A STUDY ON THE EFFECT OF THICKNESS AND STACKING SEQUENCE ON THE STIFFNESS OF COMPOSITE LAMINATES UNDER QUASI-STATIC LOADING

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Article History: Received 28 June 2023; Revised 12 July 2023; Accepted 24 July 2023

ABSTRACT: *The quasi-static loading characteristics of symmetric carbon fibre reinforced epoxy matrix composites loaded to a peak of 2500 N and then unloaded were evaluated in terms of the characteristics of the response, bending stiffness and energy consumed for lay-up configuration in the families of* $[0/90/\pm45]_s$, $[\pm45/0/90]_s$ *and* $[0/90/0/90]_s$. *The test samples were manufactured measuring 100 x 150 (mm) and during testing they were held firmly with toggle clamps on the support fixture placed on the bed of an instrumented Tinius Olsen universal testing 25ST machine. The macro-mechanical behaviour of laminates with respect to quantities of the laminate extensional and bending stiffness matrices were compared in relation to the experimentally obtained normalized plate bending stiffness; also, the energy absorbed quantities related to the bending stiffness of the different categories of the laminates. The results obtained reveal that the ratios of the extensional stiffness to the bending stiffness elements of the matrices are relevant quantities affecting the load – displacement plot, energy absorbed and the bending stiffness. Also, the increase in the number of surface cross plies in composites is a good approach to increase resistance to major damage for composite structures.*

KEYWORDS: *reinforced composites; quasi-static test; laminate theory; bending stiffness; energy absorbed.*

1.0 INTRODUCTION

The use of composite materials in modern day industrial applications is continuously on the increase, particularly in the aviation industries [1]. Composite were initially used as part of secondary structural materials in the aerospace industries, but with the increase in knowledge and performance they are now part of the primary structures such as the wings and fuselage. At least 50% of next generation aircraft structures are likely to be manufactured with composite materials. The primary characteristics that have made continuous fibre reinforced composites and the composites reinforced with fabrics attractive for the aviation industries are the high strength to weight ratio and good capacity to absorb kinetic energy; other properties include light weight and corrosion resistance. In multi-directional composite laminates, the stacking sequence could be used to control the stiffness and strength and hence achieve a specific design requirement [2].

Buluta and Erklig [3] conducted quasi-static indentation test on hybrid composite plates to understand the dynamic effect of low velocity impact; from the investigation the energy absorbed, and strength were estimated and concluded that the failures modes were affected by types of fibres and the stacking configuration. Spronk et al. [4] noted major differences between the results of static indentation and low-velocity impact test of carbon/epoxy and glass/polyamide-6 composite laminates and reported that it is not necessary to change test method in respect of material characterisation. Xie et al. [5] presented an analytical method to estimate the delamination threshold load of fibre reinforced composite under transverse load using the concept of cohesive zone modelling and the Rayleigh-Ritz solution technique.

Zopp et al. [6] report about the bending properties of non-hybrid and hybrid composites made of carbon, glass, and aluminium as reinforcement in thermoplastic matrix for the mechanical characteristics under static indentation and three-point fatigue tests. The stiffness and strength performance were good for static testing and the composite was able to take one million load cycles under fatigue loading without a significant damage and the hybrid composite with aluminium presented a relatively low bending strength. Andrew et al. [7] examined the characteristics of damaged glass/epoxy composite laminates repaired with glass and Kevlar woven fabrics intra-ply hybrid patches under bending load and observed that the use of patches of the same fibre volume fraction showed a good result compared to the undamaged composite sample.

Hofmann et al. [8] conducted a study on the bending and tensile behaviour of carbon fibre reinforced silicon. The load – displacement results from the bending tests revealed that increase in angle between the reinforcement fibres and the loading direction reduces the stiffness. Nikhil et al. [9] conducted experimental and finite element studies on the mode 2 failure behaviour of glass fibre composite using the three-point bend loading and reported that inter-laminar delamination between the layers contributed significantly to failure. The end characteristics of a composite structure manufactured from different materials is not only a function of the reinforcing fibres and the matrix, but also a function of how the individual plies or components are designed into the structure. This work looks at the effect on the extensional and bending stiffness matrices in relation to the bending stiffness and energy consumed for various classifications of composite stacking configurations manufactured and tested under quasi-static loading.

