrix

The inorganic matrix is specifically designed by each manufacturer of the FRCM composite system to a) provide optimal fresh state and workability properties, and b) form an optimal (chemical/mechanical) bond with the fabric and the substrate. The constitutive components of the mortar are not very different that traditional cement but some of the dry additives are proprietary in nature and each fabric is used with its specific mortar. The matrices analyzed in this work are cementitious mortars enriched with short fibers in a percentage less than 5%. Only the mortar used with "G fibers" is lime based. Table 2 shows the main measurable mechanical properties and the corresponding experimental standards adopted. Some of the values were experimentally verified on mortar samples made and cured for 28 days in laboratory ambient conditions of 20 °C and 60 % relative humidity, while others were taken from the technical data-sheets provided by the producers. Some of the mechanical properties of the matrix were not reported in the data-sheets. Reasonable values were estimated on the basis of a few tests.

Specimen geometry and preparation

The test coupons were all rectangular and manufactured using a manual impregnation technique in a flat rectangular mold by first applying a thin layer (5 mm) of the cementitious matrix, followed by pressing a layer of the fabric into the mortar. The top layer of mortar matrix was then applied as flat as possible with a finishing trowel. The cCarbon fabric had retained some curvature from the roll it comes from and was placed in an oven at 60°C for 10 minutes the night before so the coating could soften and the fabric sheet flattened out. All FRCM systems were made with one fabric layer, but additionally, coupons were made with overlap splice for PBO and carbon (PBO-FRCM and C-FRCM), and with two fabric layers for coated carbon (cC-FRCM).

The fabricated panels were cured at laboratory ambient conditions at temperature 20°C and 60% relative humidity for 28 days before cutting the individual coupons using a diamond-tipped wet saw. The coupons tested with the clevis grip had nominal dimensions equal to 410 x 50 x 10 mm and were cut from larger panels of 430 x 560 mm. The coupons tested with clamping grips were made in a similar way, but each coupon was prepared in a flat mold separately.

Test set-up

Gripping

Adhesive tension and shear grips were implemented with a clevis. Metal tabs of 3 mm thickness with a bond length equal to 150 mm were fixed at the coupon ends with epoxy resin. The grip had multiple degrees of freedom providing a pinned end support. This configuration reduces bending moments and allows slippage of the fabric at the grip ends.

For complete mechanical characterization of the system clamping grips were selected. The two extremes of the coupon were fixed into the grips of a standard testing machine, with the lower grip allowing for torsional rotation thus ensuring specimen alignment prior to test start. In this case the clamps can produce high compressive stresses (4-5 MPa) at the end of the coupons so GFRP tabs (dimensions 60 x 40 x 2 mm) were applied using epoxy resin in order to avoid damage in the matrix and guarantee an homogeneous stresses distribution.

Instrumentation

For the tests performed with clevis grip, a test frame with a maximum capacity of 130 kN was used with displacement control at a rate of 0.25 mm/min. Axial deformation was measured using a clip-on extensometer with a 100 mm gauge length, placed mid-length of the coupon (Figure 5a).

For the tests performed with clamping grip, a test frame with load capacity of 100 kN was used with displacement control at a rate of 0.1 mm/min during the first phase (before matrix cracking), and 0.3 mm/min thereafter. Deformation was measured using an extensometer with a gauge length of 100 mm positioned in the central area of the coupon (Figure 5b). Since the dimension of the coupon was 400 x 40 x 10 mm, the distance between the two grips of the testing machine was 280 mm. Therefore the extensometer gauge length of 100 mm covered about 1/3 of the free surface of the coupon giving an adequate measurement of the strain field.

Influence of different elongation measurements and gauge length

Extensometers are installed on the external surface of the specimens and can provide only an average deformation of the mortar matrix in the gauge length segments. The deformation through the cross-section of the FRCM material is not homogeneous and difficult to measure. While the mortar is brittle with a relatively high axial stiffness (AE) and low tensile strength, the fabric has a lower axial stiffness and very high tensile strength. Additionally, the telescopic behavior of the fabric yarns where the fibers experience internal frictional sliding cannot be measured with classical strain measurement instruments installed on the exterior of the material.

The most common approach to FRCM strain measurement is with point-to-point instruments such as extensometers and linear variable differential transformers (LVDT). With point-to-point, location within the specimen width is important because the deformation can be different on each side due to uneven crack widths. Thus, the measurements can be referred only to the midsection. Furthermore, when any crack develops outside the instrument's gauge, the immediate response measured by the instrument, can be of partial contraction. Particular attention in determining the first transition point should be paid when the very first crack appears outside the instrument gauge.

When the failure mode includes fiber debonding and slippage (Figure 6a), the instrument records the slippage which occurs outside the gauge length. When slippage is prevented by clamping grips, the strain in the fibers in the outer part of the bundles is equal to the strain experienced in the matrix. Once the crack occurs, the fibers within the crack opening are then free to deform according to their own properties. The length of the fibers that are free to deform is longer that the crack width (Figure 6b).

Brittle matrix composites develop multiple cracks along the coupon length which form part of its damage progression mechanics. The crack size and distribution within the coupon is a separate measurement which cannot be captured with elongation measurement instruments. This information, while not considered during application design, is part of the characteristic tensile behavior of the composite and is often analyzed. Peled and Mobasher (2006) and Carozzi (2015) studied the crack formation pattern. Peled and Mobasher (2006) determined that the crack formation is a function of stress and fabric volume and are the primary mode of displacement. Also that crack spacing diminished during loading and reached a steady state where no more cracks appear calling this the point of crack saturation after which fiber debonding becomes the secondary mode of displacement. Carozzi (2015) further determined that the spacing of cracks is related to the fabric geometry, in particular, the spacing, width, and thickness of the weft yarns.

