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# Effect of fiber angle orientation on a laminated composite single-lap adhesive joint

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In the case of composite laminates with lap joints, one of the factors acting on the bonded joint behavior is the stacking sequence, most of research presented in the literature do not separate global effects (membrane and bending stiffness modification) and local effect (ply orientation near the adhesive layer). This study deals with the characterization of such effects in the case of single-lap joints of carbon/epoxy laminates. In order to isolate the local effects, specific quasi-isotropic quasi-homogeneous stacking sequences are used. When the stiffness properties are maintained constant, strength variations of more than 30% are observed with respect to remoteness position of 0°-ply orientation. Tests performed with a symmetric laminate with bending anisotropy show that the bending stiffness also plays an important role in the joint behavior. Fracture behavior of delamination occurs between these plies and also depends on an out-of-plane position of 0°-ply laminate near the adhesive layer.

**Keywords:** adhesive bonding; composite laminates; stacking sequence; delamination.



## 1. Introduction

The influence of stacking sequence on behavior of bonded joints has preoccupied many authors, starting with Renton and Vinson [1] in the mid-1970s. They studied the joints with a single-layer substrates laminated glass/epoxy type with unidirectional, 0° or multidirectional, 45/0/45/0 specimens. Their results show that static strength is little influenced by orientation ply interfaces, but fatigue strength is strongly degraded when moving from unidirectional to multidirectional, with a cohesive failure mode in adhesive in the first case, and intralaminar on first ply of the laminate in the second case. Matthews and Test [2] show the resistance increases with the proportion of 0° plies, the maximum being reached for a unidirectional sequence perfectly. In this case, the rupture is cohesive in the adhesive. They also highlight the influence of bending stiffness, the best results being obtained when the 0° plies are arranged outside of the substrates. Johnson and Mall [3] study the interfaces between 0/0, 45/45, and 90/90. For the case of 0/0, crack propagates in adhesive. In the case of 45/45, it spreads in the first ply and finishes in the inter-plies 45/0. In the case of 90/90 interface, a transverse crack appears and produces an inter-ply delamination. In order of strength, 45/45 interfaces perform better than interfaces of 0/0. The interfaces of 90/90 provide the worst results. Kairouz and Matthews [4] conduct the cross-ply 0/90, a transverse fracture is initiated at the corner of the bonded joint

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and is spread by an interlaminar shear at the interface 90/0. In the case of a first layer at 0°, the crack is initiated again near the bead of adhesive, and is spread by intralaminar cracking in the first layer to 0°. In both cases, the authors observe that the joint strength is improved with increasing bending stiffness of the substrates. Ferreira et al. [5] and Apalak et al. [6] in studies comparing the behavior of joints with a single-layer substrate glass/polypropylene sequence $[0]_7$ and [45/−45/45/0/45/−45/45] found that the fatigue of the second sequence leads to 30% lower performance than the first. They conclude that there are differences in stiffness between two sequences. Meneghetti et al. [7] studied behavior of bonded simple joints and are particularly interested in orientation of plies at interface with adhesive.[8,9]

All previous studies show a real influence of the stacking sequence rupture of bonded joints. But, some of the results seem paradoxical, even contradictory. The main explanation for these anomalies appears to be strong coupling between local and global behavior through a distribution of orientations of plies. But unfortunately, none of these studies mentions this coupling, invoking to explain differences in strength between orientations, sometimes explanations based on bending and membrane stiffness, sometimes on local cracking mechanisms. It therefore seems necessary to achieve decoupling of these effects, which can only be achieved if we have the right tools for sizing laminates.

The present paper focuses on experimental approach that the sequences stacking of quasi-isotropic quasi-homogeneous (QIQH) were an interesting solution to decouple local and global properties of laminates. Our goal is modification of orientation of the plies near the adhesive bonding without a variation in global elastic behavior of substrates. It remains to define a number of assumptions to restrict the scope of the experimental campaign while exploring a significant number of combinations. We will add a sequence called 'quasi-isotropic' which is frequently used in the aerospace field. The lay-up angles that are most widely used in the industry are 0°, 90°, 45°, and −45°. The study will be limited to combinations of these four directions.