The residual strength of a composite after loading will depend on details of the damage state and that the anisotropy properties of fibrous polymeric composites can be controlled through the choice of the influencing parameters and the ply stacking sequence. The primary concern of this study is to contribute to the existing knowledge on the effect of fibre orientations and stacking sequences of composite laminates subjected to loading. The results from three categories of laminates subjected to quasi-static loading have been discussed. The category 1 and 2 laminates all have the 0°, 90° and ±45° plies but at different locations to compare the differences in the response to static loading, and category 3 laminates consisting of only 0° and 90° plies.

2.0 THEORETICAL BACKGROUND

In composite laminates manufactured with continuous unidirectional fibre reinforced plies, for the macro-mechanical analysis the resultant forces (N_x N_y N_{xy}) and moments (M_x M_y M_{xy}) acting on it is related to the extensional stiffness matrix [A], coupling stiffness matrix [B], and the bending stiffness matrix [D], by the relation shown in equation 1. This equation is well known and fully described in most textbooks on composite structures, such as Matthew and Rawlings [10].

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{21} & A_{22} & A_{26} & B_{21} & B_{22} & B_{26} \\ A_{61} & A_{62} & A_{66} & B_{61} & B_{62} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{21} & B_{22} & B_{26} & D_{21} & D_{22} & D_{26} \\ B_{61} & B_{62} & B_{66} & D_{61} & D_{62} & D_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \varepsilon_{xy}^0 \\ k_x \\ k_y \\ k_{xy} \end{bmatrix} \qquad [1]$$

The *A B D* matrix characterises the mechanical behaviour of the fibre reinforced laminate, as it relates the cross-sectional loads to the mid-plane strains and curvatures. The laminates adopted for this study are all symmetric and hence the *B* matrix is zero, that is no coupling between forces and curvatures and strains.

3.0 MATERIALS

The laminates used in this investigation were produced with carbon fibre unidirectional epoxy matrix tape of 60% fibre volume fraction, 0.3 mm thickness and areal weight of 300 g/m^2. This material was procured from Easy Composites Ltd. The typical mechanical properties of this material are shown in Table 1 [11] and the stacking configuration of composite plates used in Table 2 revealing the relative orientation of the different fibre directions.

Table 1: Typical elastic constants for unidirectional carbon-epoxy ply [Ref: de Moura & Marques (11)]

E_{11} (GPa)	$E_{22} = E_{33}$ (GPa)	$\nu_{12} = \nu_{13}$	ν_{23}	$G_{12} = G_{13}$ (GPa)	G_{23} (GPa)
109.34	8.82	0.342	0.52	4.32	3.2

Table 2: Laminate stacking configurations

Category 1	Category 2	Category 3
$[0/90/\pm45]_s$	$[\pm45/0/90]_s$	$[0/90/0/90]_s$
$[0_2/90/\pm45]_s$	$[\pm45_2/0/90]_s$	$[0_2/90/0/90]_s$
$[0/90_2/\pm45]_s$	$[\pm45/0_2/90]_s$	$[0/90_2/0/90]_s$
$[0/90/\pm45_2]_s$	$[\pm45/0/90_2]_s$	$[0/90/0_2/90]_s$
	$[\pm45_3/0/90]_s$	$[0/90/0/90_2]_s$

The laminates chosen for this study are all symmetric, hence the $[B] = 0$. Testing these composites under static loading will reveal the performance of their 0°, 90° and 45° combinations under bending and effect of their locations within the stacking configuration. In fibre reinforced composites the 0° and 90° plies absorb in-plane load, while the ±45° laminae take care of the shear loading effects, hence this study included various configuration of laminates with these directions of lay-ups.