Experimental results

A variety of FRCM systems with one fabric layer were tested. Coupons with a layer splice overlap (PBO and C-FRCM) and with two fabric layers (cC-FRCM) were also tested. Their stress-strain behavior and failure modes were analyzed. A detailed description of the results obtained can be found in (Arboleda 2014, Carozzi et al. 2015). In this paper the results are summarized and critically analized to highlight the comparison of the two testing procedures. All specimens demonstrated multiple cracking of the matrix, perpendicular to the direction of the load, throughout the length of the coupon. The point at which no more cracks develop is termed crack saturation.

For all specimens, the stress was determined by dividing the load by the nominal cross-section area of the fabric only,3 because after the specimen starts to crack, the load transfer occurs mainly through the fabric. Naturally, when the uncracked portion of the response curve is determined using the actual cross-section of the specimen, the resulting first crack stress and modulus of elasticity are comparable to that expected of the mortar only. Furthermore, since the specimen cross-section has significantly more variability than the nominal fabric cross-section, the high variability noticed in this first phase is reduced when first crack is based on gross area.

Clevis grip on one layer specimens

The typical failure mode obtained with this test set up was slippage of the fabric within the matrix after crack saturation. The fabric slippage is a combination of pull-out and tensile failure of the fibers. The stress-strain behavior is bilinear with the first phase identified as the un-cracked specimen behavior; when the first cracks appear the slope decreases and slippage between fibers and mortar is eventually observed.

The modulus of the un-cracked specimen was calculated as the slope between the origin and the intersection of the linear trend of the first portion of the experimental curve and the linear trend of the second portion of the experimental curve. On the segment of the response curve corresponding to cracked behavior after the transition, two points are selected at a stress level equal to 0.90 f_{fu} and 0.60 f_{fu} (AC 549 2013). The slope of the line that connects these two points represents the tensile modulus of elasticity at that region as summarized in equation (1):

$$\boldsymbol{E_f} = \frac{\Delta f}{\Delta \varepsilon} = \frac{0.9f_{fu} - 0.6f_{fu}}{\varepsilon_{@0.9f_{fu}} - \varepsilon_{@0.6f_{fu}}} \qquad (1)$$

The segment between 0.90 f_{fu} and 0.60 f_{fu} was selected based on a statistical analysis of representative curves in order to ensure consistency of results. Table 3 summarizes average results with coefficient of variation and Figure 7 shows the tensile response of the different FRCM materials. The G-FRCM and cG-FRCM were not tested with the clevis grip.

Clamping grip on one layer specimens

With this gripping system, the typical failure mode is by damage to the fabric fibers close to the main cracks. In a few instances, fiber slippage is observed and is attributed to poor bond to the matrix. The stress strain behavior is predominantly tri-linear with exceptions based on the type of FRCM material tested. Results show a large variability in the localization of transition points. This is caused by a) the variability in dimensions of the specimen section; b) the presence of cracks not visible to the naked-eye; and c) the location of the first crack with respect to the extensometer (Bertolesi et al. 2014).

Tensile tests on C-FRCM and PBO-FRCM show a tri-linear behavior, G-FRCM and cG-FRCM show a behavior where the second transition point is not evident due to the low elastic modulus of the glass fibers. When the slope of the third branch is lower than the elastic modulus of the dry fabric, a possible slippage phenomenon is occurring.

The modulus of all three phases is evaluated as the ratio between stress and strain of the first and last point of each phase. For the first phase only, in which the mortar is un-cracked, tensile stress (σ^*_{t1}) and elastic modulus (E^*_1) were also evaluated using the composite cross section in order to compare the cracking tensile stress and the elastic modulus with the mortar properties. The stress reached at the end of the first phase should be similar to the mortar tensile strength. As previously described, due to possible problems in sample preparation or in the curing phase (no planarity, different shrinkage, micro-cracking) this value could be lower than the mortar tensile strength.

Table 3 summarizes average results with coefficient of variation and Figure 8 shows the tensile response of four different FRCM materials (cC-FRCM not tested). The third phase shows most of the differentiation due to the different elastic moduli and tensile strengths of the fibers.

Figure 9 and Figure 10 show the comparison between the stress-strain curves obtained with the two gripping methods for PBO-FRCM and C-FRCM coupons. The characteristic behavior in the first phase is not expected to be very different for both gripping methods, however, since the stress is computed with respect to the textile cross-section area, the variable dimensions of the cross section area of the matrix as well as the location of the first crack with respect to the gauge length have a significant influence on the analyzed results. For tests performed with clevis grip the second phase reached higher strain due to fiber slippage, and the third phase was not present.

Clevis grips on two layer specimens

In order to analyze the efficiency of multiple layers, clevis grip tests were performed on coupons with two layers of coated carbon (cC) fabric. Six tests were performed; Figure 11 and Table 3 show the stress-strain curves and the results summary. The failure mode was by slippage of the fabric after crack saturation. The bi-linear behavior was observed consistent with one layer coupons. A post failure phase showed increased "pseudo-ductility" due to the friction between the two fabric layers and the mortar.

Clevis grips on splice specimens

Investigation of fabric splicing with clevis grips showed that generally, the overlap length must be greater than or equal to the tab length used for load application which itself is a function of the fabric development length within the matrix. Preliminary results demonstrate that an overlap of 100 mm is insufficient and must be increased to a minimum of 150 mm. In PBO-FRCM tests the transition point occurs at a greater stress in the coupon with overlap due to the increase in matrix thickness, after the cracking phase, the slippage phenomena develops between fabric and mortar. Figure 12 compares the results for PBO-FRCM with the two griping systems.

