Microstructural design of textile composites

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Textile composites are emerging as viable alternatives to other forms of composites in various structural applications. Understanding the dependence of overall mechanical properties of textile composites on its microstructure is important to derive an effective design. The present study is on the effect of geometrical and material properties of woven fabric (WF) composite microstructure on its overall mechanical properties. It is seen that the microstructural properties of WF composites give large flexibility to a designer to derive the required structural properties by judiciously varying both the geometry and material parameters.

Keywords: textile composites; microstructure; mechanical properties; design

Introduction

Any structural design involves the determination of the deformation when subjected to a load. The extent of deformation of the structures is strongly dependent on the materials making up the structure and specific to fiber reinforced composite materials is the direction of the loading and relative properties of constituent materials. In the case of composite materials, the material combination choices are many and are increasing rapidly with the introduction of new types of reinforcements and matrix materials. With the advent of textile composites, the option horizon has opened up greatly, as in addition to the materials, the structure of the fiber/yarn preform adds to the list of variables. Hence, during the past few years, it has become much less practical than in the past to determine simply by experiments the properties of composites formed by these constituents. On the other hand, the number of parameters available to control the textile composite properties give the designer flexibility to design the material to suit the requirement perfectly. To implement this effectively, the designer needs to know the effect of each parameter on the overall composite behavior. As mentioned earlier the number of poten-

tially interactive combinations is too great, both in terms of testing and time, hence, analysis methods need to be used to study the sensitivity of each of the parameters. In the present article the existing analytical methods¹⁻⁵ are used to study the behavior of one class of textile composites, i.e. woven fabric reinforced composites (WF). Both the geometrical and material variables are considered in the present study.

Fabric geometry

The behavior of WF composites depends upon the type of weave, fabric geometry, fiber volume fraction, laminate configuration and the material system used. A biaxial plain weave fabric is formed by interlacing warp and fill yarns in a regular sequence of one under and one over. A schematic representation of a plain weave fabric is shown in *Figure 1*. The important fabric geometrical parameters are: yarn cross sectional geometry, yarn fineness, number of counts and the weaving conditions like balanced or unbalanced. Even though, the exact cross sectional area of the yarn cannot be controlled during weaving, yarn width (a) and yarn thickness (h) can be controlled.

The fabric count is the number of yarns per unit length along the warp or fill direction. Based on the fabric count and width of the yarn, the gap between adjacent yarn (g) can be found. The length of gap

Figure 1 Schematic representation of plain weave fabric

between the adjacent yarns is termed as gap for further discussions. A fabric is tightly woven if there is no gap between adjacent yarns. In the case of open weaves, there is some gap between the adjacent yarns. Linear density is the weight of yarn per unit length which is a measure of the fineness of the yarn and is given by tex number (g/km). The yarn crimp is a measure of the degree of undulation. The yarn crimp is defined as the difference between the straightened yarn length and fabric sample length as a percentage of fabric sample length. Yarn crimp depends upon a , h and g . The length of the yarn as a part of fabric sample length/unit cell can consist of straight length and undulated length within the interlacing region. The undulated length within the interlacing region is termed as the undulated length (u). Depending upon the yarn cross sectional geometry, the undulated length can vary.

A plain weave fabric can be balanced or unbalanced

depending upon the number of counts and the yarn properties. If the yarn properties, such as cross sectional geometry, tex, crimp and the material properties and the number of counts are the same along both the warp and fill directions, the fabric is called a balanced one. The unbalanced fabric can be used if the properties required along the warp and fill directions are different. In the present study, a balanced orthogonal plain weave fabric with the same a , h , g and yarn tex along both the warp and fill directions is considered.

The yarn and weave parameters, such as yarn tex, width and thickness of yarn and the number of count can be controlled during weaving. In turn, balanced or unbalanced, tightly woven or open weave can be obtained. But the actual cross sectional area and the undulated length can be obtained either by photomicrographs or mathematical shape functions.

The term yarn is used here to represent untwisted fiber bundles, twisted fiber bundles or rovings. The property translation efficiency factor will have to be used to derive the properties of the yarn from the properties of the filament.

WF lamina

A WF lamina is formed by impregnating matrix into the fabric preform. The fabric preform geometry undergoes a change during this process and the extent of change would depend on the type of processing method. For the present studies, the fabric cross section as shown in *Figure 2* with $u/a = 1$ and $h_w = h_f = h_t/2$ is considered. In *Figure 3*, two configurations of the unit cell are shown with $(a + g)$ constant. The configuration with continuous line shows an open weave whereas the

Figure 2 A general plain weave fabric lamina geometrical representative unit cell

Figure 3 Representative unit cells for analysis with (a) constant $a + g$ and h ; (b) constant h/a and varying g/a

Figure 4 Effect of h/a on fiber volume fraction

Figure 5 Effect of g/a on fiber volume fraction

configuration with dotted lines shows a tightly woven fabric with interyarn gap equal to zero.

