ADVANCED WAVINESS MODELLING OF THERMOPLASTIC TAPE BRAIDS

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ABSTRACT

Tape braiding technology, utilizing fully consolidated thermoplastic tapes as braiding yarns, represents a novel, high rate preforming process for manufacturing composite structures with thermoplastic matrix material. The braided tape-preforms are especially characterized by the very low height to width ratio of the tapes which affects the degree of undulation of the fibers within the braid and result in enhanced mechanical properties of the final part.

As the cross sectional area of thermoplastic UD tapes is rather rectangular compared to the lenticular one of dry fibre braids, the common sinusoidal description of the fibre path to calculate the mechanical properties becomes increasingly inapplicable. Thus this investigation aims at developing a new model which is more appropriate for modelling the undulation path of tape braids. Experimental validation of the description was made by a computer tomographic (CT-) structural analysis. Based on this new undulation description method a micromechanical model to predict the homogenised laminate properties for biaxial or triaxial tape braids has been elaborated.

1 INTRODUCTION

The increasing demand for energy-efficient transportation systems, e.g. in the aviation and automotive industry, requires an increase in the efficiency of both the production processes and the products themselves. The principle targets are high performance components with high production rates at low costs. In recent developments [1] braiding technology with braiding of fibre reinforced thermoplastic tapes addresses these requirements by high efficiency and automation of the preforming process for structurally loaded fibre reinforced thermoplastic (FRT) profile structures. The so called tape-preforms are manufactured from fully consolidated fibre reinforced unidirectional (UD) thermoplastic tape products and are the key product in multiple process chains to efficiently manufacture semi-finished and functionalized FRT profile structures. Multiple advantages arise from the combination of pre-consolidated thermoplastic tape products with braiding technology. Braiding delivers high processing speeds with a high level of automation. Additionally the use of pre-consolidated tapes saves the challenging and time-intensive process step of impregnating the filaments, which in return significantly reduces processing time during the consolidation.

Figure 1: Manufacturing process for tape based FRT profile structures [1]

To ensure consistent dimensioning of high quality tape-braid based functionalized CFRP structures, not only the tape's material properties need to be considered, but also the influences on the properties occurring during the process steps of preforming, consolidation and functionalization. Braiding as the preforming process step significantly influences the resulting mechanical properties not only due to the global orientation of the fibres but also due to the yarn undulations caused by the textile structure of the braid. To take this into account this work shows an analytical approach to predict the effective laminate properties of biaxial and triaxial thermoplastic UD tape braids with a novel waviness approach appropriate for tape braids.

2 BACKGROUND

Many suggestions were made in the literature to analytically predict the effective laminate properties of braided composite components, which all show the same reasonable strategy. First a micromechanical model is used to predict the unidirectional laminate properties based on the fibres and matrix properties. Then these are combined with the textile undulation path and the braids layup to calculate the effective laminate properties.

One of the most widely used micromechanical models is the "modified rule of mixture" by Chamis [2], which gives a formulation for a transversely isotropic laminate the five independent elastic properties. Using this, Hashin and Rosen [3] as well as Christensen [4] developed a micromechanical concentric cylinder model of fibres surrounded by matrix in the boundaries of a unit cell for better evaluation of the transversal shear modulus G_{23}. Latest "bridging models", e.g. by Huang [5, 6] consider plastic deformations by connecting the internal stresses generated in the matrix with those in the fibres, which are depended on the constituent geometric and material properties. The model assumes perfect bonding between fibres and matrix. With this the overall compliance matrix of orthotropic materials can be derived using existing plastic flow theories, e.g Prandtl-Reuss flow relations, of the constituent isotropic materials.

To analyse the influence of the textile preforming, in this case for braiding, the textile architecture needs to be well known. Pierce [7] gave one of the earliest geometric characterizations of woven textile architectures with the assumption of tows having a circular cross-section. Robitaille [8] suggested that any fabric can be described by vectors of the tow centreline together with the tows' cross-section defining the volume. For dry fibre textiles he only considered transverse shear deformation to affect the vectors, but not the tow cross-sections. The approach was implemented in the open source software package "TexGen". Compared to that Lomov et al. [9] developed a textile geometry describing tool, called WiseTex, using an energy minimization algorithm to determine the resulting pattern of a textile in its relaxed state. The model shows good agreement between computed and measured parameters but requires a significant amount of input data e.g. tow bending rigidity versus tow curvature, information about the transverse tow compressive behaviour as well as frictional properties between the tows.