4.0 MANUFACTURE OF TEST SAMPLES

The composite laminates were produced by the autoclave curing process. When the roll of prepreg was removed from the freezer, it was allowed to thaw for a minimum of 5 hours; to attain room temperature before the polythene bag is removed. Using a 45° square and sharp blade appropriate sizes (150 mm x 100 mm) of composite plies were cut from the roll of carbon fibre unidirectional epoxy matrix tape and stacked according to the appropriate sequence by hand. This dimension chosen was in accordance with of ASTM-D7136 [12] test standard for impact as this was the available support fixture, but in this study, samples were tested under static loading. After stacking up the plies, a roller was used to further press the composite together; purpose of which is to reduce any possible air gaps and porosities and maintain good interlaminar strength. The laminate was then place in between release films on an aluminium plate and then with breather cloth, vacuum bag and sealed round its perimeter with a tape. The whole assembly was placed under as vacuum pressure of 0.9 bar for about 4 hours before curing in the autoclave. The vacuum process helps to eliminate residual air trapped within the laminate. The thickness of the test samples produced are shown in Table 3.

Table 3: Thickness of manufacture composite samples

Category 1		Category 2		Category 3	
Laminate	Thickness (mm)	Laminate	Thickness (mm)	Laminate	Thickness (mm)
$[0/90/\pm45]_s$	2	$[\pm45/0/90]_s$	2	$[0/90/0/90]_s$	2
$[0_2/90/\pm45]_s$	2.5	$[\pm45_2/0/90]_s$	3	$[0_2/90/0/90]_s$	2.5
$[0/90_2/\pm45]_s$	2.5	$[\pm45/0_2/90]_s$	2.5	$[0/90_2/0/90]_s$	2.5
$[0/90/\pm45_2]_s$	3	$[\pm45/0/90_2]_s$	2.5	$[0/90/0_2/90]_s$	2.5
		$[\pm45_3/0/90]_s$	4	$[0/90/0/90_2]_s$	2.5

The carbon fibre tape used to manufacture the laminates was procured from Easy Composites Limited and the material data sheet recommended the cure temperature between 120°C and 130°C for a period between 1 to 2 hours. After the vacuum pressure is released, the assembly was transferred to the autoclave for curing. The laminate was gradually heated to a temperature of 121° C and maintained at this temperature for a period of 90 minutes and then gradual cooling to the room temperature of 20° C. After completion of curing process in the autoclave, the assembly was carefully taken out the unit; the sealant and bagging material removed, followed by the breather cloth and release film before taking out the samples. The edges of the manufactured test samples were trimmed using an abrasive cutter.

5.0 EXPERIMENTAL METHODS

In these series of experiments carbon fibre/epoxy composites were supported on a steel fixture having a rectangular open window in the centre on an instrumented Tinius Olsen universal testing 25ST machine and clamped at two opposite sides with the toggle clamps as shown in Figure 1. The test machine has a crosshead mass to create a maximum force of 25 kN and attached to it is a 25 mm diameter hemispherical indenter. The geometrical ratio of the indenter to the test sample dimension is suitable to produce indentation and not penetration. The samples were loaded at the crosshead speed of 10 mm/min, which was a slow loading. Figure 2 shows a representative photograph of the test sample.

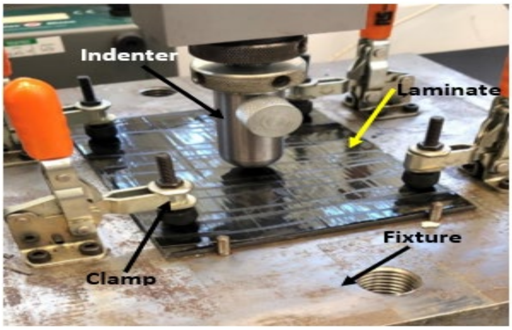

Figure 1: Experimental set-up, with test sample supported with toggle clamps.

