Bearing Strength of Bolted Joints in CFRP Wing Fittings

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Abstract

A research is being carried out at the Turin Polytechnic University to investigate the behaviour of bolted joint fittings in CFRP. Several tests are being carried out in order to evaluate the bearing strength of two CFRP specimen types. A solid graphite/epoxy laminate 4.3 mm thick; a sandwich construction with skins having the same lay-up and core of Rhoacell 51 rigid foam 9mm thick reinforced with micro-spheres. Tests are being performed on several specimens of each type in a single bolt, double-lap joint configuration representative of wing-spar section joints. M40J/916 pre-preg was used for manufacturing the specimens. The fittings have been designed in order to avoid net tension failure, shear-out failure or cleavage failure. 2D FEM models have been generated by using MSC/Patran/ Nastran code, in order to predict the experimentally measured strains and displacements. Proper Young's modulus along fibre direction has to be introduced in the analysis to more accurately represent the experimentally observed stiffness characteristics of CFRP plate. Comparison between experimental and numerical calculations are reported. Several modifications are in progress in order to increase by 50% the bearing strength of the joint. Fatigue tests are also carried out and reported.

1. Introduction

A research was carried out at our Technical University, thanks to the financial support of the Italian Space Agency (ASI), with the aim to design the HAVE-UAV Solarpowered Platform HELIPLAT® and manufacturing a scale-sized solar-powered prototype. Because of the limited financial support, only a small part of the research has been completed; nevertheless a great amount of experience has been gained in this field [1-8]. The research project Helinet (Network of stratospheric platforms for traffic monitoring, environmental surveillance and broadband services, Co-ordinator: Politecnico di Torino) has been financed, since January 2000, by the European Commission, within the 5th Framework Program in the Information Societies Technology Action, to develop a European project in the field of stratospheric platform. The Helinet project, carried out by several European universities and partner companies, is based on the HAVE-UAV HELIPLAT®. The main objectives of the 3-year project, from the aeronautical point of view, are:

1. To design an automatic HAVE-UAV that is capable of remaining aloft for very long periods of time (about 6-9 months) thanks to a solar-powered and fuel cells system.
2. To gain a thorough understanding of the feasibility of a near-term aerodynamic HAVE concept, especially concerning low-Reynolds profiles and propellers.
3. To design the entire advanced composite wing (about 75 m long), payload housing, booms and tail structures.
4. To verify the platform production cost.
5. To manufacture a 1:3 scale-sized technological demonstrator and perform static tests on it.
6. To assess the safety and regulatory aspects of the platform.

The fuel cells system and the brushless motor and solar cell system are being designed by the Dept. of Energy and Dept of Electric Eng. of our University, respectively.

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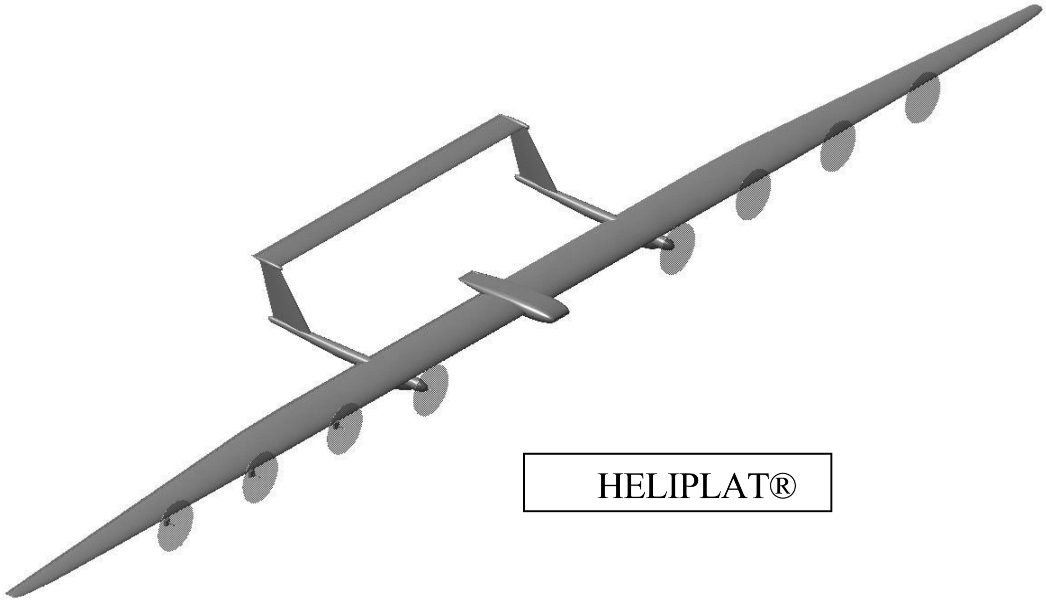