## 2. Experimental program

### 2.1. Test specimens

The specimens of 24 laminate lay-ups led to single-lap joints on a quasi-static traction machine (Adamel DY36) with 10 kN of load cell and cross-head speed 0.3 mm/min. For each set of parameters, five specimens were tested. Figure 1 shows that the specimen geometry does not change during the experimental phase because it is not a parameter that is studied. Similarly, the chosen materials for joints are the same. The stacking sequence of laminate substrates is only variable. The specimens consist of two assembled substrates with an adhesive. The ends of the specimens are reinforced by supports that are positioned for pulling force which is applied in plane of the adhesive joint. The base material of laminated substrate is carbon/epoxy

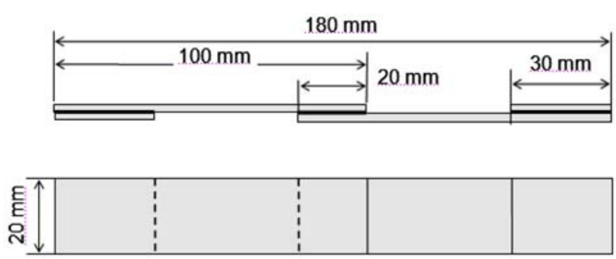



Figure 1. Geometry of tensile specimen with quasi-static test.

Table 1. Mechanical properties of unidirectional ply.[14]

| | Theoretical calculation | Experimental measurement |
|---|---|---|
| $E_L$ (MPa) | 220,732 | 222,000 ± 2000 |
| $E_T$ (MPa) | 6947 | 6900 ± 230 |
| $\upsilon_{LT}$ | 0.32 | |
| $G_{LT}$ (MPa) | 3260 | |
| $G_{TT}$ (MPa) | 3030 | |
| $X_r$ (MPa) | | 800 |
| $Y_r$ (MPa) | | 17 |

prepreg from Hexcel's composite (Ref. NCHM 6376/34%/106/M40 J) consisting of carbon fibers (54% vol.) impregnated with an epoxy matrix. Each ply thickness is about 0.1 mm, so a through-thickness laminated specimen is 2.4 mm.

The selected adhesive is a paste-like glue component epoxy, reference Permabond ESP 110. It is responsible for aluminum particles (up to 30% by weight) to increase its mechanical properties at high temperatures. The mechanical properties of the fibers and resin were obtained separately. The properties of the plies are reconstructed from the law of mixtures and simplified approaches to behavior of a unidirectional ply, as described by Berthelot [10]. The Young's modulus of M40 J fibers and resin 6376 is provided by manufacturers.[11,12]. This gives the properties of unidirectional ply which are compared in Table 1 with the properties measured experimentally. For experimental measurements, tensile tests were conducted on specimens made of unidirectional material: three testing in fiber direction and three in transverse direction can obtain the values of longitudinal and transverse Young's moduli (EL and ET) and stress values corresponding to tensile strengths.

The results show that the rule of mixtures gives a very good estimate of longitudinal Young's modulus, and a simplified approach gives a very good estimate of transverse Young's modulus. One can also observe that the dispersion on measurement of the transverse modulus, which depends only on properties of matrix, is slightly larger than the longitudinal modulus, which depends mainly on fiber properties. As for adhesive, properties tests were also carried out on samples of type 'dumbbell' to determine the constitutive law. A typical stress–strain curve is shown in Figure 2, where it is compared to a curve measured by Pires et al. [13].

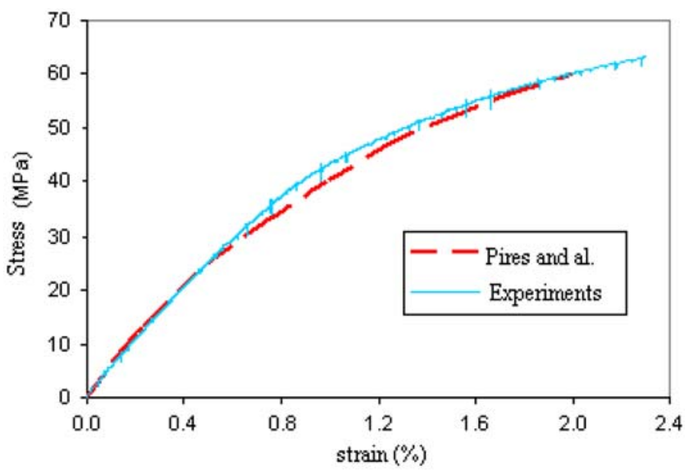



Figure 2. Stress–strain obtained curve with Permabond ESP110 specimens.[14]

