Mechanical characterization of basalt woven fabric composites: numerical and experimental investigation

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ABSTRACT. Basalt fabric composite, with different twill wave reinforcements, i.e. twill 2/2 and twill 1/3, have been studied in this work by means of experimental tests and numerical finite element (FE) simulations. As fabric reinforcements show repeating undulations of warp and fill yarn, simple mixtures law cannot be applied. As a consequence, the mesoscopic scale, lying between the microscopic and the macroscopic one, has to be taken into account to mechanically characterize a fabric reinforced composite. The aim of this work is to evaluate the stiffness of a fabric reinforced composite in warp and fill direction. In particular a numerical FE model, assuming elliptical sections and sinusoidal shape of the yarns, has been implemented and experimental tests have been carried out in order to validate the proposed model. Finally, the strength and the failure modes of the composite material, for each analysed structure and textile orientation, have been experimentally investigated.

SOMMARIO. Diverse tipologie di tessuti compositi con fibre di basalto, i.e. tessitura 2/2 e tessitura 1/3 con fibre di basalto sono stati studiati in questo lavoro mediante prove sperimentali e simulazioni agli elementi finiti (FE). Poiché i tessuti rinforzanti sono caratterizzati da ondulazioni ripetute di trama e ordito la semplice legge delle misture non può essere applicata. Per questo motivo la scala mesoscopica, via di mezzo tra quella microscopica e macroscopica, è utilizzata per la caratterizzazione meccanica di questa tipologia di compositi.
Scopo del presente lavoro è quello di determinare la rigidezza sia nella direzione della trama che in quella dell'ordito dei compositi rinforzati con tessuti. In particolare è stato implementato un modello numerico agli elementi finiti, (FE) realizzato ipotizzando le sezioni dei fasci di forma ellittica e con andamento sinusoidale e i risultati ottenuti sono stati validati mediante confronto sperimentale. Infine, si è investigato sulla resistenza e il modo di cedimento del materiale composito, per ogni struttura analizzata ed orientazione del tessuto.

KEYWORDS. Basalt fibre, Basalt fibre reinforced plastic, Fabric reinforcement, Woven fabric, Tensile testing, Representative Volume Element (RVE).

INTRODUCTION

Woven fabric (WF) composite materials are of particular interest in the scientific community due to their mechanical performances compared to the unidirectional laminates. In particular, textile composites offer better dimensional stability over a large range of temperatures, better impact resistance and tolerance; subtle conformability and deep draw moldability, compared to the common unidirectional laminated composites.

The variety of manufacturing methods have made the textile composites cost-competitive, therefore they are used in many application fields and they are being considered for intra and interlaminar strength and damage resistance.

Among the various textile forms, woven fabrics are the most widely used in composites, they provide more balanced properties in the fabric plane and the interlacing of yarns provides higher out of plane strength, which can take up the secondary loads due to load path eccentricities, local buckling, etc.

Simplified theoretical approaches to predict the mechanical behaviour of such a kind of composite material are quite little, in fact most of the models are limited to the unidirectional reinforced layers and they use the homogenization technique.

Several studies, on 2-D and 3-D geometries, have been carried out to model and analyse the mechanical properties of the reinforced composite materials. In particular, Barbero et al [1], developed an accurate model of a plain wave fabric in order to evaluate its mechanical properties assuming a sinusoidal shape of the tow fibres. Stress and strain averaging procedure has been studied by Yiwie Jiang et al. [2], for local/global analysis of plain-weave fabric composites, where, within a representative volume cell, using uniform stress and uniform strain assumptions, the constitutive equations are averaged along the thickness direction. Chou and Ito [3] analysed the strength and failure behaviour of plain weave composites. In particular, the geometrical characteristics of yarn shape, laminate stacking configuration, fibre volume fraction, and yarn packing fraction were investigated using three-dimensional geometrical models. Based on the geometrical characteristics, iso-strain approach was developed to predict elastic properties, stress distributions, and strengths under tensile loading.

N. K. Naik et al. [4] developed a two-dimensional closed-form analytical method for the thermo-elastic analysis of two-dimensional orthogonal plain weave fabric laminas, considering the volume fraction of fibres and the possible gap between the two adjacent strands.

Finally, analytical models of the plain weave laminated composites to evaluate the elastic properties of woven fabric composites are reported in [5].

However, most of these works are related to plain wave fabrics, while not many efforts to study the twill wave type have been carried out.

The aim of this work is to evaluate the stiffness of a fabric reinforced composite in warp and fill direction. In particular a numerical FE model, assuming elliptical sections and sinusoidal shape of the yarns, has been implemented and experimental tests have been carried out in order to validate the proposed model.