Figure 2: Representative photos of cured composite laminates

During the test, a force transducer detects the contact and measures the resistive force exerted by the sample on the indenter and the displacement of the indenter. The data were stored in the software for subsequent display and analysis. The load – displacement data were obtained for loading and unloading of the test samples. The work done by the indenter on the laminate was consumed through elastic deformation and on the surface of the sample was seen the permanent indentation.

6.0 TEST RESULTS

The combinations of fibre reinforced composite structures in respect of the stacking sequence usually result to combination of properties such as modulus, rigidity, stiffness, strength, aeroelastic flexibility etc., which are usually preferred compared to conventional materials. The composites used for this study were all reinforced with carbon fibres and the results of the static indentation shown from Figures 3 to 5. The curves reflect the different characteristics of the laminates stacking sequence.

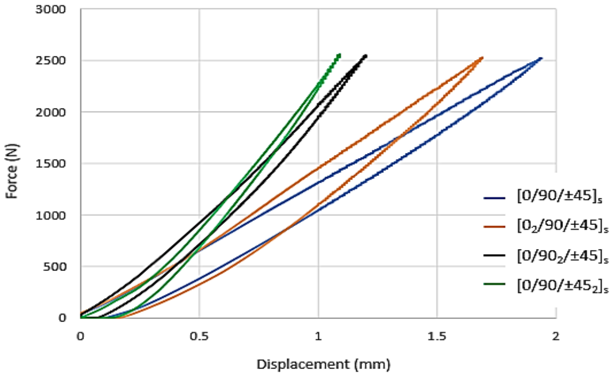

Figure 3: Quasi-static test results for composite laminates of category 1.

In Figure 3 is the plot of force – displacement of the group of composites with stacking sequence $[0/90/\pm45]_s$, $[0_2/90/\pm45]_s$, $[0/90_2/\pm45]_s$ and $[0/90/\pm45_2]_s$. All the laminates were loaded to 2500 N and then gradually unloaded back to zero. The $[0/90/\pm45]_s$ laminate suffered for high bending deflection of 1.94 mm, which is the highest compared to the other; this being an indication of weakness and least resistance to through the thickness loading. A 100% increase in the configuration of mid-plane plies seems to be a good approach for damage resistance for the kind of composite stacking sequence as shown by the results displayed by the $[0/90/\pm45_2]_s$ laminate. The duplication of the 45° cross plies increased the bending resistance as shown in Figure 3 compared to the others in this group. This is likely because of the combined effect of the mid-region four 45° plies absorbing the bending energy.

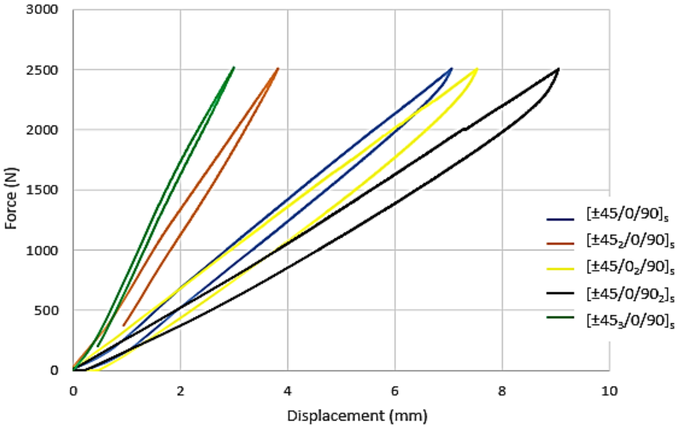

Figure 4: Quasi-static test results for composite laminates of category 2.