With the unidirectional properties and the textile architecture different approaches were adopted to predict the resulting textile properties. Ishikawa and Chou used the classical laminate theory to determine the mechanical behaviour of woven textile composites ignoring the undulation of the fibres and describing the textile geometry with a so called "mosaic model" [10]. Later they considered undulations and continuity with the help of crimp-models, where the undulation path has been subdivided into small sections of appropriate length [11]. There the crimp zone itself has been described using a linear or sinusoidal expression. Each section was analysed using the classical laminate theory and the average compliance was determined assuming constant stress in direction of the weaves' warp yarn. Compared to Ishikawa and Chou, Byun [12] analyses triaxial braided textiles with axial yarns showing lenticular cross-section after infiltration and curing. The lenticular axial yarns give the braiding yarns an undulation path, which was approximated with an arc-function. Using this undulation path description, an averaged stiffness matrix along the path was determined for each yarn direction and finally superpositioned by their volumetric content. He experimentally examined his approach using carbon fibre yarns infiltrated with epoxy resin by a resin transfer moulding process. The theoretical results from his averaging approach showed good agreement to the experimental results compared to a laminate theory approach. A similar approach has been performed by Queck et al. [13] with the difference of using a sinusoidal fibre path for the undulation as this shows better accordance for biaxial braided composites. Nevertheless, the identical superpositioning of the averaged stiffness matrices of the braiding yarns and the matrix was done, which leads to stronger deviations in the predicted results of the shear moduli. So Potluri et al. [14] performed a modified laminate analysis step to overcome these deviations of the shear moduli. Therefor he used the averaged stiffness matrices by transformation along an arc undulation path and figured an alternate laminate layup of braiding yarn layers and a separate matrix layer. With this representative layup and the classical laminate theory he predicted the effective properties of the resulting braiding layer. Another approach, by Shokrieh et al. [15], did not separate the braiding architecture into yarn and matrix layers but into real composite layers, which already consider the matrix before transformation of the stiffness along the braiding path. In their experimental investigations they showed better accordance of the shear moduli compared to the Queck prediction model.

All above stated authors performed their work with dry fibre braids, using braiding yarns with lenticular cross-section areas, which were infiltrated with a thermoset matrix system. Compared to that this investigation uses fibre reinforced thermoplastic tapes as braiding yarns, which show deviant undulation behaviour. Additionally the characteristic reduction of the undulation amplitude during consolidation of hybrid fibre-thermoplastic braids has not been considered so far.

3 TAPE BRAIDING ARCHITECTURE

Using a maypole braider during the braiding process, the bobbins move on the inside of the braiding wheel on sinusoidal paths in clockwise and counter clockwise direction, as a consequence crossing each other and forming the specific biaxial braiding pattern. Additionally to the braiding yarns it is possible to insert axial yarns in between the braiding yarns yielding a triaxial braiding pattern. These yarns are depositioned on a braiding mandrel, which is guided through the centre of the braiding wheel, e.g. with a robot. The type of pattern and number of stacked braiding layers depends mainly on the structural requirements given by the assumed load spectrum.

3.1 Description of the braiding architecture

Considering a circular braiding mandrel each yarn forms a helical path on it with the helix angle θ, called braiding angle. All yarns together form a uniform braiding pattern, which can be described by a representative unit cells (RVE's) based on the basic braiding parameters like yarn number N, braiding angle θ, the width of a braiding yarn w_b and the mandrel diameter d *(Figure 2).*

