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Influences of hygrothermal environment and fiber orientation on shear correction factor in orthotropic composite beams

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Abstract. In this study, a simple method for the determination of the shear correction factor for composites beam with a rectangular cross section is presented. The plane stress elasticity assumption is used after simplifications of the expression of the stress distribution in the beam. The different fiber orientation angle and volume fraction are considered in this work. The studied structure is subjected to various loading type (thermal and hygrothermal). The numerical results obtained show that there is a dependence of the shear coefficient on the orientation of the fibers. The evolution of the shear correction factors depends not only on the orientation of the fibers and also on the volume fraction and the environment. the advantage of this developed formula of the shear correction factor is to obtain more precise results and to consider several parameters influencing this factor which are neglected if the latter is constant.

Keywords: beams; correction factors; fiber orientation; hygrothermal environment; shear; stress distribution

1. Introduction

For thin beams, the classical theory of beams developed by Euler-Bernoulli is used, because this theory neglects the effect of transverse shear and natural stresses. The vibratory characteristics of orthotropic beams without embedding without including shear strain and rotational inertia have been studied by Abarcar and Cunnif (1972), Miller and Adams (1975). Vinson and Sierakowski

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1986 have proposed an exact solution for the free vibration of composite beams simply supported without shear strain and rotational inertia, this approach is based on classical laminate theory.

Timoshenko (1921, 1922) developed for the first time a theory of beams including the effect of transverse shear strain to remedy the drawbacks of the classical theory of beams. These effects are taken into account for composite girders, because of the high ratio of transverse shear modulus. Using an energy approach including shear and rotational inertia, Teh and Huang (1979) presented a theoretical analysis of the free vibrations of non-embedded and orthotropic beams. These mathematical models include the effects of transverse shear strain and rotational inertia. Also, there are several analytical and numerical methods for the analysis of structures and materials and their global behavior under different loading conditions, among these works those of Yaylaci and his co-workers who deal with contact problems (Yaylaci and Birinci 2013, Adiyaman *et al.* 2015, Öner *et al.* 2015, Yaylaci 2016, Yaylaci *et al.* 2020ab and 2021abc).

During the last decades, several researchers (Chow 1971, Whitney 1972, Vlachoutsis 1992, Cowper 1966, Bert 1973, Moghtaderi *et al.* 2018) have studied the shear correction factors of beams and plates. Chow (1971) presented a method to calculate the shear correction factor of a symmetrically laminated plate assuming a normal stress distribution across the cross section. Guttmann (2001) calculated the shear correction factors for arbitrarily shaped beam cross sections using the linear elasticity equations and other assumptions for the field of stresses. Whitney (1972) suggested methods for calculating shear correction factors for general orthotropic laminated composite beams and plates, respectively. A procedure for the shear correction factor and applied it to the analysis of the shell has proposed by Vlachoutsis (1992). Cowper (1966) presented a method for the determination of coefficient k for an isotropic material and he showed that coefficient depends on the Poison's ratio. Moghtaderi *et al.* (2018) used a resulting approximate solution for the elasticity field with the introduction of two shear correction factors consistent with the Cowper and energy approaches. For a non-isotropic material, a new formulation of the shear correction coefficient must be determined, because there is a dependence of the coefficient k on the property of the material (Poison ratio). A new method valid only for orthotropic beams has been developed by Dharmarajan and McCutchen (1973). This new expression shows that the coefficient k depends on the elastic constants and at the same time on the Poisson's ratio. This during the orthotropic beam considered is a special case of an orthotropic beam in general and therefore the re-examination of the method of determining the k coefficients is necessary. Several methods for determining the shear correction factors for composite plates have been presented by Bert (1973). Some authors (Vrabie 2017, Wang 2015, Jun *et al.* 2015, Eslami 2014, Chen 2012) have been interested in recent years in the bending vibrations of beams. The vibrations are of great interest even in the simplest cases of a uniform beam, the validity of these theories is still under discussion, so are the physical parameters that should be used there such as the shear coefficient (Timoshenko) k. In Timoshenko's beam theory TBT, an adjustment parameter is introduced to evaluate the shear force at the cross section of a beam in terms of the shear strain on the centroid axis. For a beam of rectangular section the values commonly used are $k=\frac{5}{6}$, $=\frac{\pi^2}{12}$ etc., but these values differ from one study to another and no agreement exists on these values. Several authors (Kaneko 1975, Stephen and Levinson 1979, Renton 2001, Hutchinson 2001, Stephen 2002, Chan *et al.* 2011) have attempted to theoretically determine with precision the values of the shear coefficient. On the other hand, experimental studies are rare, because the frequency measurements must be measured in the Bernoulli-Euler regime (Hearmon 1958, Rosinger and Ritchie 1977, Mendez-Sanchez *et al.* 2005). In this paper, a simple method is used for determination of

