EXPERIMENTAL STUDY OF THE MECHANICAL BEHAVIOR OF CARBON FIBER FABRICS REINFORCED THERMOPLASTIC AND THERMOSET COMPOSITES MATERIALS

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Résumé

Afin de s'affranchir des problèmes liés à l'utilisation des résines thermodurcissables (stockage, processus de réticulation, drapage manuel, défauts non-réversibles), les résines thermoplastiques hautes performances sont aujourd'hui envisagés pour des applications aéronautiques. En effet, un procédé de thermoformage permet d'obtenir en quelques étapes des stratifiés à matrice thermoplastique possédant des formes variées. D'où la nécessité d'étudier leurs propriétés mécaniques. Cette étude vise ainsi à comparer le comportement mécanique de stratifiés aéronautiques soumis à divers états de contraintes. Les matériaux composites étudiés sont différenciés par le matériau constituant la matrice : époxy (résine thermodurcissable) ou PPS (résine thermoplastique haute performance). La résine est renforcée par un tissu satin de fibres de carbone. Outre les essais conventionnels réalisés sur les matériaux composites pour déterminer les propriétés élastiques, des essais sur joints boulonnés double recouvrement (essai de matage) ou simple recouvrement (essai de simple enture) ont été effectués. Ces essais sont d'une importance majeure pour la conception des composites stratifiés généralement assemblés par des liaisons vis-écrou ou des rivets dans les applications aéronautiques.

Mots clés *: Etude expérimentale ; époxy, PPS, tissu de fibres de carbone, essais sur joints boulonnés*

Abstract

In order to tackle the issues associated with the use of thermosetting resins (storage, difficult reticulation process, handmade draping, irreversible defects), high performance thermoplastic resins are now being considered for applications in aeronautics. Indeed, it is possible to get thermoplastic based laminates with various shapes in few stages thanks to a thermoforming process. Thus, their mechanical behavior needs to be investigated. This study aims at comparing the mechanical behavior of two aeronautical laminates submitted to different stress states. The studied composite materials consist of two different materials for the matrix : epoxy (thermosetting resin) or PPS (high performance thermoplastic resin). The matrix was reinforced with the same carbon fiber satin fabrics. Beyond the usual tests performed on composite materials to get the elastic properties, single-bolt double lap bolted joint (bearing test) and single-bolt single lap bolted joint tests were carried out. Such tests are very important for the design of composite laminates usually joined with bolts or rivets for aeronautical applications.

Keys words *: Experimental study, epoxy, PPS, carbon fiber fabrics, bolted joint tests.*

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ملخص

لتجنب المشاكل المتعلقة باستعمال رزينات الترموالصلبة، ابتدء استعمال الرزينات الترموبلاستيكية ذاة الجودة العالية في ميدان التكنلوجيات الجوة. حيث ان عملية الترموالصناعي يمكن تصميم ببعض المراحل السطاتفيات الترموبلاستيكية باحجام مختلفة. منها التزام دراسة الخصائص الميكانيكية. في هذه الدراسة نريد المقارنة السلوك الميكانيكية تحت ضغوطات مختلفة.
ان التجارب المخبرية لها اهمية كبيرة لتصميم المعادن السطاتفية المجمعة عميا بابرغي و صمولة اوبالبرشام في التجارب و الاستعمالات الجوية.

الكلمات المفتاحية: *ادراسات التجريبية ، الابوكسي ،التجارب على القطع المحزقة*

In advanced engineering fields such as aeronautics, composite materials have found many applications because of their high strength/weight ratios. Thus, thermoset resin based composite materials have been extensively used over the past 30 years. Even if they do present interesting mechanical properties, they are also characterized by undeniable drawbacks such as the necessity of storing at low temperatures, a difficult-to - control reticulation process, a very long curing process and a handmade draping that generates most of the non reversible defects of the manufacturing process. In this context, high performance thermoplastic resins (PPS or PEEK) are a promising alternative. Though mechanical properties of PPS resin are a little weaker than those of PEEK resin, PPS is relatively cheaper than PEEK.

