Influence of Composite Adherents Properties on the Dynamic Behavior of Double Lap Bonded Joint

P. Saleh, G. Challita, R. Hazimeh, K. Khalil

***Abstract*—**In this paper 3D FEM analysis was carried out on double lap bonded joint with composite adherents subjected to dynamic shear. The adherents are made of Carbon/Epoxy while the adhesive is epoxy Araldite 2031. The maximum average shear stress and the stress homogeneity in the adhesive layer were examined. Three fibers textures were considered: UD; 2.5D and 3D with same volume fiber then a parametric study based on changing the thickness and the type of fibers texture in 2.5D was accomplished. Moreover, adherents' dissimilarity was also investigated. It was found that the main parameter influencing the behavior is the longitudinal stiffness of the adherents. An increase in the adherents' longitudinal stiffness induces an increase in the maximum average shear stress in the adhesive layer and an improvement in the shear stress homogeneity within the joint. No remarkable improvement was observed for dissimilar adherents.

***Keywords*—**Adhesive, Composite adherents, Impact shear, Finite element.

I. Introduction

NOWADAYS bonding is becoming a widespread technique of assembling parts. This technique offers many advantages comparing to traditional means of assembling such as riveting, bolting or welding: simplicity of bonding, low cost, no disruption of the substrates, light weight. On the other hand, composite materials are known by their high strength to density ratios, thus combination between adhesives with composite adherents leads to strong and light bonded structures. However, such structures suffer an important aspect: heterogeneity of the stress field within the layer. This aspect is observed under both static and dynamic loading. Normal and shear stresses concentrate with peak values at the extremities of the joint and take low values at the middle of the layer's length thus the stress measured in the joint is an average stress.

There were plenty of analytical, experimental and numerical studies carried out on bonded assemblies under static loading while less works could be found for dynamic loading case, especially numerical investigations. One of the first numerical studies of bonded assemblies was the work of Adams and Wake [1] who simulated through FEM analysis tapered substrates and spew fillets at the end of the joint in order to improve the strength and the homogeneity of the stress field. Wada et al. used Ansys to simulate dynamic test on dissimilar bonded cylinders. Transverse impact on glass-epoxy composite joints constituted the main interest of Kim et al. [3]. Sawa and Ishikawa [4] used the FEM analysis to examine the stress distribution in stepped-lap adhesive joint under static and impact tension. Also, the effect substrates' modulus of elasticity, adhesive thickness and number of steps were also investigated. Vaidya et al. [5] compared between in-plane quasi-static and transverse impact of bidirectional composite joint. Carlberger and Stigh [6] investigated fracture in Aluminum joints under tensile loading. Challita and Othman [7] studied numerically through Abaqus the accuracy impact shear test of the Split Hopkinson Pressure Bar technique (SHPB) for metallic double lap joint. Liao and Sawa [8] proved that normal stress increases with the ratio of adherent's stiffness to adhesive stiffness. Liao et al. [9] studied the effect of the overlap length, the adherents' modulus of elasticity and the strain rate on the behavior of single lap joint subjected to impact tensile laod. Hazimeh et al. [10] used 3D FEM analysis to study the quasi-static and impact shear in double lap joints with unidirectional composite laminates similar substrates. They extended the study for dissimilar substrates in [11]. Recently, Liao et al. [12] examined the propagation and stress distribution at the interface of dissimilar substrates of single lap joint. Prakash et al. [13] investigated numerically the influence of the adhesive thickness on high-speeds transverse impact behavior of ceramic/metal composite joints.

In the present work, a 3D FEM analysis will be carried out on double lap bonded joint under dynamic shear stress using the SHPB method to measure the maximum average shear stress in the adhesive layer and to quantify the homogeneity of this stress field along the overlap length. Three fibers textures of composite substrates will be studied: unidirectional, 2.5D and 3D. In addition the effect of substrates' rigidity, thickness and dissimilarity will be examined.

