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LONGITUDINAL STIFFNESS CHARACTERISTICS OF UNIDIRECTIONAL FIBRE REINFORCED POLYMERIC COMPOSITES SUBJECTED TO TENSION

BY

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Abstract. Unidirectional fibre reinforced polymer (FRP) composite elements are utilized nowadays as reinforcing bars for concrete members or for externally bonded laminates applied on the tension side of reinforced concrete beams in the so called *plate bonding strengthening technique*. Since these composite products are subjected to tension in both cases it is important to know the longitudinal tensile modulus of elasticity, in the fibres direction. The properties of a FRP composite depend on the properties of its constituents and on their distribution characterized by constituents volume fractions. To avoid time consuming and expensive experimental procedures analytical models have been proposed to determine the effective longitudinal modulus of the composites in terms of constituent material properties. The main models utilized in micromechanics of fibrous composites are analysed and exemplified in the paper on FRPs made of thermosetting polymers and various reinforcing fibres made of glass and basalt. It has been found that the rule of mixture constitutes a rapid and precise tool for the analytical determination of the longitudinal modulus. Other more sophisticated models and the experimental results obtained by the authors of this paper confirm the appropriatness of the rule of mixtures for the analytical evaluation of the tensile longitudinal modulus.

Key words: stiffness; longitudinal modulus; analytical models; composite constituents.

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1. Introduction

Fibre reinforced polymer (FRP) composites represent a class of materials that has attracted attention of engineers in construction of civil structures (Bakis *et al*., 2002). The classification of certain materials as composites is often based on cases where significant property changes occur as a result of the combination of constituents.

Some authors (Agarwal *et al*., 2006) consider that the property changes are generally most obvious when one of the phases is in fibrous form, when fibre volume fraction exceeds 10%, and when the property of strong and stiff constituent is at least five times greater than the other component. In fibrous polymeric composites, fibres with high strength and high stiffness are embedded in and bonded together by the low modulus continuous polymeric matrix.

In the case of FRP composites the reinforcing fibres constitute the backbone of the material and they determine its strength and stiffness in the direction of fibres, although some "lateral contributions" are not excluded. The polymeric matrix binds together the fibres and protects their surfaces from damage. It disperses the fibres, separates them and also transfers stresses to them.

The matrix should be chemically and thermally compatible with the reinforcing fibres. The interface region controls the overall stress–strain behavior of the composites and has a decisive role in the failure mechanisms and fracture toughness of the polymeric composites (Barbero, 2011).

Most composite structures made of fibrous composites, consist of several distinct unidirectional laminas. A lamina is a flat or curved arrangement of unidirectional or woven fibres in a support matrix. The unidirectional lamina (Fig. 1) is the basic building block in a laminated FRP composite material.

A unidirectional composite consists of parallel fibres embedded in a matrix. The direction parallel to the fibres is called the *longitudinal direction* (axis *1* or *L*) and the direction perpendicular to the fibres in the *1-2* plane is called the *transverse direction*. Any direction in the *2-3* plane is also a transverse direction. These axes are also referred to as the material axes of the lamina. A similar system of axis can be attached to a FRP reinforcing bar (Fig. 2 – Ţăranu, 2011).

The properties of a composite material depend on the properties of its constituents, their distribution and physical and chemical interactions. These properties can be determined by experimental measurements but one set of experimental measurements determines the properties of a fibre-matrix system produced by a single fabrication process. When any change in the system variables occur, additional measurements are required.

These experiments may become time consuming and cost prohibitive; therefore, a variety of methods have been used to predict the properties of composite materials (Agarwal *et al.*, 2006; Daniel & Ishai, 2006). The mechanics of materials approach is based on *micromechanics.* In most composite studies, micromechanics means the analysis of the effective composite properties in terms of constituent material properties.

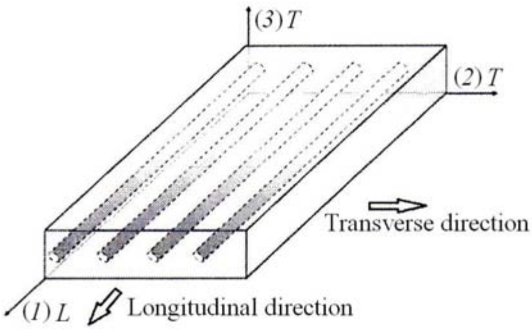


Fig. 1 – A unidirectional fibre reinforced lamina and principal material axes.