Results in terms of stress-strain response and stiffness, for the different analysed structures are reported and discussed.

Finally, the strength and the failure modes of the composite material, for each analysed structure and textile orientation, have been experimentally investigated.

MATERIALS AND TEST PROCEDURES

Woven fabric composites made in continuous basalt fibres and polymeric matrix has been investigated. Test panels have been produced by placing hand all the constituent layers, as shown in Fig. 1, and a curing treatment at room temperature in vacuum bag has been carried out, in order to get the final product.

All test panels have been produced using the same epoxy matrix system [6] and two different orientations of the fibres have been considered, as reported in Tab. 2. According to the German standard DIN EN 2747 [7], each panel has been processed with the aim to get a thickness of approx. 2 mm.

Two different fabric types have been used in this investigation, i.e. twill 2/2 and twill 1/3, details are reported in [5]. The corresponding layups and technical data, according to the provided data sheet [12] are listed in Tab. 2.

Tensile test specimens, with plane dimensions of 250 x 25 mm [7], have been obtained by water jet cutting from the panel produced in autoclave as shown in Fig. 2. In order to avoid the failure of the specimens near to the gripping zone, due to the local stress concentration, and with the aim to prevent eccentricity of load and limit bending phenomena during the setup, tabs have been bonded to both the ends of each sample, Fig. 3. According to [7], they were made of glass fiber reinforced plastics with a ±45°-layup and with dimensions of 25 x 45 x 1.5 mm.

The volume fraction of fibre has been evaluated by calculating the mass variation of a sample after heat treatment. In particular, a certain number of specimens, with plane dimensions of 20 x 10 mm, has been collected from the created panels, and each of them has been weighted by using a precision balance METTLER TOLEDO 204-S. A heat treatment, needed to completely burn the polymeric matrix without effecting the reinforcement [8-11], has been performed by using a Muffle furnace CARBOLITE EML 11/6 for 15 minutes at 620 °C. After cooling, all the treated samples have been weighted again, therefore, the density of the matrix and fibres and, consequently, the fibre volume content, φ_f , according to the standard DIN EN 2559 [13], has been calculated as below:

$$\varphi_f = \frac{V_f}{V_c} = \frac{V_f}{V_c + V_m} = \frac{\dfrac{m_f}{\rho_f}}{\left(\dfrac{m_f}{\rho_f} + \dfrac{m_c - m_f}{\rho_m}\right)} \qquad (1)$$

where the subscripts *f*, *m* and *c* indicate the fibre, matrix and composite properties, respectively, V is the volume, m is the mass and ρ is the density.

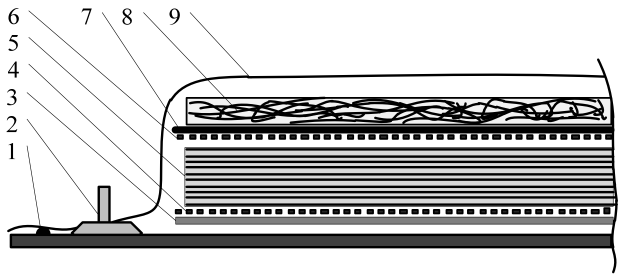

Figure 1: Scheme of the layup used in the processing: 1 sealant tape, 2 vacuum connector, 3 release film, 4 peel ply, 5 composite layup, 6 peel ply, 7 perforated foil, 8 bleeder, 9 vacuum bag.

Basalt fibres		**Epoxy resin**	
Mechanical Property	*Value*	*Mechanical Property*	*Value*
Density, ρ	2.75 g/cm³	Density, ρ	1.15 g/cm³
YOUNG's modulus, E_1	89 GPa	YOUNG's modulus, E	2.65 GPa
YOUNG's modulus, E_2	89 GPa	Shear modulus, G	0.98 GPa
Shear modulus, G_{12}	21.7 GPa	POISSON's ratio, ν	0.35
Shear modulus, G_{23}	21.7 GPa		
POISSON's ratio, ν_{12}	0.26		
POISSON's ratio, ν_{23}	0.26		

Table 1: Mechanical properties of basalt fibres [12] and epoxy resin [6].

Fabric type	Yarn type	Specific weight in g/m²	Warp yarns per cm	Fill yarns per cm	Layup	Layers	Thickness in mm	Fibre volume content ρ_f in %
Twill 2/2	Thread of direct roving	334	16	9	$[0°/90°]_6$	6	~1,8	51.85
Twill 2/2	11.5 µm 110 tex	334	16	9	$[90°/0°]_6$	6	~1,8	47.88
Twill 1/3	Direct roving	362	18	8	$[0°/90°]_6$	6	~1,9	49.17
Twill 1/3	11.5 µm 110 tex	362	18	8	$[90°/0°]_6$	6	~1,8	54.75

Table 2: Types of fabrics, specific weights and layups.