Figure 1

A computer program has been developed to design the platform by taking into account the solar radiation change over one year, the altitude, masses and efficiencies of the solar and fuel cells, and the aerodynamic performances. The parametric studies have shown how fuel cells and solar cells efficiency and mass have the most influence on the platform dimensions.
A wide use of high modulus CFRP has been made in designing the structure in order to minimise the airframe weight. A first configuration of HELIPLAT® (HELIos PLATform) was worked out, following a preliminary parametric study (Fig. 1). The platform is a monoplane with 8 brushless motors, a twin-boom tail type with a long horizontal stabilizer and two rudders.
A preliminary design of a 1:3 scale-sized technological demonstrator was completed with the aim of manufacturing a proof-of-concept structure (Fig. 2). A FEM analysis was carried by using the Msc/Patran/Nastran code to predict the static and dynamic behaviour of the UAV structure. [9-11]
One of the main activities within the project involves the investigation of the behaviour of bolted joint fittings in Carbon Fibre Reinforced Plastic (Fig. 3). In heavily loaded primary aircraft structures, mechanical joints, although have a relatively low efficiency, will be preferred to adhesively bonded joints, as for their low transverse inter-laminar strength as well as their disassembly simplicity.
Unlike isotropic materials, the introduction of a bolted joint connection in composite aircraft primary structures reduces the load carrying efficiency of the structure by around 50 percent even when the joint has been properly designed and manufactured. This serious reduction in joint strength is largely due to the fact that fibre reinforced composite materials are unable to take advantage of stress-reducing plastic deformation and yielding at the hole edge because they are basically elastic until failure. Furthermore, a very high stress concentration factor (up to 8-9) should be possible around holes of anisotropic panels, producing a failure at a lower applied load. A theoretical analysis has been already developed, by author [12], for the calculation of stresses around holes in anisotropic plates under uniaxial or biaxial tension/compression and shear loading. The Lekhnitskii theory has been used to determine the complex functions that must satisfy the specified boundary conditions, and including load combination. Under loading, damage can initiate at an early stage in bolted composite joints and accumulate inside the laminate as the

load increases. This accumulation of damage and the mode of failure strongly depend upon the material selection, ply stacking sequence, laminate thickness, joint geometry, edges effects, bearing, clamping effect and loading condition. 2D FEM model has been generated