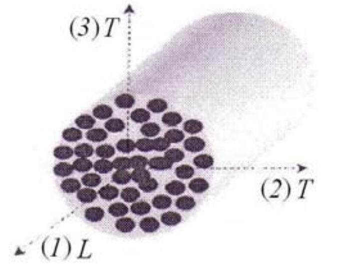


Fig. 2 – A unidirectional fibre reinforced round bar and its principal axes.

The unidirectional composite shows different properties in the material axes directions. Thus, this type of composites are *orthotropic* with their axes *1*, *2*, *3* as axes of symmetry (Figs. 1 and 2). These unidirectionally fibre reinforced composite elements have the strongest properties in the longitudinal direction; material behaviour in the other two directions (*2, 3*) is nearly identical because of the random fibre distribution in the cross section. Therefore, a unidirectional composite can be considered to be transversely isotropic, that is, it is isotropic in the *2-3* plane.

2. Constituents of FRP Composites

Fibres are used in polymeric composites because they are strong, stiff and lightweight. Fibres are stronger than the bulk material that constitutes the fibres due to their preferential orientation of molecules in the fibre direction and because of the reduced number of defects present in the fibre compared to the bulk material. Fibres are used as continuous reinforcements in unidirectional composites by aligning them in elementary layers. A unidirectional lamina has maximum values of mechanical properties (strength and modulus) along the fibres direction and minimum values for the same properties in the direction normal to the fibres.

The most common isotropic fibres are made of glass (*E*-glass, *S*-glass and ECR-glass). *E*-glass is the least expensive of all glass types and it has a wide application in fibre reinforced plastic industry. *S*-glass has higher tensile strength and higher modulus than *E*-glass. However, the higher cost of *S*-glass fibres makes them less popular than *E*-glass (Gay & Hoa, 2007). Alkali-resistant glass fibres (ECR-glass) contain an amount of zirconium which helps prevent corrosion by alkali attacks in cement matrices. For applications requiring high temperature and chemical resistance, mechanical resistance and low water absorption, basalt fibres are recommended (Şerbescu *et al*., 2008). The main properties of glass fibres and basalt fibres are summarized in Table 1.

Table 1
Typical Properties of Glass and Basalt Fibres for FRP Composites

Fibre type	Density kg/m^3	Tensile strength MPa	Young modulus GPa	Ultimate tensile strain %	Poisson's coefficient
E-glass	2,500	3,450	72.4	2.4	0.22
S-glass	2,500	4,580	85.5	3.3	0.22
ECR-glass	2,670	3,500	80.5	4.7	0.22
Basalt	2,750	4,800	89	3.15	0.20

Matrix in a polymeric composite can be regarded as a structural or a protection component. The main functions of a matrix are the following: binds the reinforcements together, transfers stresses to the fibres, protects the reinforcements from environments and mechanical abrasion, provides the composite with a solid form, controls the transverse properties, allows the strength of the fibres to be used to their full potential by providing effective load transfer from external forces to the reinforcement, holds reinforcing fibres in the proper orientation so that they can carry the intended loads and determine the thermal stability and maximum temperature use of the FRP composite (Ţăranu & Bejan, 2005).

Table 2
Typical Properties for Thermosetting Matrices

Property	Matrix		
	Polyester	Epoxy	Vinyl ester
Density, [kg/m^3]	1,200...1,400	1,200...1,400	1,150...1,350
Tensile strength, [Mpa]	34.5...104	55...130	73...81
Longitudinal modulus, [Gpa]	2.1...3.45	2.75...4.10	3.0...3.5
Poisson's coefficient	0.35....0.39	0.38...0.40	0.36...0.39

Most FRP composites utilized in structural applications for civil engineering are based on *thermosetting polymers*. These polymers have strong bonds both within and between the molecules. They develop a network structure that sets them in shape. If they are heated after they have been cured, they do not melt and will retain their shape until they begin to thermally decompose at high temperature. The most common thermosetting resins are epoxy, polyesters and vinylester. Their main properties are given in Table 2.