Clamping grips on spliced specimens

Tensile tests were performed on coupons with a fabric overlap in the midsection to determine the minimum overlap length. Two fabric layers were placed in the coupons, with a central splice overlap of 100 mm. Six tests were performed on PBO-FRCM coupons, and five tests were performed on C-FRCM. The fabric area was considered equal to one layer. The failure mode was slippage of the fabric between the two layers from the coupon center, for this reason the slope of the third phase and the maximum strength are lower than the one obtained with one layer coupons. These results indicate that a length of overlap equal to 100 mm is not sufficient to guarantee a proper stress transfer for the systems tested.

Influence of different gripping methods

As demonstrated by several studies (Contamine et al. 2011, Bianchi et al. 2013, Arboleda 2014, Carozzi et al. 2015) , the resulting mechanical behavior for tensile tests is dependent on the gripping at the ends of the coupon, specifically, trilinear for clamping grip, and bilinear for clevis grip. This consideration must be clearly understood when defining a procedure to be used for material characterization. Clearly, the maximum strength is the parameter wanted, but this is not possible to achieve as installed.

When the goal of the characterization is to determine the maximum possible strength of the composite, then clamping grips are necessary. However, when the goal of characterization is to determine the parameters useful for design when the material is installed per manufacturer’s instructions (wet layup or spray), then a clevis grip that permits failure by slippage is required. It is possible, however, for an installation to take place with anchoring of the material at the ends in order to prevent the slippage phenomena in which case the maximum strength of the composite could be the sought after design parameter.

Contribution towards the development of a test protocol for characterization of FRCM composites

On the basis of the series of experiments performed, the following steps are proposed as part of a testing procedure for characterization of FRCM coupons in tension:

Specimen geometry:

- The yarns should be positioned symmetrically with respect to the axial midline of the width that should be equal to a multiple of the fabric spacing. The textile should be straight and positioned in the mid-plane of the coupon.
- The length of the coupons should be adequate to minimize the local effects of the clamping or provide sufficient development length for the fabric in the case of clevis grip. It should be at least greater than the sum of the tabs length plus the extensometer length and double of the specimen width.
- The coupon geometry must be controlled to verify the straightness and thickness variation. An admissible tolerance must be defined for both quantities. The thickness should be measured in at least five positions along the coupon length.
- The coupons should not present evident cracks before the test.
- The differential shrinkage of the two sides of the coupons can cause a curvature that is detrimental for the test because it can cause cracks when the coupon is fixed into the

grips of the testing machine. Therefore the planarity of the coupons is very important and must be controlled.

Gripping:

- The choice of the gripping system depends on the final objective of the experimental investigation. If the objective is the characterization (“initial type testing”) of the FRCM system the clamping grips that allow for torsional rotation can provide a complete evaluation of the mechanical properties and all the parameters that characterize the trilinear stress-strain curves can be determined.
- When the objective is the investigation of the maximum load bearing capacity of the system for the reinforcing application, the clevis type grips are preferred. These are also suggested in the case of on-site acceptance tests of the material and the system.

Measurements:

- Extensometers are ideal to assess the deformations in the coupons. The optimum setup would include four LVDTs placed on the opposite sides of the coupons but it was demonstrated that even a single extensometer with an adequate gauge length provides reliable results. In the literature there are discussions of the ideal measurements [Contamine et al, 2011].

Conclusions

Uniaxial tensile testing of composite material specimens was performed for the main purpose of determining the characteristic mechanical behavior of the material under controlled loading conditions. It is the most accepted method for obtaining material parameters needed for design calculations. The influence of different test set-ups and measurement techniques was presented through the results of an extensive experimental investigation. The selection of the two gripping systems was based on the following considerations. The "clevis grip" is preferred to reproduce the actual behavior that FRCM materials present in the field. With this boundary condition, the tensile behavior was characterized by an initial elastic phase and then a second, lower modulus phase due to cracking of the matrix and slippage between fabric and matrix. The "clamping grip" was selected to obtain a complete characterization of the composite and to produce a tensile failure of each of the constitutive materials of the composite. With this boundary condition, the experimental data confirmed that the behavior of FRCM materials in tension is characterized by trilinear curves. The first part corresponds to the un-cracked phase of the mortar while in the second phase the cracks develop and in the third phase only the fiber reinforcement can carry the applied load. In this phase the measured stiffness and ultimate strength of the specimens correspond to the relevant values of the dry fabrics.

A critical analysis was reported regarding the influence of the elongation measurement techniques. Accurate measurements of the deformation behavior of FRCM systems is difficult because elongation measurement instruments are designed to be placed on the exterior surface of specimens, thus capturing only the average deformation experienced by the mortar matrix. Moreover, the deformation through the cross-section of the FRCM is not homogeneous, and the telescopic behavior of the fibers in the yarns cannot be measured with instruments installed on the exterior surface of the material.

The investigation of the overlap of the fabric with clevis grips showed that generally, the overlap length must be greater than or equal to the tab length used for load application which itself is a function of the fabric development length within the matrix. This investigation is still in progress, but preliminary tests performed both with clamping grips and clevis grips demonstrate that an overlap of 100 mm is insufficient and must be increased to a minimum of 150 mm.

These results highlight the importance for guidelines and recommendations that allow a complete characterization of FRCM composite systems. The two test set-ups investigated in this paper demonstrated the two perspectives involved in the mechanical characterization of the tensile behavior of the material, both, the full capacity of the system and its behavior in field applications.