### *2.2. Quasi-isotropic quasi-homogenous lay-ups*

Preliminary work from Galliot [14] showed that cracking of substrates did not exceed the third-ply into configurations that were studied. We therefore limit combinations to the first four plies in contact with the adhesive. It is easy to take stock of each of the unique combinations possible: this inventory reflects the role played by identical layers at 45° and −45°. This gives 12 different distributions of the first four plies presented in Table 2. The stacking sequences of type QIQH four directions (Table 2) contain at least 24 layers. There are exactly six, presented below [15].

[A]: [0 45 90 −45/90 −45 45 −45/0 90 0 45/0 45 −45 45/90 0 90 −45/90 −45 0 45]
[B]: [0 −45 90 45/90 45 −45 45/0 90 0 −45/0 −45 45 −45/90 0 90 45/90 45 0 −45]
[C]: [0 45 −45 90/−45 90 45 90/0 −45 0 45/0 45 90 45/−45 0 −45 90/−45 90 0 45]
[D]: [0 −45 45 90/45 90 −45 90/0 45 0 −45/0 −45 90 −45/45 0 45 90/45 90 0 −45]
[E]: [0 90 45 −45/45 −45 90 −45/0 45 0 90/0 90 −45 90/45 0 45 −45/45 −45 0 90]
[F]: [0 90 −45 45/−45 45 90 45/0 −45 0 90/0 90 45 90/−45 0 −45 45/−45 45 0 90]

Each of these sequences can be further rotated by 45°, −45°, or 90° for another local distribution. The following table (Figure 3) summarizes all combinations of the four outer layers that can be obtained from these six sequences. The fifth layer is given for information. The color code identifies each unique combination (45° and −45° equivalents). It is noted that it would be possible to study different combinations of four plies. For our 12 configurations, the stacking sequences and angles are in suitable rotation. It is found that the sequences [A], [B], [C], [D], [E], and [F] give similar combinations in pairs (with reversing the direction 45° and −45°). It therefore holds for this study sequences [A], [C], and [E] and all their rotations, which gives us the 12 different combinations. From these three sequences QIQH [A], QIQH [C], and QIQH [E], we can manufacture single-lap joints with identical elastic properties and different orientations of simply plies laminates. Table 3 shows the elastic properties of laminates calculated by the classical theory of laminates. Each sequence leads naturally to the same result, which is expressed for QIQH in only two parameters: Young's modulus and Poisson's ratio. A comparison with the experimental results obtained by testing in several directions is quite satisfactory. As classical theory of laminate mentioned above shows a polar representation of the modules of elasticity in membrane and bending laminates QIQH (Figure 4), i.e. laminates which are isotropic not only in membrane, but also in bending. Of course, these sequences, although non symmetrical, are uncoupled.

Table 2. Twelve different distributions of first four plies.

| | |
|---|---|
| First ply of 0°: | 0/45/90/−45… |
| | 0/45/−45/90… |
| | 0/90/45/−45… |
| First ply of 45° (or −45°): | 45/90/−45/0… |
| | 45/90/0/−45… |
| | 45/0/−45/90… |
| | 45/0/90/−45… |
| | 45/−45/90/0… |
| | 45/−45/0/90… |
| First ply of 90°: | 90/−45/0/45… |
| | 90/45/−45/0… |
| | 90/0/−45/45… |

