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STIFFNESS PROPERTIES ALONG PRINCIPAL MATERIAL AXES OF FIBRE REINFORCED POLYESTER PULTRUDED PLATE ELEMENTS

BY

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Abstract. Glass fibre reinforced polyester (GFRP) composite plate components fabricated by pultrusion are increasingly being used in civil infrastructure applications.

Structural members made of GFRP composites are often constructed from plate like pultruded shapes. Verification of serviceability limit states requires good knowledge of stiffness properties, in particular along the principal axes of the material. The paper analyses the main stiffness characteristics, the available analytical formulas to evaluate them and experimental verification of the calculated values for a plate composite product fabricated by pultrusion.

Key words: glass fibres; polyester resins; pultrusion; elastic moduli.

1. Introduction

The pultrusion fabrication method represents a continuous manufacturing process where unidirectional filaments (UF) associated with continuous strand mats (CSM) are impregnated with resins and pulled through a heated die to produce constant cross-section shapes of any lengths.

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The raw materials are liquid resin mixtures which may contain fillers or additives, and reinforcement consisting of principal longitudinal reinforcing fibres, completed with secondary reinforcement made of mat. The most utilized resins are unsaturated polyesters with ultraviolet (UV) inhibitors and/or vinyl esters, and glass fibres as reinforcing component.

There are many benefits of using GFRP structural shapes: corrosion resistance, low thermal and electrical conductivity, nonmagnetic characteristics, lightweight, high strength, dimensional stability, low maintenance, custom colours. Pultrusion provides a great flexibility in the fabrication procedure of GFRP elements, from simple plates to heavy structural shapes (Fiberline Design Manual, 2012; The Pultrex Pultrusion Design Manual, 2004).

Composite products are used as internal and external reinforcement to repair and/or strengthen the structural members made of traditional construction materials such as reinforced concrete (RC) columns (Ţăranu *et al.*, 2009), RC beams (Oprişan *et al.*, 2012) and RC slabs (Ţăranu *et al.*, 2013), steel beams (Munteanu *et al.*, 2012), timber beams and columns (Oprişan *et al.*, 2004), brick masonry walls, arches and vaults (Ţăranu *et al.*, 2010). The advantages of pultruded GFRP profiles are recognized by professional architects, civil and structural engineers as having important applications in civil infrastructure, chemical processing, defence sector, transportation, oil and gas industry, etc.

The design of GFRP pultruded beams requires a detailed knowledge of all stiffness characteristics in the principal material direction (the longitudinal elastic modulus, the transverse elastic modulus, the shear modulus of elasticity and the Poison's ratios) needed for verification of the serviceability limit states (Bank, 1990).

This paper includes significant results on the stiffness properties of GFRP composite pultruded plates calculated for the currently utilized fibre volume fractions, experimentally verified for a particular plate product with known mass fibre fraction.

2. The Composite Constituents and Their Properties

A first assessment of the mechanical characteristics of fibre reinforced polymer composites can be achieved using the micro-mechanics approach. Knowing the properties of individual phases the designer can establish the values of principal elastic constants.

The selection of the matrix material, (Table 1 – Miracle *et al.*, 2001), and of glass fibres types, (Table 2 – Quinn, 2002), depend largely on the use of the structural element made of pultruded glass fibre reinforced polymer composites.

An example of a composite plate (Fig. 1) made of a thermosetting resin (polyester or vinylester) and glass fibres resulted from pultrusion reveals the main reinforcing fibres oriented in the longitudinal direction and the surface treatment, made of glass mat, needed to resist the non principal axes stresses, diminish shrinkage and provide acceptable aesthetical features.