II. Numerical Model

A. Geometry of the Specimen

The geometry proposed is the double lap joint (DLJ) shown in Fig. 1 by front and side views. It consists of 3 rectangular plates each of length 16 mm and width 12 mm bonded together. The central adherent, whose thickness of 4mm is twice the thickness of each of the upper and lower adherents (which are similar), is shifted by 2 mm parallel to the length. This shift is responsible to convert the axial load applied on

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the central adherent to a shear within the adhesive joint. This means that the overlap length is 14 mm. The thickness of the adhesive layer is 0.1 mm.

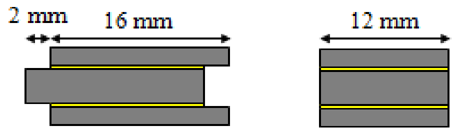


Fig. 1 Double lap joint geometry

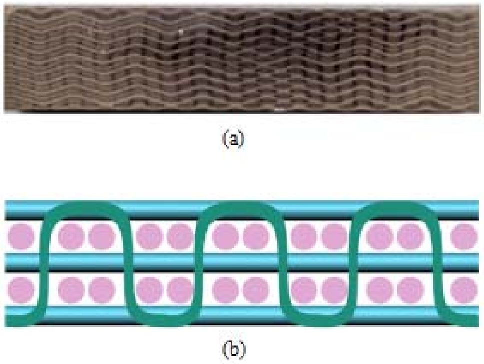


Fig. 2 Types of fibers textures (a) 2.5 D interclock H2 (b) 3D orthogonal

TABLE I
PROPERTIES OF UNIDIRECTIONAL ADHERENTS

Symbol	Unit	Value
E_{xx}	MPa	92825
E_{yy}	MPa	4248
E_{zz}	MPa	4248
G_{xy}	MPa	1748
G_{xz}	MPa	1748
G_{yz}	MPa	1574
ν_{xy}	-	0.321488
ν_{xz}	-	0.321488
ν_{yz}	-	0.35

TABLE II
PROPERTIES OF 2.5 D INTERLOCK H2 ADHERENTS

Symbol	Unit	Value
E_{xx}	MPa	27540
E_{yy}	MPa	53920
E_{zz}	MPa	7230
G_{xy}	MPa	3212
G_{xz}	MPa	3379
G_{yz}	MPa	2868
ν_{xy}	-	0.037
ν_{xz}	-	0.3616
ν_{yz}	-	0.3691

TABLE III
PROPERTIES OF 3D ORTHOGONAL ADHERENTS

Symbol	Unit	Value
E_{xx}	MPa	56190
E_{yy}	MPa	60050
E_{zz}	MPa	16090
G_{xy}	MPa	3760
G_{xz}	MPa	3170
G_{yz}	MPa	4640
ν_{xy}	-	0.063
ν_{xz}	-	0.339
ν_{yz}	-	0.305

TABLE IV
PROPERTIES OF ARALDITE 2031

Symbol	Unit	Value
E	MPa	1000
ν	-	0.4

B. Materials of the Specimen

All three substrates are made of T-300 J carbon fiber, Tex 396 from Torayca SOFICAR and RTM 6 epoxy resin from Hexcel [14]. The adhesive is Araldite 2031 black epoxy system from Hunstman suitable for composite bonding [10].

Three types of architectures for the textile composites are studied: classical unidirectional type, 2.5D interlock-type H2 [14] and 3D orthogonal [14]. The latter two types are shown in Figs. 2 (a) and (b) respectively. Each of the three types has 39.6% fiber volume. All mechanical properties of adherents and adhesive are summarized in Tables I-IV. It should be noticed that for unidirectional, mixing law is used to find the properties [10] while the properties of 2.5D interlock-type H2 and 3D orthogonal are extracted from [14].

C. FEM Analysis

A 3D FEM analysis using explicit module of the commercial software Abaqus 6.6 is applied. According to the direct impact technique described by [15] in which the striker bar hits directly, the incident bar could be removed from the model hence the specimen and the output bar are kept. Furthermore, since the specimen and the bar present two planes of symmetry, only one quarter of the model could be kept which saves huge quantities of memory for calculation in addition to time saving. Lateral motion is blocked.

The output bar is sufficiently long such as the test finishes before the wave reflectss back to the specimen. The bar is made from steel of 200 GPa Young's modulus and 0.3 Poisson's ratio. A frictionless contact at the interface between one end of the bar and the upper adherent is considered. The displacement at the other end of the bar is blocked.