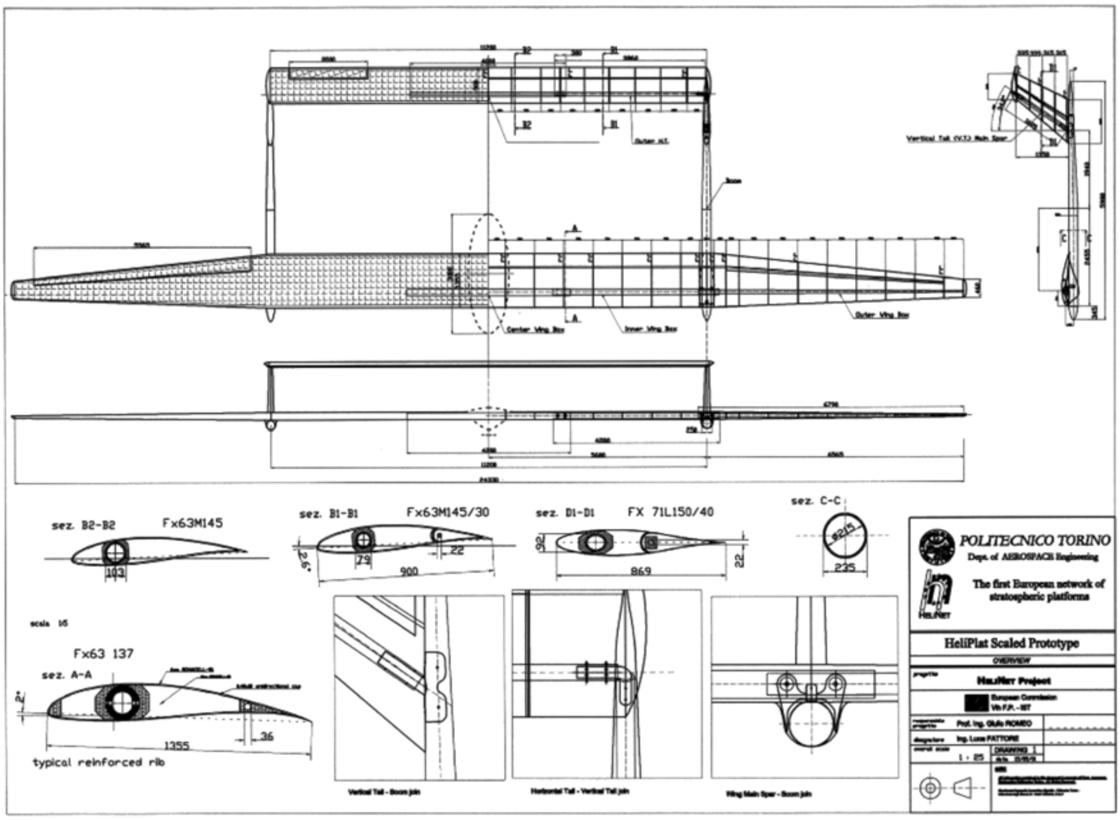

Figure 2

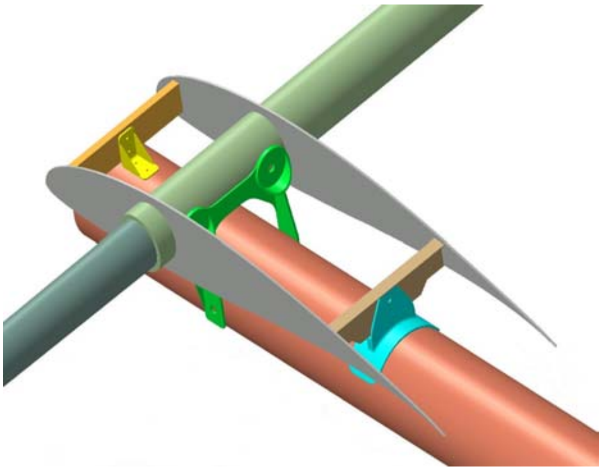

Figure 3

by using MSC/Patran/Nastran code, in order to predict the experimentally measured strains and displacements. Models were modified with a high-density mesh region below the loading hole to improve accuracy in this region of high magnitude and non-linear strain behaviour. Proper Young's modulus along fibre direction has to be introduced in the analysis to more accurately represent the experimentally observed stiffness characteristics of CFRP plate. A solid graphite/epoxy laminate and a sandwich construction will be compared. The sandwich has the skins with the same lay-up and thickness of the solid specimens. A core of Rohacell 51 rigid foam 9 mm thick reinforced with micro-spheres has been introduced.

A new hole reinforcement has been designed in order to increase the failure of the composite bolt-hole junctions.

The high level loads reached in wing box connections cannot be dealt with the pure composite structure if a light weight construction has to be performed. Furthermore the modular aspect of the new light structures cannot be overcome without the introduction of special connection parts. It requires a new design philosophy that is focused to the increase of the bearing capacity of the composite hole. The assessment of this new concept has been described in this paper. The comparison between composite and reinforced specimen will be presented in the subsequent sections. Both the solid composite specimen and the sandwich one have been considered in the investigation. Interesting design indications will come up.

2. Testing set-up

Several tests are being carried out in order to evaluate the bearing strength of two CFRP specimen types. A solid graphite/epoxy laminate, 4.3 mm thick; a sandwich construction with skins having the same lay-up and thickness of the previous specimens and with core of Rohacell 51 rigid foam 9 mm thick reinforced with micro-spheres. Tests are being performed on several specimens of each type in a single bolt, double-lap joint configuration representative of wing-spar section joints. M40J/916 pre-preg was used for manufacturing the specimens. The fittings have been designed in order to avoid net tension failure, shear-out failure or cleavage failure.

The testing setup is shown in figures 4 and 5.

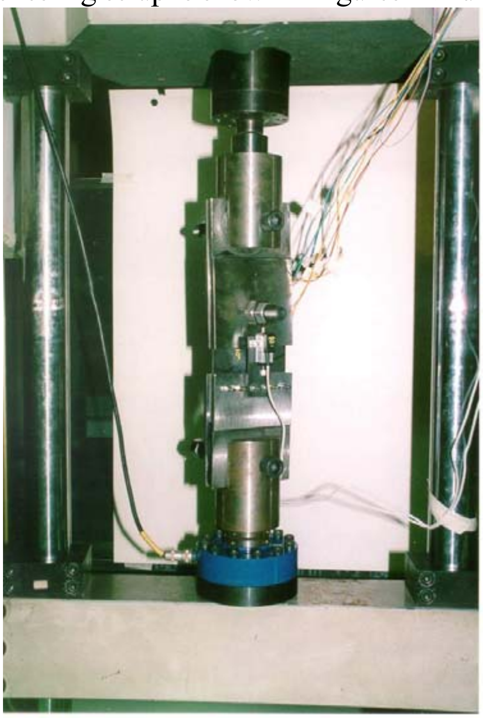

Figure 4

A classical tension compression machine has been modified in order to perform the investigation. Two special joints easy disassembling, have been designed as indicated. An expected loading distribution is obtained at one of the loaded edge by means of bolted steel plates. The applied load has been introduced by one bolt. 10 back-to-back strain gauges were bonded to all specimens in consistent locations (Figure 6). in order to obtain the strain distribution useful for subsequent analysis. In particular, strains are measured very close to the hole just below the loaded bolt-hole and laterally to the hole where a very high strain concentration is expected. The compressed area under the hole should be significant from the bearing failure point of view. Two extensometer transducers were employed to determine bolt-hole elongation under loading. A correct load displacement curve should consider the effective hole displacement, by means of a specific experimental system as for the classical bearing test.