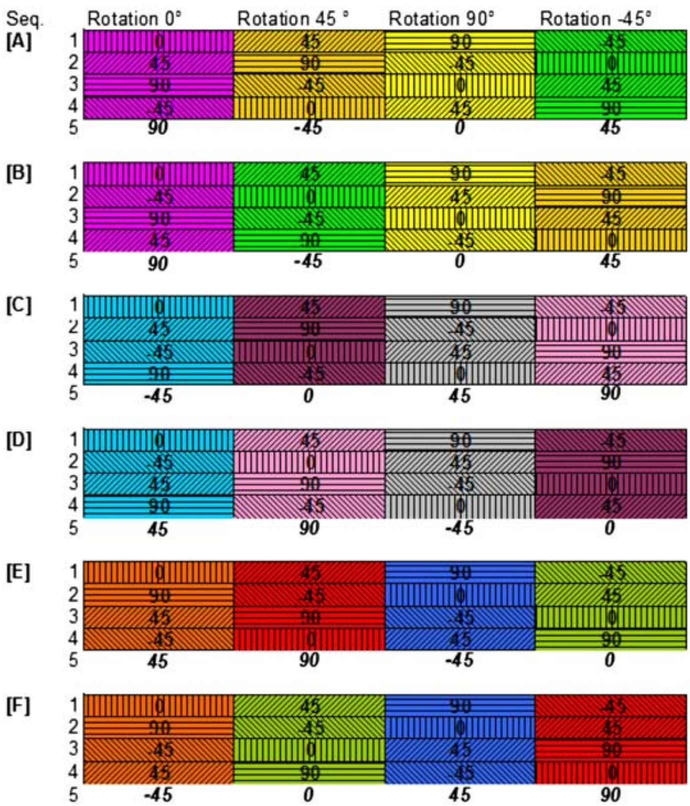



Figure 3. All possible configurations with modification of orientation.

Table 3. Elastic properties of sequences QIQH.

| | Young modulus *E* (GPa) | Poisson ratio |
|---|---|---|
| Classical theory of laminate | 78.5 | 0.32 |
| Experiment | $80 \pm 2$ | $0.30 \pm 0.02$ |

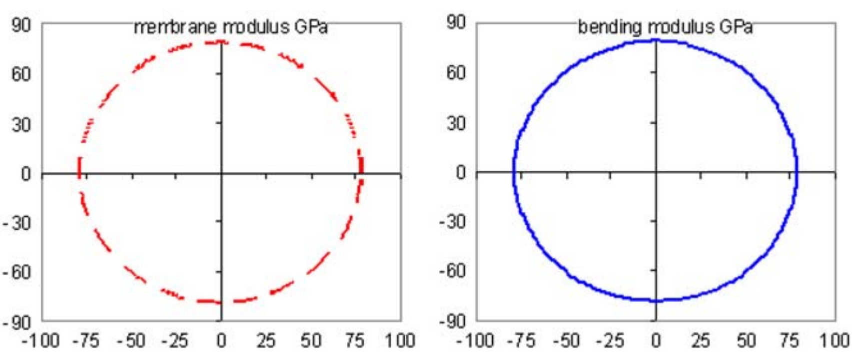



Figure 4. Polar moduli in membrane and bending of laminates QIQH.

### 2.3. Classical lay-ups

The second type of the stacking sequence chosen in this study is the sequence called 'quasi-isotropic' [10] which is composed of repeating plies 0°, 45°, 90° and −45°. The principle is to use each of these orientations the same number of times, varying the orientation of 45° between two successive plies, and impose the symmetry of the sequence. We obtain type of sequences $[45/90/-45/0]_{NS}$, $N$ can take any integer value depending on the desired thickness. The succession of plies by varying up to 45° provides a better behavior of delamination, such as impact, by not creating too much variation in bending stiffness between two plies (bending mismatch). The distribution of equal numbers of each orientation allows for isotropic in the membrane, and the symmetry removes all possible couplings. The interest of this isotropic is that it does not upset the design principles used in rigidity in design works. In the aviation industry, these sequences, when used with carbon fibers, are called 'black metal' [16], which illustrates preferred properties: lightweight structures, without questioning methodologies. However, the peculiarity of this type of sequence is not its properties of isotropic in bending, in contrast to the sequences shown above. Indeed, the symmetry condition requires that the two outer layers of the multilayer are necessarily oriented in the same direction. From the perspective of bending behavior, this will cause stiffening in that particular direction.