3. Elastic Modulus of FRP Composites in the Longitudinal Direction

A quick analytical evaluation of the stiffness properties along fibre direction can be performed using the *elementary mechanics of materials models* adopted in the elastic range and based on the following assumptions (Halpin, 1992; Jones, 1999; Agarwal *et al*., 2006):

a) A unidirectional composite may be modelled by assuming fibres to be uniform in properties and diameter, continuous, perfectly aligned and parallel throughout the composite.

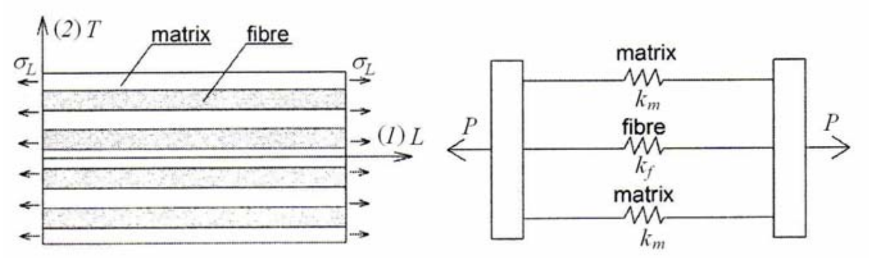
b) It may be assumed that a perfect bonding exists at the interface, so that no slip occurs between fibre and matrix materials.

c) The fibre and matrix materials are assumed to be homogeneous and linearly elastic. The matrix is assumed to be isotropic, but the fibre can be either isotropic or orthotropic.

d) Both components, fibres and matrix, are void free.

e) Since it is assumed that the fibres remain parallel and that the dimensions do not change along the length of the element, the area fractions must equal the volume fractions.

f) The composite lamina is initially stress free and macroscopically orthotropic.



a *b*

Fig. 3 – Model for FRP composite for predicting composite behaviour: *a* – composite lamina constituents; *b* – parallel model.

Let us consider the model of the unidirectional composite shown in Fig. 3. Since no slippage occurs at the interface and the strains of fibre, matrix and composite in the longitudinal direction are equal, we can write

$$\varepsilon_f = \varepsilon_m = \varepsilon_c \,, \tag{1}$$

where subscripts *f*, *m* and *c* refer to fibre, matrix and composite, respectively. For the model shown in Fig. 3 *a*, the load is shared between the fibres and the matrix as illustrated in Fig. 3 *b* by the springs-in-parallel model (Jones, 1999).

For static equilibrium (Eq. (2)) the force acting on the lamina cross section must equal the sum of the forces acting on the fibre and matrix corresponding to their volume fractions

$$\sigma_L = \sigma_f V_f + \sigma_m V_m , \tag{2}$$

where: σ_L , σ_f, σ_m are the direct stresses in the composite, fibre and matrix in the longitudinal direction; V_f, V_m – volume fractions of fibre and matrix.

Eq. (2) can be differentiated with respect to strain, which is the same for the composite, fibres and matrix (Agarwal *et al.*, 2006)

$$\left(\frac{\mathrm{d}\sigma_c}{\mathrm{d}\varepsilon_c}\right)_L = \left(\frac{\mathrm{d}\sigma_f}{\mathrm{d}\varepsilon_f}\right)V_f + \left(\frac{\mathrm{d}\sigma_m}{\mathrm{d}\varepsilon_m}\right)V_m . \tag{3}$$

If the stress–strain curves of the materials are linear, the slopes ($\mathrm{d}\sigma/\mathrm{d}\varepsilon$) are constants and they can be replaced by the corresponding elastic modulus in eq. (3). Thus

$$E_L = E_f V_f + E_m V_m , \tag{4}$$

where: E_L is the longitudinal modulus of the unidirectional composite in the fibre direction; E_f , E_m – the fibre and matrix modulus, respectively, in the longitudinal direction (the constituents are isotropic in our case).

Relationships (2) and (4) are known under the name of *rule of mixtures* indicating that the contributions of the fibres and the matrix to the composite stress and elastic modulus, respectively, are proportional to their volume fractions. The constituents involved in eq. (4) are considered isotropic, assumption that is valid for all types of glass and basalt fibres and also for the polymeric matrices. The predictions of the rule of mixtures for the longitudinal elastic modulus are very close to the experimental results (Țăranu *et al.*, 2010).

Eq. (4) can be also written as

$$E_L = E_f V_f + E_m \left(1 - V_f\right) , \tag{5}$$

and it predicts a linear variation of the longitudinal modulus, E_L, with fibre volume fraction as shown in Fig.4.