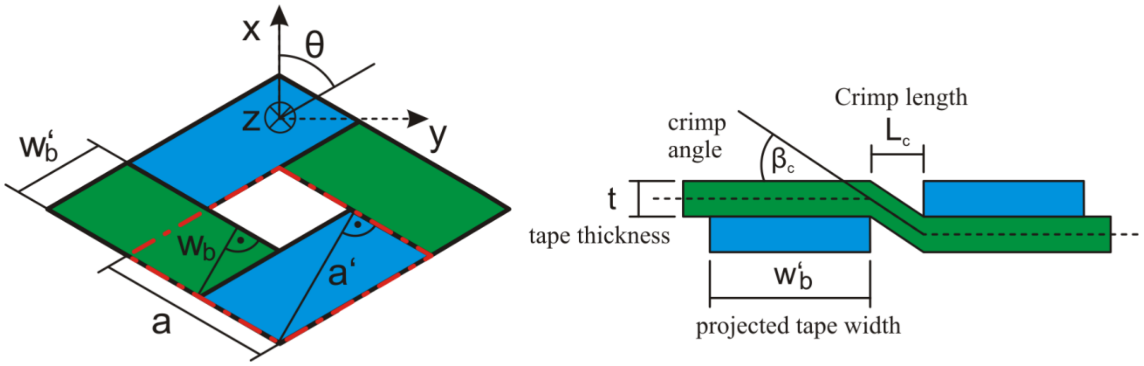

Figure 2: Braiding pattern unit cell *(left)* and linear crimp model *(right)*

To determine the resulting laminate properties of braids the wavelength L_b of a single yarn, the layer thickness after consolidation t_c and the volumetric contents V_{ax} and $V_{\pm\theta}$ of each braiding orientation is necessary. As the type of braid that is specified by the undulation repeating sequence, e.g. a regular braid with 1x1 or a twill braid with 2x2, significantly affects the laminate properties, the general geometrical description of a triaxial braided 2x2 braid is stated here. The procedure follows always the same sequence that at first the wavelength of a single yarn and then the volumetric contents together with the consolidated laminate thickness are predicted.

Simple geometric relations give the wavelength L_b of the single yarn as follows

$$L_b = 2p * a \tag{1}$$

$$a = \frac{\pi d}{N sin\theta} \quad , \tag{2}$$

where p is the pattern factor, e.g. with $p=1$ for a 1x1 braid or $p=2$ for a 2x2 braid.

The crimp zone is approximated with a linear crimp model to determine the crimp length L_c, the crimp angle β_c and using these, the resulting volumetric contents of the braiding architecture:

$$L_c = \frac{3t}{2tan\beta_c} = \frac{1}{sin\theta}\left(\frac{\pi d}{N} - \frac{w_b}{2cos\theta}\right) . \tag{3}$$

Where t is the thickness of a single tape yarn, having the indices *“p”* for the preform tape thickness, i.e before consolidation and *“c”* for the consolidated tape thickness, i.e. after consolidation. Knowing the undulation path with a linear crimp zone, the volumes of the biaxial and axial yarns within the unit cell and the unite cells total volume are predicted, according to

$$V_\theta(2x2) = p(a + w'_b + L'_c)w_b t_p \quad , \tag{4}$$

$$V_{ax}(2x2) = cos(\theta)w_b t_p \, 2pa \ , \tag{5}$$

$$V_{RVE}(2x2) = p^2 aa' 3t_p \ . \tag{6}$$

As no further resin infiltration during the consolidation step takes place all resin filling up the gaps in between the braiding pattern is provided by the thermoplastic matrix within the braiding yarns . So the resulting RVE volume is identical to the volumetric sum of the single yarns within in the RVE. Taking this into account the change of the thickness during the consolidation process from the unconsolidated preform to the consolidated structure, called billowing and described by the bulge factor B, is predicted to

$$V_{triax}(2x2) = 2V_\theta(2x2) + V_{ax}(2x2) \ , \tag{7}$$

$$B = \frac{V_P(2x2)}{V_{triax}(2x2)} \quad , \tag{8}$$

$$A = \frac{3}{2} t_c = \frac{3t_P}{2B} \quad , \tag{9}$$

where A is denoted as the resulting amplitude of the yarn undulation in the braiding architecture.

3.2 Tape appropriate waviness approach

As stated in chapter 2 the commonly used undulation path for braided architectures is described with a sinusoidal correlation, which becomes increasingly inapplicable for braiding yarns of rectangular cross section with a low height to width ratio. Hence, different mathematical approaches as in this case sinusoidal, tanh-, exponential-, polynomial, root- and logarithmic-functions were compared to improve the quality of the analytical models for thermoplastic tape braids. The results show the exponential description (10) as the most suitable approach, which was addressed further during this work. In (10) v describes the crimp angle with gr as accuracy factor.

$$f(x) = -e^{c-vx} + A \tag{10}$$

$$c = -\ln(A) \tag{11}$$

$$v = \frac{4\ln\left(\frac{A}{gr}\right)}{L_b} \tag{12}$$

To verify the novel waviness approach the melting character of thermoplastics was utilized as infinite metallic yarns, which serve as resonance yarns for computer tomographic scans, were fused together with the tape material before the textile preforming took place. Due to the increased resonance level the undulation path of the braided architecture could be extracted precisely and analyzed with a MatLab scripted image analysis algorithm. There the measured undulation path is plotted together with the theoretical sinusoidal and exponential description *(Figure 3)* and compared by their goodness of fit level *(Table 1).*