Therefore, the joining of composites to other structures (metals or composites) with mechanical fasteners is often required. The joining of structures with bolts or rivets contributes to decrease the strength of the structures because of the stresses concentration occurring around the hole area. Thus, for monotonic loadings, notches have an significant effect on the growth of damaged zones, hence on the mechanical properties of the notched laminate. The comparison of these properties and the behavior between thermoset and thermoplastic composites is necessary to understand the failure of thermoplastic based laminates in order to consider them for aeronautical applications. Indeed, PEEK and PPS matrix exhibit high strain-to-failure behavior leading to damage modes and deformation mechanisms very different from those of conventional “brittle” epoxy based composites. In brittle matrix composite laminates, the damage consists of many interacting mechanisms such as transverse cracking, longitudinal splitting of the matrix, delaminations and transverse ply cracking. The combination of these damage mechanisms strongly depends on the staking sequence, the material properties and the geometry of the laminate. In the literature, many works report the influence of a notch on the response of “brittle” composites such as thermoset based laminates. A good review of the behavior of notched thermoset composites is given by Awerbuch and Madhukar [1]. A few authors investigated the response of notched laminates consisting of thermoplastic resin under tensile or compression loadings [2-10]. Touchard-Lagattu and Lafarie-Frenot [11], then Lagattu et al. [12] compared the damage and inelastic deformation mechanisms in notched thermoset (T300/914) and thermoplastic (AS4/PEEK) laminates submitted to a tensile loading in order to highlight the role of the overstress accommodation around the hole and the notch sensitivity of each composite system. Kawai et al. [13] investigated the effects of matrix ductility (thermoplastic nylon 6) and progressive damage on strengths of unnotched and notched carbon fiber fabrics laminates. They emphasized the importance of the strength of the notched laminates of the progressive and extensive delamination in the case of carbon/epoxy composites. In the meantime, the specific failure mechanism of carbon/thermoplastic does not consist in delamination but rather in a plastic deformation located around the hole. Delamination appears to have a much more pronounced positive influence on the relative strength of the laminate than the properties of the constituents (i.e. ductility of the resin and stiffness of the fibers). Most of these works focused on the behavior of notched UD carbon/PEEK laminates but none investigated the response of notched carbon fabric/PPS laminates. That is why our work aims at studying the failure mechanisms occurring in these composite systems and analyzing the role of the resin ductility on the stress redistribution around the hole.

1. EXPERIMENTAL SET UP

The different tests were carried out on a servo-hydraulic MTS 810 machine. Three composite materials will be studied but only two were tested so far : carbon/epoxy (914 thermoset resin) and carbon/PPS (high performances$ thermoplastic resin). PEEK is another high performance thermoplastic that will be tested further. Matrix is reinforced with the same G803 carbon fiber 5 satin fabric. According to the test performed, the stacking sequence is $[0]_8$, $[45]_8$ or $[0/45/45/0]_S$ and the fibers to volume ratio (60%) of the laminates was the same for the different materials. The lay-up is quasi-isotropic considering that the fabric is balanced (50% weft-50% warp). The tests were performed at room temperature (18°C). The carbon/epoxy samples were supplied by the Hexcel company whereas the carbon/PPS composite were supplied by the Porcher company.

2. RESULTS AND ANALYSIS

2.1. Tensile behavior of the carbon/PPS laminate constituents

The first interesting observation that can be made about carbon/PPS laminate is the highly ductile behavior of the plain PPS resin and the almost elastic-brittle behavior of the carbon/PPS laminate governed by the carbon fiber fabric behavior (figure 1). The stacking sequence is also an important feature to be taken into account in order to control the combined ductile behavior and structural property of the laminate as it is indicated on (figure 2) in the case of a $[45]_8$ lay-up.