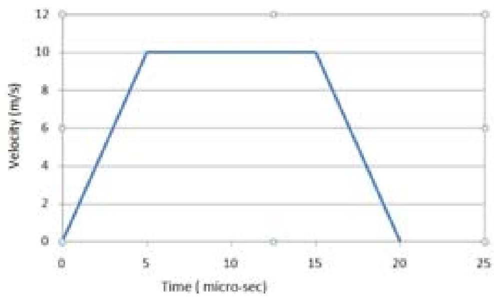


Fig. 3 Velocity impact pulse

The impact signal is modeled by a velocity input shown in Fig. 3. It is applied at the lateral face of the central adherent. The speed is 10 m/s. The duration of the input is 20 µs. The duration of each simulation is 40 µs, the output (joint shear stress) is recorded each 0.5 µs. Tied node-to-surface is imposed at the interfaces adhesive-adherents. The C3D8R-8 node solid element is used. The mesh size of the bar is 1 mm while the mesh size of the adherents is 0.2 mm and 0.025 mm for the adhesive. Because of singularity at the edges of the adhesive layer, a refined mesh at the adhesive edge of 5 μm through the thickness is considered. The model is shown in Fig. 4. Adherents are considered as elastic anisotropic while the adhesive's behaviour is elastic isotropic.

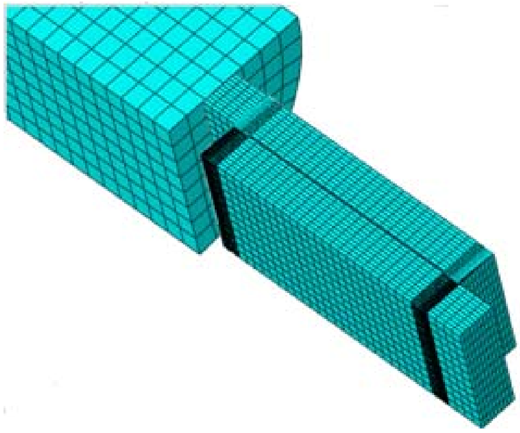


Fig. 4 Numerical mesh of the model

D.Average Shear Stress and Homogeneity Coefficient

We denote by τ(x,y,z,t) the shear stress measured in the adhesive layer where x is the direction of the overlap length L_0, y the direction of the width and z the direction of the thickness. The shear stress is assumed to be constant along the width and the thickness, thus an average value of the stress along the overlap length could be calculated at any time t of the impact by:

$$\tau_{av}(t) = \frac{1}{L_0}\int_0^{L_0} \tau(x,t)dx \quad (1)$$

The interesting value is the maximum of this average stress which will occur at a specific time. It is denoted by τ_{av}^{max}.

To quantify the quality of the shear stress distribution along the overlap length, a homogeneity coefficient denoted by α is defined according to:

$$\alpha(t) = \sqrt{\frac{1}{L_0}\int_0^{L_0} \frac{|\tau(x,t) - \tau_{av}(t)|^2}{|\tau_{av}(t)|^2}dx} \quad (2)$$

For high values of α the stress field is heterogeneous. When α approaches to zero, the stress field is close to be perfectly homogeneous.

The variation of those two quantities will be investigated in the coming lines of this paper.

III. Reference Model

Since the study is based on changing parameters and examining their influence on the shear stress and the homogeneity, it is worth to define a set of default values referred to geometric and material parameters of the double lap joint and then, one parameter is only changed and the simulation is repeated in order to investigate the influence of the changed parameter exclusively without interaction of other parameters. This set of values is called the reference model. It is summarized in Tables V and VI.