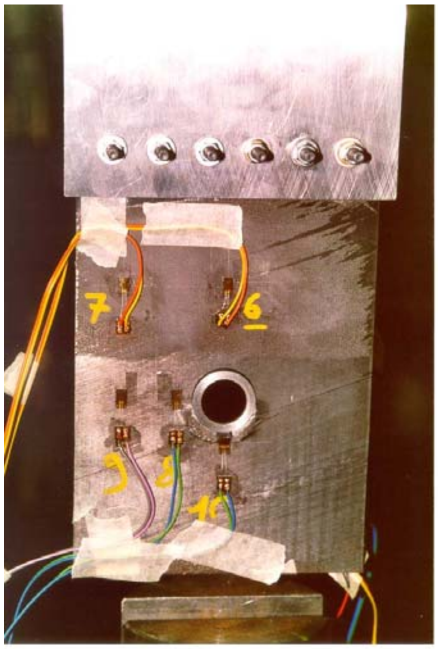

Figure 5

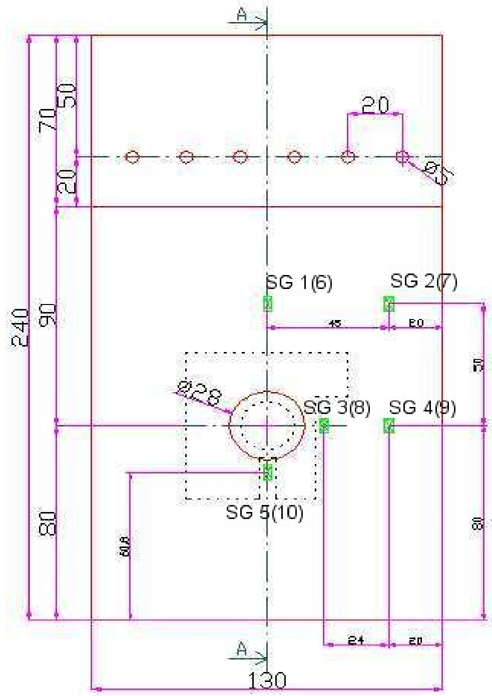

Figure 6

In this case the bolt-hole displacement curve can be obtained. A disturbing effect of the bolt could be inserted into the experimental data.

The same kind of system is used during the fatigue load condition. The steel fittings are designed in order to not fail after applied fatigue life to the specimen. The machine is designed in order to apply different amplitude loads and frequency to the specimen.

3. Numerical and experimental comparison

A wide experimental activity has been performed. Several static tension tests have been developed ad a lot of specimens have been tested. The solid and sandwich specimens have been tested reinforced and not. The maximum loads of the not reinforced specimen have been reached during tests. The modes of failure have been pointed out. The failure load was not reached for all of the reinforced specimens under test. In this case the maximum load of 100 kN was considered because of the machine limit. 2D finite element models (Fig. 7) have been generated, by

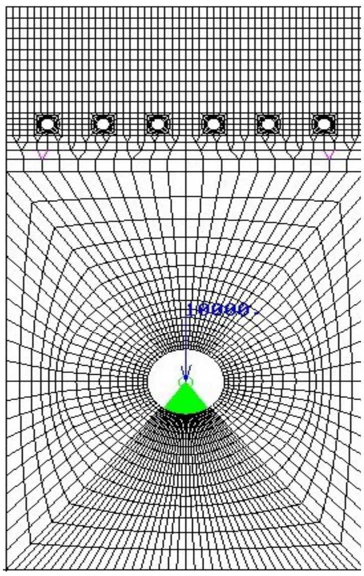

Figure 7

using the MSC/Patran/Nastran code, in order to predict experimentally measured strains and displacements of the solid and sandwich specimens. Models were modified with a high-density mesh region below the loading hole to improve accuracy in this region of high magnitude and non-linear strain behaviour. Proper Young's Modulus along fibre direction has to be introduced in the analysis to more accurately represent the experimentally observed stiffness characteristics of CFRP plate. A preliminary linear model with an assumed loading distribution (fig. 8a) is compared to a non linear different model considering the solution of contact problem (fig.8b). In the first case the assumed contact area is wider than the second case that is quite close to the actual one. This implies only a slight modification in the strain distribution near the hole edge. The experimental results are reported in succession. The reported experimental strains are mean values between the various tested samples if no indication are supplied. The introduction of different material characteristics are reported: a longitudinal E1 modulus of 215 Gpa obtained by experimental characterisation, two E1 modulus of 208 Gpa and 235 Gpa as supplied by data base handbook. The strains corresponding to strain gauges n.1 and 6 (SG1-6), far from the hole in a quasi-uniform area, are compared with the numerical results in figure 9.