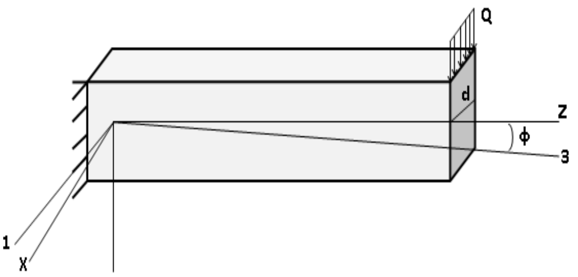

Fig. 1 Geometry of orthotropic beam

coefficient k in the general case of orthotropic beams with a rectangular cross section including both the fiber orientations and the effect of hygrothermal environment. The studied structure is modeled based on the Timoshenko's beam theory which takes into account the effect of transverse shear deformation. The proposed formula of the shear correction coefficient can consider the different parameters influencing the transverse shear stresses which are neglected in the correction factors found in the literature.

2. Theoretical formulation

In the case of a state of plane stresses in elasticity, the stress distribution is simplified for the beam and a new formulation of the coefficient k is proposed.

The studied beam of rectangular section is represented in Fig. 1. The beam has the following dimensions: length L, width d and height h. Bending moment and torque are generated by a vertical force applied to the free end of the beam.

Under the action of bending and torsion, it is difficult to formulate expressions from the distribution of stresses in the beam. Assuming the state plane stress, complexity due to coupling with the torque can be eliminated.

The shear stresses in the direction x ($\bar{\tau}_{zx}$ and $\bar{\tau}_{yx}$) are therefore neglected, in the case where the width of the beam is sufficiently small.

At the edge at $x=d/2$ the surfaces are free of all constraints, we can assume that the normal stress in the x direction is zero at the levels of these surfaces if the Poisson's ratio effect is ignored.

The last hypothesis requires that the deformations of the beam be small.

2.1 Basic equations of elasticity probleme in plane stress

The mean values of the stresses and displacements components are given by the integrals of the displacements and stresses taken across the width and divided by the width. The mean values of the components of the stresses were given by the relations 1

$$\bar{\sigma}_y = \frac{1}{d}\int_{-d/2}^{d/2} \sigma_y \, dx \tag{1a}$$

$$\bar{\sigma}_z = \frac{1}{d}\int_{-d/2}^{d/2} \sigma_z \, dx \tag{1b}$$

$$\bar{\tau}_{yz} = \frac{1}{d}\int_{-d/2}^{d/2} \tau_{yz} \, dx \tag{1c}$$

The mean values of the components of the displacement were given by the relations 2

$$\bar{v} = \frac{1}{d}\int_{-d/2}^{d/2} v\,dx \tag{2a}$$

$$\bar{w} = \frac{1}{d}\int_{-d/2}^{d/2} w\,dx \tag{2b}$$

$$\bar{u} = \frac{1}{d}\int_{-d/2}^{d/2} u\,dx \tag{2c}$$

The relation between the stresses and the strains for a beam orthotropic can be written in the following form:

$$\begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \gamma_{23} \\ \gamma_{13} \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & 0 & 0 & S_{16} \\ S_{21} & S_{22} & S_{23} & 0 & 0 & S_{26} \\ S_{13} & S_{23} & S_{33} & 0 & 0 & S_{36} \\ 0 & 0 & 0 & S_{44} & S_{45} & 0 \\ 0 & 0 & 0 & S_{54} & S_{55} & 0 \\ S_{61} & S_{62} & S_{63} & 0 & 0 & S_{66} \end{bmatrix} \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{23} \\ \sigma_{13} \\ \sigma_{12} \end{Bmatrix} \tag{3}$$

S_{ij} are the elements of flexibility matrix.

