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REVIEW

On the self-piercing riveting of aluminium blanks and carbon fibre composite panels

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Abstract In the present paper the possibility to join aluminium alloys blanks and carbon fibre composites panels by self-piercing riveting operation is considered. In particular a few case studies were carried out at the varying of the process parameters. The effectiveness of the obtained joints was tested through tensile tests and through fatigue ones; what is more the process mechanics was highlighted through proper macro and micro observations of the transverse sections of the joints. The failure mechanics of the obtained joints were also considered in order to highlight the mechanisms which occur and determine the lost of the load carrying capability of the joints. Finally a numerical model of the process was carried out and the residual stress state after piercing was highlighted. The developed experiments and simulations demonstrated that self-piercing riveting can be effectively used to join carbon fiber composite panels and aluminum blanks.

Keywords Self-piercing riveting · Hybrid joints · Failure · Carbon fiber

Introduction

Composite materials reinforced with carbon fibre long found wide structural applications in technologically advanced fields such as aeronautics, but also in those industrial sectors where the need to obtain high mechanical properties at high performance and great productivity is aimed at. Although they are materials characterized by high resistance and in particular by resistance to weight ratios, and also by good resistance to fatigue, composites materials are still treated very carefully as they have to be joined to other materials (or to composites themselves) in structures that must ensure high reliability and safety.

In the present paper self-piercing riveting is taken into account as joining techniques to be used to link metal blanks to carbon fibre composites panels. Self-piercing riveting is a relatively new joining method in the automotive field where it can be used to join thin sheet material [1, 2]. Over the years, new and existing joining technologies have been introduced to automotive manufacturers to achieve lightweight vehicle goals. Among these, self-piercing riveting is receiving more recognition as a possible and effective solution to join body panels and structures.

Self-piercing riveting is essentially a cold forming operation, in which a semi-tubular rivet is pressed by a punch into two sheets of material that are supported on a small die. Unlike the traditional riveting process, there are no pre-drilled or pre-punched holes required in the self-piercing riveting process. The materials to be joined are stacked, with a punch above the stack and die underneath it. The punch impacts the rivet, piercing the top panel and partially piercing the bottom. The die on the underside of the materials causes the rivet to flare under the force, creating a mechanical interlock [3]. The entire process of piercing and forming the joint is carried out in a single operation. The considerable number of variables present in a riveted connection requires complex design procedures to completely understand the structural behavior of such connections. Tests on lap-shear joints using self-piercing rivets also compared with other types of connections [4–6] showed the influence of some process parameters on the static strength and fatigue life of self-

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piercing riveted joints in aluminium alloy. The mechanical behaviour of this type of connection is not influenced just by the geometrical characteristics of the joint, i.e. number and dimensions of the rivets, distance from the edges, thickness of the plates and so on, but also by process parameters, as the die pressure, pre-clamping force and die shape.

Though the self-pierce riveting process was originated around half a century ago, it is only in the last 20 years that such technology has significantly progressed [7–10]. A few comments can be drawn from such literature. First of all, since it is very difficult to predict the strength of a self-piercing riveted connection without experimental tests and since there is a lack of analytical description of the strength and hence complete understanding of a joint mechanism leading to failure, numerical modelling can be a solution to overcome these problems. Finally, it should be observed that just rare investigations are found out regarding the possibility to use self-pierce riveting to develop hybrid joints with metal and composite materials, highlighting the relevant lack of knowledge in this specific field.

Fratini and Ruisi have studied the possibility to joint fibreglass composite panels and aluminium blanks, in particular the composite laminates must be placed at the top of the joint, i.e. close to the punch of the riveting system [11].

Many studies have been made about the riveting process to study the deformations that occur and the load–displacement curve by means of numerical models [12].

In the present paper the possibility to join aluminium alloys blanks and carbon fibre composites panels by self-piercing riveting operation is considered. In particular a few case studies were considered at the varying of the process parameters. The effectiveness of the obtained joints was tested through tensile tests and fatigue ones; what is more the process mechanics was highlighted through proper macro and micro observations of the transverse sections of the joints. What is more a simplified numerical simulation of the process was carried out in order to insight the process mechanics and also to highlight the residual stress state conferred to the blank and the composite panel at the end of the SPR process. Such piece of information is definitively important with reference to the fatigue life of the hybrid joint.