Table 1

Properties of the Matrices Used for the GFRP Pultruded Plate Element

Property / Matrix	Density kg/m^3	Tensile strength MPa	Young's modulus GPa	Ultimate tensile strain %	Poisson's coefficient
Polyester	1,200...1,300	75	3.40	3.3	0.38
Vinylester	1,200...1,300	80	3.59	4	0.38

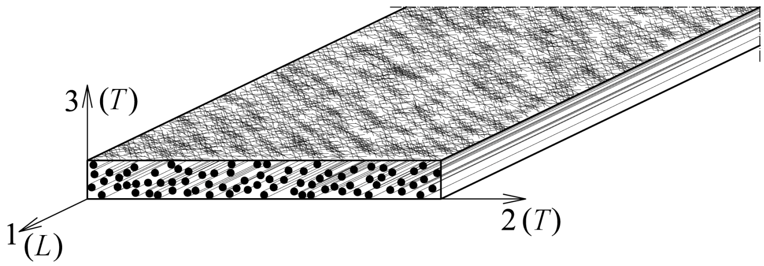


Fig. 1 – The structure of a GFRP pultruded plate.

For a better protection of the pultruded GFRP elements and to improve the corrosion resistance as well as the product handling, the manufacturer may also use surface veils.

Table 2

Properties of the Currently Used Glass Fibres

Property / Fibre type	Density kg/m^3	Tensile strength MPa	Young's modulus GPa	Coefficient of thermal expansion 10^{-6}/°C	Poisson's ratio
E-Glass	2,620	3,450	72.35	5.0	0.22
S-Glass	2,500	4,590	89	5.6	0.22
A-Glass	2,500	3,050	69	8.6	0.22

The longitudinal elastic modulus, E_1, can be evaluated with mechanics of materials approach, based on the following assumptions (Agarwal *et al.*, 2006):

a) the unidirectionally reinforced composite may be modelled by assuming fibres to be uniform in properties and diameter, continuous, 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 isotropic, homogeneous and linearly elastic.

Based on the above assumptions a rule of mixtures (RM) can be established for the evaluation of the elastic modulus in the principal 1 direction (Ţăranu, *et al.*, 2013):

$$E_1 = E_f V_f + E_m V_m , \tag{1}$$

where: E_1 is the longitudinal modulus of elasticity, [GPa]; E_f – the fibre modulus of elasticity along the fibre axis, [GPa]; V_f – the fibre volume fraction; E_m – the modulus of elasticity of the matrix, [GPa]; V_m – the matrix volume fraction.

Using formula (1) a graphical representation for the elastic modulus E_1 range has been constructed (Fig. 2). A value equal to 33.05 GPa has been obtained for the effective fibre volume fraction of the pultruded plate ($V_f =$ $= 0.432$); after performing a standard tensile test (ASTM D3039/ D3039M-08, 2008) on the pultruded specimen (Fig. 3), in the longitudinal direction the experimental value for the longitudinal modulus was found equal to 32.11 GPa (Fig. 2).

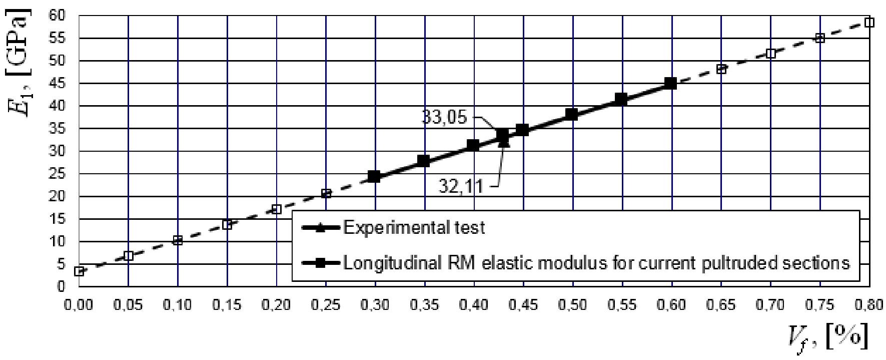
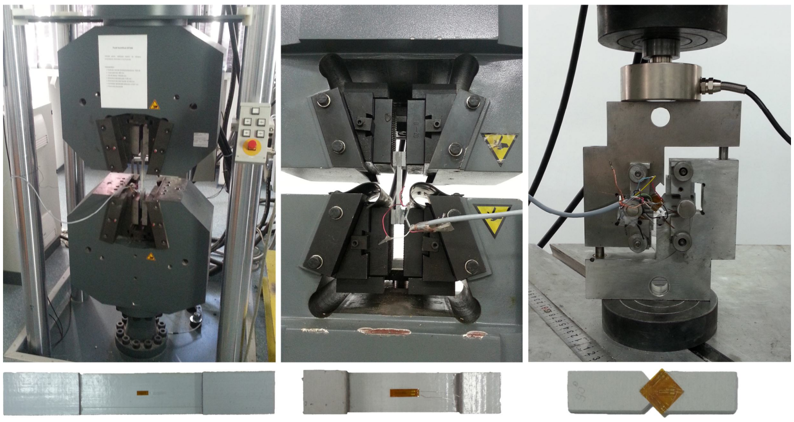