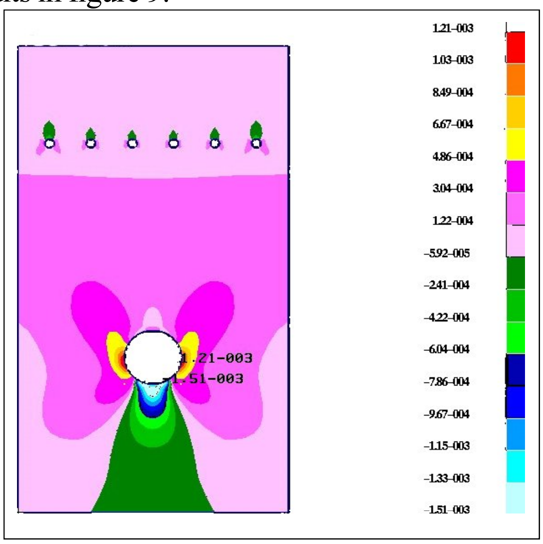

Figure 8a

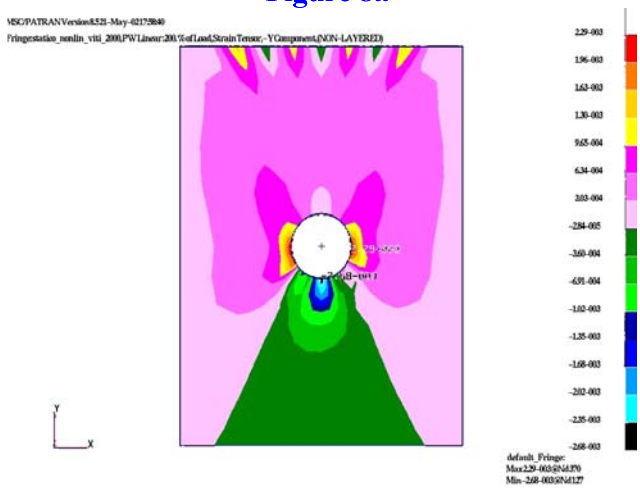

Figure 8b

A good correlation has obtained shown a quite good load distribution far from the hole position. The SG2-7 is quite close to the SG1-6 so it is considered only in order to avoid any kind of load misalignment and it is not reported.

The strain concentration is pointed out by the figure 10 for a load of 20 kN in function of the lateral distance (X) from the hole centre. The strain gauges SG3-8 and SG4-9 are compared to the numerical Fem results. A quite good correspondence is obtained showing an about three times reduction in strains by the SG-4-9. The behaviour of the SG3-8 average value and actual value of different samples in function of the load is also reported in figure 11 and 12 respectively. A very little scatter between different specimens are determined.

