INFLUENCE OF STACKING SEQUENCES ON THE STRENGTH OF COMPOSITE BONDED JOINTS

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Abstract

The behavior of joints made of adhesively bonded composite laminates can be influenced by the whole stacking sequence as well as the local distribution of the plies near the interfaces. However, changing the stacking sequence modifies several parameters at the same time, so it is difficult to assess their respective influence.

A method for designing stacking sequences developed by the authors makes possible to control and vary independently the parameters in the joints. Four 24-ply laminates were selected to investigate separately the influence of membrane stiffness, bending stiffness and ply orientations near the interfaces. The influence of loading rate was also investigated: specimens were tested under quasi-static and impact tensile load.

Among various results, an important one is the fact that the effect of orientations at the interface is not limited to the first ply but involves from one to 3 or 4 plies next to the adhesive, depending on the sequence.

1 Introduction

1.1 Layup effect

The influence of stacking sequence on mechanical properties of composite structures is widely recognized and studied. The overall elastic properties are well described by the classical laminated plate theory. Recent experimental and numerical works covering non linear aspects have shown significant differences on overall values as well as on micro mechanisms [1], [2]. However, changing the sequence generally modifies several parameters at the same time, so that it is difficult to discriminate between these parameters and assess their influence.

Even limiting to quasi-isotropic laminates, different sequences possess the same in-plane stiffness, however they differ for in-plane strength [3] and fatigue limit, and the values and directions of symmetry of the bending properties are different: these bending parameters are certainly influential on the buckling behavior, and possibly on the in-plane behavior after damage occurs in some plies.

In the case of adhesive joining of composite laminates, the difficulty is even greater, as the behavior of the joints can be influenced by the total stacking sequence as well as the local distribution of plies near the interfaces.

Consequently, the powerful method for designing stacking sequences, developed by Verchery and co-workers, as presented in ref. [4], can be of foremost importance in conducting experimental studies, as it makes possible to control and vary independently the parameters in the specimens. This is applied in the present study, to composite adhesive joints.

1.2 Adhesive joints of laminates

Adhesive bonding is generally considered as a very suitable method for assembling structures made of composite laminates. The strength of such joints is not only dependent on the quality of the bonding, but also on the mechanical properties of the adherends. Some general rules to optimize the joint strength have been previously published [5] and numerical studies have been conducted to assess the effects of the laminate elastic properties [6], but few experimental studies can be found for confirmation. Matthews and Tester [7] presented some results showing the influence of the stacking sequence on the strength of single lap joints. However, from such a study, it is not possible to assess clearly the influence on the fracture initiation of the overall elastic properties governing the stresses in the adhesive layer and the orientations of the plies next to the interface. The aim of the present study is to contribute to this question by varying the parameters separately as much as possible.

1.3 Criteria for laminate design

For this study, we chose to work with 4-direction (0, 45, 90 and -45°) quasi-isotropic laminates. Indeed, although more complex than cross-ply laminates often studied in academic research, they are more representative of those used in industrial applications. Among all the potential quasi-isotropic sequences, we retained two 24-ply quasi-isotropic quasi-homogeneous sequences [4], i.e. laminates which are isotropic not only in membrane, but also in bending. Of course, these sequences, although non symmetrical, are uncoupled. They are given in Table 1 under the names QIQH-1 and QIQH-2.

These two laminates are fully isotropic for their overall elastic behavior, which means that they behave like elastic homogeneous materials (such as elastic metals) in circumstances involving only the gross behavior. However, when the local distribution of matter is involved, such as for bonded joints, difference with homogeneous materials may occur: while metallic adherends are homogeneous everywhere and under all circumstances, adherends composed of laminated materials show a local heterogeneity, which may induce specific effects. QIQH-1 and QIQH-2 materials are appropriate to analyze the influence of material micro-structural heterogeneities on the failure of the joints.