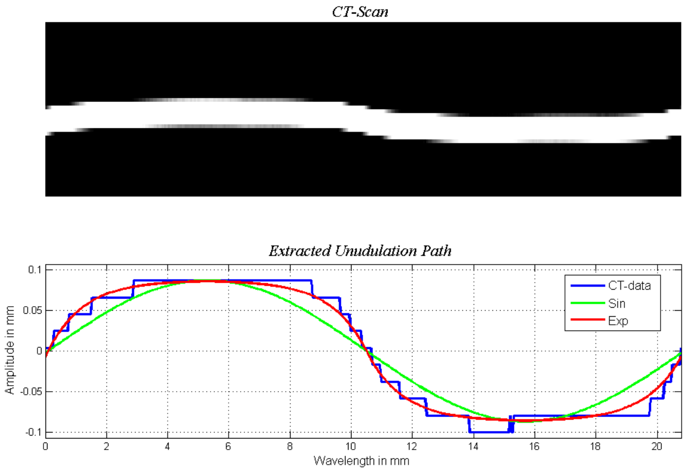

Figure 3: Comparison of undulation description methods with measured CT-data

The mean root of the square residuals *(RSME)* is three times more accurate for the exponential description than the sinusoidal one. Additionally the overall goodness of fit factor with the R^2 method was investigated and indicates with 0,96 to 1 a high overall fitting accuracy for the exponential approach. Thus this novel approach describes the undulation of thermoplastic tape braid more precisely and will lead to higher accuracy in predicting the resulting elastic properties of tape braids and is used as following.

Undulation description		*sinusoidal*	*exponential*
RSME	[%]	342	100
R^2	-	0,884	0,959

Table 1: Goodness of fit for analysed undulation approaches

4 EFFECTIVE LAMINATE PROPERTIES

As braiding undulations represent periodic fibre waviness, it is sufficient to consider a representative section of the undulation path to analytical predict the resulting elastic laminate properties. For that purpose this undulation section is subdivided into infinitesimal thin slices of the length dx, where x is the direction aligned to the braiding yarn's axis. Each slice's compliance is separately predicted and transformed from its local *123*-coordinate system into the braiding yarns's *x'y'z'*-coordinate system. The resulting compliance of the undulation section is then integrated along the undulation path and averaged by its length *(Figure 4)* [16]. Finally the elastic laminate properties of the braid are calculated by the volumetric content of each fibre orientation within the braid using their averaged compliance matrices.

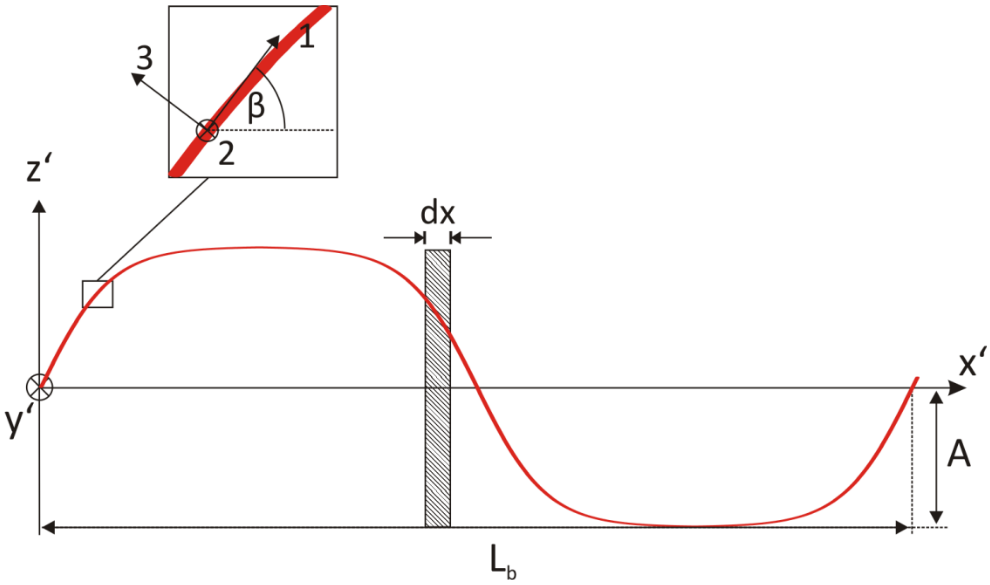

Figure 4: undulation path of braided tow representative layer

The stress strain state is described with the universal constitutive equation and the transformed compliance matrix $[\overline{S_{ij}}]$ given with equation (13), where $[R_{ij}]$ is the Reuter matrix and $[T_{ij}]$ the transformation matrix around the y'-axis.