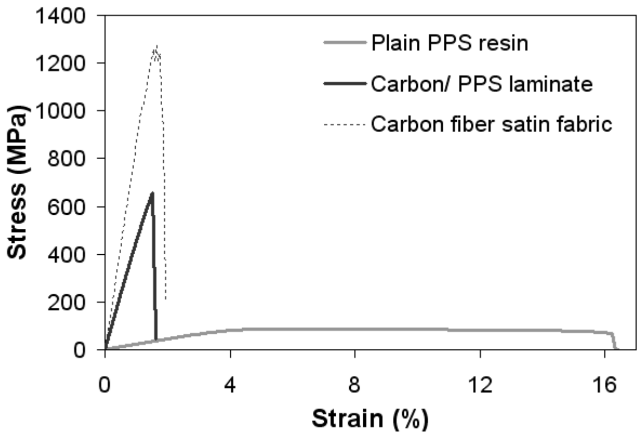


Figure 1 : Tensile stress-strain curves for the constituents of a $[0]_8$ carbon/PPS laminate

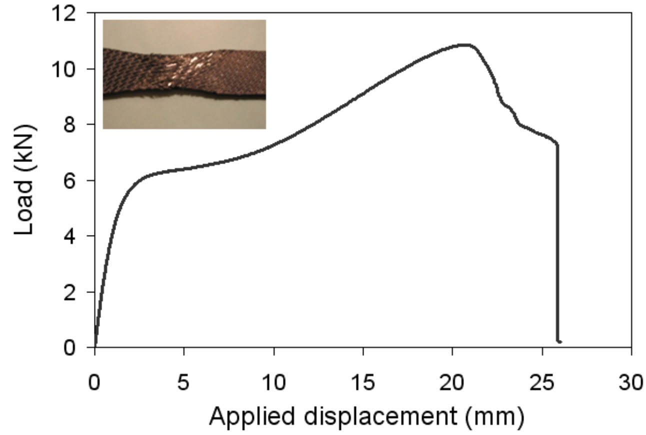


Figure 2 : Load-displacement curves for an inplane-shear test on a $[45]_8$ carbon/PPS laminates

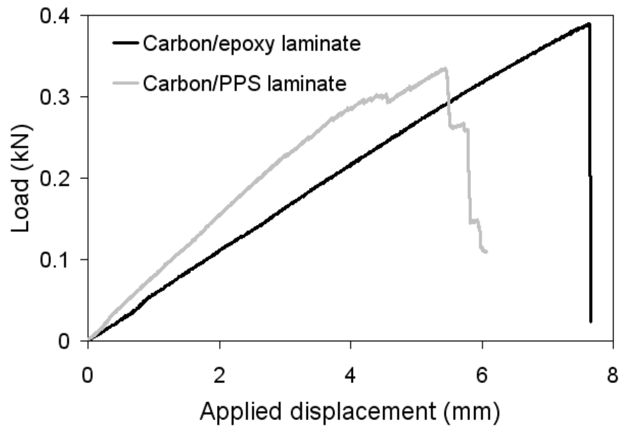


Figure 4 : Load-displacement curves for three-points bending tests on $[0/45/45/0]_S$ carbon/epoxy and carbon/PPS laminates

2.2. Interlaminar shear and three-points bending

In order to understand the failure mechanisms of PPS based composites related to the ductile nature of the resin, "classical" tests performed on composites materials, such as interlaminar shear and three points bending, allowed us to compare the mechanical properties and the response of each kind of material. The interlaminar shear test highlights differences in the load transfer. In the case of carbon/epoxy laminates, the increasing load is transferred from one ply to another via the shearing of resin until the laminates reaches a constant stiffness due to the fibers. For PPS based laminates, the elastic shearing of the resin is quickly followed by its plastification which prevents the load from transferring between the plies (figure 3). Along with the breakage of the first fibers, a progressive damage is observed while the resin still follows its plastification. This load transfer mechanism gives a lower interlaminar shear stress (τ_u = 50.9 MPa) in relation to the carbon/epoxy laminates one (τ_u = 75.4 MPa). The same observation can be done for the three-points bending test (figure 4).