A further step is to look for more complex overall elastic properties of the adherends in order to assess the influence of the gross elastic behavior on the failure mechanisms. This can be obtained by:

1. keeping isotropic stiffness in membrane and changing the bending stiffness to orthotropic,
2. changing the in-plane stiffness to orthotropic while keeping isotropic stiffness in bending.

In fact, such a target can be obtained following the method described in refs. [3] and [8]. The equations to solve are presented hereafter. With n being the number of plies of the laminate and δ_k the stacking angle of the k^{th} ply, uncoupling or isotropy are obtained when the following equations are satisfied at the same time:

$$\begin{aligned} I_1(a) &= \sum_{k=1}^{n} a_k \cos 2\delta_k = 0 \\ I_2(a) &= \sum_{k=1}^{n} a_k \sin 2\delta_k = 0 \\ I_3(a) &= \sum_{k=1}^{n} a_k \cos 4\delta_k = 0 \\ I_4(a) &= \sum_{k=1}^{n} a_k \sin 4\delta_k = 0 \end{aligned} \tag{1}$$

where

$$\begin{aligned} & a_k = 1 && \text{for in-plane isotropy} \\ & a_k = 2k - n - 1 = b_k && \text{for uncoupling} \\ & a_k = 3(2k - n - 1)^2 + 1 = d_k && \text{for bending isotropy} \end{aligned} \tag{2}$$

Finally, orthotropy is obtained by equating to zero the quantity:

$$\begin{aligned} I_5(a) = 2 \sum_{k=1}^{n} a_k \cos 2\delta_k \sum_{k=1}^{n} a_k \sin 2\delta_k \sum_{k=1}^{n} a_k \cos 4\delta_k - \\ - \sum_{k=1}^{n} a_k \sin 4\delta_k \left[\left(\sum_{k=1}^{n} a_k \cos 2\delta_k \right)^2 - \left(\sum_{k=1}^{n} a_k \sin 2\delta_k \right)^2 \right] \end{aligned} \tag{3}$$

Hence, an in-plane orthotropic stacking sequence must satisfy:

$$\begin{aligned} I_1^2(b) + I_2^2(b) + I_3^2(b) + I_4^2(b) + I_1^2(d) + I_2^2(d) + \\ + I_3^2(d) + I_4^2(d) + I_5^2(1) = 0 \end{aligned} \tag{4}$$

while, for a bending orthotropic stacking sequence, it becomes:

$$\begin{aligned} I_1^2(b) + I_2^2(b) + I_3^2(b) + I_4^2(b) + I_1^2(1) + I_2^2(1) + \\ + I_3^2(1) + I_4^2(1) + I_5^2(d) = 0 \end{aligned} \tag{5}$$

Solving the above equations, we can obtain several stacking sequences with the required elastic behaviors. However, a further condition is desirable: in order to avoid changing the local parameters, we have to impose the stacking angles of the four first plies close to the interface. We chose QIQH-1 as a reference, so the sequences should have the form: [0/45/-45/90/…].

A practical factor has also to be considered, i.e. the request to limit the cost and time of specimens manufacturing, by designing sequences capable to provide different specimen configurations by turning them upside down. As a consequence, this leads to look for stacking sequences having the general form: [0/45/-45/90/…/0/-45/45/90].

With all these conditions, only the stacking angles of the inner sixteen plies remain as variables for the design process. All the 4^{16} potential solutions were computed and classified, in order to obtain the one which exhibits the highest orthotropy in membrane, called thereafter ORTHO-M, and the one which has the highest orthotropy in bending, named ORTHO-B (Table 1).