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Table of figures

Table 1 – Mechanical properties of the yarns

Fabric	# yarns	Cross section area [mm^2]	# tests	Average stress at failure [GPa]	C.o.V. [%]	Elastic modulus [GPa]	C.o.V. [%]
PBO fiber	1 yarn	0.41	6	3.9	3.2	216	20.8
	4 yarns	1.64	4	3.4	7.3	-	-
C fiber	1 yarn	0.42	3	1.9	14.9	203	9.8
	4 yarns	1.68	3	1.9	10.4	-	-
cC fiber	1 yarn	2.68	3	1.3	9.2	263	11.2
G fiber	1 yarn	0.24	4	1.4	11.4	49	-
cG fiber	1 yarn	0.90	5	1.2	2.7	56	30.5
	3 yarns	2.70	5	1.1	1.3	-	-

Table 2 – Mechanical properties of the matrix

Matrix type	Tensile EN 12390-6		Compressive EN 1015 -11		Flexural EN 1015 -11		Elastic modulus
	Strength (MPa)	**CoV (%)**	**Strength (MPa)**	**CoV (%)**	**Strength (MPa)**	**CoV (%)**	**EN 14580 (GPa)**
Mortar used with **PBO** fabric	4.75 (7)*	4.05	33.90 (5)	10	> 2 (ds)	-	> 6 (ds)
Mortar used with **C** fabric	3.30 (5)	3.6	24.02 (5)	2.5	3.5 (ds)	-	> 7 (ds)
Mortar used with **cC** fabric	3-5 (ei)	-	> 45 (ds)	-	7 (ei)	-	7 (ei)
Mortar used with **G** fabric	2-4 (ei)	-	10 (ds)	-	3 (ei)	-	5 (ei)
Mortar used with **cG** fabric	3-5 (ei)	-	27.13 (7)	4.1	8.4 (14)	13.15	8 (ds)

**Note: Within brackets # of tested coupons or source of data (ds = data sheet; ei= estimated interval)*

Table 3 – Results of tensile tests

Material	Grip type (#)*	Value type	E_1 (GPa)	E_2 (GPa)	E_3 (GPa)	σ_{t1} (MPa)	σ_{t2} (MPa)	σ_u (MPa)	ε_{t1} (%)	ε_{t2} (%)	ε_u (%)	E^*_1 (GPa)	σ^*_{t1} (MPa)
PBO-FRCM	Clevis	Average	1805	128	-	375	-	1664	0.017	-	1.75	-	-
4 yarns	(10)	CoV (%)	25	12	-	22	-	5	25	-	8	-	-
C-FRCM	Clevis	Average	512	80	-	458	-	1031	0.102	-	0.99	-	-
4 yarns	(5)	CoV (%)	25	23	-	10	-	5	44	-	14	-	-
cC-FRCM	Clevis	Average	1570	56	-	381	-	1296	0.023	-	1.64	-	-
3 yarns	(9)	CoV (%)	55	14	-	36	-	12	33	-	14	-	-
cC-FRCM	Clevis	Average	465	52	-	149	-	1133	0.025	-	1.79	8	3
2-PLY	(5)	CoV (%)	24	17	-	24	-	10	37	-	25	15	22
PBO-FRCM	Clamp	Average	1181	76	216	890	1100	3316	0.082	0.5	1.69	5	4
4 yarns	(34)	CoV (%)	20	33	9	15	13	14	31	34	18	20	15
C-FRCM	Clamp	Average	1102	68	186	482	620	1492	0.06	0.24	0.74	5	2
4 yarns	(10)	CoV (%)	18	28	22	21	19	19	13	20	21	18	21
G-FRCM	Clamp	Average	1029	41	56	545	691	1292	0.064	0.44	1.82	2	2
4 yarns	(8)	CoV (%)	31	59	36	25	7	8	25	28	47	31	25
cG-FRCM	Clamp	Average	1310	32	64	460	431	872	0.045	0.38	0.69	6	2
3 yarns	(17)	CoV (%)	33	34	17	30	20	21	41	13	38	34	30