Where the six deformation components are the mean deformation values which are equal to:

$$\bar{\varepsilon}_x = \frac{\partial \bar{u}}{\partial_x} \; ; \bar{\varepsilon}_y = \frac{\partial \bar{v}}{\partial_y} ; \bar{\varepsilon}_z = \frac{\partial \bar{w}}{\partial_z}$$
$$\bar{\gamma}_{xy} = \frac{\partial \bar{u}}{\partial_y} + \frac{\partial \bar{v}}{\partial_x} ; \bar{\gamma}_{yz} = \frac{\partial \bar{v}}{\partial_z} + \frac{\partial \bar{w}}{\partial_y} ; \bar{\gamma}_{zx} = \frac{\partial \bar{u}}{\partial_z} + \frac{\partial \bar{w}}{\partial_x} \tag{4}$$

Neglecting the forces of volume using the mean values of stress components, the equilibrium equations are given by the relation 5 and 6

$$\frac{\partial \bar{\sigma}_y}{\partial_y} + \frac{\partial \bar{\tau}_{yz}}{\partial_z} = 0 \tag{5}$$

$$\frac{\partial \bar{\tau}_{yz}}{\partial_y} + \frac{\partial \bar{\sigma}_z}{\partial_z} = 0 \tag{6}$$

The compatibility equation is given by relation 7

$$\frac{\partial^2 \bar{\varepsilon}_z}{\partial y^2} + \frac{\partial^2 \bar{\varepsilon}_y}{\partial z^2} = \frac{\partial^2 \bar{\gamma}_{yz}}{\partial y \partial z} \tag{7}$$

2.2 Distribution of stresses and displacements

2.2.1 Expression of stresses

Substituting the expressions of $\bar{\varepsilon}_x, \bar{\varepsilon}_y, \bar{\gamma}_{xy}$ from relation (3) in relation (6) and using the functions of stresses given by relation (8)

$$\bar{\sigma}_y = \frac{\partial^2 \varphi_s}{\partial z^2} \; ; \overline{\sigma_z} = \frac{\partial^2 \varphi_s}{\partial y^2} \; ; \bar{\tau}_{yz} = -\frac{\partial^2 \varphi_s}{\partial y \partial z} \tag{8}$$

Eq. (6) can be written in the form

$$S_{33}\frac{\partial^2 \varphi_s}{\partial y^4} + (S_{55} + S_{22} + S_{23})\frac{\partial^2 \varphi_s}{\partial y^2 \partial z^2} + \frac{S_{22}\partial^4 \varphi_s}{\partial z^4} = 0 \tag{9}$$

Assuming that the stress function is in the form

$$\varphi_s = A(L-z)y + By^2 + C(L-z)y^2 + Dy^3 + E(L-z)y^3 \tag{10}$$

Considering the following conditions:
a) The longitudinal surfaces are free at $y=\pm h/2$.
b) The load Q applied to the end is the sum of the shear stress distribution;
c) The constraints must balance the extreme force and the moment.

Through each side of the beam with the help of expressions of bending moment and shearing force

$$N_{ij} = \int_s \sigma_{ij}\, ds \tag{11}$$

$$M_{ij} = \int_s \sigma_{ij}\, y ds \tag{12}$$

The application of a vertical force Q at the free end of the orthotropic beam generates a distributed stress which can be written as follows

$$\overline{\sigma_z} = -\left(\frac{Qy}{I_X}\right)(L-z)\,; \overline{\sigma_y} = 0\,;\ \bar{\tau}_{yz} = \left(\frac{Q}{2I_X}\right)\left(\frac{h^2}{4} - y^2\right) \tag{13}$$

2.2.2 Expression of displacements

By applying the law of Hooke and taking into account relation (13), we will have

$$\overline{\varepsilon_z} = \partial\overline{w}/\partial z = -\left(\frac{S_{33}Qy}{I_x}\right)(L-z)\,; \overline{\varepsilon_y} = \frac{\partial\bar{v}}{\partial y} = -\left(\frac{S_{23}Qy}{I_x}\right)(L-z) \tag{14}$$