The value of V_f = 1 is only hypothetical since the maximum fibre volume fraction cannot exceed 0.785 in case of square fibre array and 0.907 in case of hexagonal fibre array.

To take into account the potential imperfections in fibre alignments, a modified rule of mixture was proposed by Tsai & Hahn (1980)

$$E_1 = k\left(V_f E_f + V_m E_m\right), \tag{6}$$

where k is the fibre misalignment factor that varies between 0.9 and 1.0. It is an experimentally determined constant, depending to a large extent on the manufacturing process.

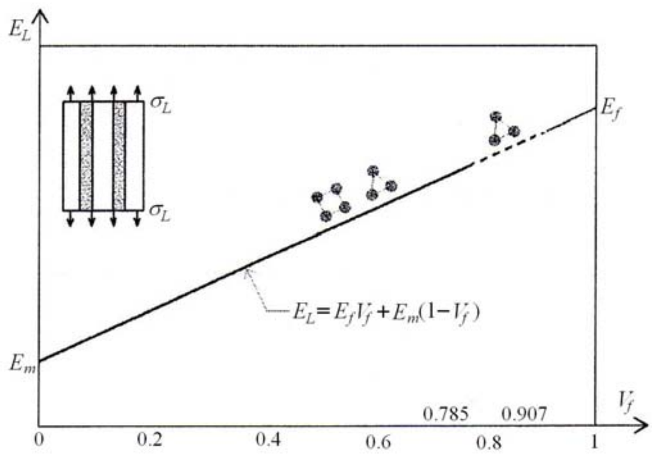


Fig. 4 – Variation of predicted E_L *vs*. fiber volume fraction.

4. Other Analytical Models for Longitudinal Modulus

4.1. Bounds for Elastic Modulus E_L

Since the 1960s analytical and experimental research work has been carried out for apropriate formulations of the main elastic characteristics of fibre reinforced composites. The upper and lower bounds of the longitudinal elastic modulus constants of transversely isotropic unidirectional composites have been determined by Cooke (1995). The corresponding formulas involve the elastic constants of fibres and matrix and their volume fractions. The plus and minus signs denote upper and lower bounds

$$E_{L+} = E_f V_f + E_m V_m + \frac{4\left(\nu_f - \nu_m\right)^2 V_f V_m}{\dfrac{V_f}{k_m} + \dfrac{V_m}{k_f} + \dfrac{1}{G_f}}, \tag{7}$$

$$E_{L-} = E_f V_f + E_m V_m + \frac{4\left(\nu_f - \nu_m\right)^2 V_f V_m}{\dfrac{V_f}{k_m} + \dfrac{V_m}{k_f} + \dfrac{1}{G_m}}, \tag{8}$$

where: ν_f, ν_m are the Poisson's coefficients of fibre and matrix respectively; G_f, G_m – the shear moduli of elasticity for fibre and matrix respectively,

$$G_f = \frac{E_f}{2\left(1+\nu_f\right)} > G_m = \frac{E_m}{2\left(1+\nu_m\right)}; \tag{9}$$

k_f , k_m – the plane strain bulk moduli for fiber and matrix, respectively. These relationships are valid for transversely isotropic unidirectional fibre reinforced composites for which

$$k_f = \frac{E_f}{2\left(1-\nu_f-\nu_f^2\right)} > k_m = \frac{E_m}{2\left(1-\nu_m-\nu_m^2\right)} \tag{10}$$

4.2. The Composite Cylinder Assemblage (CCA) Model

This model is considered to be one of the most suitable since it enables the exact analytical evaluation of the effective elastic moduli (Jones, 1999). The model consists of an assemblage of composite cylinders (Fig. 5), each made of a circular fibre core and a concentric matrix shell (ASME, 2001). The magnitude of the outer radii, R_i , may be selected at will and the size of fibre radii, r_i , is restricted by the requirement that in each cylinder the fibre volume fraction is kept constant (also meaning that the ratio r^2/R^2 is the same). For various values