A WF lamina consists of resin impregnated yarns and the pure matrix region. Because of the presence of the pure matrix regions, the fiber volume fraction within the resin impregnated yarn and the overall fiber volume fraction within the unit cell are different. The overall fiber volume fraction (V_f^o) can be determined experimentally and is defined as the ratio of fiber volume within the unit cell to the volume of the unit cell. Using V_f^o and the yarn geometry, the fiber volume fraction within the resin impregnated yarn (V_f^s) can be determined. This is defined as the ratio of the volume of the fiber within the unit cell to the total volume of the resin impregnated yarns within the unit cell.

Both these fiber volume fractions are dependent on the fabric geometry. To study the effect of fabric geometry on V_f^s and V_f^o , two fabric geometrical parameters h and g were varied and the corresponding fiber volume fractions determined. The results are presented in Figures 4 and 5. Here, V_f^s was kept constant

at 0.8 and the variation of V_f^o was studied. This was done as it is practical to control the V_f^o during processing and hence the designer would be interested in knowing the effect of the fabric geometry on V_f^o .

Interestingly, it is noted from Figure 4 that V_f^o remains constant with varying h/a , i.e. crimp. This is true as the variation of h/a would correspondingly vary the total thickness of the lamina and the volume of the pure matrix regions, thereby keeping V_f^o constant. Figure 5 shows, the variation of V_f^o and V_f^s as a function of g/a . Here, it is seen that V_f^o reduces as gap increases with V_f^s constant. This is obvious as with the increase in gap, the pure matrix pockets would become larger hence reducing the V_f^o . Hence, a zero gap would give the largest V_f^o for a given fabric geometry.

WF laminate

A WF laminate is formed by stacking WF laminae one

Figure 6 Stacking of WF laminae in symmetric configurations

over the other possibly with different orientations as in the case of laminates formed by unidirectionally reinforced laminae (UD). In UD laminates, a variety of laminate configurations can be obtained by varying the orientations of the layers as a variable. In the case of WF laminates, different stacking patterns can be achieved even without considering the orientation of the layers as a variable. This is achieved by shifting the WF laminae of the laminate such that the yarns of one lamina are not in exact alignment with the adjacent lamina yarns. This shift can be in warp, fill and/or thickness direction. In an actual laminate, the relative movements of the fabric layers are affected by, friction between fabric layers, local departure in strand perpendicularity, possible variation of number of counts from place to place in the fabric and constraints on the relative lateral movement of layers during lamination. Hence, an actual laminate would have scattered zones of different combinations of shift.

For the present study, three idealized cases of laminate configurations are considered for analysis. *Figure 6* presents the stacking of four WF laminae in the three idealized laminate configurations. In configuration 1 (C1), there is no relative shift between the adjacent laminae, i.e. each lamina is exactly stacked over the adjacent lamina. In configuration 2 (C2), the adjacent laminae are shifted with respect to each other by a distance $(a + g)/2$ both in the fill as well as warp directions. By giving maximum possible shift to the laminae in C2 in thickness direction, such that the peaks of one fabric layer enters into valleys of the adjacent layers, the laminate configuration 3 (C3) is formed. This configuration of the laminate is also

Figure 7 Effect of h/a on compaction

termed as compact laminate. The compact laminates provide higher V_f^o . The maximum z-shift possible between two layers is a function of h/a and g/a . *Figure 7* shows the plot of maximum z-shift vs. h/a ratio for different g/a ratios. It is seen that the maximum z-shift increases linearly with the increase in h/a and the rate of increase is higher for larger gaps. Here, V_f^o remains constant for all the h/a ratios for a given g/a and V_f^s . *Figure 8* shows the plot of maximum z-shift vs. g/a ratio for different h/a ratios. Again, there is an increase in maximum z-shift with the increase in g/a and the rate of increase is higher for larger h/a . Here, for the constant V_f^s , as g/a increases V_f^o decreases. The variation of V_f^o for a constant V_f^s as a function of the number of laminae in a compact laminate is shown in *Figure 9*. The V_f^o for C1 and C2 are the same irrespective of the number of laminae in the laminate, whereas V_f^o of C3 increases with the increase in the number of laminae in the laminate. The increase is very steep initially up to 10 laminae for the weave geometry considered and later stabilizes at approx. 25 layers. The V_f^o of laminate C3 tends towards V_f^s , but cannot be equal to V_f^s as some amount of pure matrix is present even after the maximum possible z-shift is obtained. The V_f^o calculation for C3 is for quasi-symmetric stacking of WF layers.