After integration, the expression of displacement can be written by the relation (15) and (16)

$$\overline{w} = -\left(\frac{S_{33}Qy}{I_x}\right)\left(Lz - \frac{z^2}{2}\right) + f(y) \tag{15}$$

$$\bar{v} = -\left(\frac{S_{23}Qy}{2I_x}\right)(L-z) + g(z) \tag{16}$$

The derivation of Eq. (15) with respect to y and (16) with respect to z and taking into account the relation 13 and knowing that the deformation $\overline{\gamma_{yz}} = \frac{\overline{\partial_v}}{\partial_z} + \frac{\overline{\partial_w}}{\partial_y}$, we obtain the relation (17)

$$-\left(\frac{S_{33}Qy}{I_x}\right)\left(Lz - \frac{z^2}{2}\right) + \partial f(y)/\partial y + \frac{S_{23}Q_y^2}{2I_x} + \frac{\partial g(z)}{\partial z} = \left(\frac{S_{55}Q}{2I_x}\right)\left(\frac{h^2}{4} - y^2\right) \tag{17}$$

By separating the variables of the differential equations, we see that the left side of Eq. (17) does not depend on (z) while the right side does not depend on (y). As a result, it can be concluded that the only solution for that Eq. (17) must satisfy for all values of z and y that the members would be constant. After some operations one can write

$$\overline{w} = -\left(\frac{S_{33}Qy}{I_x}\right)\left(Lz - \frac{z^2}{2}\right) + \frac{S_{23}Q_y^3}{6I_x} + \left(\frac{S_{55}Q}{2I_x}\right)\left(\frac{h^2 y}{4}\right) - \frac{y^3}{3} \tag{18}$$

$$\bar{v} = -\left(\frac{S_{23}Qy}{2I_x}\right)(L-z) + \left(\frac{S_{33}Q}{I_x}\right) + \left(\frac{Lz^2}{2} - \frac{z^3}{6}\right) \tag{19}$$

2.3 Shear Factors correction

In the theory of beams the transverse arrow (v) is defined as the displacement of the neutral axis. A small distortion of the cross section is inevitable. All the points in the cross section are going to move in a different way, so we'll define V as the mean deflection of the cross section

$$V = \frac{1}{d}\int_{-h/2}^{h/2} \bar{v}\, dy \tag{20}$$

Another basic parameter of beam theory is Φ which is the rotation of the average angle of the section around the neutral axis which can be defined by

$$\emptyset = \frac{1}{I_x}\int_{-h/2}^{h/2} y\bar{w}\, dy \tag{21}$$

To determine the relation between the mean deflection V, the mean rotation of the angle Φ and the distortion of the beam, we define the mean value relative to the width of the residual displacements: $\overline{v_y}, \overline{w_z}$

$$\bar{v} = V + \overline{v_y} \tag{22}$$

$$\bar{w} = W + y\emptyset + \overline{w_z} \tag{23}$$

Where

$$W = \frac{1}{d}\int_{-1/h}^{1/h} \bar{w}\, dy \tag{24}$$

Considering Eqs. (20) to (23) and the relation stress-strain, $\overline{\gamma_{yz}} = S_{55}\tau_{yz}$ from Eq. (3), the mean displacement of the section transversal in direction (z) can be rewritten as following

$$\frac{\partial V}{\partial z} + \emptyset = \frac{1}{d}\int_{-h/2}^{h/2} S_{55}\,\overline{\tau_{yz}} - \frac{\partial \overline{w_z}}{\partial y})dy \tag{25}$$

Knowing the expressions of displacements (relations 18 and 19), after integration of relation 25, we have

$$\frac{\partial V}{\partial z} + \emptyset = Q\frac{S_{55}}{kd} \tag{26}$$

Where k is the shear factor correction of an orthotropic beam given by

$$k = \frac{5}{\left(6 + \frac{S_{23}}{S_{55}}\right)} \tag{27}$$

Note that the shear correction coefficient k depends on the properties of the materials, but also on the orientation of the reinforcing fibers. The ratio $\frac{S_{23}}{S_{55}}$ is the only term that is variable. For a fiber orientation given, the ratio of Young's modulus to shear modulus E_{zz}/G_{zy} is the main factor that affects the variation of shear factors correction. The ratio $\frac{S_{23}}{S_{55}}$ of Eq. (27) becomes negligible for the great reports of E_{zz}/G_{zy}. In general, a constant value of 5/6 is often assigned for the shear correction coefficients in the case of dynamic responses of orthotropic beams. The effects of material properties and fiber orientation are often unequal.