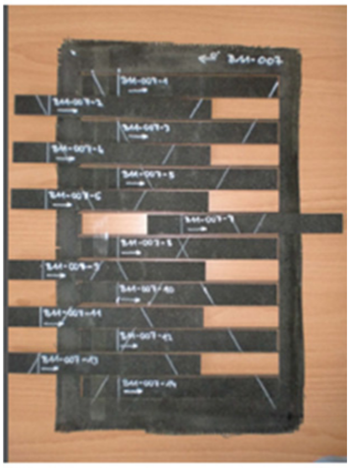

Figure 2: Typical composite plate after cutting using water jet in order to produce tensile test samples.

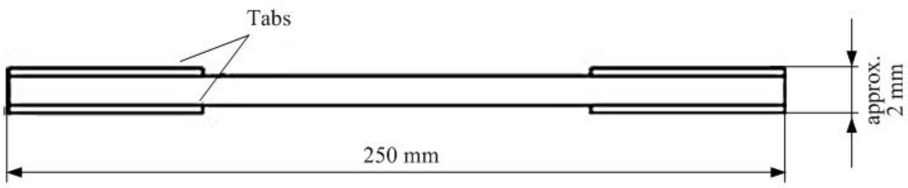

Figure 3: Side view of the tensile test specimens with tabs according to German standard DIN EN 2747 [7].

Experimental tensile tests, in order to evaluate the mechanical properties of the fabric composites, in terms of stiffness and strength, have been carried out according to [7]. Each test has been performed using a universal servo-hydraulic testing machine (Instron 8500), at room temperature T=298 K and the strain has been measured by a resistance extensometer with a gauge length of 20 mm.

Finite-Element-Analyses

A representative volume element (RVE) of the fabric composite has been geometrically defined and numerically modelled.

In order to evaluate the geometric dimensions of the RVE, top view of the dry fabric and side view of a cross-section of the test panels have been investigated using an optical microscope. Information about length and width have been obtained and they have been properly matched with the geometric dimensions provided in the data sheet.

Fig. 4 shows a depiction of the cross-section of a single lamina for both of the analysed structures. The height of the RVE has been simply obtained by dividing the thickness of the test panel by the number of constituent laminas.

The geometry of the RVE has been carefully modelled, in different steps, by using a commercial CAD software as follows:

1. Modeling of warp and fill yarn (corresponds to the dry fabric);
2. Separately modeling of the surrounding matrix;
3. Assembling of the fabric and matrix in order to get the final geometric model of the RVE.

Fig. 5 shows a 3-dimensional depiction, in wireframe, of the final obtained RVEs for both of the fabric reinforcements.

According to [5], in order to better simulate the real shape of the fabric composite, the trend of the warp and fill yarn have been modelled using a sinusoidal shape which can be expressed as [5, 14]

$$y = A \cos\left(\frac{2\pi x}{c}\right) \tag{2}$$

where A is the amplitude, and c is the pitch of the tow path curve, Fig. 6(a). An elliptical shape has been assumed to model the cross-sections of the warp and fill yarn [15, 16].

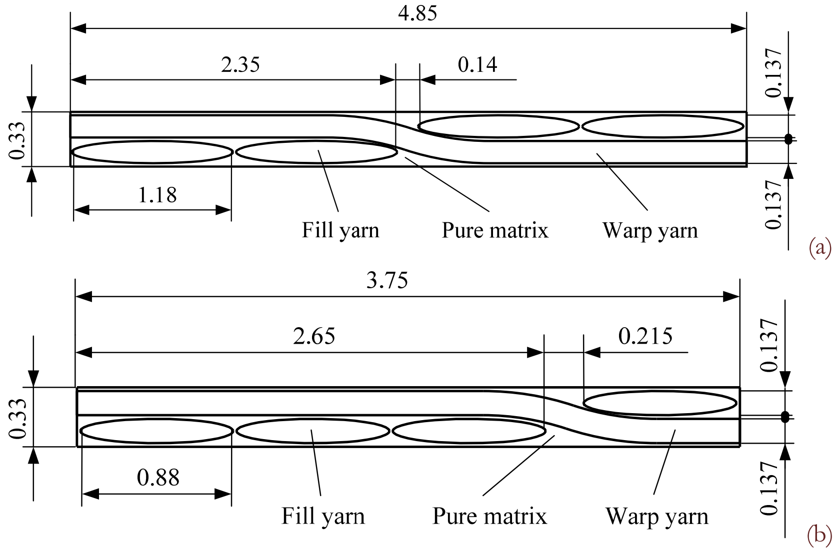

Figure 4: Schematic depiction of sample cross-sections for the two types of dry fabric reinforcements. (a) Twill wave 2/2; (b) Twill weave 1/3.