Fig. 2 – The longitudinal elastic modulus, E_1, values obtained by using the rule of mixtures.

The transverse modulus of elasticity, E_2, can be evaluated using the inverse rule of mixtures (IRM) rule. The formula has been established accepting the same assumptions regarding the material behaviour and the series model (with equal direct stress on composite and all constituents in the transverse direction):

$$E_2 = \frac{E_f E_m}{E_m V_f + E_f V_m} , \tag{2}$$



a *b* *c*

Fig. 3 – Experimental tests on pultruded coupons: *a* – tensile test along the fibres (1); *b* – tensile test normal to the fibres direction (2); *c* – shear test in the plane (1, 2).

In eq. (2) E_f is the transverse elastic modulus of the glass fibres (in our case equal to the longitudinal fibre modulus). The formula (2) gives only approximate results and a better match is obtained using the Halpin-Tsai eqs.

$$E_2 = E_m \frac{1+\zeta_1 \eta_1 V_f}{1-\eta_1 V_f}, \quad (3) \qquad \eta_1 = \frac{E_f / E_m - 1}{E_f / E_m + \zeta_1}, \quad (4)$$

where: ζ_1 is an empirical parameter, the value ζ_1 = 2 being recommended for circular fibres (Agarwal *et al.*, 2006).

A graphical representation of E_2 variation with respect to the fibre volume fraction is illustrated in Fig. 4.

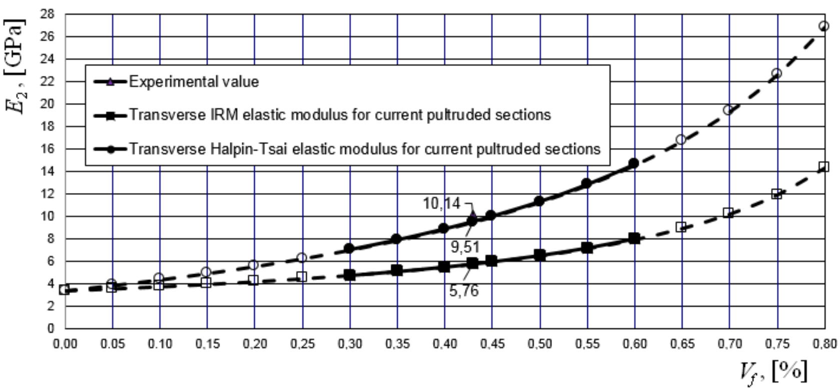


Fig. 4 – The transverse elastic modulus E_2 values obtained using the inverse rule of mixtures (IRM) and Halpin-Tsai equations.

The experimental values are much closer to the results obtained from Halpin-Tsai eqs. than those calculated with the rule of mixtures; for our particular pultruded plate with a fibre volume fraction equal to 0.432 the experimental value matches very well the Halpin-Tsai results.