QIQH-1	[0/45/-45/90/-45/90/45/90/0/-45/0/45/ 0/45/90/45/-45/0/-45/90/-45/-90/0/45]
QIQH-2	[0/90/45/-45/45/-45/90/-45/0/45/0/90/ 0/90/-45/90/45/0/45/-45/45/-45/0/90]
ORTHO-M	[0/45/-45/90/-45/90/45/0/90/0/0/0/ 0/0/90/0/90/45/0/-45/0/-45/45/90]
ORTHO-B	[0/45/-45/90/0/-45/45/-45/45/90/90/90/ 0/90/45/-45/0/0/45/-45/0/-45/45/90]

Table 1. Stacking sequences

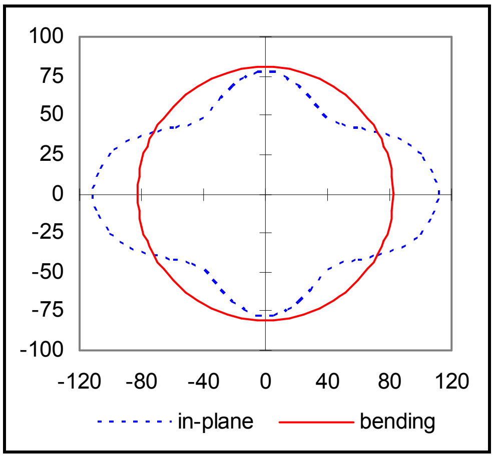

Fig. 1. Polar variation of in-plane and bending moduli for ORTHO-M laminate

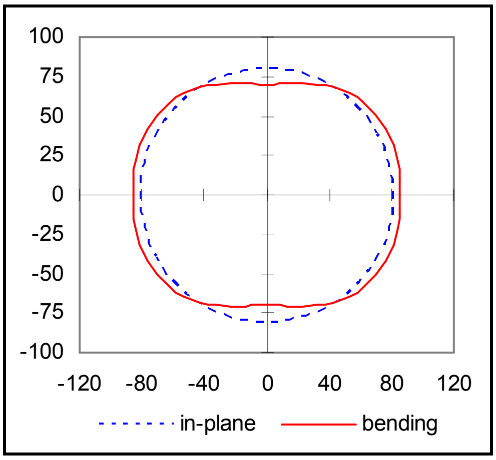

Fig. 2. Polar variation of in-plane and bending moduli for ORTHO-B laminate

2 Specimen preparation

Four types of plates were manufactured from a unidirectional prepreg made of high modulus carbon fiber and epoxy resin (Hexcel NCHM 6376 / 34% / M40J). The measured mechanical properties of the unidirectional elementary ply are given in Table 2.

E_L (GPa)	E_T (GPa)	ν_{LT}
222.0 ± 2.0	6.9 ± 0.2	0.32

Table 2. Experimental mechanical properties of the unidirectional elementary ply

Sequences QIQH-1 and QIQH-2 are both quasi-isotropic quasi-homogeneous. As a consequence they have the same overall elastic properties even if they have different local plies distributions: for QIQH-1 the relative orientation of the two first plies is 45°, for QIQH-2 it is 90°.

The main elastic properties of the four laminates were measured and found in accordance with prediction. The two quasi-isotropic quasi-homogeneous laminates have an elastic modulus of 81 GPa. The polar variations of the in-plane and bending Young moduli E_1 (in GPa) of both laminates ORTHO-M and ORTHO-B are given respectively in Fig. 1 and Fig. 2.

Single-lap specimens were manufactured from the four previous plates with a single part epoxy adhesive with aluminum filler (Permabond ESP110). The tensile behavior of the adhesive has been measured on bulk specimens. Fig. 3 presents a typical stress-strain curve.

Fig. 4 and Fig. 5 show the geometry of quasi-static and dynamic test specimens. The dynamic specimen geometry is specific to the designed test machine: the end tabs are bonded on the adherend outer faces and are drilled. Using these holes, the specimens are bolted on the grips in order to limit slipping during the impact.