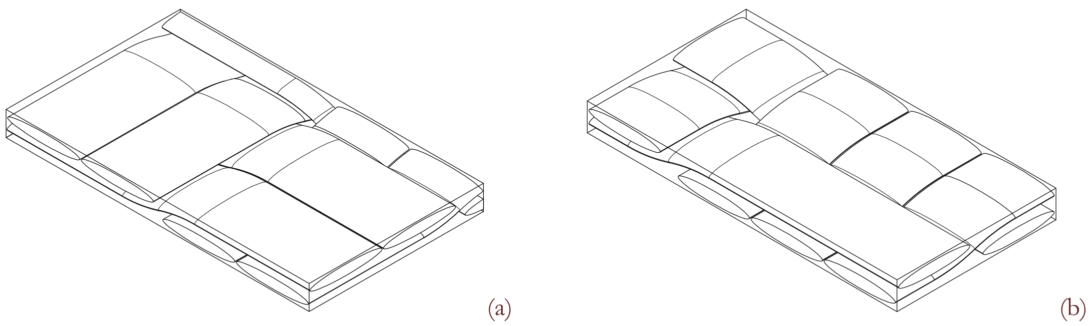

Figure 5: 3D models of the RVE. (a) Twill weave 2/2; (b) Twill weave 1/3.

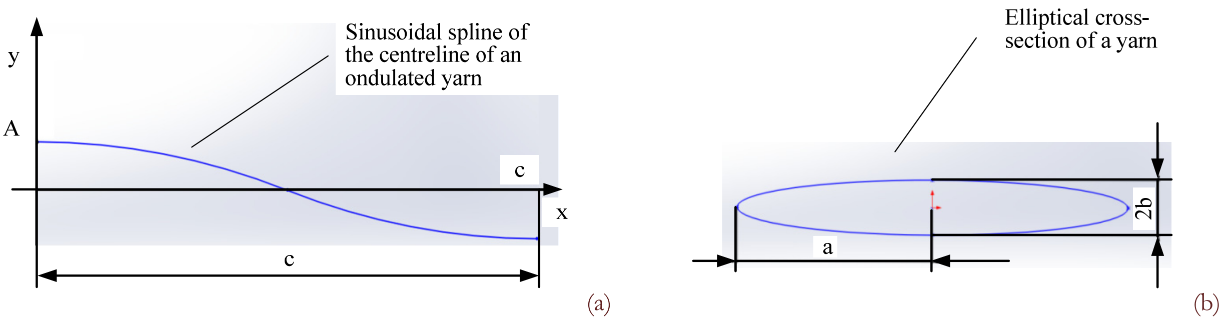

Figure 6: Simplifying assumptions for analytical description of the geometry: (a) Sinusoidal spline about centreline of an undulated yarn; (b) Elliptical cross-section of a yarn.

Starting from the created geometry, the FEM model has been generated by using a commercial finite element software. The mesh distribution, with a proper size, has been generated by means of an automatic option of the FEM software and a depiction of the meshed RVE for the twill weave 2/2 and twill weave 1/3, respectively, is shown in Fig. 7.
As a first approach an idealized contact has been obtained by imposing the coincidence of nodes in the matrix-fibres interface, therefore failure mechanisms and friction effects were neglected. Furthermore, this assumption results in no relative displacement between the three different regions, i.e. warp yarns, fill yarns and pure matrix.
In order to properly assign the mechanical properties of each component of the RVE, i.e. matrix and fibres tow, two different reference systems have been considered, respectively. Linear elastic properties have been imposed to the yarns, but, in order to simulate the orthotropic behaviour of the material two additional reference systems have been introduced:

the one to assign the mechanical properties of the warp yarns and the other one to assign the fill yarns properties, respectively. Isotropic linear elastic properties have been assumed for the matrix and data listed in Tab. 1 have been assigned to it. This assumption requires no further specification of the mesh orientation.