Thermo-elastic properties

Stiffness is one of the important engineering requirements a designer will be looking for during the design process. Hence, the effect of fabric geometry on Young's modulus was studied for both varying h/a and g/a . The results are presented in *Figure 10*. Here, it is noted that at high h/a , as the g/a increases, the E_x increases and latter decreases, whereas, at lower h/a , there is a monotonic drop in E_x with increase in g/a . This behavior can be explained as follows: the effect of gap is twofold. As the gap is increased, V_f^o decreases

Figure 8 Effect of g/a on compaction

Figure 9 Effect of number of laminae on fiber volume fraction

for the same V_f^s (Figure 5), in turn the E_x would reduce. On the other hand, the presence of gap reduces crimp and hence E_x would increase. At higher h/a , the yarn crimp is so high that the introduction of a gap reduces crimp showing a net increase in the E_x , in spite of the reduction of V_f^o . Such a behavior is not seen at small h/a as already the yarn has a small crimp. Interesting to note here is that there exists an optimum gap value at which the E_x is maximum. In practice, its importance is twofold: (i) as some gap is introduced, V_f^o is less than the maximum possible for this fabric geometry, hence a higher stiffness is obtained with lesser fiber; (ii) introduction of gap will assist better impregnation of matrix resulting in better quality of the final product.

Next, the material constituents were varied to study their effect on the stiffness properties E_x , G_{xy} and thermal expansion coefficient (α_x). Here, the geometrical parameter varied is h/a as it was seen earlier that

Figure 10 Effect of g/a on Young's modulus

stiffness properties are sensitive to h/a . The material systems considered are T-300 carbon/epoxy, E-glass/epoxy and T-50 graphite/epoxy. The results are presented in Figures 11–13. It is seen from Figure 11, that E_x drops with increasing h/a for all the material systems. While the rate of drop is small for E-glass/epoxy, it is the largest for T-50 graphite/epoxy. With the increase in h/a , the crimp increases. An increase in crimp means an increase in the yarn transverse properties contributing to the WF composite stiffness. Hence, for material systems having large E_L/E_T ratio, the rate of drop is larger and vice versa. The variation of G_{xy} as a function of h/a is presented in Figure 12. For T-50 graphite/epoxy, G_{xy} decreases as h/a increases, whereas for T-300 carbon/epoxy, G_{xy} is practically constant. This can be attributed to nearly equal values of G_{LT} and G_{TT} for T-300 carbon/epoxy and a higher value of G_{LT} than G_{TT} for T-50 graphite/epoxy. For E-glass/epoxy, G_{xy} increases marginally as h/a increases. This is because G_{TT} is

Figure 11 Effect of h/a on Young's modulus for different material systems

Figure 12 Effect of h/a on shear modulus

Figure 13 Effect of h/a on thermal expansion coefficient

higher than G_{LT} for this material system. The effect of material system on α_x is seen in Figure 13. Higher values of α_x are obtained with increasing values of h/a . This is because, as crimp increases, the contribution of transverse properties of the yarn to the WF composite properties also increases. As yarn α_T is greater than α_L , an increase in α_x is seen with the increase in h/a .

Failure behavior

The interpretation of failure behavior of composite materials, in general, is by an order of magnitude more difficult than the problem of physical properties behavior. This is due to the complex failure process and the existence of a number of failure modes. In the case of

Figure 14 Effect of g/a on strength

textile composites, the difficulty increases due to the complex geometry of the fabric preforms. The complex geometry gives rise to additional non-linearities and failure modes. Even in the simplest textile geometry like the WF composites, in addition to all the failure modes that exists for UD composites, we have progressive failure in yarns and pure matrix regions. In the present study, as we are looking at the effects of the geometrical parameters on the overall WF composite behavior, the ultimate failure strength, which reflects the various failures preceding it, forms the basis for comparison. Also, designers would be interested initially in the ultimate strength for design.

To study the strength behavior, two combinations of variable were considered. In the first case, g/a was

Figure 15 Effect of h/a on strength

varied for different values of h/a , while in the second case, h/a was varied for different values of g/a . Both these studies were conducted on T-300 carbon/epoxy material system, constant $V_f^s = 0.70$ and the three cases of idealized laminate geometry. The results are presented in the form of *Figures 14* and *15*, respectively.

From *Figure 14* the strength is seen to increase initially with the increase in g/a . Later at larger g/a the strength drops. This behavior is similar to the one seen in the case of E_x . The difference seen is that the increase in the strength value initially is pronounced. This is because, at smaller fiber orientation angles, the UD composite strength does not reduce significantly, whereas the stiffness reduction is considerable, especially for highly orthotropic material systems. An other interesting behavior is that at smaller h/a , laminate C1 has a higher failure strength than C2 for all g/a values, whereas for higher h/a , this is seen at smaller gaps only.

The variation of strength with respect to h/a is seen in *Figure 15*. The failure strength does not vary significantly in the range of smaller h/a (< 0.05). There is a small increase in the failure strength at smaller h/a for laminate C3. At larger h/a the strength reduces with increasing h/a . This is because, at larger h/a the pure matrix regions are stressed more and fail earlier due to their lower strength. This triggers the failure process resulting in lower WF composite failure strength. At smaller gaps C1 has higher strength than C2 for the material system considered.

Conclusions

The existing analytical methods were used to study the dependence of the overall mechanical properties of WF composites on the microstructural properties. Both the geometrical and material properties were considered for the present study. It is seen that the microstructural properties of WF composites give large flexibility to a designer to derive the required structural properties by judiciously varying both the geometry and material parameters.

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