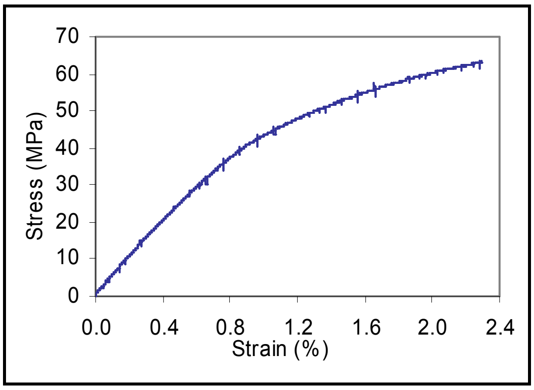

Fig. 3. Typical stress-strain tensile measured on bulk specimen of the Permabond ESP110 adhesive

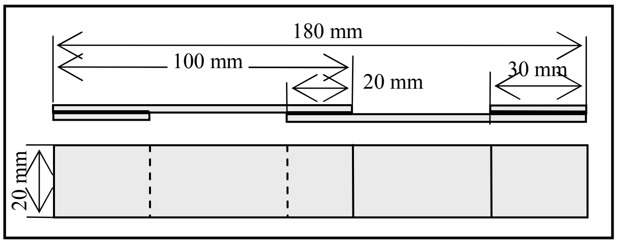

Fig. 4. Static test specimen geometry

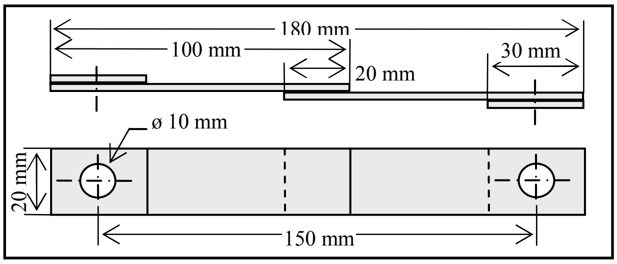

Fig. 5. Dynamic test specimen geometry

All specimens were made of two identical adherends, which means from the geometry of the single-lap joints that the plies orientations on each side of the adhesive layer are not symmetrical. For example, two opposite plies oriented at 0° or 90° are aligned, whereas two opposite plies oriented at 45° are orthogonal.

3 Experiment

Specimens were tested under quasi-static and impact tensile load. For each set of parameters, three specimens were tested.

The quasi-static tests were performed at the rate of 0,3 mm/min on a classical testing machine.

A falling weight testing device, as shown on Fig. 6, was used to impact the specimens in tension at velocities from 1 to 4 m/s. A complete description of the device and the experimental procedure can be found in ref. [9].

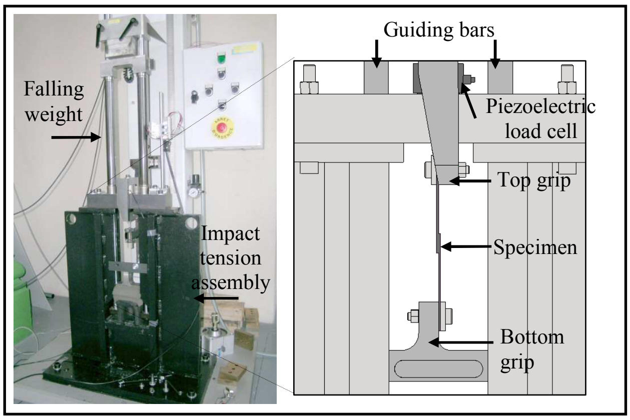

Fig. 6. Falling weight testing device

4 Quasi-static tests

4.1 Local parameters

4.1.1 Ply distributions

We investigated the influence of the local distribution of plies near the interfaces using the quasi-isotropic quasi-homogeneous laminates previously described, as they make possible to vary the orientation of the laminates in the adherends without changing their overall stiffness.

Adherends were cut in different directions in the laminated plates QIQH-1 and QIQH-2. Three orientations for QIQH-1 and two for QIQH-2 finally gave five different local plies distributions, as presented in Table 3.