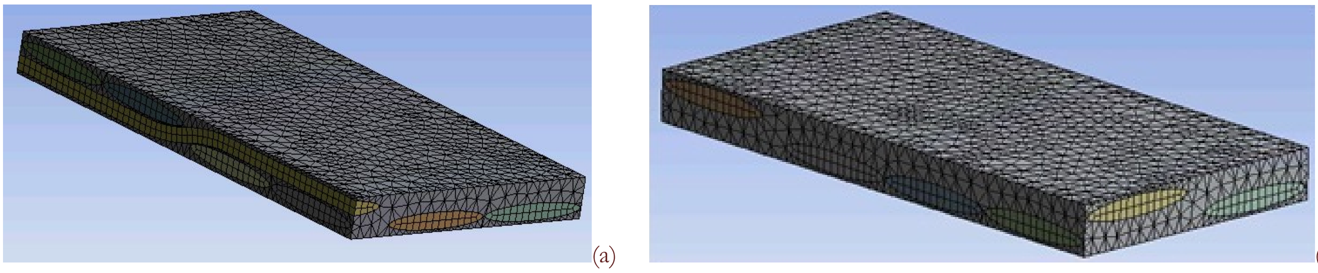

Figure 7: FE models of the RVEs (a) Twill weave 2/2; (b) Twill weave 1/3.

In order to correctly assign the mechanical properties to the yarns, it has to consider that each tow is characterized by a big percentage of fibres immersed in epoxy matrix. Furthermore, the calculation of the material properties should be based on the experimentally determined values of the fibre volume content φ_f, previously described. However, the latters have been calculated based on a bigger volume of material than the RVE, therefore, in order to match the data and to correctly assign the material properties to the yarns, the fibre volume content of the yarns in the RVE, $\varphi_{f,y}$, has been determined by modifying the one experimentally calculated, φ_f, as below:

$$\varphi_{f,y} = \frac{V_{RVE}}{V_y}\varphi_y = \frac{1}{X_y}\varphi_f \tag{3}$$

where V_{RVE} is the RVE volume, V_y is the tow volume of the RVE, x is the relative volume of yarns in the RVE. Details of the new data are listed in Tab. 3.

Fabric type and test direction	φ_f experimentally determined	Region in the RVE	Relative volume x in the RVE	$\varphi_{f,y}$ based on exp. values	$\varphi_{f,y}$ standardized to 50 % in the RVE
Twill weave 2/2 Warp	51.85 %	Warp and fill yarns Polymeric matrix	76.00% 24.00%	68.22%	65.79%
Twill weave 2/2 Fill	47.88 %	Warp and fill yarns Polymeric matrix	76.00% 24.00%	63.00%	65.79%
Twill weave 1/3 Warp	49.17 %	Warp and fill yarns Polymeric matrix	79.00% 21.00%	62.24%	63.29%
Twill weave 1/3 Fill	54.75 %	Warp and fill yarns Polymeric matrix	79.00% 21.00%	69.30%	63.29%

Table 3: Calculated fibre volume content, $\varphi_{f,y}$, to used in FE-analyses.

The new calculated values of the fibre volume content $\varphi_{f,y}$ are based on the relative volumes ratio of the different phase of the RVEs and on the fibre volume content experimentally calculated, φ_f. Therefore, the geometric dimensions of the yarns, the thickness of the RVEs [15, 16, 18] as well as the accuracy of the experimental determination of φ_f, affect this calculation.
The yarn is considered as a unidirectional reinforced phase with a transversally isotropic behaviour, therefore, nine elastic constants (five are independent) are required to assign the transversally isotropic properties to the reinforced regions of the RVE. The evaluation is described in the following.
In particular, in the predominant direction the stiffness can be calculated by means of the mixture law, as below:

$$E_1 = \varphi_{f,y} E_f + \left(1 - \varphi_{f,y}\right) E_m \tag{4}$$

As the basalt fibre and the polymeric matrix can be considered as homogeneous isotropic materials, the respective shear moduli can be calculated by $G=E/2(1+\nu)$, where the corresponding values are listed in Tab. 1. Mixture law, according to Chamis [19, 22], can be applied in order to calculate three more independent linear-elastic properties of the yarns, namely:

$$E_1 = E_2 = \frac{E_m}{\left(1-\sqrt{\varphi_{f,y}}\left(1-\frac{E_m}{E_f}\right)\right)} \tag{5}$$

$$G_{12} = G_{13} = \frac{G_m}{\left(1-\sqrt{\varphi_{f,y}}\left(1-\frac{G_m}{G_f}\right)\right)} \tag{6}$$

$$\nu_{12} = \nu_{13} = \varphi_{f,y}\nu_f + \left(1-\varphi_{f,y}\right)\nu_m \tag{7}$$

The remaining parameters, needed to fully define the material properties of the RVE, have been calculated exploiting the Maxwell-Betti's law, $E_i\,\nu_{ji}= E_j\,\nu_{ij}$, as below:

$$\nu_{21} = \nu_{31} = \frac{E_2}{E_1}\nu_{12} \tag{8}$$

Finally, the last independent parameters, i.e. G_{23}, G_{32}, ν_{23} and ν_{32} have been calculated

$$G_{23} = G_{32} = \frac{G_m}{\left(1-\sqrt{\varphi_{f,y}}\left(1-\frac{G_m}{G_{f,23}}\right)\right)} \tag{9}$$

$$\nu_{23} = \nu_{32} = \left(\frac{E_2}{2G_{23}}\right) - 1 \tag{10}$$

Finally, appropriate boundary conditions have been applied to the RVE in order to:

1. ensure a purely longitudinal deformation;
2. allow contraction of the cross-sections due to Poisson's effects;
3. avoid twisting and bending effects.