Using this type of sequence, we want to study the possible interactions between the local effects of the stack and the overall effects due to anisotropy in bending stiffness. To compare the results with those obtained for QIQH, we use a sequence with 24 plies: $[0/45/90/-45]_{3S}$ to be named later in this document as sequence AERO. The sequence will be developed and compared to the laminate QIQH [A], which is chosen as it has on one side of the same sequence as the local laminate AERO.

AERO : [***0 45 90 −45***/ 0 45 90 −45/ 0 45 90 −45/−45 90 45 0/ −45 90 45 0/ −45 90 45 0]
QIQH[A]: [***0 45 90 −45***/ 90 −45 45 −45/ 0 90 0 45/0 45 −45 45/ 90 0 90 −45/ 90 −45 0 45]

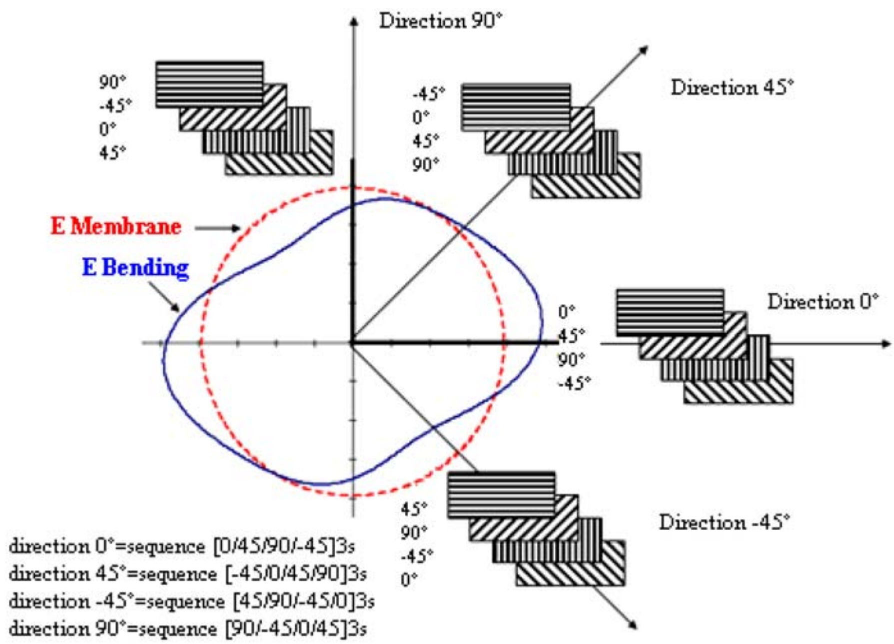



Figure 5. Polar moduli in membrane and bending of laminate AERO.

Table 4. Elastic properties of laminate AERO compared with reference values of QIQH.

| | Membrane (GPa) | Bending (GPa) |
|---|---|---|
| Reference QIQH | 78.5 | 78.5 |
| E@ tension 0° | 78.5 | 97.6 |
| E@ tension 45° | 78.5 | 82.2 |
| E@ tension 90° | 78.5 | 69.7 |
| E@ tension −45° | 78.5 | 61.0 |

For the sequence $[0/45/90/-45]_{3S}$ considered, Figure 5 shows the polar representation of the modules of elasticity in bending and membrane stacks AERO obtained from the classical theory of laminates. There is isotropic membrane and anisotropic bending. And that figure are also listed the different directions of single-lap adhesive joints and orientations encountered from the surface of the laminate. The modulus values expected in these directions are given in Table 4. It is found that flexural modulus is maximal in direction 0°, and minimum in direction −45°.