QIQH-1		QIQH-2	
0°	[0/45/-45/90/...]	0°	[0/90/45/-45/...]
45°	[45/90/0/-45/...]	90°	[90/0/-45/45/...]
90°	[90/-45/45/0/...]		

Table 3. Local distributions of plies near the interfaces

4.1.2 Influence of plies orientations on strength

Results obtained with laminate QIQH-1 emphasize the influence on the failure load of the local distribution of the plies near the interfaces (Fig. 7). Joints with a ply adjacent to the adhesive layer oriented at 0° have the lowest strength, although it is generally published that it leads to the highest performances [10]. The strongest joints in the present research are those with a first ply at 90°.

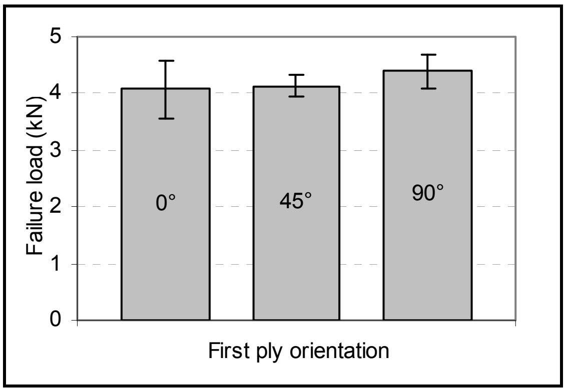

Fig. 7. Strength of joints made of QIQH-1 laminate vs first ply orientation

With laminate QIQH-2 opposite results are observed: joints with a first ply at 0° give the highest strength (Fig. 8).

These results prove that the strength of the joints does not depend only on the orientation of the first ply in contact with the adhesive layer: it is necessary to take into account the orientation of more that one ply next to the interfaces.

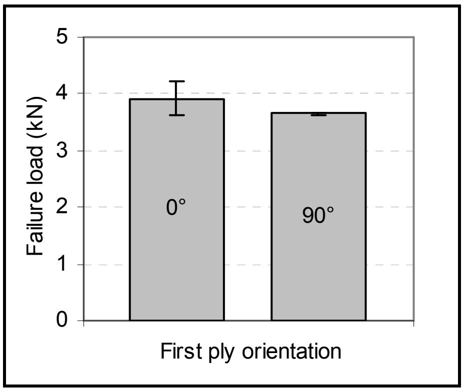

Fig. 8. Strength of joints made of QIQH-2 laminate vs first ply orientation

4.1.3 Influence of plies orientations on fracture

A first important comment is that for all configurations, the fracture during the static tests is symmetrical inside the adherends: the fracture initiates at the end of the overlap, where the peel and shear stresses are the highest, and then propagates inside the first plies until the adherend breaks. No adhesive fracture has ever been observed at any time. A typical lateral view of a broken joint is presented in Fig. 9: the adhesive layer is intact, the upper adherend has failed while the lower one is only partially fractured.

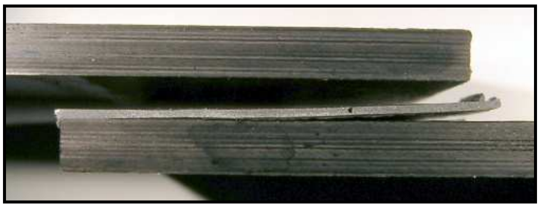

Fig. 9. Typical failure of the adhesively bonded single-lap composite joints

The second point is that the fracture involves from one to three plies, depending on the laminate configuration.

This is illustrated in Fig. 10 and 12, which present the failure modes of different configurations of joints made of quasi-isotropic quasi-homogeneous laminates with various orientations at the interface. On the left of each photograph, a sketch shows the sequence of the plies next to the interfaces, the ply at the interface being the first one (on the extreme left). The darker zones present the damaged areas.