RESULTS AND DISCUSSION

Experimentally and numerically determined stiffness

Results, in terms of stress-strain response, for both of the fabric reinforcements, i.e. twill 2/2 and twill 1/3, are reported in Fig. 8(a) and Fig. 8(b), respectively.

Figures clearly exhibit an high repeatability of the response in all the cases. This can be attributed to a constant material quality over the whole test panel. However, whereas the 2/2 fabric type shows a clear difference, in terms of stiffness and strength, along the warp and fill direction, the 1/3 fabric type does not show substantial variations. Furthermore, the textile exhibits higher stiffness and strength along the warp direction than the fill one for both of the fabric types.

Using the weighted average method, as a first approximation [21, 22], the stiffness of the specimens have been calculated as secant modulus $E_{s.0.5\%}$ at a strain value of ε=0.5% and tangent modulus $E_{t.0.1\%}$ (as a Secant Modulus at a strain of ε=0.1%) according to German standard DIN EN 2747 [7].

For each textile specimen and layup the average values and standard deviations have been calculated, respectively [23-25]. Fig. 9 and Fig. 10 show the stiffness related to each textile semi-finished product as secant modulus $E_{s.0.5\%}$ and tangent modulus $E_{t.0.1\%}$ with the respective standard deviations. In particular, whereas Fig. 9 shows the secant moduli and tangent moduli based on the experimentally determined values of the fibre volume content, Fig. 10 shows the values standardized to a fibre volume content $\varphi_f=50\%$.

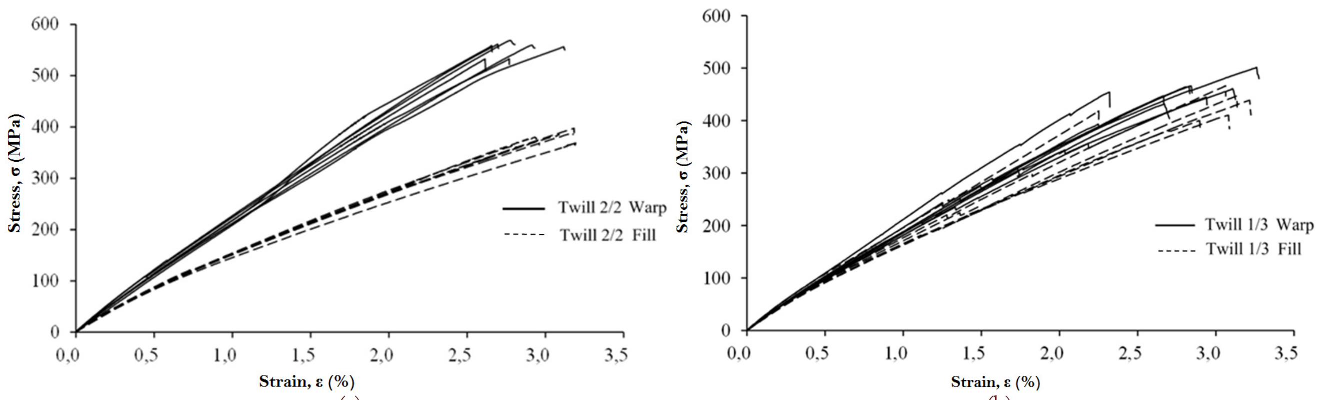

Figure 8: Stress-strain diagrams as results of the experimental tensile tests: (a) fabric type twill 2/2 in warp and fill direction; (b) Fabric type twill 1/3 in warp and fill direction.