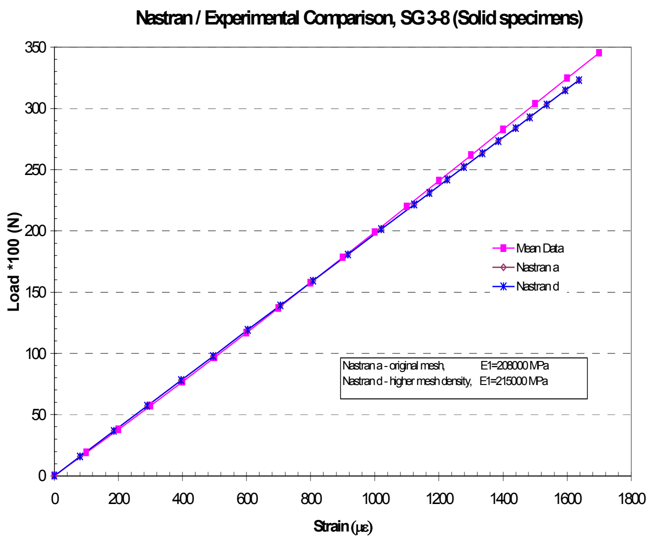

Figure 11

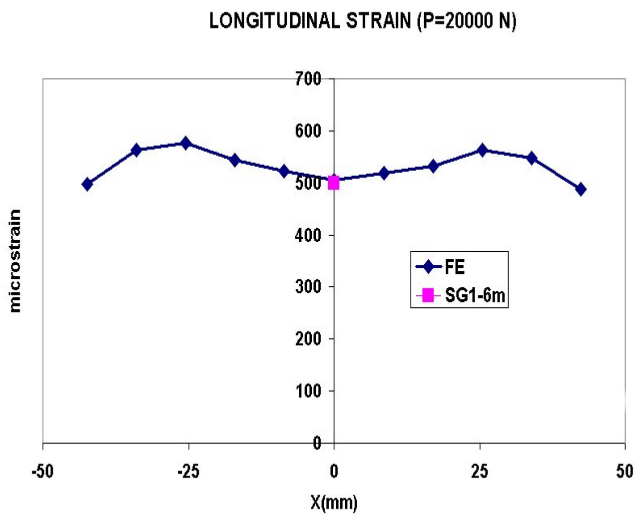

Figure 9

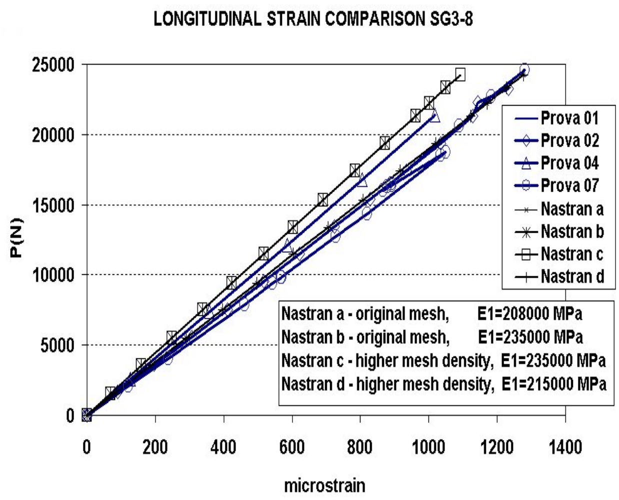

Figure 12

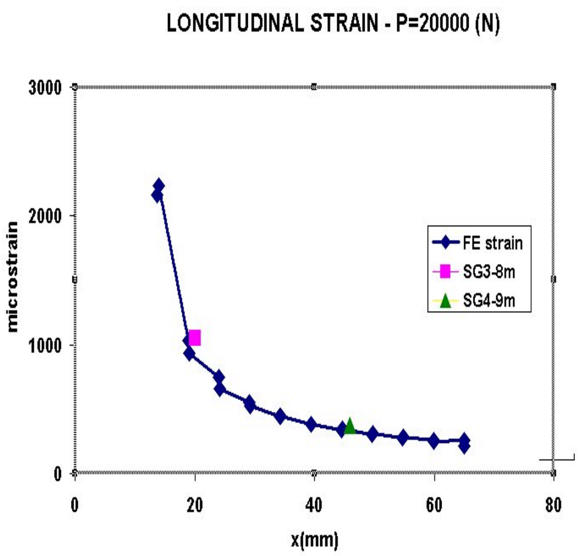

Figure 10

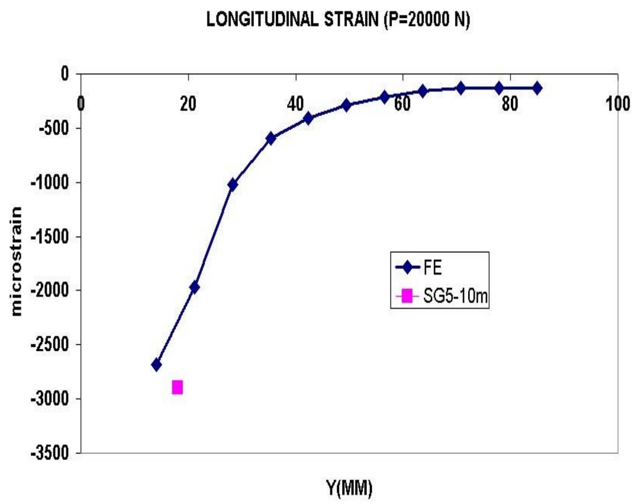

Figure 13

There is a light difference between the back to back strain gauges, not reported here, that could be due to the presence of a little not uniformity in the two faces of the specimen. A misalignment of the load from the fittings to the hole bolt, could arise for the mould effect during the cure. In figure 13 the SG5-10, placed below the hole, is reported in function of the longitudinal co-ordinate below the hole position. At this load the experimental result shows a difference with the numerical calculation due to the approaching failure condition. This is a bearing effect in the hole. A typical bearing failure is presented in figure 14.

The not reinforced sandwich samples showed a similar behaviour as the solid ones, so they are not repeated here.

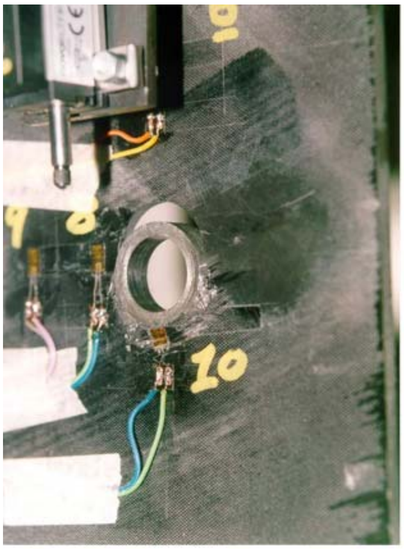

Figure 14

The introduction of the special reinforcement is investigated (fig. 17). A different FE model is defined in this case. The steel reinforcement has been introduced by means of solid elements such as for the adhesive film, the hole reinforcement and the bolt (fig.15). The load is applied on the two ends of the bolt such as in the experimental case. A very thin layer of solid elements is positioned around the bolt in order to define a loaded area. This group represent the effect of manufacturing of the hole and bolt that is not a perfect contact. A good correlation between experimental deflection (fig 16) is obtained with such approximate solution. It is important to notice that the total displacement of the bolt is the sum of the hole bearing effect plus the bending-shear of the bolt plus the effect of the reduction in the hole-bolt coupling. No gap was determined during the joint assembly that is the bolt and hole fit together without eccentricity, so it was preferable to assume such simplified model.