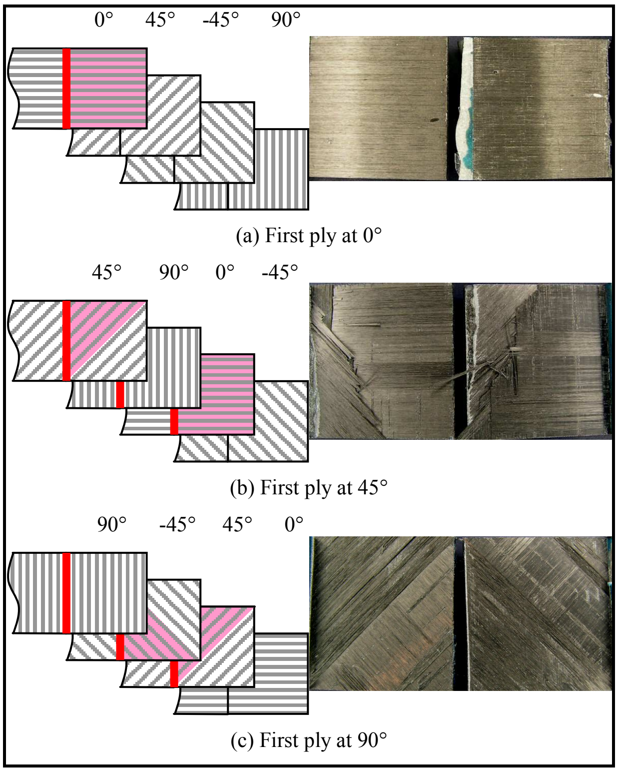

Fig. 10. Fracture in the adherends for different local ply distributions in laminate QIQH-1

<u>QIQH-1 0°:</u> the failure is intralaminar and occurs inside the first layer. A SEM observation shows that only a small fraction of the 0° fibers (estimated to 20% of the ply thickness) breaks before the crack propagates inside the ply along the fiber direction (Fig. 11).

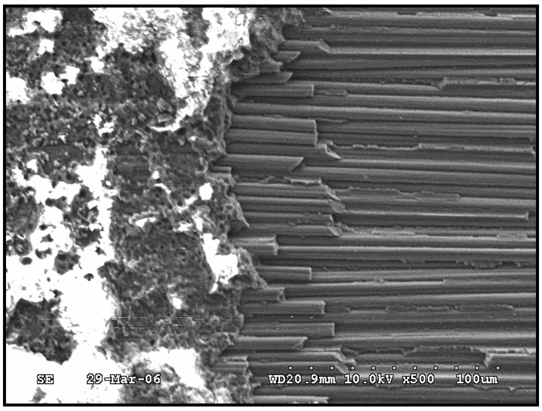

Fig. 11. SEM observation of the fracture of 0° fibers in the first ply next to the adhesive layer

QIQH-1 45°: the crack initiated in the first ply propagates along the fibers. However, because of the orientation of the fibers, the crack deviates toward the side of the adhesive joint: it grows in the ply plane sweeping a triangular area. That means that the first ply failure does not cause the joint failure. The second ply, at 90°, is of little strength in the loading direction. The crack propagates in the matrix through the thickness of the ply, and finally into the third ply at 0°, which fails in a similar manner to that presented above.

QIQH-1 90°: in this case the first ply at the interface is the weakest. The crack reaches immediatly the next plies, which are oriented at respectively -45° and 45°. While in the case of the QIQH-1 at 45° it has been observed that the failure of one ply at 45° alone cannot cause the joint failure, joints made of laminates QIQH-1 at 90° show that two adjacent plies at ±45° actually can. The failure occurring in these two plies is complex but it seems that both plies are equally responsible of the failure.

Fig. 12 presents the failure modes of the different configurations of joints made of laminate QIQH-2. In both cases, the failure occurs in the ply oriented at 0°. The failure is intralaminar and is similar to those observed for laminate QIQH-1 presented above.

QIQH-2 0°: the failure is intralaminar inside the first ply and is identical to the failure of the adherend made of QIQH-1 with a first ply at 0°.