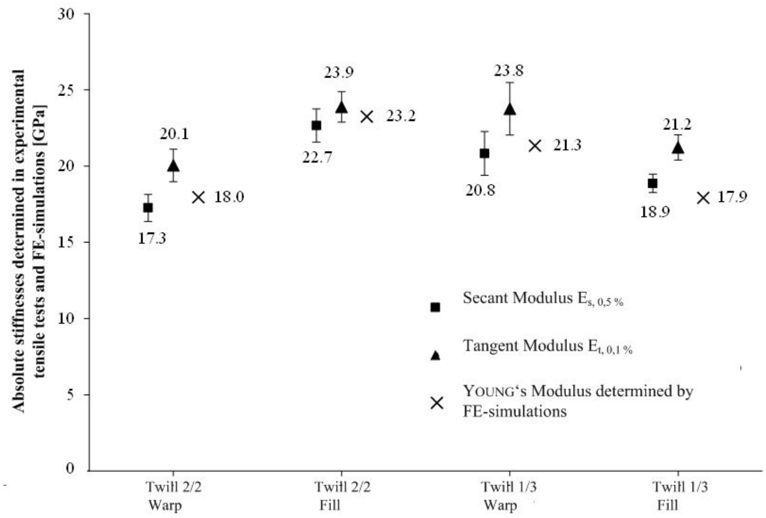

Figure 9: Secant modulus and tangent modulus of the respective textile semi-finished products based on the experimentally determined values of the fibre volume content of φ_f.

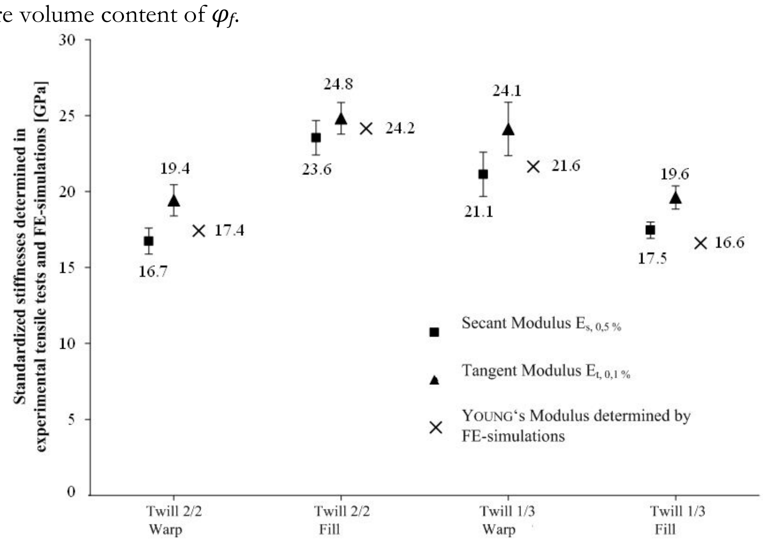

Figure 10: Secant modulus and tangent modulus of the respective textile semi-finished products standardized to a fibre volume content of $\varphi_f=50\%$.

The stiffness values, numerically calculated, show good agreement with the corresponding experimental ones in both the considered cases, i.e. experimental and standardized, $\varphi_f=50\%$, fibre volume content. In particular, the stiffness determined by the FE-analyses lies in the range of the secant modulus $E_{s.0.5\%}$ and the tangent modulus $E_{t.0.1\%}$. As an exception the numerical results for the stiffness of the twill weave 1/3 in fill direction yield slightly lower values than the experimental ones.

Experimentally determined strengths and corresponding failure modes

Tensile strength values $\sigma_{z.B}$, based on the experimental results, have been calculated, according to [22] and [12], and shown in Fig. 12, respectively. In particular the experimental values related to the twill weave 2/2 reinforcement are higher than the ones calculated by the indicated values in the data sheets, while a good agreement has been observed for the twill weave 1/3 reinforcement.
With the aim to provide a proper interpretation of the experimental tensile tests a careful analysis on the failure modes and crack path propagation has been carried out.
In particular, in Fig. 11 is shown a depiction of a typical fracture mode of a specimen with twill weave 2/2 reinforcement. Woven fabric with 0°-90° and 90°-0° orientation exhibited analogous failure modes. The crack started in the gauge length and proceeded perpendicularly to the applied load.

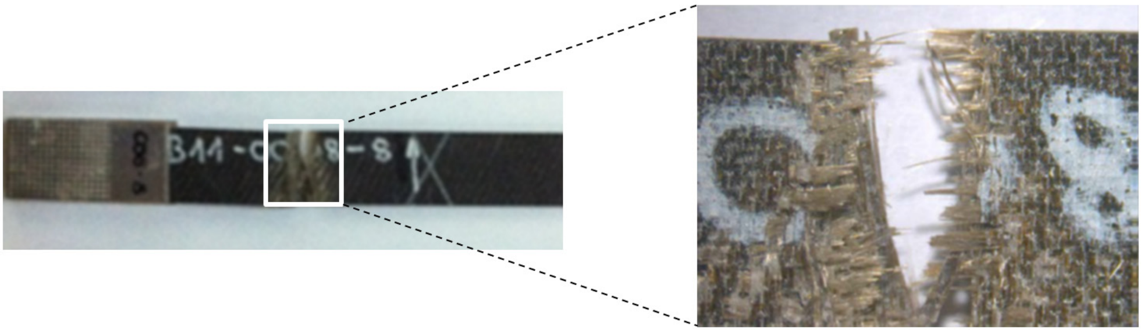

Figure 11: Fractured specimen with twill weave 2/2 fabric reinforcement in the warp direction. The area enclosed in the square box show details of the damage mechanism.