*Note: *Within brackets (#) number of tested coupons*

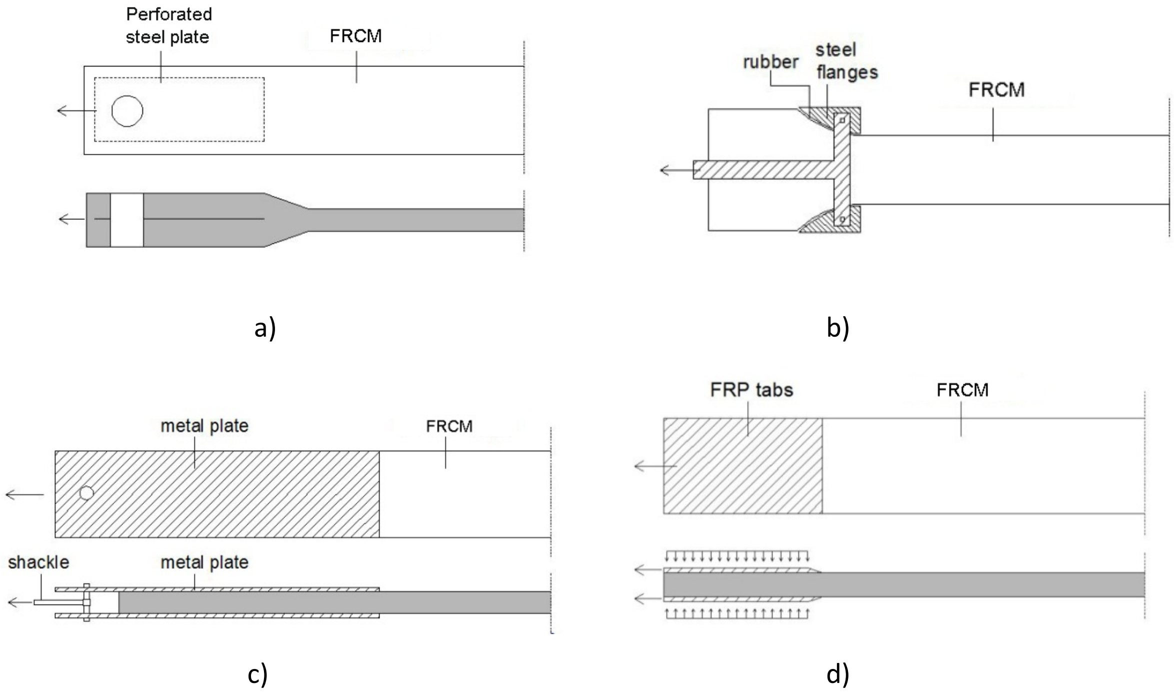


Figure 1. Test set-ups: a) steel plate inside specimen; b) steel flanges; c) clevis (adhesive tension and shear) grips; d) clamping grips

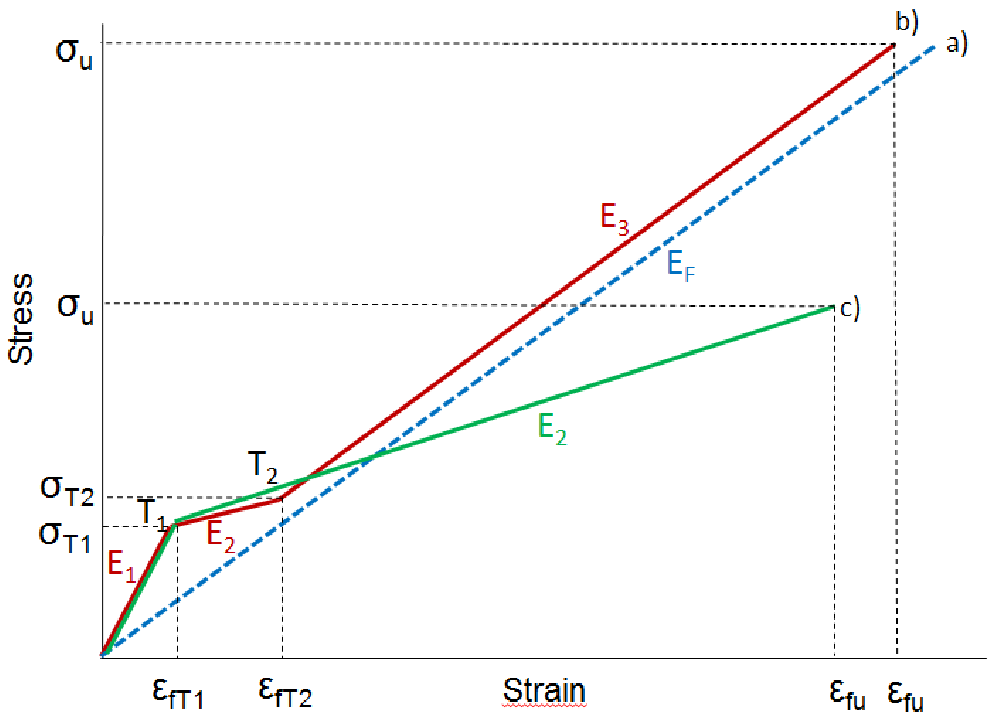
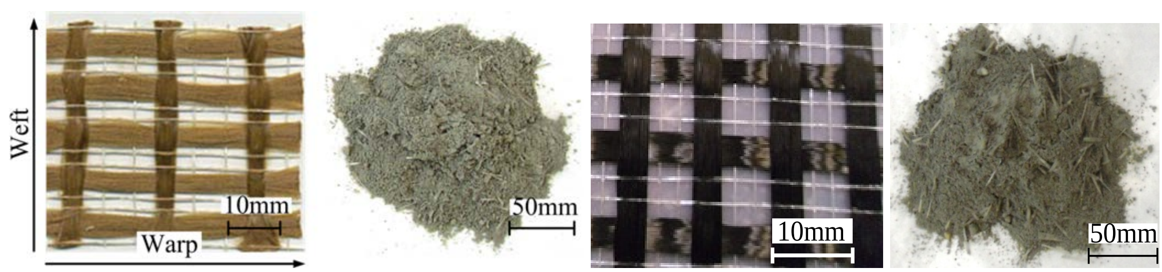
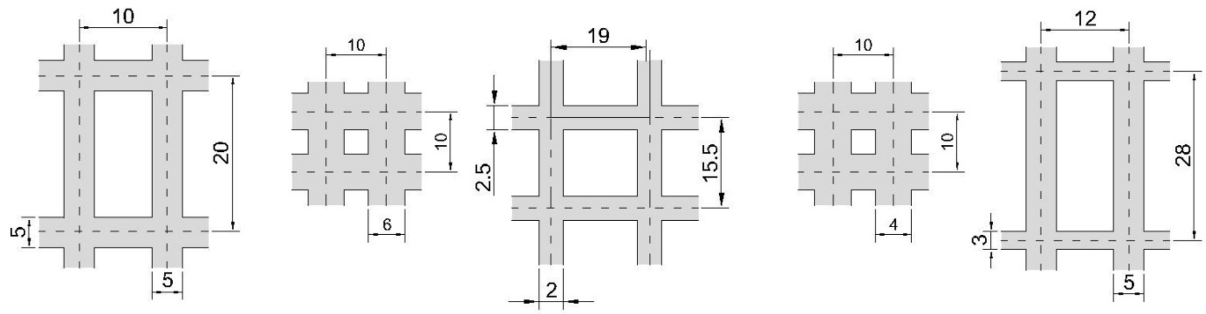