TABLE V
REFERENCE VALUES FOR ADHERENTS

Quantity	Unit	Value
Thickness of outer adherents	mm	2
Thickness of central adherent	mm	4
Mechanical properties of UD	MPa	Table I
Mechanical properties of 2.5D	MPa	Table II
Mechanical properties of 3D	MPa	Table III

TABLE VI
REFERENCE VALUES FOR ADHESIVE

Quantity	Unit	Value
Thickness of adhesive layer	mm	0.1
Overlap length	mm	14
Mechanical properties of adhesive	MPa	Table IV

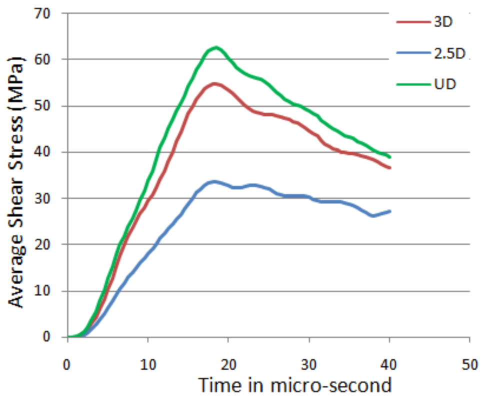


Fig. 5 Average shear stress in the adhesive layer

Fig. 5 illustrates the variation of the average shear stress along the time for the three types of fibers textures. It is clear that for any type the maximum average stress occurs at 19.5 μs. However, the highest shear stress is observed for the unidirectional composite substrate and the lowest one for the 2.5D substrate.

On the other hand Fig. 6 (a) shows the variation of the homogeneity coefficient with the time. It could be remarked that in the first microseconds of the test, the homogeneity coefficient is too high which means that the shear stress distribution is highly heterogeneous which is expected since the dynamic equilibrium is not yet established and the reflections of the wave within the specimen are still running. Moreover, at the beginning the pulse arrives at the first extremity of the joint to generate stresses before arriving at the other extremity. This whole phenomenon leads to a dynamic heterogeneity. This type of heterogeneity vanishes after a short time when the equilibrium is established which explains the drop of the value of α. In fact, according to Fig. 6 (a), after almost 8 μs the value of α drops and stabilizes to a certain non zero value, which means that there is another type of heterogeneity which remains after the equilibrium. This is the structural heterogeneity which is intrinsic to the assembly and does not disappear. This heterogeneity depends on geometrical and material parameters of the assembly. Fig. 6 (b) illustrates the zoom in made on the stable zone of α in Fig. 6 (a) for the three types of textures. This graph shows that the UD adherents give the better homogeneity (lower α of about 15%) while the 2.5D adherents lead to the highest heterogeneity (higher α of about 25%).

TABLE VII
FOUR CONFIGURATIONS OF ADHERENTS THICKNESSES

Bottom	Central	Top
1 mm	2 mm	1 mm
3 mm	6 mm	3 mm
4 mm	8 mm	4 mm
5 mm	10 mm	5 mm

TABLEVIII
PROPERTIES OF 2.5 LAYER-TO-LAYER ADHERENTS

Symbol	Unit	Value
E_{xx}	MPa	68080
E_{yy}	MPa	70180
E_{zz}	MPa	10590
G_{xy}	MPa	7750
G_{xz}	MPa	6860
G_{yz}	MPa	4940
ν_{xy}	-	0.037
ν_{xz}	-	0.297
ν_{yz}	-	0.304

It should be noticed that all adherents of same specimen have similar fibers architecture.

IV. PARAMETRIC STUDY

A. Adherents Thickness

All the parameters of the reference model will remain unchanged except the thicknesses of the substrates. Besides the values the reference model, four thicknesses configurations are examined according to Table VII.

The four configurations are applied for 2.5D interlock H2 and 3D orthogonal substrates since the UD was investigated in [10]. Results are depicted in Figs. 7 (a) and (b). Fig. 7 (a) shows that the increase in adherents' thickness is accompanied with an increase in the maximum average shear stress and a decrease in α thus an improvement in the homogeneity. Indeed, when the thickness increases, the longitudinal stiffness of the substrates increases which yields to the results obtained. Furthermore, the maximum average shear for 3D orthogonal is higher and the homogeneity is better. In fact the longitudinal modulus of elasticity E_{xx} is higher for 3D orthogonal than 2.5D type H2. It should be reminded that the loading is applied parallel to the overlap length thus parallel to the x-axis and this for all the cases studied.

One interesting finding is the presence of a potential "optimum" with 2.5D interlock H2 adherents; the homogeneity coefficient seems to reach a minimum value and then starts to increase again, the maximum average shear stress reaches a maximum but for the 10 mm thicknesses the value drops again. This observation will be an interesting topic that should later consume deep efforts and examinations.