In Fig. 13 is shown a depiction of a typical fracture mode of a specimen with twill weave 1/3 reinforcement. Similar to the previous case study, the orientation of the woven fabric did not affect the failure mode and the crack started in the gauge length. However, the crack path is inclined of approx. 45° to the applied load axis.

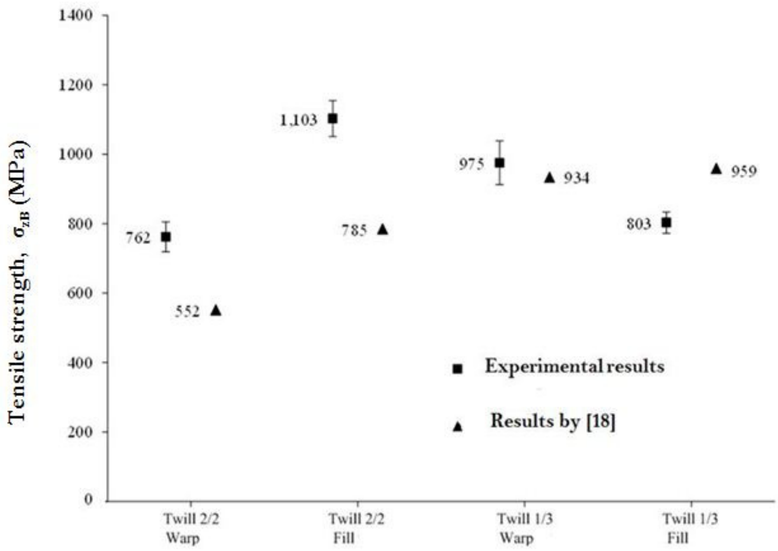

Figure 12: Calculated tensile strengths of the respective textile semi-finished products standardized to a fibre volume content of $\varphi_f=50\%$.

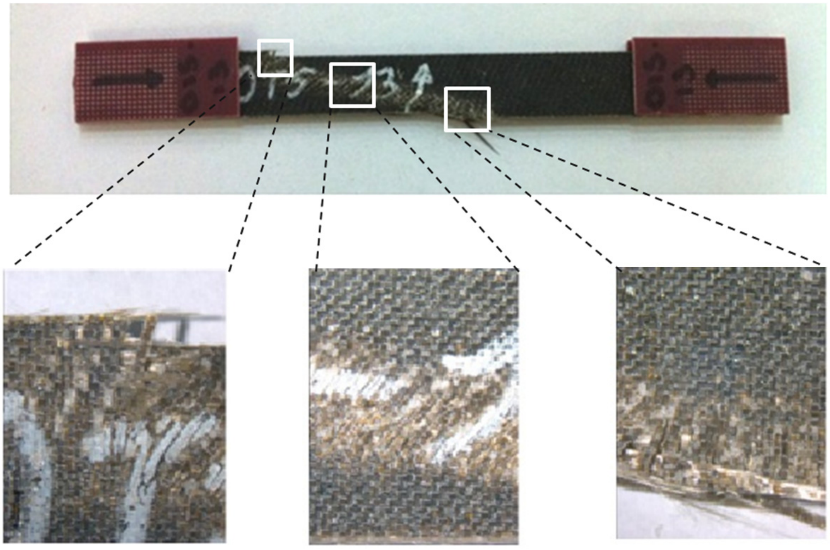

Figure 13: Fractured specimen with twill weave 1/3 fabric reinforcement in the fill direction. The areas enclosed in the square boxes show details of the damage mechanism leading to sample failure.

CONCLUSIONS

Basalt fabric composite, with different twill wave reinforcements, i.e. twill 2/2 and twill 1/3, have been studied in this work by means of experimental tests and numerical finite element (FE) simulations. In particular, the mechanical response and the stiffness of a fabric reinforced composite in warp and fill direction has been analysed. The numerical FE model has been properly implemented assuming elliptical sections of the tows and sinusoidal shape of the yarns and particular attention has been applied to generate the RVEs geometry. The obtained results have been compared with the experimental data in order to validate the proposed model and a good agreement has been observed.

Therefore the FE-method can be considered an adequate way to predict the stiffness of woven fabric composite with different geometries in the mesoscopic scale or even different kind of fibre reinforcement.

Finally, the strength and the failure modes of the composite material, for each analysed structure and textile orientation, have been experimentally investigated.

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