Typical failure mode is shown in figure 17 . The failure load of the laminate is reached without bearing.

The experimental measured strains in SG4-9 are compared with different FE results in figure 18.

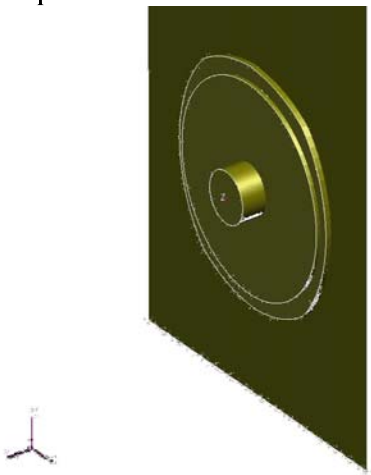

Figure 15

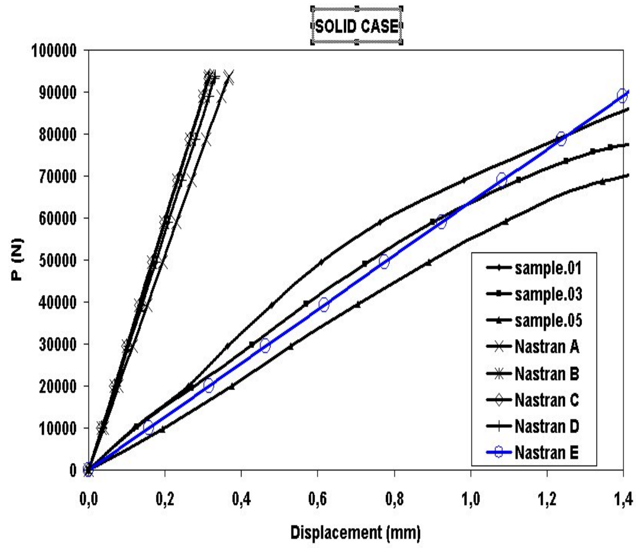

Figure 16

Table n.1

solid sample n.	not reinforced	reinforced
02 (03)	21327 (N)	93862 (N)
04 (05)	21401 (N)	93646 (N)
07 (11)	18714 (N)	95294 (N)
sandwich s.	not reinforced	reinforced
12 (02)	39326	97971(N)
05(07)	37500	98924 (N)
01 (08)	41618	98193 (N)

The experimental results show a non linear behaviour approaching the failure condition in correspondence of maximum applied load. Table n.1 summarises the failure loads of the different tested specimens. The reinforced sandwich samples results show an increase of the failure load by a factor of about 2 with respect to the not reinforced ones. The reinforced solid specimens show a failure load of the same level as the sandwich ones: the two configuration are equivalent. The not reinforced samples reveal a lower failure load than the corresponding sandwich one. The little misalignment of the loading application by means of a centre ring could have introduced a premature failure initiation in the solid samples.

Figure 17

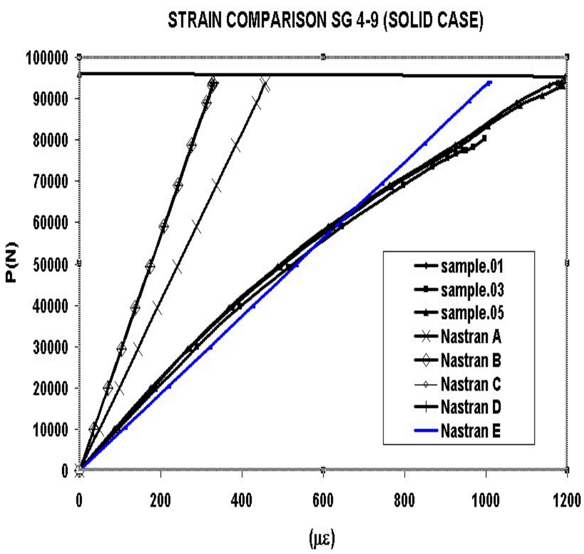

Figure 18

The presence of the reinforcement is quite evident in the strain of the SG-4-9 that is positioned quite close to the reinforced area (figure 18). A good distribution of the applied load is performed by the reinforcement. This alleviate the hole bearing and the concentration around the hole. A good correlation between numerical and experimental results is reached.