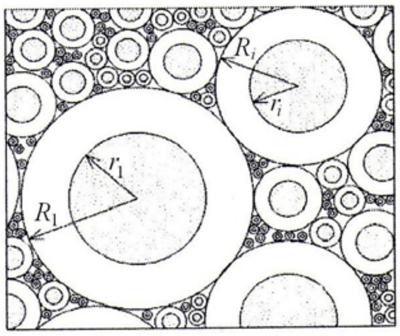


Fig. 5 – Composite cylinder assemblage (CCA).

of longitudinal loading, each composite cylinder behaves as an equivalent homogeneous cylinder. The volume of the material is progressively filled out with composite cylinders with different radii. Since the radii of the cylinders may be chosen arbitrarily small, the remaining volume can also be extremely small. Consequently, the properties of the assemblage approach the properties of one composite cylinder, namely

$$E_L = E_f V_f + E_m V_m + \frac{4\left(\nu_f - \nu_m\right)^2 V_f V_m}{\dfrac{V_f}{k_m} + \dfrac{V_m}{k_f} + \dfrac{1}{G_m}}. \tag{11}$$

4.3. The Self-Consistent Model

The model gives one of the most exact solutions and it is described in engineering terms by Whitney and Riley in 1966 (Halpin, 1992). This model has a single fibre embedded in a concentric cylinder of matrix material (Fig. 6) (Genta, 1982).

The volume fraction of the fibre embedded in the composite cylinder is the same as all fibres in the composite material.

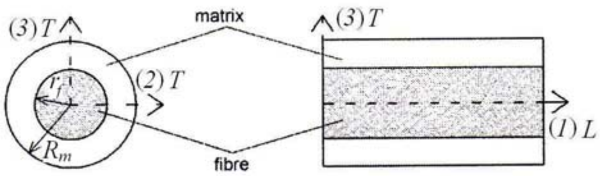


Fig. 6 – Self-consistent model.

The following relation has been developed to determine the longitudinal modulus:

$$E_L = E_m V_m + E_f V_f + \\ + \frac{4V_f V_m \left(\nu_m - \nu_f\right)^2 E_f V_f}{E_f V_f \left(1-2\nu_m\right)\left(1+\nu_m\right) + E_m V_m \left(1-2\nu_f\right)\left(1+\nu_f\right) + E_f \left(1+\nu_m\right)}. \tag{12}$$

The values calculated with eq. (12) are slightly larger than those evaluated with the rule of mixture.

5. Comparative Results

A comprehensive comparison among all results for the longitudinal elastic modulus, E_L, is presented in Table 3, which gives the detailed values of the calculation results, utilizing the described models. It can been seen that the determined values are very close to the rule of mixtures results, as illustrated in Figs. 7 and 8. The longitudinal modulus values obtained with the rule of mixtures formula are in agreement with those obtained in the experimental work carried out by the authors (Ţăranu *et al.*, 2010; Banu *et al.*, 2011), which were

Table 3

Longitudinal Elasticity Modulus of Composites with Various Reinforcement

Model	V_f	*E*-glass		*S*-glass		ECR		Basalt	
Rule of mixtures	0	3		3.00		3.00		3.00	
	0.1	9.94		11.25		10.75		11.60	
	0.2	16.88		19.50		18.50		20.20	
	0.3	23.82		27.75		26.25		28.80	
	0.4	30.76		36.00		34.00		37.40	
	0.5	37.70		44.25		41.75		46.00	
	0.6	**44.64**		**52.50**		**49.50**		**54.60**	
	0.7	51.58		60.75		57.25		63.20	
	0.8	58.52		69.00		65.00		71.80	
	0.9	65.46		77.25		72.75		80.40	
	1.0	72.40		85.50		80.50		89.00	
Inferior and superior limits	0	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
	0.1	9.95	10.05	11.26	11.37	10.76	10.87	11.61	11.72
	0.2	16.90	17.02	19.52	19.66	18.52	18.65	20.22	20.36
	0.3	23.84	23.97	27.77	27.91	26.27	26.41	28.82	28.96
	0.4	30.78	30.90	36.02	36.15	34.02	34.15	37.42	37.55
	0.5	37.72	37.83	44.27	44.38	41.77	41.88	46.02	46.13
	0.6	**44.66**	**44.75**	**52.52**	**52.61**	**49.52**	**49.61**	**54.62**	**54.71**
	0.7	51.60	51.66	60.77	60.83	57.27	57.33	63.22	63.28
	0.8	58.53	58.58	69.01	69.06	65.01	65.06	71.81	71.86
	0.9	65.47	65.49	77.26	77.28	72.76	72.78	80.41	80.43
	1.0	72.40	72.40	85.50	85.50	80.50	80.50	89.00	89.00
Composite cylinder assemblage	0	3.00		3.00		3.00		3.00	
	0.1	9.95		11.26		10.76		11.61	
	0.2	16.90		19.52		18.52		20.22	
	0.3	23.84		27.77		26.27		28.82	
	0.4	30.78		36.02		34.02		37.42	
	0.5	37.72		44.27		41.77		46.02	
	0.6	**44.66**		**52.52**		**49.52**		**54.62**	
	0.7	51.60		60.77		57.27		63.22	
	0.8	58.53		69.01		65.01		71.81	
	0.9	65.47		77.26		72.76		80.41	
	1.0	72.40		85.50		80.50		89.00	
Self-consistent	0	3.00		3.00		3.00		3.00	
	0.1	9.94		11.25		10.75		11.60	
	0.2	16.88		19.50		18.50		20.20	
	0.3	23.82		27.75		26.25		28.80	
	0.4	30.76		36.00		34.00		37.40	
	0.5	37.70		44.25		41.75		46.00	
	0.6	**44.64**		**52.50**		**49.50**		**54.60**	
	0.7	51.58		60.75		57.25		63.20	
	0.8	58.52		69.00		65.00		71.80	
	0.9	65.46		77.25		72.75		80.40	
	1.0	72.40		85.50		80.50		89.00	