Figure 2. Idealized stress-strain curves a) stand-alone fabric, b) clamped FRCM, c) pinned FRCM



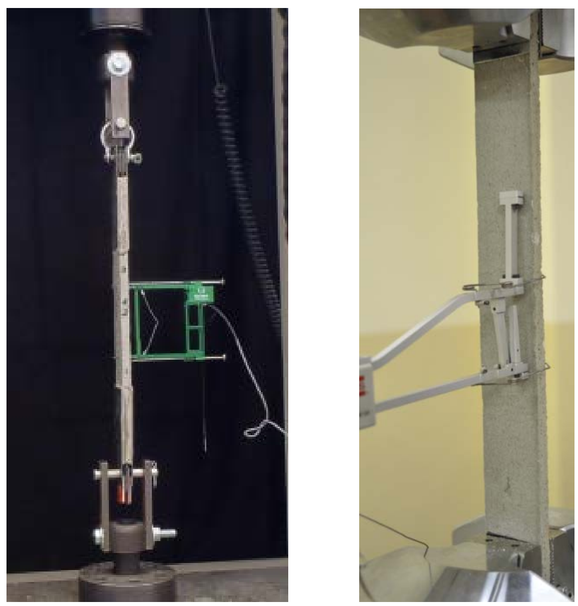
a) b)

Figure 3. a) PBO-FRCM system; b) C-FRCM system



a) b) c) d) e)

Figure 4. Fabric geometry: a) PBO; b) glass; c) coated glass; d) carbon; e) coated carbon (dimensions in mm)



a) b)