The shear modulus of elasticity required for the evaluation of the shear structural response can be calculated using the inverse rule of mixtures

$$G_{12} = \frac{G_f G_m}{G_m V_f + G_f V_m} , \quad (5)$$

where: G_{12} is the shear modulus of elasticity for the GFRP pultruded composite element, while G_f and G_m are the same moduli of the phase components and the Halpin-Tsai eqs.

$$G_f = \frac{E_f}{2(1+\nu_f)} , \quad (6)$$

$$G_m = \frac{E_m}{2(1+\nu_m)} , \quad (7)$$

where: ν_f and ν_m are the Poisson's ratios for fibre and matrix, respectively (Tables 1 and 2). A graphical representation of the G_{12} values with respect to the fibre volume fraction is illustrated in Fig. 5.

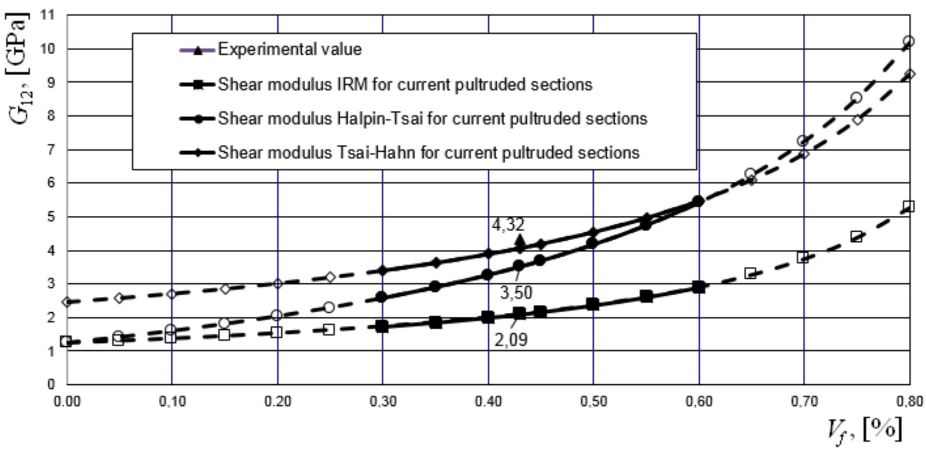


Fig. 5 –The evaluation of the shear modulus G_{12} using three analytical methods.

The shear modulus of elasticity calculated with inverse rule of mixtures is also only a rough evaluation of the real value. Therefore, the Halpin-Tsai eqs. (Ţăranu *et al.*, 2013) for the shear modulus have been utilized:

$$G_{12} = G_m \frac{1+\zeta_2 \eta_2 V_f}{1-\eta_2 V_f}, \tag{8}$$

in which:

$$\eta_2 = \frac{\left(G_f / G_m\right) - 1}{\left(G_f / G_m\right) + \zeta_2}, \tag{9}$$

the authors recommending $\zeta_2 = 1$.

Values closer to the experimentally obtained ones were calculated using the relation

$$\frac{1}{G_{12}} = \left(\frac{1}{V_f + V_m}\right)\left(\frac{V_f}{G_f} + \frac{\eta_3 V_m}{G_m}\right), \tag{10}$$

for which Tsai and Hahn (Tsai *et al.*, 1980) suggested the value $\eta_3 = 0.5$. The formula is mainly suitable to fibre volume fractions typically utilized for pultruded plate elements reinforced unidirectionally.

The shear modulus have been measured using standardized Iosipescu test method (ASTM D5379/D5379M-12, 2012) and the value 4.32 GPa illustrated in Fig.4 represents the average value obtained on six samples.

The stiffness of the pultruded GFRP specimen is represented by five elastic properties presented above and used in the analytical calculus and numerical modelling.

Assuming that no slippage occurs at the interface and the strains experienced by the composite, fibre and matrix are equal: and that the widths are proportional to the volume fractions, the following formula is obtained for the major Poisson ratio:

$$\nu_{LT} = \nu_f V_f + \nu_m V_m. \tag{11}$$

Eq. (11) represents the rule of mixtures for the major Poisson ratio of a unidirectional composite. The plot of ν_{LT} with respect to the fibre volume fraction is linear and the extreme values of this characteristic are ν_m (maximum, for $V_f = 0$) and ν_f (for $V_f = 1$). The graphical representation of ν_{LT} for the volume fraction interval analysed before is illustrated in Fig. 6.