calculated with other analytical models analysed in the paper. The significance of the notations and symbols utilized in Table 3 is: $f(V_f) = E_L$, calculated with

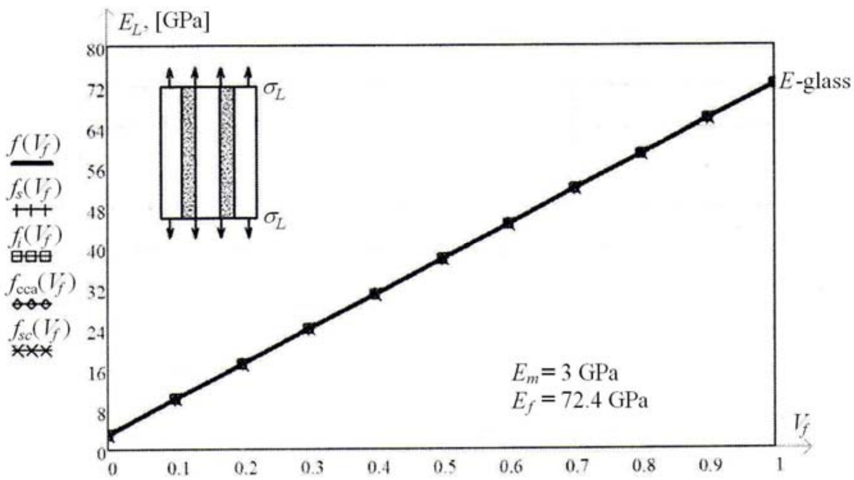


Fig. 7 – Longitudinal elasticity modulus variation of *E* glass reinforced composite in several models.

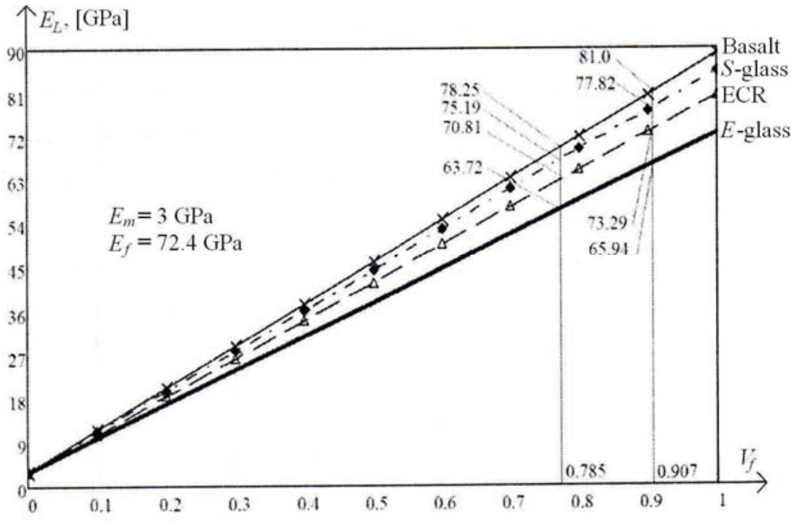


Fig. 8 – Longitudinal elasticity modulus variation of composites with variate reinforcement.