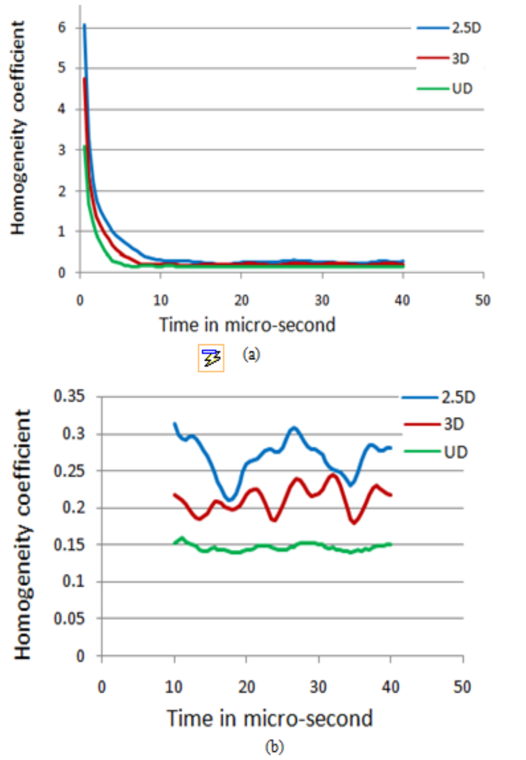


Fig. 6 Homogeneity coefficient (a) Global (b) Zoom in

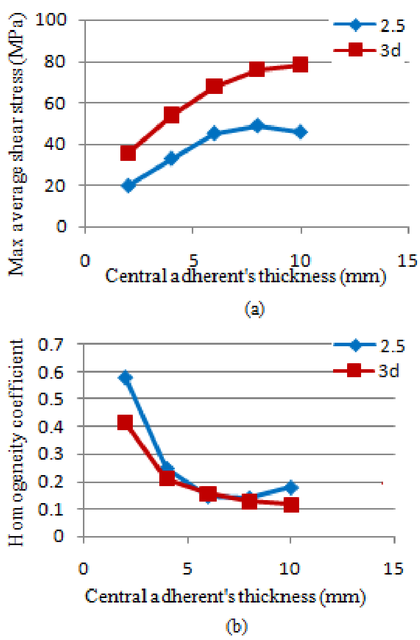


Fig. 7 Adherents thickness on (a) Maximum average shear stress (b) Homogeneity coefficient

B. Adherents Materials

The adherents' material is changed, and therefore, the properties. Four architectures of the 2.5D interlock woven composite are tested: the type 1 or H2 (that was used earlier in the reference model), the type 71 and the type 69. Those three types are made of the same carbon fiber T300J-Tex 369 and matrix resin RTM 6. The fourth type that is studied is the layer-to-layer configuration of the 2.5D interlock composite, which is made of a different carbon fiber, and a different matrix, Hercules AS4, and 3 M-PR 500 epoxy resin respectively. Their properties and texture form are detailed in [14] from which Figs. 8 (a)-(c) and Table VIII are extracted.

Results are plotted in Figs. 9 (a) and (b) and show that H2 type induces the worst homogeneity, and then come the 69 and 71 types, while the layer-to-layer type induces the best homogeneity. In the same order, the type H2 enables the lowest maximum average stress structure and the type layer-to-layer the highest one.

Comparing the longitudinal modulus of elasticity of these interlocks, it could be deduced that they are H2, 69, 71 and layer-to-layer in an ascending order. Hence, the stiffest adherent yields the best behavior, while the softer one yields the worst behavior. Additionally, the loading applied is along one axis which is the x-axis, the results show that the properties of the material that are not in the direction of the load will not intervene as much as does the longitudinal Young's modulus.