$$\{\varepsilon_i\} = [\overline{S_{ij}}]\{\sigma_i\} \quad , \tag{13}$$

$$[\overline{S_{ij}}] = [R_{ij}][T_{ij}]^{-1}[R_{ij}]^{-1}[S_{ij}][T_{ij}] = [T_{ij}]^T[S_{ij}][T_{ij}] \quad , \tag{14}$$

$$[T_{ij}] = \begin{bmatrix} m^2 & 0 & n^2 & 0 & 2mn & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ n^2 & 0 & m^2 & 0 & -2mn & 0 \\ 0 & 0 & 0 & m & 0 & -n \\ -mn & 0 & mn & 0 & m^2-n^2 & 0 \\ 0 & 0 & 0 & n & 0 & m \end{bmatrix} , \tag{15}$$

$$m = \cos\beta\,, \quad n = \sin\beta \quad ,$$

$$(i,j = x', y', z', q', r', s') \ .$$

Considering each layer of the braiding architecture to be transversely isotropic, the compliance matrix $[S_{ij}]$ is defined as followed (7):

$$[S_{ij}] = \begin{bmatrix} S_{11} & S_{12} & S_{12} & 0 & 0 & 0 \\ S_{12} & S_{22} & S_{23} & 0 & 0 & 0 \\ S_{12} & S_{23} & S_{22} & 0 & 0 & 0 \\ 0 & 0 & 0 & 2(S_{22}-S_{23}) & 0 & 0 \\ 0 & 0 & 0 & 0 & S_{66} & 0 \\ 0 & 0 & 0 & 0 & 0 & S_{66} \end{bmatrix} \tag{16}$$

The compliance indices can be derived with diverse laminate theories, but the Christensen [17] modified 3-D laminate theory involving stress terms in the thickness direction, is here recommended to be applied, as undulations in thickness direction are given.

To calculate the transformed compliances the properties over one wavelength section and the local transformation angle β are related to the wave parameters A and L_b as follows:

$$\tan(\beta) = \frac{df}{dx'} = ve^{c-vx} \ , \tag{17}$$

$$\cos(\beta) = \frac{1}{\sqrt{1+\tan^2(\beta)}} = \left[1 + v^2 e^{2(c-vx)}\ \right]^{-\frac{1}{2}} \ , \tag{18}$$

$$\sin(\beta) = \frac{\tan(\beta)}{\sqrt{1+\tan^2(\beta)}} = ve^{c-vx}\left[1 + v^2 e^{2(c-vx)}\ \right]^{-\frac{1}{2}} \ . \tag{19}$$

The resulting averaged compliance matrix $[\overline{S_{ij}}]$ is found by integration along the undulation path:

$$\overline{S_{ij}} = \frac{4}{L_b}\int_0^{L_b/4} S_{ij}\ dx' \quad . \tag{20}$$

Carrying out the above stated integration (20) for all compliances, the transformation invariants I_{ij} are derived

$$I_1 = \frac{4}{L_b}\int_0^{L_b/4} m^4\, dx' = \frac{2}{vL\_b}\left(ln\left(\frac{ab+1}{a+1}\right) - \frac{1}{ab+1} + \frac{1}{a+1}\right) + 1 = 1 - I_3 - I_8 \ ,$$

$$I_3 = \frac{4}{L_b}\int_0^{L_b/4} m^2 n^2\, dx' = \frac{2}{vL\_b}\left(\frac{1}{ab+1} - \frac{1}{a+1}\right) \ ,$$

$$I_5 = \frac{4}{L_b}\int_0^{L_b/4} n^4\,dx' = \frac{2}{vL\_b}\left(ln\left(\frac{a+1}{ab+1}\right) - \frac{1}{ab+1} + \frac{1}{a+1}\right) = I_8 - I_3 \quad ,$$

$$I_6 = \frac{4}{L_b}\int_0^{L_b/4} m^2\,dx' = \frac{2}{vL\_b}\left(ln\left(\frac{\frac{1}{b}+a}{a+1}\right)\right) \quad ,$$

$$I_8 = \frac{4}{L_b}\int_0^{L_b/4} n^2\,dx' = \frac{2}{vL\_b}\left(ln\left(\frac{a+1}{ab+1}\right)\right) \quad . \tag{21}$$

With the variables a and b:

$$a = v^2 e^{2c} \qquad , \qquad b = e^{-\frac{vL\_b}{2}} \tag{22}$$

Conduction the integration it appears that

$$\int_0^{L_b/4} m^3 n\ dx = \int_0^{L_b/4} n^3 m\ dx = \int_0^{L_b/4} mn\ dx = 0 \tag{23}$$

and with this the transformed compliances $\overline{S_{15}}$, $\overline{S_{25}}$, $\overline{S_{35}}$ and $\overline{S_{46}}$ are equal to zero. Thus braided composites with plane fibre waviness remain orthotropic on their average material behaviour.