rule of mixtures; $f_s(V_f)$ = superior limit of E_L (E_{L-}), $f_i(V_f)$ = inferior limit of E_L (E_{L+}), $f_{\text{cca}}(V_f) = E_L$ determined with CCA model, $f_{sc}(V_f) = E_L$ evaluated with self-consistent model, $f_E(V_f) = E_L$ of composite with E glass reinforcement, $f_S(V_f) = E_L$ of composite with S-glass reinforcement, $f_{\mathrm{ECR}}(V_f) = E_L$ of composite with ECR reinforcement, $f_B(V_f) = E_L$ of composite with basalt reinforcement.

It can be noticed in Table 3 that the longitudinal elastic modulus determined with different analytical models described earlier and the rule of mixtures are very small.

A comparative analysis has been performed for the fibre volume fraction $V_f = 0.6$, a common value for FRP composite elements subjected to tension.

It has been found that the values calculated with the rule of mixtures and the self consistent model practically coincide; the values calculated with rule of mixtures are smaller than those obtained with CCA by 0.037% (for basalt fibres) and 0.045% (for E-glass); the same magnitude differences are determined when the rule of mixtures results are compared to the inferior limit.

Compared to the results calculated with superior limit, the rule of mixtures results are smaller by 0.20 % (for basalt fibres) and 0.24% (for E-glass).

Similar conclusions can be formulated concerning Fig. 7. Fig. 8 illustrates the different variation graphs of the longitudinal modulus depending on the type of reinforcing fibres.

The values of V_f (0.785 and 0.907) marked on the horizontal axis represent the maximum theoretical values of fibre volume fractions for square and hexagonal arrays, respectively.

6. Conclusions

Unidirectionally reinforced FRP composite elements are mainly loaded in tension when they are utilized as internal reinforcing bars for concrete elements or as externally bonded strips in strengthening solutions.

The longitudinal elastic modulus is a stiffness characteristic that must be known especially when the all-composite structures or hybrid framing systems with composite reinforcement are checked against serviceability limit states.

The experimental determination of the elastic modulus of FRP composites are very expensive and time consuming.

Micromechanics of fibrous composites is a viable alternative enabling the evaluation of the longitudinal elastic modulus based on the properties of individual constituents.

The rule of mixtures, a very simple analytical model, gives a convenient and rapid evaluation of this stiffness characteristic.

It can be seen, from the graphical representations and from the tables, that the more refined models existing in the specialized literature lead to results that are very close to those given by the rule of mixtures.

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RIGIDITATEA LONGITUDINALĂ A MATERIALELOR COMPOZITE POLIMERICE ARMATE UNIDIRECŢIONAL LA SOLICITAREA DE TRACŢIUNE

(Rezumat)

Elementele din materiale compozite polimerice armate cu fibre (CPAF) unidirecționale, se utilizează în prezent la bare pentru armarea elementelor din beton sau pentru placarea exterioară a grinzilor din beton armat la partea întinsă în vederea consolidării acestora. Intrucât elementele din CPAF sunt solicitate la întindere în direcția fibrelor este necesară cunoaşterea modulului de elasticitate al compozitului în această direcție. Proprietățile CPAF sunt determinate de caracteristicele constituentelor lor şi de distribuția acestora exprimată prin fracțiunile volumetrice. Determinarea pe cale experimentală a proprietăților necesare proiectării elementelor din CPAF necesită timp îndelungat şi costuri ridicate, de aceea este benefică elaborarea unor modele analitice pentru evaluarea acestora. În lucrare sunt analizate principalele modele analitice utilizate şi prezentate în raport cu regula amestecurilor la compozitele din polimeri termorigizi armați unidirecțional cu fibre din sticlă sau bazalt. Se stabileşte concluzia că regula amestecurilor este un mijloc rapid şi convenabil pentru stabilirea modulului de elasticitate longitudinal, iar modelele mai rafinate şi unele rezultate experimentale obținute de autori confirmă adecvarea acestui mod de calcul.