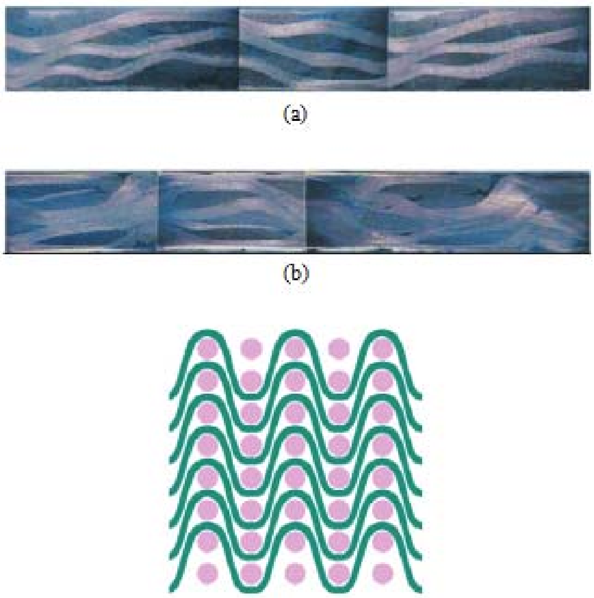


Fig. 8 2.5D composite type (a) 71 (b) 69 (c) Layer-to-layer

C. Adherents Dissimilarity

In this section, the central adherent was assigned different materials than the extreme ones. The possible configurations are: UD – 2.5D – UD; UD – 3D – UD; 2.5D – UD – 2.5D; 2.5D – 3D – 2.5D; 3D –UD – 3D; 3D – 2.5D – 3D. Average shear stress and zoom in on the stable zone of the homogeneity coefficient for all configurations are shown in Figs. 10 (a), (b); 11 (a), (b); and 12 (a), (b).

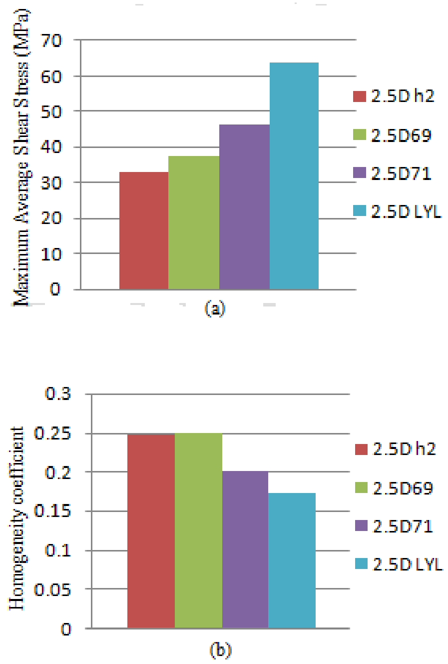


Fig. 9 Effect of adherents material on (a) Maximum average shear stress (b) Homogeneity coefficient

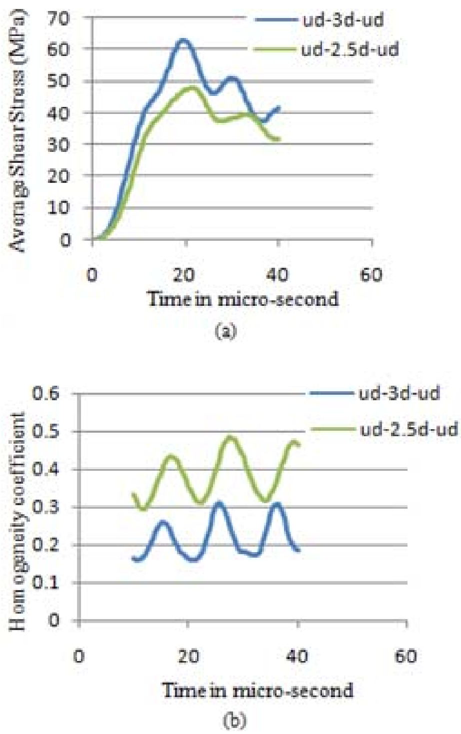


Fig. 10 Effect of interchangeability of the UD central adherent on (a) Maximum average shear stress (b) Homogeneity coefficient

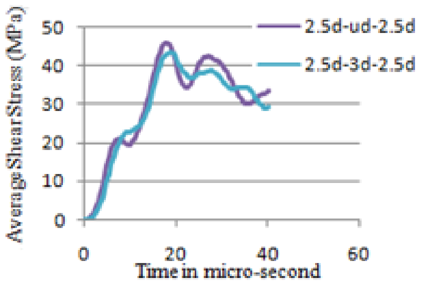
Comparing the results with those of the reference model (similar adherents) it could be observed that the instant at which the maximum average shear stress occurs, remains unchanged equal to 19.5 µs. Changing the central adherent from UD to 3D does not alter the maximum average stress which remains almost equal to 63 MPa however it drops to 47 MPa when it is replaced by 2.5D composite. However, the heterogeneity increases since it jumps from 0.15 for UD central adherent to almost 0.25 when it is replaced by 3D composite and 0.4 when it is replaced by 2.5D composite.