The following relationship, presented in macromechanics of composites exists between engineering constants

$$\nu_{TL} = \nu_{LT} \frac{E_T}{E_L}, \tag{12}$$

which can be expanded to:

$$\nu_{TL} = \left[\nu_f V_f + \nu_m \left(1 - V_f\right) \right] \frac{\left(E_f E_m\right) / \left[E_f \left(1 - V_f\right) + E_m V_f \right]}{E_f V_f + E_m \left(1 - V_f\right)} . \tag{13}$$

As it can be seen from Fig. 6 the ν_{TL} values are always smaller than ν_{LT} ones since $E_T << E_L$.

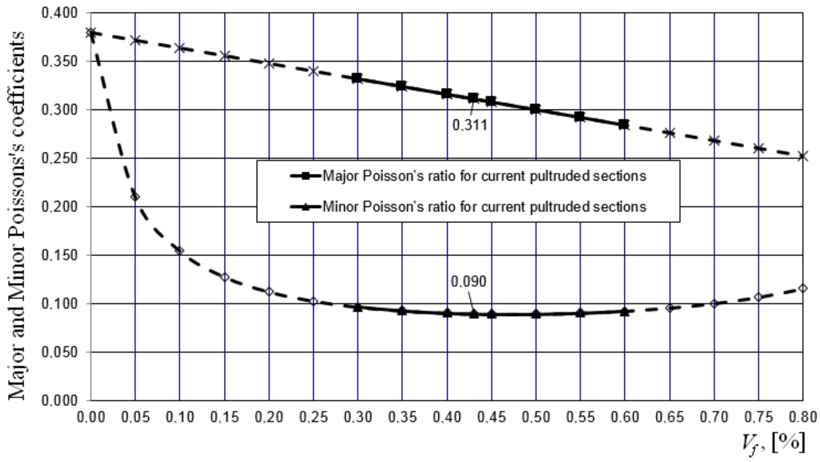


Fig. 6 – Poisson's coefficients in terms of the percentage of the reinforcement, V_f.

5. Conclusions

In this paper, the authors analyse the stiffness characteristics of plate elements fabricated by pultrusion.

All stiffness properties are strongly influenced by the nature of the components (fibres and matrix), the fibre volume fractions of the constituents.

The longitudinal elastic modulus and the major Poisson's ratio can be precisely determined using the rule of mixtures.

The inverse rule of mixtures utilized to determine the transverse elastic modulus and the shear modulus of elasticity gives only approximate values that are far apart from the experimental results. Therefore, the Halpin-Tsai eqs. and the Tsai-Hahn formula are recommended for more precise values.

All analytical models can be successfully applied in the fibre volume fraction range currently utilized for pultruded plates made of glass reinforced polyesters.

The experimental values are close to the theoretical ones for the effective fibre volume fraction determined on the studied composite pultruded element.

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CONSTANTELE ELASTICE ÎN LUNGUL AXELOR PRINCIPALE ALE PLĂCILOR PULTRUDATE REALIZATE DIN COMPOZITE POLIMERICE ARMATE CU FIBRE

(Rezumat)

Poliesterii armaţi cu fibre de sticlă (PAFS) sub formă de platbande compozite obţinute prin pultrudere sunt din ce în ce mai utilizaţi în aplicaţiile din ingineria civilă.

Verificarea stării limită de serviciu necesită o bună cunoaştere a proprietăților de rigiditate, în special de-a lungul axelor principalelor ale materialului.

Se analizează principalele caracteristici de rigiditate în lungul axelor principale ale materialului, formulele analitice disponibile pentru evaluarea acestora, verificând experimental valorile calculate pentru un produs plat fabricat prin pultrudere.