The compliance components received from equation (20) are the compliances in the x'y'z'-coordinate system. In order to quantify the compliances in the global xyz-system *(Figure 2)* another transformation procedure with a similar transformation like in equation (14) by rotating around the z-axis. The transformation matrix $[T_{kl}]$ is stated as follows:

$$[\overline{S_{kl}}] = [T_{kl}]^T [S'_{kl}][T_{kl}] \quad ,$$

$$[T_{kl}] = \begin{bmatrix} p^2 & q^2 & 0 & 0 & 0 & 2pq \\ q^2 & p^2 & 0 & 0 & 0 & -2pq \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & p & -q & 0 \\ 0 & 0 & 0 & q & p & 0 \\ -pq & pq & 0 & 0 & 0 & p^2-q^2 \end{bmatrix} \quad , \tag{15}$$

$$p = \cos\theta \ , \quad q = \sin\theta \ ,$$

$$(k,l = x,y,z,q,r,s) \ .$$

Though the undulation affects the properties in thickness direction, the single layer of one specific braiding orientation stays orthotropic. Contrary, after transforming the compliances to the global laminate coordinate system the laminate becomes nonorthotropic.

Considering one braiding layer as a unit cell of two layers of ±θ° for a biaxial and three layers of ±θ° and 0° for a triaxial braid and applying some load in the x-direction, each layer can be assumed of constant strain. Thus the stiffness of each layer is averaged according its volumetric content, determining the braiding laminates stiffness matrix. Here for example for a triaxial braid, where V_{triax} is the total volume of the unit cell, V_{ax} the one of the axial yarns and $V_{-\theta}$, $V_{+\theta}$ the ones of the braiding yarns

$$[C_{triax}] = [C_{ax}]\frac{V_{ax}}{V_{triax}} + [C_{-\theta}]\frac{V_{-\theta}}{V_{triax}} + [C_{+\theta}]\frac{V_{+\theta}}{V_{triax}} \quad . \tag{16}$$

Then the stiffness matrix *$[C_{triax}]$* is inverted to the compliance matrix *$[S_{triax}]$*, which finally gives the results for the global engineering constant of the braided textile. So that all engineering properties are derived by applying uniaxial loads to all directions x, y and z and pure shear to the various coordinate planes. Doing this the resulting elastic properties due to braiding can be predicted as follows:

$$E_x = \frac{1}{S_{11}} \; ; \; E_y = \frac{1}{S_{22}} \; ; \; E_z = \frac{1}{S_{33}} \; ;$$

$$\nu_{xy} = -\frac{\bar{\epsilon}_y}{\bar{\epsilon}_x} \; ; \; \nu_{xz} = -\frac{\bar{\epsilon}_z}{\bar{\epsilon}_x} \; ; \; \nu_{yx} = -\frac{\bar{\epsilon}_x}{\bar{\epsilon}_y} \; ; \; \nu_{yz} = -\frac{\bar{\epsilon}_z}{\bar{\epsilon}_y} \; ; \; \nu_{zx} = -\frac{\bar{\epsilon}_x}{\bar{\epsilon}_z} \; ; \; \nu_{zy} = -\frac{\bar{\epsilon}_y}{\bar{\epsilon}_z} \; ;$$

$$G_{yz} = \frac{1}{S_{44}} \; ; \; G_{xz} = \frac{1}{S_{55}} \; ; \; G_{xy} = \frac{1}{S_{66}} \; . \tag{17}$$

5 CONCLUSION

Based on the novel thermoplastic tape braiding manufacturing technology this paper presents an analytical model with a new tape appropriate undulation path description method to finally calculate the properties of biaxial or triaxial braided composites. By coordinate transformation, averaging of stiffness and compliance based upon the volume of each reinforcement layer, the final properties are derived. The prediction uses only the constituent fibre and matrix properties and the geometric relations of the braiding architecture.

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