Figure 5**.** Tensile test set-up: a) clevis grip; b) clamping grip

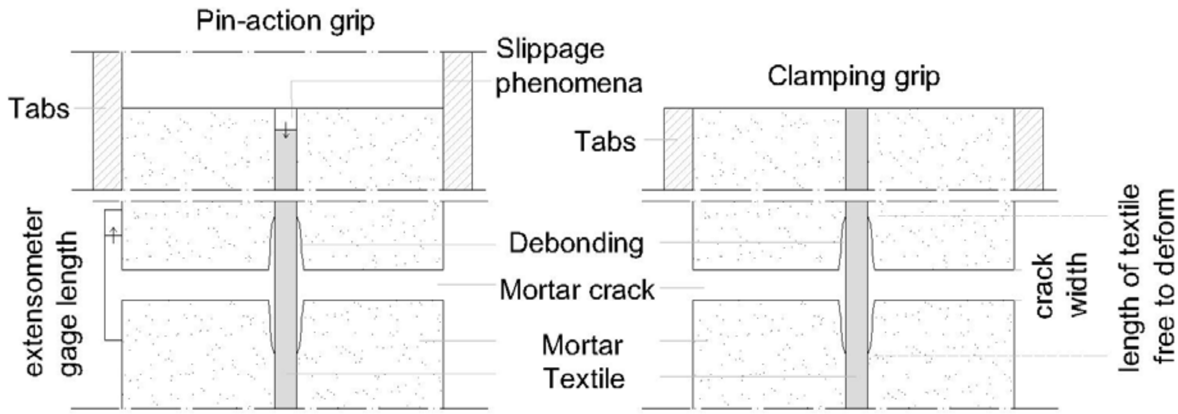


Figure 6. Differences in strain measurement based on grip type

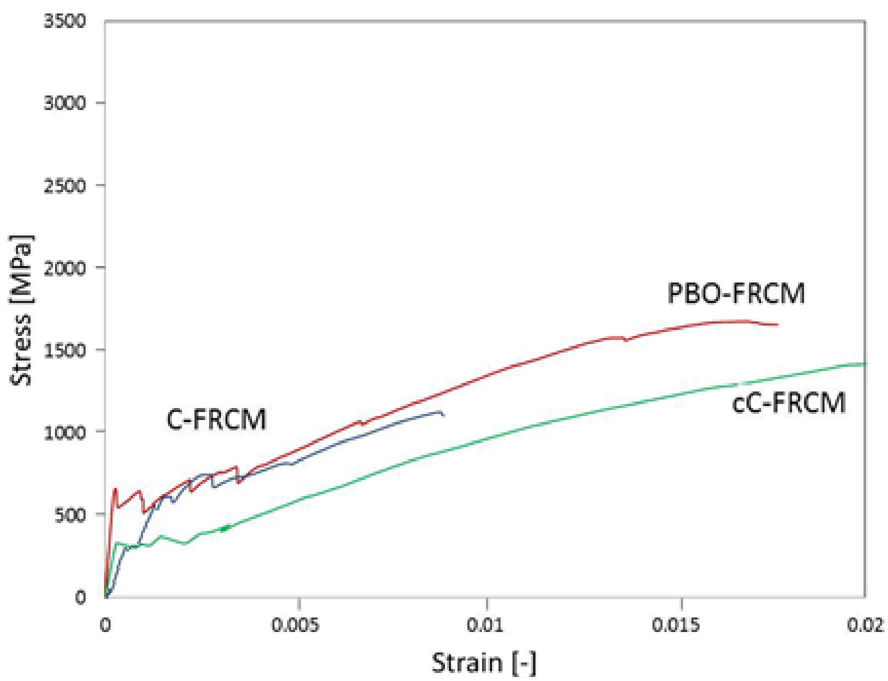


Figure 7. Stress-strain curves with clevis grip of different FRCM materials

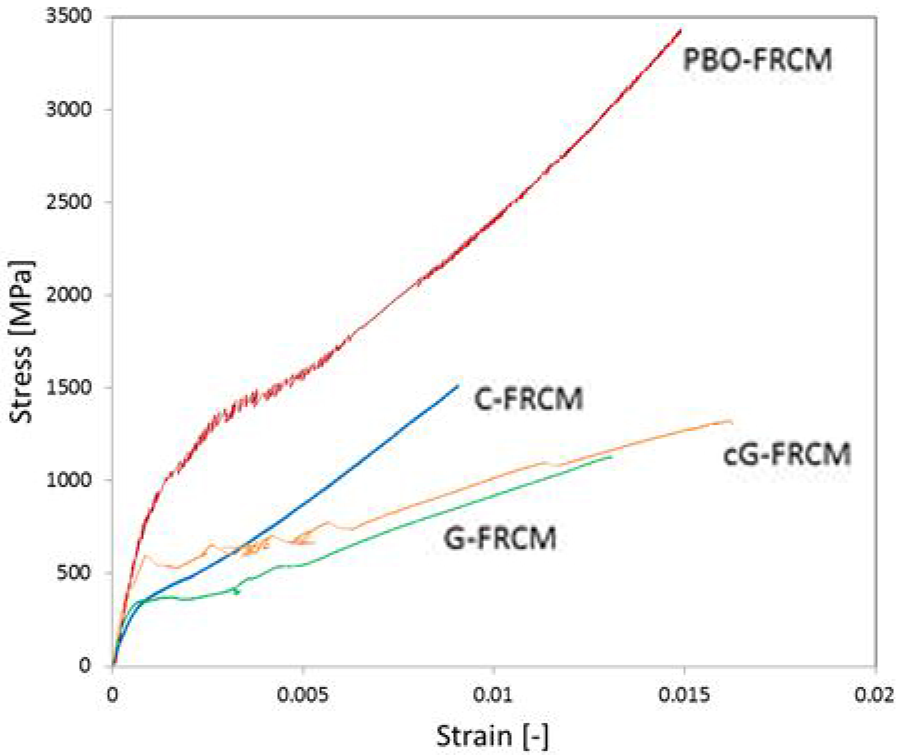


Figure 8. Stress-strain curves with clamping grip of different FRCM materials