## 3. Result and discussion

### *3.1. Influence of local properties*

In all the results during the experimental procedures, Figure 6 summarizes the results obtained in terms of failure force of the tested samples, sorted increasingly. The corresponding stacking sequences are also shown in Figure 6. Examination of this figure is used to make an initial finding. The value of the rupture force seems to be correlated with the position of the layer oriented at 0° in the four plies studied. This layer is more remote from an interface with the adhesive and seems a more resistant joint. If it brings in 'families' of stacks sequences by distance of the layer 0°, we obtain four categories, including average forces at failure are shown in Figure 7. The influence of the position of the 0° layer becomes obvious in this case. The observations are summarized in following figure (Figure 8). For each case, scenarios involve rupture of one or more failure modes of laminates: interlaminar fracture (delamination), intralaminar fracture, fiber breakage, and rupture of matrix. It also illustrates

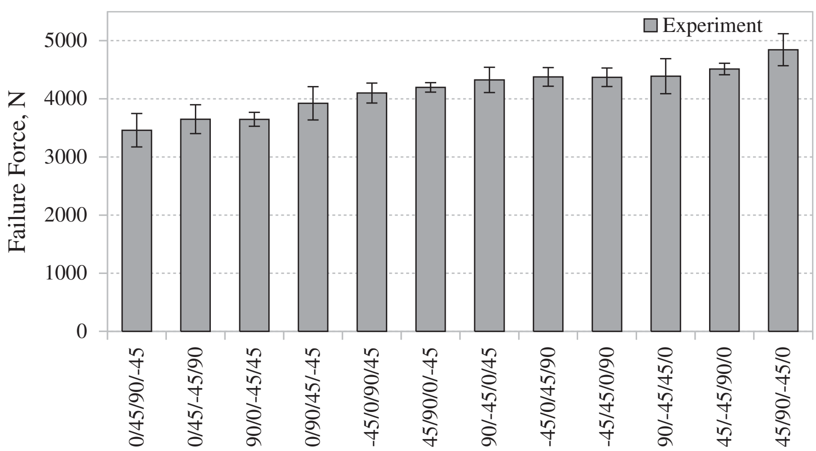



Figure 6. Average failure forces and standard deviations of 12 different sequences.

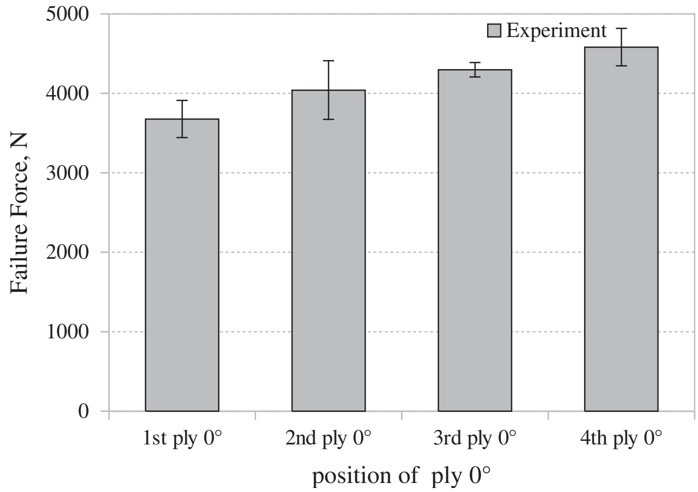


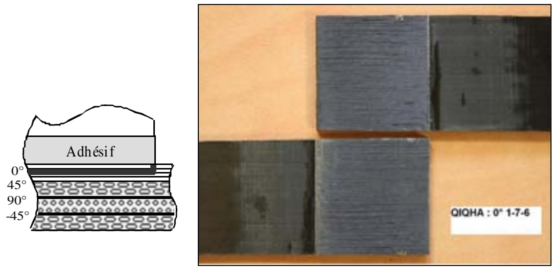

Figure 7. Regrouped failure forces as a function of 0° ply.



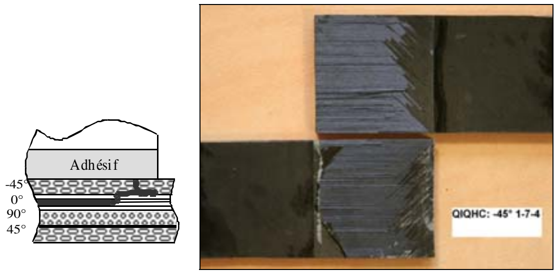
the average rupture value of each position of ply 0° and standard deviation calculated. We note that the crack is always initiated at the edges of the adhesive epoxy since in this area peel stresses and shear stresses are the highest. Depending on the distribution of the plies, this crack will then follow a path more or less complex in substrate. It is represented by a thick black line in Figure 8. Ultimately, we observed that each orientation is associated with a specific type of failure, the layer at 90° is crossed by transverse fracture matrix and so appears almost 'transparent', layers at 45° and −45° cannot alone cause complete rupture of the joint and separate into two triangular parts with a greater or lesser proportion of broken fibers. The 0° layer, finally, is still the seat of a superficial cracking intralaminar which automatically resulted in eventual failure of the assembly. Different combinations of these layers, and thus, their failure modes lead to the type of failure mechanisms described above.