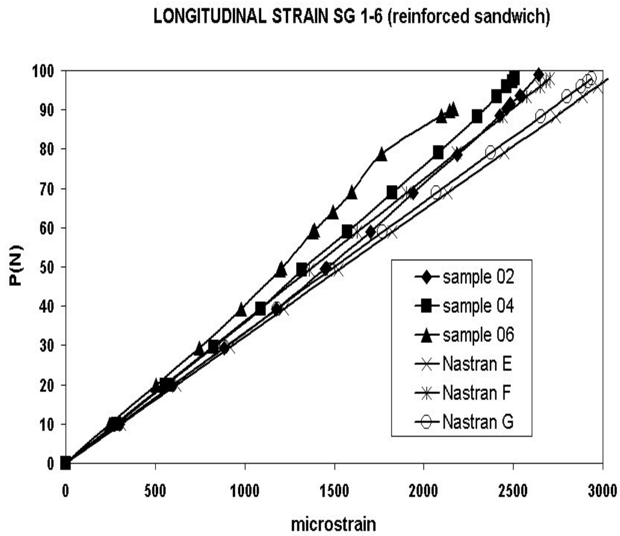

Figure 19

The experimental strains behaviours for the sandwich reinforced joints are quite similar to those of the solid ones. The longitudinal strains of the SG1-6 are reported in figure 19 as an example. A similar good comparison is obtained.

4. Fatigue experimental results

The presence of high strain concentration and the repetitive nature of the actual load on this kind of junction enforce the designer to investigate the fatigue behaviour of the proposed original solution. It is well known [13] that composite material shows no damage grow under fatigue loads if the strain level is lower than a specific limit.
Furthermore tri-dimensional effects can arise near the hole edges introducing some level of damage with a reduction in strength of the structural detail. An experimental investigation of the fatigue behaviour of this joints is necessary. Both solid and sandwich specimens were tested with a quasi-pulsating load cycle. The maximum load reaches the actual limit load expected for that specimen while the minimum load was assumed to have a sufficient traction in the joint.

About three hundred thousands cycles where applied to the not reinforced solid specimen as shown in figure 20. The curve are not continue because of the night – day interval. Imperfect setup of the displacement measuring system each day introduced the shown misalignment in the different curves, not he same for the load curves.

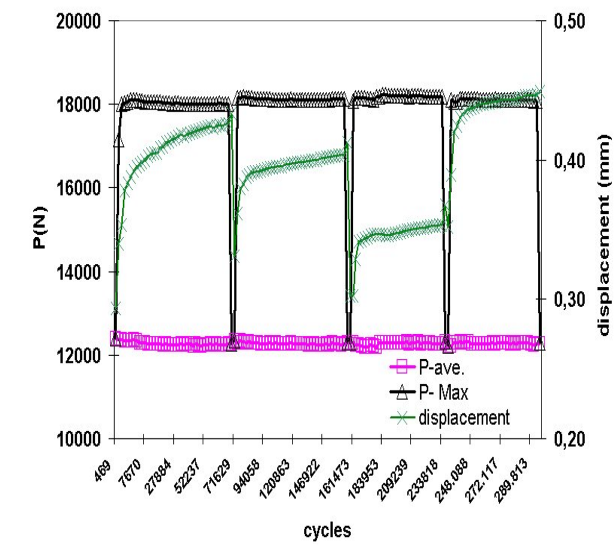

Figure 20

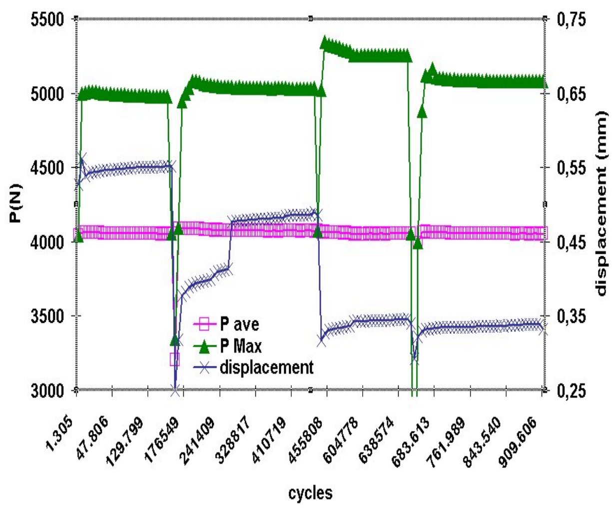

Figure 21

The sandwich reinforced fatigue results are reported in figure 21 up to about one million cycles. The same observation can be done as for the solid case. No fatigue effect seems to be detected in the two cases. New test activity is under development in order to point out this characteristic.

5. Conclusion

On the basis of experimental results and Nastran comparison, the following findings were made: in general, Nastran models predicted strain with good qualitative representation in all cases; in some tests, strain resulted 10% greater than experimental. High density mesh returned 2% improvements in prediction. All test specimens failed in bearing mode. Solid specimens failed catastrophically through compression induced shear cracks below loading hole. Sandwich specimens experienced less visible damage. Concluded that CFRP composites were poor in bolt-bearing and that even a small degree of bolt-torque clamping had beneficial effects. A similar behaviour has been experienced by the solid and sandwich samples. The proposed modifications of the joint is able to increase by 450% the bearing strength of the solid laminate joint and by 250% the bearing strength of the sandwich laminate joint.

Preliminary fatigue tests have been performed. Expected behaviour has been pointed out. No fatigue effect has been detected after tests. Experimental activity is under development in order to investigate this important design aspect.

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