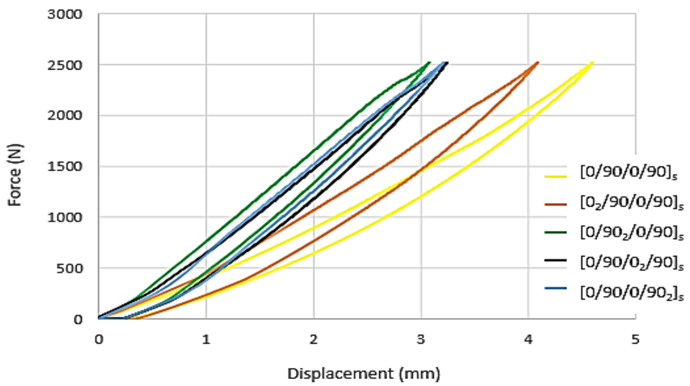

Figure 5: Quasi-static test results for composite laminates of category 3.

The area between the loading and unloading curves reflect the energy consumed by the test laminates due to micro damages such as matrix crack, indentation, and maybe minor delamination. 45° plies within a multi directional composite stacking configuration are good for the absorption of shear loads. Considering the laminates $[\pm45/0/90]_s$, $[\pm45_2/0/90]_s$ and $[\pm45_3/0/90]_s$, there exist the visible trend of the thickness for the surface cross plies and the results from the test on these samples as seen in Figure 4 shows that the more the surface cross plies the less the deformation and hence increase in the laminate resistance to bending and damage; this is in line with the discussion presented by Bulut and Erklig [3], Sutherland and Soares [13], and Yahaya et al. [14]. The report from Sutherland and Soares [13] were focused on polyester matrix composite laminates reinforced with E-glass of woven Roving, Chopped Strand Mat and Cross-Ply configurations which are commonly used in the marine industries. Figure 4 reveals that this group could be a good recommendation for energy dissipation because of the relative increase in displacement compared to the other groups. Figure 5 shows the force – displacement plots for the category 3 group of cross-ply laminate configuration, although not recommended for most applications, as this kind of laminate do not have the 45° plies which are useful for the absorption of shear loads. These laminates are symmetric and the introduction of multiple layers towards the mid-plane gives some better resistance to bending.

7.0 THE LAMINATE STIFFNESS AND (A_{11}/D_{11}) RATIO

The lamina consists of the fibre and matrix, which have different properties, hence different characteristics modulus, stresses, and strains. The stack of the laminae in the different fibre directions forms the laminate having discontinuous stress distribution through the thickness. This implies that the stress distribution for all the composites is different and hence differences in the flexure resistance. In the classical laminate theory for composites the [A], [B], and [D] matrices collectively form the stiffness matrix. In this section the results comparing and relating the laminates tested under the quasi-static loading and the ratio A_{11}/D_{11} are presented from Figs 6 to 8. The data plotted in these graphs were normalised by the laminate thickness for a fair comparison. In Figure 6 is the result comparing the category 1 group of laminates bending stiffness with ratios of the A_{11} matrix coefficient to the D_{11} bending stiffness value of the laminate stiffness matrix. The composite stacking configuration $[0/90/\pm45_2]_s$ has the highest bending stiffness and lowest ratio of A_{11}/D_{11} ; this is likely because of the ±45 double configuration in the mid-zone and the $[0/90/\pm45]_s$ composite laminate has the highest A_{11}/D_{11} ratio and a low bending stiffness.

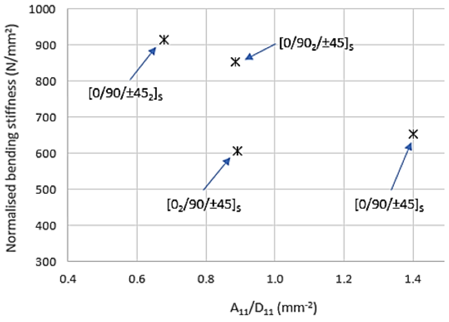

Figure 6: Laminate normalized bending stiffness and the ratio of A_{11}/D_{11} elements (category 1).

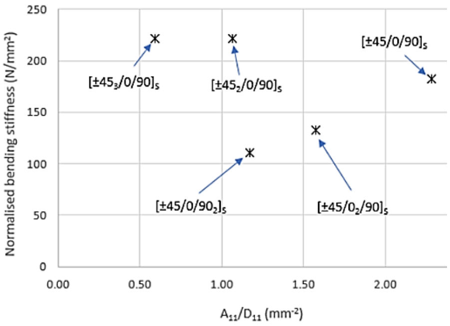

Figure 7: Laminate normalized bending stiffness and the ratio of A_{11}/D_{11} elements (category 2).