### 3.2. *Influence of global properties*

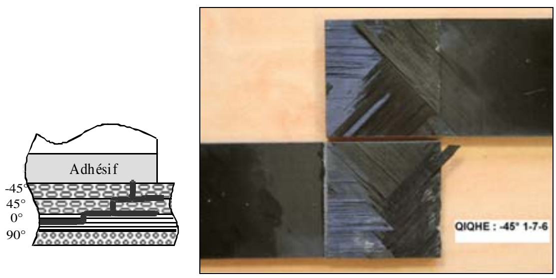
To analyze the influence of global properties, that is to say the influence of rigidity of substrates, the results obtained by varying orientation of bonding sequence AERO are systematically compared with those obtained by varying the orientation of the sequence of bonding QIQH[A], which has the same sequence of the first four plies near the adhesive layer. Figure 9 summarizes the results obtained in terms of failure load. We did not found the same hierarchy observed in the study of local properties, namely an increase in joint strength with distance from adhesive to ply 0° layer. The best performance is obtained for 45° orientation (0° ply in the second position) and the lowest at 90° (0° ply in the third position). Some notes for interpreting these differences. For laminate AERO type, −45° represents the direction of minimum bending stiffness. This flexibility, an equivalent force, results in greater rotation of the joint and therefore higher peel stresses at the ends of the adhesive joint, which can cause premature failure. So, the different percentage in bending modulus drops 22%, failure force drops 10% in −45° direction. The results are very different from those obtained with the same local sequence [45/90/−45/0] for laminates QIQH[A]. One can make the same finding for the 90° direction, since rigidity of sequence AERO in this direction is lower than that of QIQH[A] (bending modulus −11%, failure force −10%). In the 0° direction, the opposite phenomenon



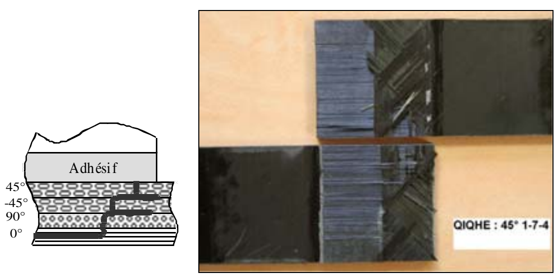

Failure mode: 1st ply-0°, 1. intralaminar failure in 0° ply ($F_{rup}$=3459 N, SD= 287 N)




Failure mode: 2nd ply-0°, 1. intralaminar failure + fiber breakage in -45° ply, 2. intralaminar failure in 0° ply ($F_{rup}$=4100 N, SD= 171 N)




Failure mode: 3rd ply-0°, 1. intralaminar failure+ fiber breakage in -45° ply, 2. intralaminar failure+ fiber breakage in 45° ply, 3. intralaminar failure+ fiber breakage in 0° ply ($F_{rup}$=4370 N, SD= 160 N)




Failure mode: 4th ply-0°, 1. intralaminar failure+ fiber breakage in 45° ply, 2. intralaminar failure+ fiber breakage in -45° ply, 3. matrix rupture in 90° ply, 4. intralaminar failure+ fiber breakage in 0° ply ($F_{rup}$=4512 N, SD= 99 N)

Figure 8. Failure modes of various local stacks laminate.