Replacing 2.5D central adherent with UD or 3D improves the maximum average shear stress from 33 MPa to almost 45 MPa. In contrary, the homogeneity is not improved.

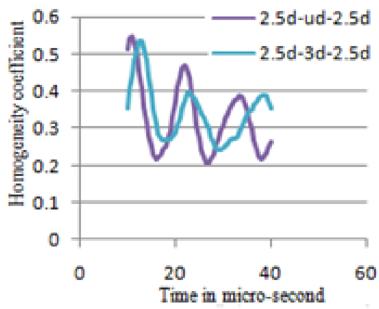
Replacing 3D central adherent with UD improves the maximum average shear stress from 55 MPa to 60 MPa while it drops from 55 MPa to 43 MPa when it is replaced by 2.5D composite adherent. Moreover, the homogeneity is not improved.

All graphs of homogeneity coefficients show that the stable value of this coefficient, which occurs at 8 µs as stated earlier, oscillates about an average value when any adherent has 2.5D or 3D texture. This is due to the obstacle formed by the fibers that are not parallel to the loading direction and thus to the wave path. The only case where α does not show any oscillations after establishment of the equilibrium is the UD-UD-UD configuration (Fig. 6 (b)).

Tables I-III show that only UD is stiffer than 2.5D and 3D along x, while the latter two types present higher stiffness along y and z than UD; this means that the main property that influences the results is E_{xx}. It should be reminded that the loading is applied along the x direction

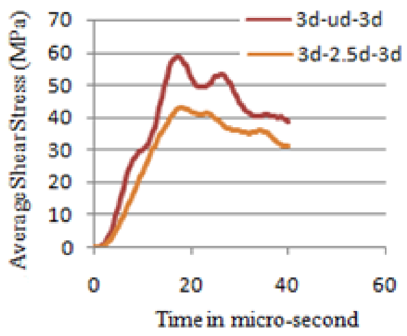


(a)

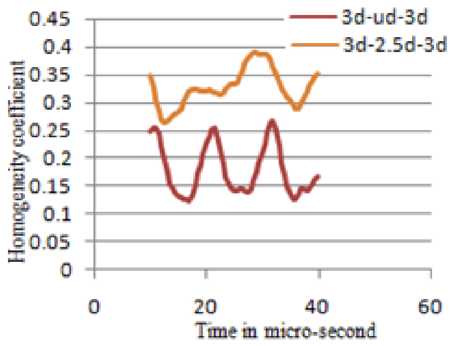


(b)

Fig. 11 Effect of interchangeability of the 2.5D central adherent on (a) Maximum average shear stress (b) Homogeneity coefficient



(a)



(b)

Fig. 12 Effect of interchangeability of the 3D central adherent on (a) Maximum average shear stress (b) Homogeneity coefficient

V. Conclusion

The stiffness of the adherent in the direction of application of the loading has the main influence among all the other mechanical properties of anisotropic composites, independently of the type of texture since the fiber volume has the same value in all three types of composites.

Since the unidirectional composite presents the highest longitudinal stiffness while the 2.5D type chosen has the least longitudinal stiffness, the maximum average shear stress is the highest in the first case and the lowest in the latter case, while the homogeneity is the best in the first case and the worst in the last case. Should the loading being applied along y for instance, the adherent having the highest stiffness along this direction is expected to give the best results for the bonded structure.

The increase of substrates' thickness yields to increase in longitudinal stiffness and thus similar tendencies are observed as those observed under the longitudinal Young's modulus effect.

A dissimilar central adherent can improve the behavior of the structure, however it increases the heterogeneity coefficient in all cases, and hence similar adherents are preferable.

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