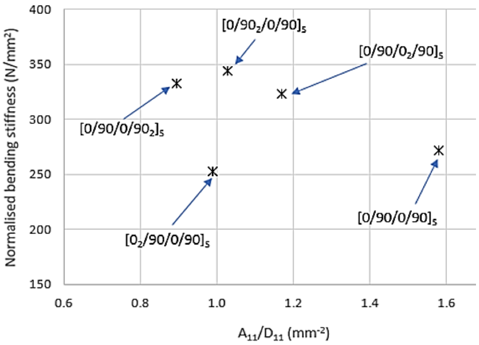

Figure 8: Laminate normalized bending stiffness and the ratio of A_{11}/D_{11} elements (category 3).

The laminates grouped in this study as category 2 with ±45 surface plies configuration has the comparison of the bending stiffness and the A_{11}/D_{11} shown in Figure7. The results show that the increase in the surface plies configuration of ±45 result in corresponding increase in the normalized bending stiffness and reduction in the value resulting from the A_{11}/D_{11} ratio with the laminate with stacking sequence of $[\pm45_3/0/90]_s$ having the highest bending stiffness and lowest value of the ratio, this likely because of the increase in the bending resistance by the number of the ±45 group. The laminates $[\pm45/0_2/90]_s$ and $[\pm45/0/90_2]_s$ have the normalized stiffness lower than the reference plate of $[\pm45/0/90]_s$. The values of their A_{11}/D_{11} ratio are different, with the reference plate having the highest value.

The third group of laminates considered in this investigation could basically be described as cross-ply composites with changes in the position of the double layer configuration. The $[0/90/0/90]_s$ plate without a double layer has the highest A_{11}/D_{11} ratio and slightly higher about the same normalized stiffness compared to $[0_2/90/0/90]_s$ which implies that increase in same layer direction surface ply has little effect on the plate bending stiffness.

8.0 COMPARISON OF ENERGY ABSORBED

Damage on composite laminates is a concern in design, manufacture, and maintenance of composite structures, and has been investigated by many researchers [11, 15] due to the detrimental effect it has on the stiffness and strength. The characteristics of the carbon fibre reinforced composites resulting to failure based on the properties is linear elastic to fracture and the lack of plastic deformation means that the damage is permanent once a certain stress level has been exceeded resulting in structural weakening; Nunes et al [16] and Hancox [17] suggested that composites are prone to impact damage due to the low transverse and interlaminar shear strength and Liu [18] declared that the primary cause of delamination in composites is the mismatch in the bending stiffness because of the different stacking configurations.

For the composite samples tested, As the indenter gets in contact with the sample and create the displacement on it due to applied force, it does work on it taken as the energy transfer. The area covered by the result presented as the force – displacement graph is the energy absorbed by the sample. The relationship between the various categories of laminates about the bending stiffness and energy consumed under quasi-static loading, investigated in this study are highlighted in Figures 9 to 11. Figure 9 shows the plot for category 1 group and there seems to be an almost linear decrease in the bending stiffness with respect to the location of the double ply direction respectively for $[0/90/\pm45_2]_s$, $[0/90_2/\pm45]_s$ and $[0_2/90/\pm45]_s$ composite laminates.

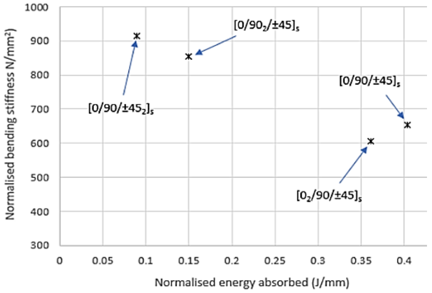

Figure 9: Bending stiffness and the energy consumed (category 1).