3. Applications

Consider an orthotropic beam, of rectangular cross-section of length L, width d and height h subjected to a vertical force generating a bending moment and a torque at the free end. The properties of the material are given in Table 1.

Table 1 Material properties

Materials	Young's Modulus GPa	Shear Modulus (GPa)	Poisson Coefficient
Fiber	230	9	0.203
Matrix	3.51-0.003T-0.142C	--	0.234

Table 2 Values of shear correction factor k for different fiber orientation angle and for different values of the volume fraction fibers (ΔT=00°C, ΔC=0)

θ	k=5/6	Vf=50%	Vf=60%	Vf=70%
		k	k	k
0	0,833333	0.833652	0.833652	0.833818
10	0,833333	0.833901	0.834066	0.834397
20	0,833333	0.834811	0.834976	0.835556
30	0,833333	0.8363	0.836714	0.837376
40	0,833333	0.838286	0.838783	0.839527
50	0,833333	0.840603	0.841099	0.842092
60	0,833333	0.842671	0.843333	0.843995
70	0,833333	0.844988	0.845319	0.845816
80	0,833333	0.846478	0.846809	0.847139
90	0,833333	0.847305	0.847305	0.847553

Table 3 Values of shear correction factor k for different fiber orientation angle and for different values of the volume fraction fibers (ΔT=500°C, ΔC=0,5%)

θ	k=5/6	Vf=50%	Vf=60%	Vf=70%
		k	k	k
0	0,833333	0.833972	0.833903	0.833834
10	0,833333	0.834249	0.834249	0.834318
20	0,833333	0.834941	0.835217	0.835632
30	0,833333	0.836462	0.836877	0.837569
40	0,833333	0.838261	0.838883	0.839575
50	0,833333	0.840543	0.841304	0.842134
60	0,833333	0.842964	0.843449	0.844209
70	0,833333	0.845178	0.845385	0.846008
80	0,833333	0.846769	0.846907	0.847391
90	0,833333	0.847322	0.84753	0.847737

For the matrix, the Young's modulus varied with temperature T and the humidity ratio C.

$$T=T_0+\Delta T \text{ and } T_0=250°C$$

$$C=C_0+\Delta C \text{ and } C_0=0$$

The influence of the volume fraction fiber on the shear correction coefficient is studied for the three cases of environment

Case 1: ΔT=00°C, ΔC=0.

Case 2: ΔT=500°C, ΔC=0,5%.

Case 3: ΔT=1000°C, ΔC=1%.

Table 4 Values of shear correction factor *k* for different fiber orientation angle and for different values of the volume fraction fibers (ΔT=1000°C, ΔC=1%)

θ	k=5/6	Vf=50%	Vf =60%	Vf =70%
		k	k	k
0	0,833333	0.833972	0.833903	0.833834
10	0,833333	0.834249	0.834249	0.834318
20	0,833333	0.834941	0.835217	0.835632
30	0,833333	0.836462	0.836877	0.837569
40	0,833333	0.838261	0.838883	0.839575
50	0,833333	0.840543	0.841304	0.842134
60	0,833333	0.842964	0.843449	0.844209
70	0,833333	0.845178	0.845385	0.846008
80	0,833333	0.846769	0.846907	0.847391
90	0,833333	0.847322	0.84753	0.847737

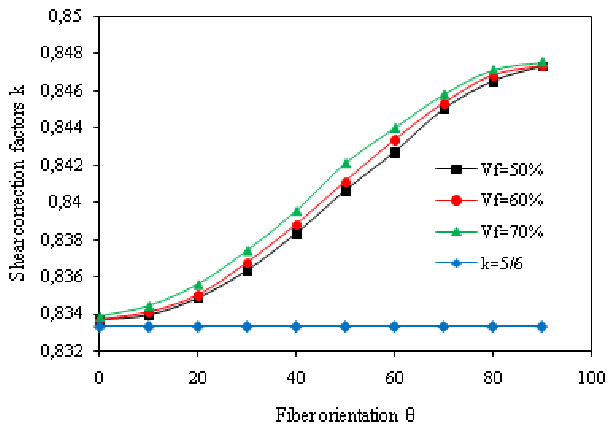

Fig. 2 Variation of SFC as a function of fiber orientation angle (ΔT=00°C, ΔC=0%)

3.1 Results

Tables 2 to 4 shows the values of shear correction factor *k*, for different values of fiber orientation angle and for different values of the volume fraction fiber for the three environmental conditions.