QIQH-2 90°: the crack grows in the matrix of the first ply and reaches the second ply, oriented at 0°. Again, an intralaminar failure inside this ply is observed.

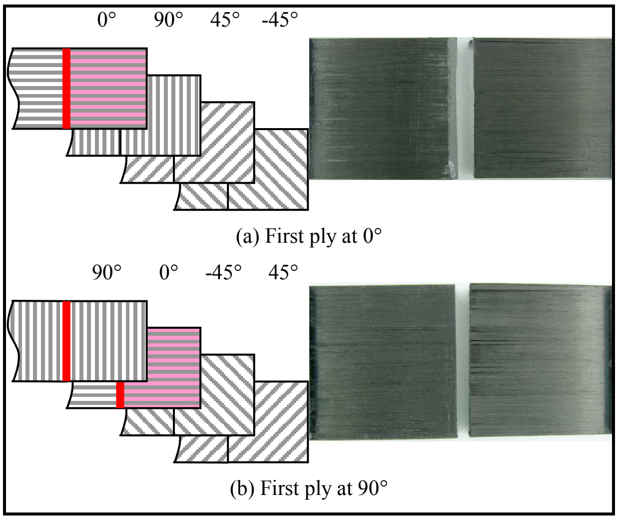

Fig. 12. Fracture in the adherends for different local ply distributions in laminate QIQH-2

4.2 Overall parameters

The overall parameters were studied by using orthotropic laminates: with specimens made of laminates ORTHO-M and ORTHO-B, we investigated separately the influence of the membrane stiffness and the bending stiffness on the strength of adhesive joints. In order to keep constant the local parameters, the local plies orientation was chosen to be the same as for the QIQH-1 laminate at 0°: [0/45/-45/90/…].

Two laminate orientations were used in the adherends, corresponding to the two principal directions of orthotropy d1 and d2 (the d1 direction corresponds to the highest stiffness while the d2 direction is for the lowest).

The ORTHO-M laminate was used to study the influence of the in-plane stiffness and the ORTHO-B laminate for the bending stiffness.

The results show that increasing the in-plane or bending adherend stiffness in the loading direction increases the strength of the joints. These results are presented and compared to the reference quasi-isotropic quasi-homogeneous joint having the same local parameters (in dotted line) in Fig. 13.

However from these results it is difficult to assess the influence of each stiffness, because the change in stiffness between directions d1 and d2 is larger in the case of the in-plane orthotropy.

Presenting these results differently show the influence of in-plane and bending stiffness separately. The influence of stiffness on strength is presented in Table 4.