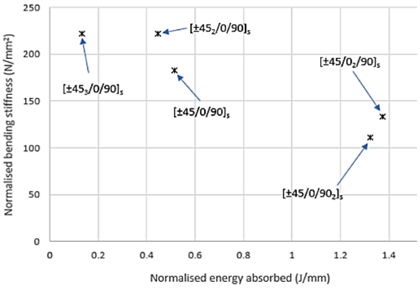

Figure 10: Bending stiffness and the energy consumed (category 2).

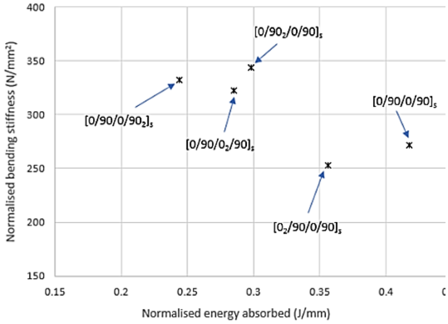

Figure 11. Bending stiffness and the energy consumed (category 3).

That is the bending stiffness decrease of the composite result in the increase of the energy dissipated. Comparing the result from the reference configuration of [0/90/±45]s and the [02/90/±45]s plate shows little difference which implies that the increase in the surface ply configuration has little effect on the behaviour under transfer loading. In Figure 10 is shown the data about the bending stiffness and energy consumed by the category 2 class of laminates. The plates with configuration [±45$_3$/0/90]$_s$, [±45$_2$/0/90]$_s$ and [±45/0/90]$_s$ showed that the increase in the laminate thickness by increase in the number of surface plies correspond to the increase in the resistance to bending. The bending stiffness for the reference plate was least compared to the other two but approximately value to the same stiffness's for [±45/0$_2$/90]$_s$ and [±45/0/90$_2$]$_s$. The interchange of the duplicate layers for 0° or 90° has negligible effect about the bending stiffness or energy absorbed under bending as seen in Figure 9 for the results of the [±45/0$_2$/90]$_s$ and [±45/0/90$_2$]$_s$ composite plates.

Cross ply laminate features being the stacking configuration characteristics of category 3 group of composites have the bending stiffness and energy absorbed under static loading compared in Figure 11. The results for the composites with configuration $[0/90/0/90_2]_s$, $[0/90/0_2/90]_s$ and $[0/90_2/0/90]_s$ shows that the location of the duplicate ply internal of the stacking sequence has little effect on the energy absorbed. The laminates $[0_2/90/0/90]_s$ and $[0/90/0/90]_s$ have the same stacking configuration with the former having double layers on the surface and the energy absorbed lower as seen in Figure 11.

9.0 CONCLUSION

The analysis reported in this investigation due to quasi-static loading on laminated composites was relatively simple but agrees with the macro-mechanical behaviour of unidirectional fibre reinforced composite plates and the following are the key findings:

- The increase in the number of mid plies is a good approach to resist damage for laminates with configuration in the likes of $[0/90/\pm45]_s$, $[0_2/90/\pm45]_s$, $[0/90_2/\pm45]_s$ and $[0/90/\pm45_2]_s$.
- The use of cross-ply configuration on the surface of laminates is good and the tolerance to transverse loading can be better with increase layers as shown by the results obtained from $[\pm45/0/90]_s$, $[\pm45_2/0/90]_s$ and $[\pm45_3/0/90]_s$ composite plates.
- The result from the reference configuration of $[0/90/\pm45]_s$ and the laminate $[0_2/90/\pm45]_s$ showed little difference, hence the increase of same direction surface ply has little effect on the behaviour under transverse loading.
- The increase in the number of surface plies of ±45 result in the reduction of the A_{11}/D_{11} ratio, but with a very high bending stiffness.

The results from this study have provided more information about the design and damage tolerance characteristics of layered composites and the observations will be useful tools to researchers and members of the composite community.

ACKNOWLEDGMENTS

The author is grateful to the University of Hertfordshire for the support given to this study.

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