3.2 Variation of shear factors correction as a function fiber orientation angle

The evolution of the shear factor correction as a function of the fiber orientation angle for the cases studied and for different volume fraction fiber is presented in Figs. 2 to 4. It can be seen that the volume fractions slightly influence the shear factor correction and this canclearly be observed for a fiber orientation angle less than 10°. The results show that the factor correction of a rectangular composite beam has the same constant value as that of an isotropic rectangular beam for values of the angle of orientation of the fibers less than 10°. The fiber orientation angle has a significant effect on the shear factor correction, for fiber orientation angle greater than 10° the

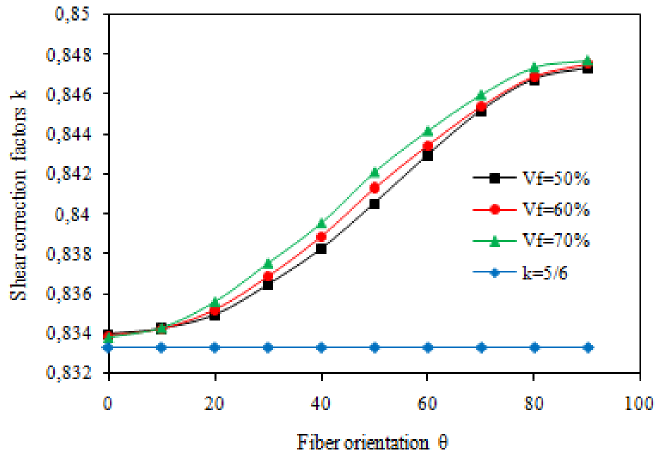

Fig. 3 Variation of SFC as a function of fiber orientation angle (b) (ΔT=500°C, ΔC=0,5%)

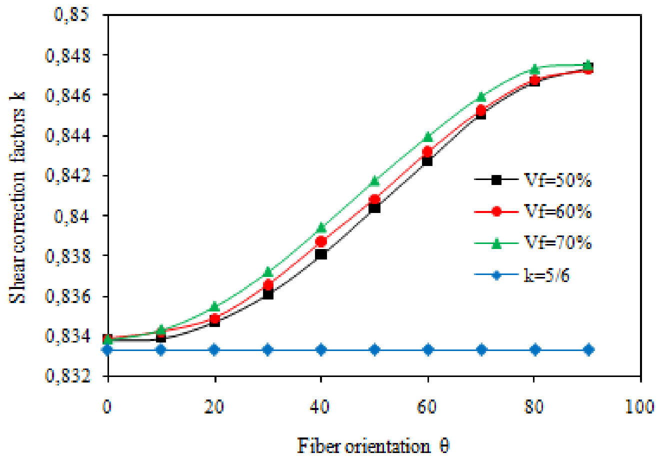

Fig. 4 Variation of SFC as a function of fiber orientation angle (ΔT=1000°C, ΔC=1%)

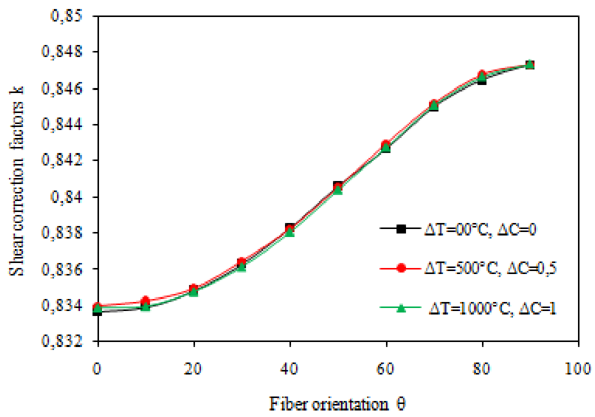

Fig. 5 Variation of the SCF k as a function of the fiber orientation angle for three environmental conditions for volume fractions fibers Vf=50%