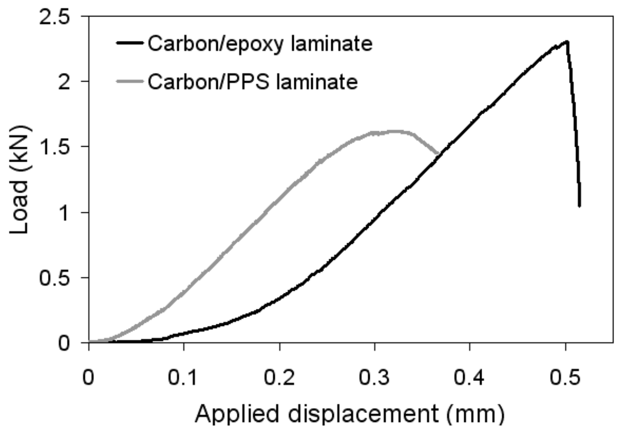


Figure 3 : Load-displacement curves for interlaminar shear tests on $[0/45/45/0]_S$ carbon/epoxy and carbon/PPS laminates.

2.2 Influence of a circular notch on the mechanical response of the laminate

The open hole tension test complies with the following French standard NF EN ISO 527-4 : Determination of the tensile properties. Part 4 : experimental set-up for isotropic and orthotropic fiber reinforced plastic composites. Dimensions of the specimen are the following : (Length L * Width W * Thickness e) = 250 * 25 * 2,3 mm. Hole diameter is D = 4,8mm. This test allowed us to examine the overstress accommodation mechanisms of studied materials.

Contrary to the carbon/thermoset laminates, there is no delamination in the carbon/PPS laminate but a plastic deformation of the PPS resin in the hole area that prevents the load from transferring between the plies of the laminate. Thus the stress relaxation of the overstressed fibers at 0° can not occur.

Hence, the hole factor defined by $C_h = \sigma_n^u / \sigma^u$ (where $\sigma_n^u = \frac{F_{ultimate}}{e(W-D)}$ and $\sigma^u = \frac{F_{ultimate}}{e\,W}$) and representing the hole sensitivity of the laminate ultimate strength is higher for the carbon/epoxy laminate (0.78) (figure5), than for the carbon/PPS laminate (0.66) (figure 6). Compared to the quasi-isotropic unidirectional laminates studied in [12] - a carbon/epoxy laminate and a carbon/PEEK laminate – the respective hole factors are 0.75 and 0.60. Other stacking sequences should be tested in order to determine the role of the fabric in the stress redistribution around the hole.

Additional tests are also required to confirm that thermoplastic based and fabric reinforced laminates present a poor notch resistance. This might be explained by the plastic deformation occurring in the hole area, a mechanism that is less efficient for accommodating overstresses around the hole, as reported in [11].

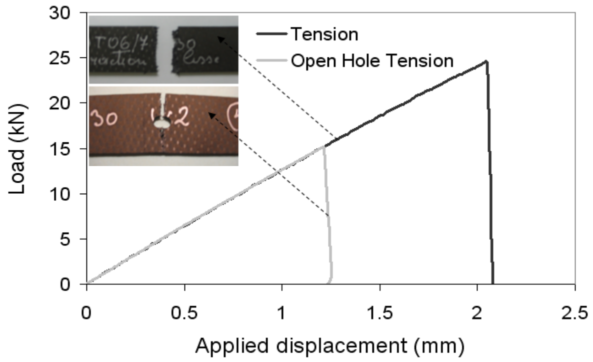


Figure 5 : Load-displacement curves and associated fracture mode for a classical tensile test and open hole tension on a $[0/45/45/0]_S$ carbon/epoxy laminate

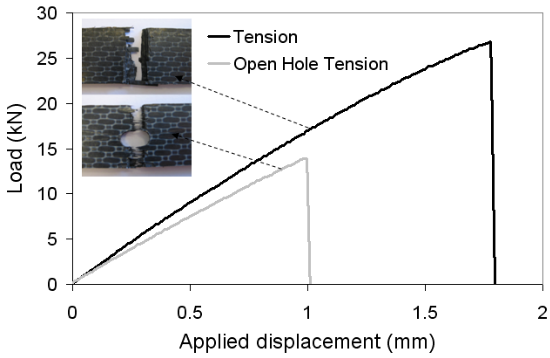


Figure 6 : Load-displacement curves and associated fracture mode for a classical tensile test and open hole tension on a $[0/45/45/0]_S$ carbon/PPS laminate

3.3 Single-bolt double lap bolted joint

This test complies with the following standard : prEN 6037 : Fibre reinforced plastics – Test method – Determination of bearing strength. Dimensions of the specimen are the following : (Length L * Width W * Thickness e) = 150 * 50 * 2,3 mm. Hole diameter is D = 6,35mm. The experimental configuration is indicated on (figure 7).