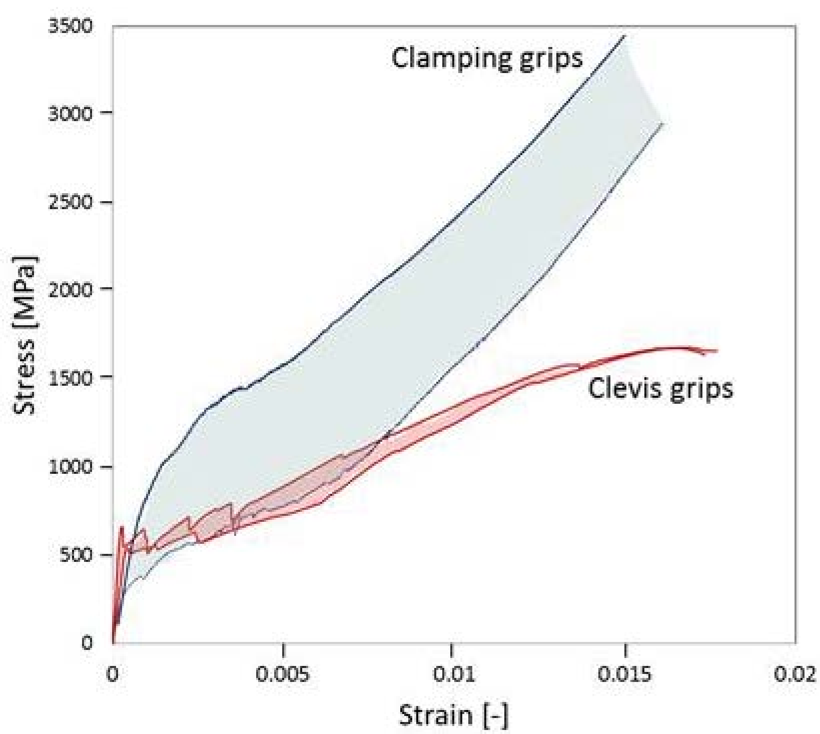


Figure 9. PBO-FRCM single layer behavior with the different test setups

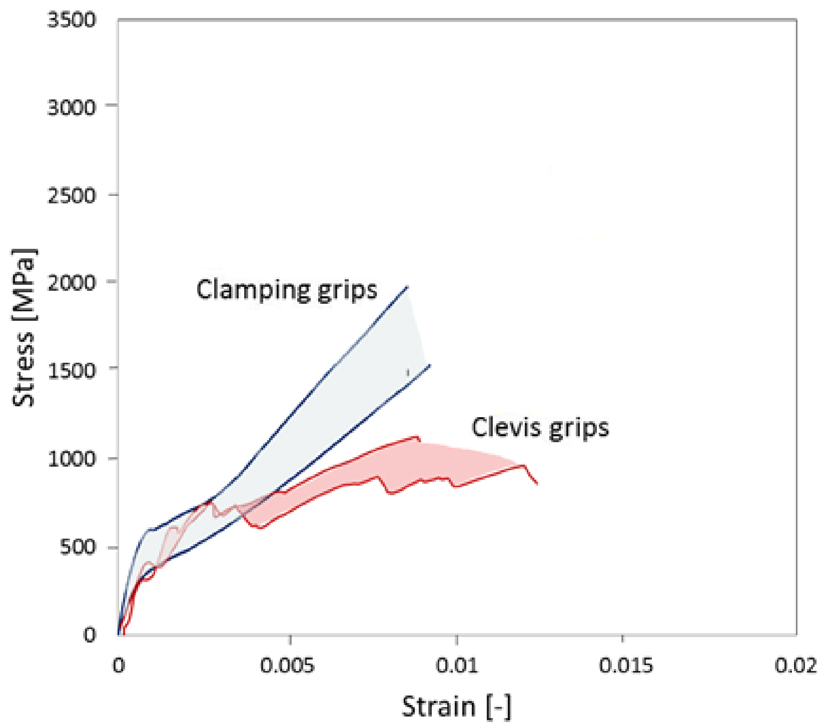


Figure 10. C-FRCM single layer behavior with the different test setups

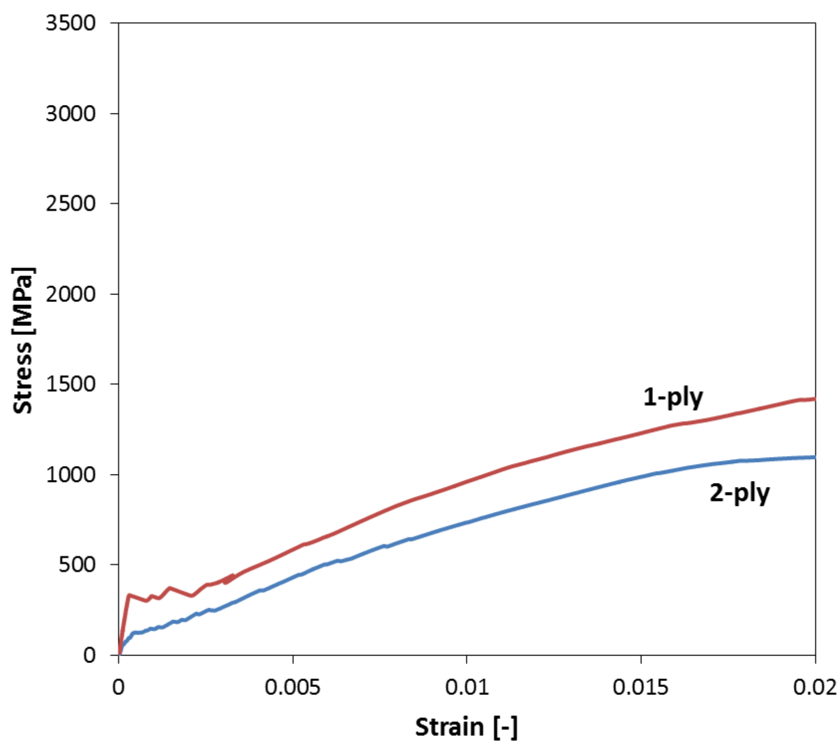


Figure 11. cC-FRCM: Two-ply vs. one-ply

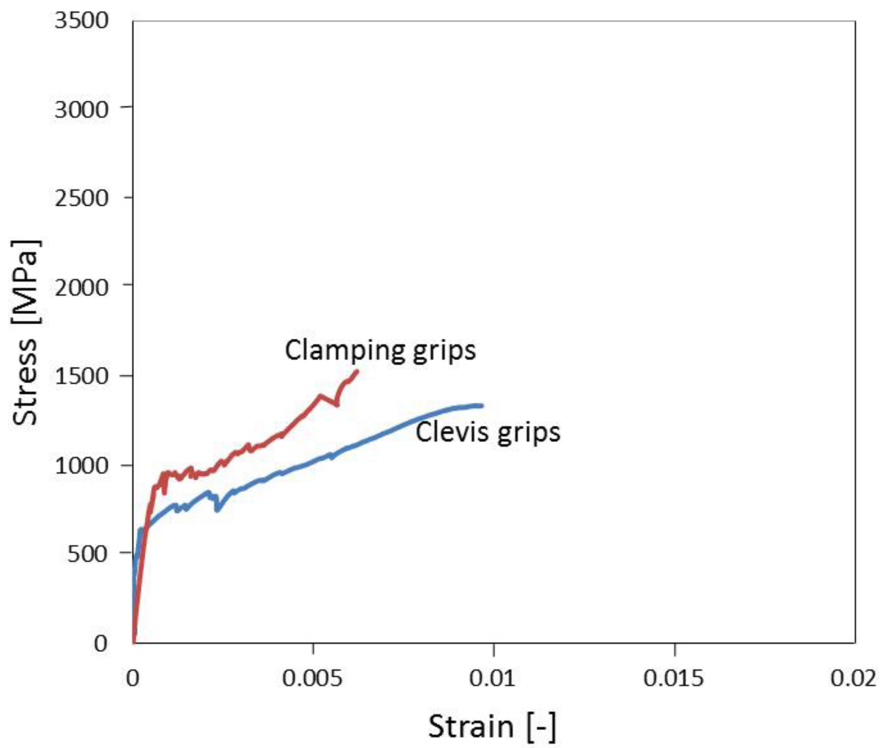


Figure 12. PBO-FRCM lap splice behavior with the different test setups