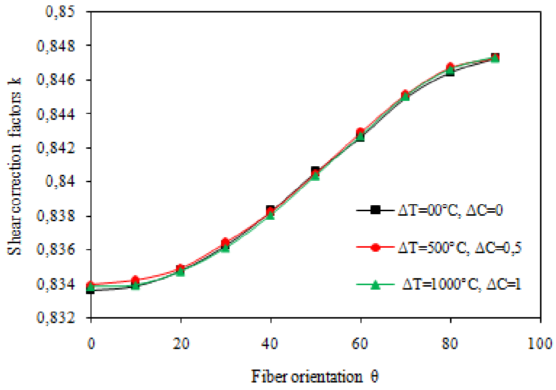

Fig. 6 Variation of the SCF *k* as a function of the fiber orientation angle for three environmental conditions *Vf*=60%

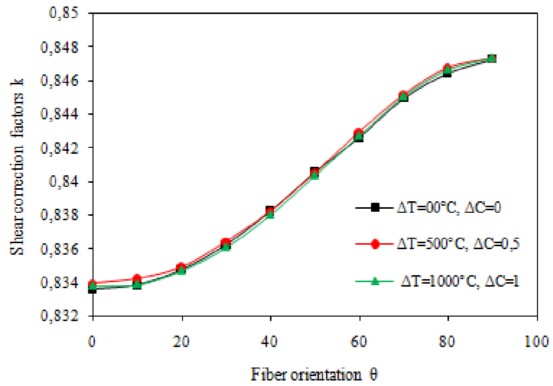

Fig. 7 Variation of the SCF *k* as a function of the fiber orientation angle for three environmental conditions *Vf*=70%

shear factor correction *k* increases with the increase of the fiber orientation angle. The values of the factor correction are substantially identical for the different volume fraction fiber.

3.3 Effect of temperature and humidity on evolution of shear factors correction

Figs. 5 to 7 present respectively the evolution of the shear correction coefficient *k* as a function of the fiber orientation angle for three environmental conditions (ΔT=00°C, ΔC=0, ΔT=500°C, ΔC=0,5% and ΔT=1000°C, ΔC=1%) for volume fractions fibers *Vf*=50, 60 and 70%. It is noted that the effect of temperature and humidity have no effect on the evolution of the shear correction factor.

4. Conclusions

In the present study, a new method is developed to determine the shear correction coefficient of an orthotropic beam from the basic parameters of the beam theory: namely, the mean deflection of

the cross section, the mean rotation angle and the distortion of the beam.
From this study, the following conclusions can be drawn:

- Shear factor correction does not depend only on properties of materials, but also the orientation of the fibers of reinforcement,
- The only term that is variable is the ratio $\frac{S'_{23}}{S'_{55}}$; this ratio becomes negligible when the ratio of the longitudinal modulus Ezz and the longitudinal shear modulus G_{zy} becomes very large.

Finally, this work can also be applied in the future to other types of materials (Attia 2017, Panjehpour 2018, Madenci 2019, Avcar 2019, Al-Osta 2019, Ahmed *et al.* 2019, Selmi 2020, Vinyas 2020, Tayeb *et al.* 2020, Timesli 2020, Hadji 2020, Yaghoobi and Taheri 2020, Katariya and Panda 2020, Rabia *et al.* 2020, Zenzen *et al.* 2020, Abderezak *et al.* 2021, Van Vinh 2021, Cuong-Le *et al.* 2022a, b, Akbas 2022, Chinnapandi *et al.* 2022, Rezaiee-Pajand *et al.* 2022, Yaylaci *et al.* 2022, Alimoradzadeh and Akbas 2022, Du *et al.* 2022, Cho 2022a, b, Azandariani *et al.* 2022, Kumar and Kattimani 2022, Ding *et al.* 2022, Choi *et al.* 2022, Man 2022, Polat and Kaya 2022, Bochkareva and Lekomtsev 2022, Hagos *et al.* 2022, Zhu *et al.* 2022, Mula *et al.* 2022, Huang *et al.* 2022, Liu *et al.* 2022, Wu and Fang 2022, Fan *et al.* 2022).

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