For a tensile loading, different failure modes can operate and combine : (a) net-section, (b) bearing, (c) shear-out or (d) cleavage (figure 7). Modes (a)-(c)-(d) represent catastrophic failures and can be avoided when distances E and W are increased for a given thickness of the laminate (figure 8). They result from excessive tension and shearing stresses. In addition, bearing is a localized damage due to the plastic deformation of the resin in the contact zone between the pin and the laminate. This progressive failure mode is related to a compression failure and can not be minimized by acting on the geometrical parameters. In most of the works done on thermoset resin based composites, the interaction between D, E and W determines the optimal resistance of the mechanical fasteners. In the case of thermoplastic based laminates, these parameters also seem to strongly influence the strength of bolted joint composites as it is shown hereafter. In this case, the hole factor $C_h = \sigma_n^u / \sigma^u = 0.27$ can be compared to the value $C_h = 0.78$ for open hole tension. Hence, the single-bolt double lap configuration weakens the strength of the notched laminate.

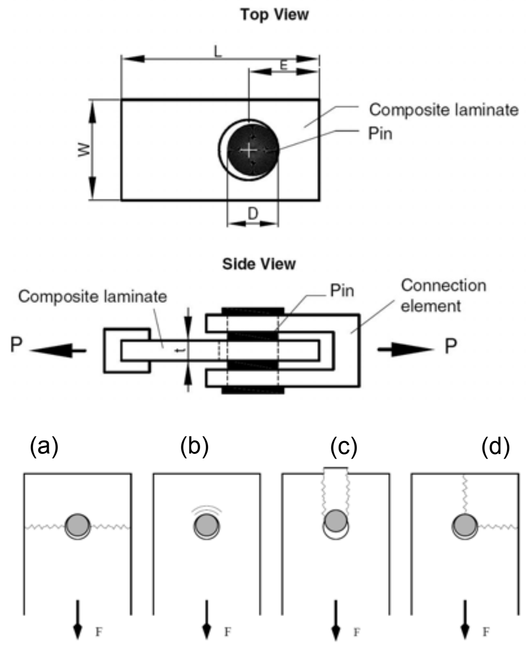


Figure 7 : Configuration of a single-bolt double lap bolted joint test on composite laminates and corresponding macroscopic failure modes [14]

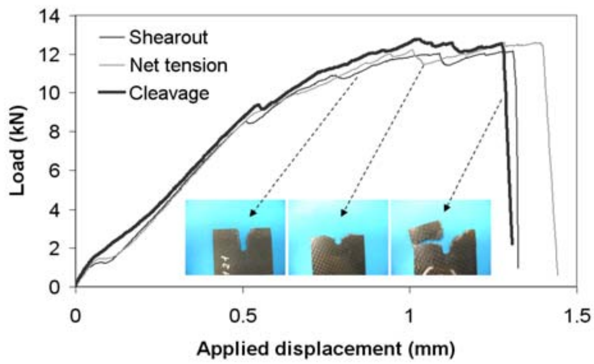
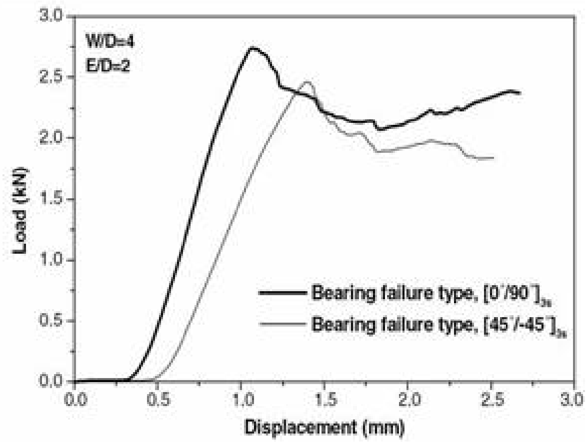


Figure 8 : Load-displacement curves and associated fracture mode for a bearing test on a $[0/45/45/0]_S$ carbon/epoxy laminate for W/D=8.