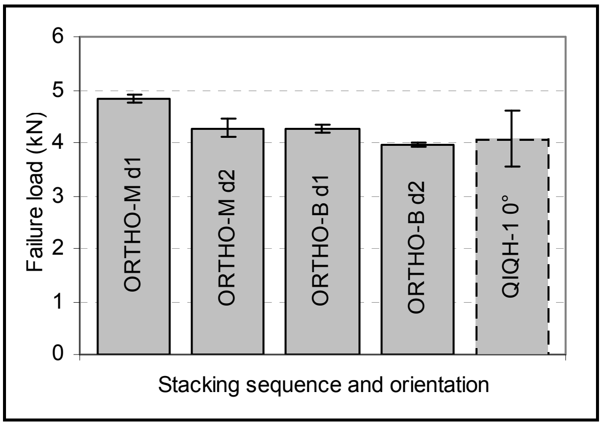

Fig. 13. Influence of global stiffness on the strength of the adhesive joints

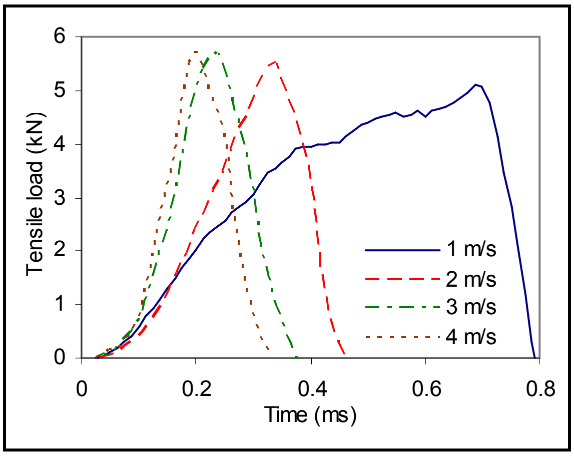

Fig. 14. Typical load-time curves measured at different impact velocities

	Stiffness increase	Strength increase
Membrane	+42.5 %	+13.3 %
Bending	+21.8 %	+7.6 %

Table 4. Influence of in-plane and bending stiffness on strength

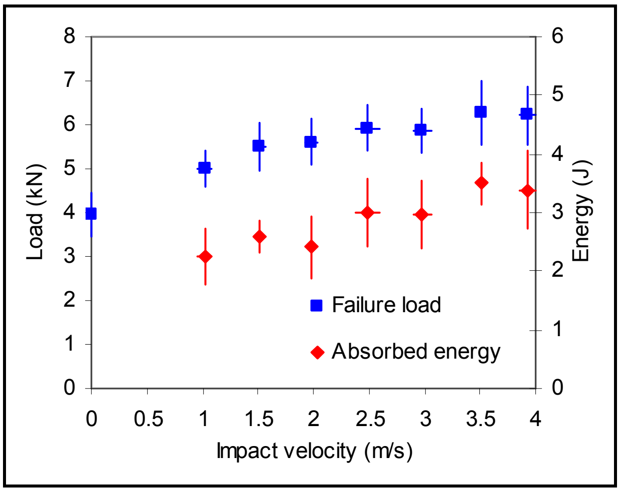

Fig. 15. Influence of loading rate on failure load and absorbed energy

Increasing the bending stiffness seems to be a little more efficient than increasing the membrane stiffness. These results confirm those obtained by Radice and Vinson [6]: using a numerical analysis, they show that increasing the bending stiffness significantly reduces the values of the critical peel stress at the end of the overlap.

5 Impact tests

Impact tension tests were performed on specimens made of laminate QIQH-1 oriented at 0°, in order to investigate the influence of the loading rate on the joints behavior.

Joints were tested at impact velocities from 1 to 4 m/s by increment of 0.5 m/s.

Fig. 14 shows typical load-time curves measured with the test device: as the loading rate increases, the failure load increases as well.

The test results are presented in their entirety in Fig. 15 (with mean and deviation). They emphasize the rate-sensitivity of the adhesive joints: the failure load and the absorbed energy increase with the impact velocity. However, the specimens extension at failure is constant whatever the impact velocity.

Impact tests have also been performed on adhesive joints with the other adherend configurations (QIQH-1 45° and 90°, QIQH-2 0° and 90°, ORTHO-M d1 and d2, ORTHO-B d1 and d2). From these experiments, which can be found in detail in ref. [11], two important results can be drawn:

1. failure modes of the impacted specimens appear to be exactly the same as those observed on the broken static test specimens;
2. the strongest joint under static load is still the strongest under impact: the loading rate changes the joint strength quantitatively but not qualitatively.

As a result, the impact design of the adhesive joints could be based on their static tensile strength design.

6 Conclusion

Stacking sequences have been designed in order to investigate separately the influence of the membrane stiffness, the bending stiffness and the plies orientation near the interfaces. Results emphasize the influence on strength and fracture of the two or three first plies in contact with the adhesive layer. One major result is that a ply adjacent to the adhesive oriented at 0° does not always give the highest performance.

The influence of the loading rate has also been investigated by testing the specimen under both static and impact tension loading. Results show a moderate rate-sensitivity of the joints. The static and dynamic failure are qualitatively the same, so the impact design of the adhesive joints could be based on a static design.

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