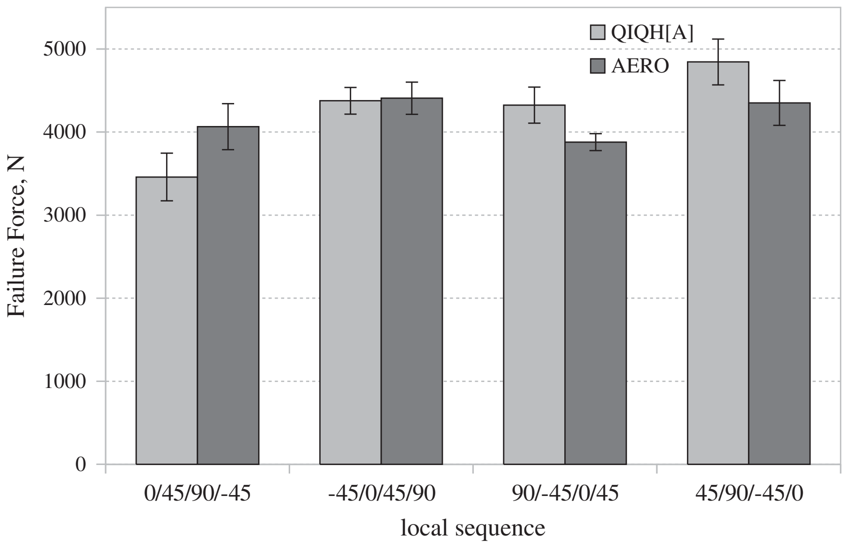



Figure 9. Comparison of failure loads between laminates QIQH[A] and AERO corresponding to different orientations of bonding.



occurs. The fact that the sequence AERO is stiffer in this direction improves the performance by reducing the stress of peeling (bending modulus + 24%, failure force + 21%). Finally in the direction 45°, the bending stiffness is slightly higher than that of sequence QIQH[A] so that we get a little gain in resistance (bending modulus + 4%, failure force + 2%). The description of the failure mechanisms associated with each sequence will not be repeated because they are quite similar to those identified for the sequences QIQH, as shown in Figure 8.

## 4. Conclusion

The presented work aimed to improve understanding of the phenomena occurring during the rupture of bonded joints in composite laminates, in order to improve prediction. The literature review showed that orientation of plies in interfaced contact with an adhesive plays an important role in the rupture, but the presented work did not decouple the local and global effects to change the stiffness of the substrates that depend on the orientation of plies. The use of QIQH, quasi-isotropic stratification permits decoupling of these properties and the systematic study of a large number of combinations of plies near the adhesive.

The first observation after testing, breaking strength, seems to be correlated to the distance of the ply at 0° to the adhesive layer, and an explanation can be offered. Indeed, since the 0° layer is still the seat of the final break, we can assume that its distance from the adhesive layer makes the path of cracking more complex and thus increases the joint strength. The results show that, in the cases studied, the local modification of orientation may lead to differences of about 30% between failure loads. These considerable variations must be taken into account in concept design. Another lesson from this experimental campaign is that, contrary to popular belief, using plies of 0°, then aligned with the direction of the loading near the adhesive joint, is not necessarily the best solution. In the case of the material and geometry studied here, we found that the breaking strength was improved when the crack path was made more complex. The possibilities of cracking intralaminar at 0° plies are not beneficial for the holding of the joint. However, the profit orientation of 0° can be connected to the gain of bending stiffness that provides in the case of laminates 'classic.' By focusing on a symmetric stratification widely used in industry, we could show that the same local orientation of plies is that the direction of the greatest bending rigidity offered a better performance. As such, the recommendation of plies at 0° can be valid.

Finally, the failure strength of the specimens is dependent on both the local orientations and the global properties of the laminates. In each studied case, the mechanism of crack propagation in the first four plies is reconstructed from the examination of the failure surfaces of the bonded joint. The 0° layer is the locus of an intralaminar delamination resulting in a rapid fracture of the specimen, so the position of this layer with respect to the adhesive layer has a real influence on the joint strength when considering QIQH sequences. Conversely, in the case of the $[0/45/90/-45]_{3S}$ sequence, a 0° layer on each side of the laminate results in an increased bending stiffness and an improved joint strength. It is therefore important to separate these interactions in order to draw a correct interpretation of the influence of the stacking sequence on the failure process.



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