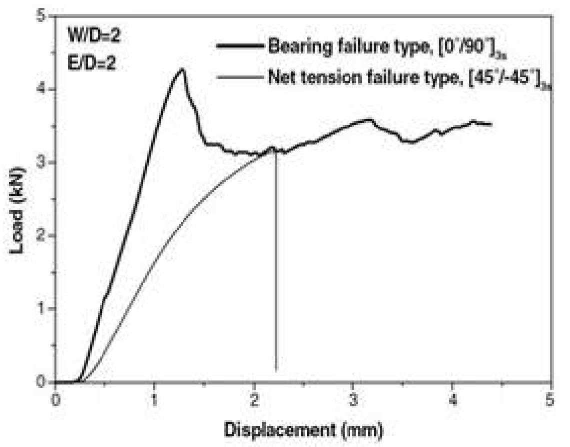
Yylmaz and Synmazcelik [15] investigated the load bearing performances of pin connected carbon/PPS UD composites under static loading conditions. They observed that pin loading performances present a narrow connection with the fiber orientation of laminates and their deformation characteristics. They also pointed out that the edge - distance ratio (E/D) and the hole-size ratio (W/D) present a predominant influence on the failure mode for a given stacking sequence of the laminate. Denq et al. [16] studied the influence of ratios (E/D) and (W/D) on the bearing strength and failure modes of PEEK with different molecular weight and carbon fiber content.

This work showed that the bearing strength increased with increasing E/D and with increasing W/D ratios. Vautey and Favre [17] investigated the hole sensitivity for different UD laminates (T300 carbon /914 thermoset resin and AS4 carbon /PEEK thermoplastic resin) whether it is filled or open. Their results indicated that the presence of a pin in the hole implies almost no change in the ultimate stress for PEEK based laminates whereas it leads to a 10%

decrease of the ultimate stress for epoxy based laminates (figure 9). These studies, dealing with PPS or PEEK thermoplastic based composites, clearly show the importance of the design in order to get a bearing failure mode that is the only progressive damage mode in relation to the others failures modes introduced previously (net-section, shear-out or cleavage).



(a)



(b)

Figure 9 : Load-displacement curves for carbon/PPS UD laminates with different W/D ratios :
(a) W/D=4 ; (b) W/D=2 [15]

2.4. Single-bolt single lap bolted joint

This test also complies with the standard : prEN 6037. Dimensions of the specimen are the following : (Length L * Width W * Thickness e) = 150 * 24 * 2,3 mm. Hole diameter is D = 4,8mm. The experimental configuration is indicated on (figure 10).

Contrary to the double-lap joints, the non-symmetric geometry of the joint generates a bending moment over the fastener. It creates a non-uniform pressure distribution through the plate thickness causing an out-of-plane deflection of the joint (mechanism known as secondary bending). A severe stress concentration appears at the shear surface of the joint and limits its strength. However, the deflection may improve the alignment of the bolt and the hole surface leading to a more uniform contact stress. The bolt-hole clearance also affects the stress concentration by releasing it when the load increases through the creation of a knife-edge like contact whose surface grows. The specificity of this test can be illustrated by the schematic representation of the load versus deflection response of the joint where partial failure in a ply can be differentiated from a total ply failure (figure 10). In this case, the hole factor $C_h = \sigma_n^u / \sigma^u = 0.51$ can be compared to the value $C_h = \sigma_n^u / \sigma^u = 0.27$ for double lap and the value $C_h = 0.78$ for open hole tension. Because of the reasons expressed previously, the single lap configuration is less critical for the strength of the notched laminate than the double lap configuration.

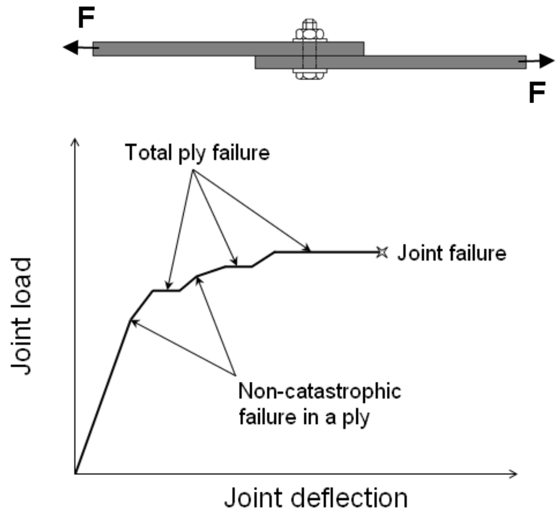


Figure 10 : Configuration of a single-bolt single lap bolted joint test and schematic representation of the overall load vs deflection response of the joint [18]

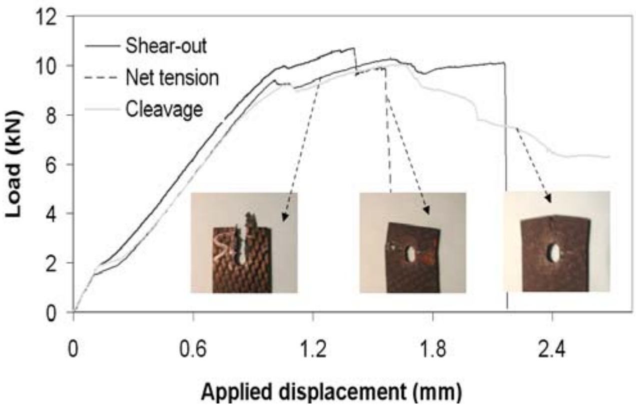


Figure 11 : Load-displacement curves and associated fracture mode for a single lap bolted joint test on a $[0/45/45/0]_S$ carbon/epoxy laminate for *W/D=5*

CONCLUSION

In this work, the mechanical properties and the behavior of epoxy and PPS resins reinforced with carbon fiber 5 satin fabric were investigated and compared (Table 1).

According to the nature of the resin, the differences observed in the load transfer from one ply to another seem to contribute specifically to the development of damages in the laminate. Particular attention was paid to the behavior of notched laminates where the mechanisms of overstress accommodation seems to be narrowly related to the different kinds of damage occurring around the hole. Thus, PPS based composites proved to be more sensitive to the presence of a hole than epoxy based laminates. These first results confirmed the observations and explanations already given in the literature about the behavior of PEEK based notched unidirectional composites. While large delamination rapidly develops in thermoset based composites, there is no interply delamination for high performance thermoplastic based composites where damage remains very small and located in the hole area [11][12].

Table 1 : Comparison of the mechanical properties of epoxy and PPS laminates reinforced with carbon fiber 5 satin fabric

Mechanical properties	Stacking sequence	Carbon/epoxy		Carbon/PPS	
		σ^u (MPa)	E (GPa)	σ^u (MPa)	E (GPa)
Tensile	$[0]_8$	690	63	789	60.6
Compression	$[0]_8$	667		458	
In plane shear	$[45]_8$	109	5.1	93.7	
Inter laminar shear	$[0]_8$	75.4		50.9	
Flexural	$[0]_8$	860	57.4	773	62.6
Plain tensile	$[0/45/45/0]_S$	450		654	
Open hole tensile	$[0/45/45/0]_S$	328		524	
Single-bolt double lap bolted joint	$[0/45/45/0]_S$	651		-	
Single-bolt single lap bolted joint	$[0/45/45/0]_S$	827		-	

It appears that the development of damages, mostly by delamination, is an efficient mechanism for accommodating the overstresses in carbon/epoxy laminates. For carbon/PPS laminates, the limited damage combined with the plastification of the resin around the hole are less efficient from the overstress accommodation standpoint, leading therefore to a relatively poor notch resistance. At last, the double lap configuration is critical for the strength of the notch epoxy based laminate and seems to have a little influence on thermoplastic based laminates [17].

In addition, other tests will be performed on carbon/PPS and carbon/PEEK laminates. For both single-bolt single lap or single-bolt double lap bolted joint tests, further analysis are required in order to get information about the failure mechanisms occurring in notched composites consisting of a ductile thermoplastic resin.

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