Experimental investigation

In the development of the present research, the electro-hydraulic riveting system, namely Textron Fastening System SN2, was used. The equipment is supplied by a hydraulic motor with an electro-hydraulic valve necessary to vary the pressure applied on the punch. In the following (Table 1), the principal characteristics of the used fixture are reported.

The electro-hydraulic riveting system was previously tested in order to determine the correlation between the oil pressure (P[bar]) of the hydraulic system and the applied load (F[N]): a linear relation was determined as follows:

$$F = 87.234 \times P + 2382.8 \quad (1)$$

A commercial rivet-die configuration was used and its geometry is shown in Fig. 1. The Fastriv designation for the rivet is FSC4865001A01. In particular, austenitic stainless steel rivets were used, and the rivet-die set was able to join components up to a total of 4-mm thickness. As far as the used materials are regarded, the following indications are given: the aluminum alloy was the AA2024-T6 received in 1×2 m blanks of 2.7 mm thickness. From the blanks, 25×100 mm specimens were derived and used for the self-piercing riveting operations. The aluminum blanks were also tested through tensile tests obtaining a yield stress equal to 345 MPa and an ultimate tensile stress of 427 MPa.

The used composite panel was made of an epoxy resin (C. SYSTEM 1010 CFS ‘A’, Cecchi), a cure agent (C.SYSTEM 1010 CFS ‘B’, Cecchi), and carbon fiber. The used reinforcement (BATAVIA 0°/90°) was made of carbon fibre material with a superficial density of 200 g/m2 (Fig. 2).

The sequence of packing was $[0°/\pm45°]_S$ and the final thickness of carbon fiber composite panels was 1,4 mm. The used laminates were obtained through the vacuum bagging technique in order to avoid voids and air inclusions and to improve the density of the fiber layers with the aim to increase the load carrying capability of the panel. The laminates underwent a depression of 0.8 atm for 8 h, were cured at about 20° for 16 h and finally were heated at 60°C for 12 h. The obtained laminates were reduced in 25×100 mm specimens as the metallic ones.

The ASTM D3039/3039 M-93 standard was used to calculate the mechanical properties, results are shown in Table 2.

As far as the mechanical performances of the obtained joints are regarded, static tension tests were conducted on a 50 t Instron machine at a constant cross head speed of 0,5 mm/min with a load cell of ±30kN.

Table 1 Characteristics of the electro-hydraulic riveting system

Characteristics	Values
Nominal power	750 W
Electrical data	230 V/50-60 Hz
Maximum oil pressure	500 bar
Maximum load	60 kN
Riveting time	2 s

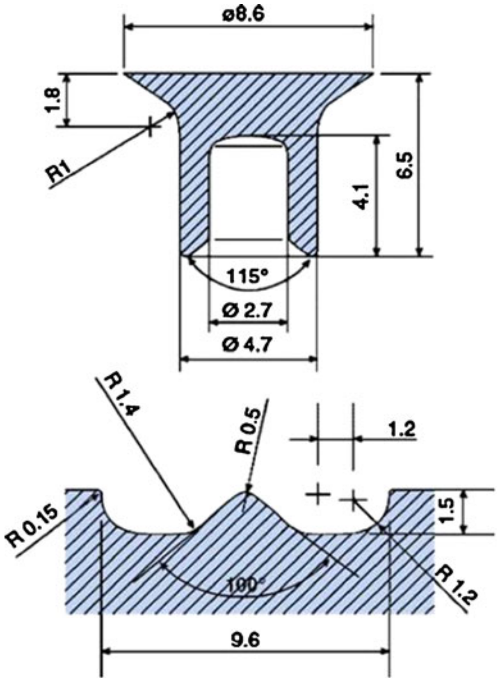

Fig. 1 The rivet-die configuration (dimensions in mm)

Dimensions for the specimens used in the lap shear tests are shown in Fig. 3. It should be observed that in a preliminary experimental campaign it was determined that even if effective joints can be obtained also placing the carbon fiber panel at the bottom of the joint, i.d. close to the die, the largest resistance values are obtained as the composite panel is placed at the top of the joint, i.e. on the rivet side. Such results is in agreement with what some of the authors found out in [11], even if it should be observed that working with fiber glass composites the only possibility to obtain sound joints was to position the composite panel at the top of the joint, namely close to the rivet.

Some further investigations were carried out with the aim to highlight the process mechanics. In particular, some of the riveted specimens were cut, mounted, attacked through Keller reagent and observed through macro-image analysis.

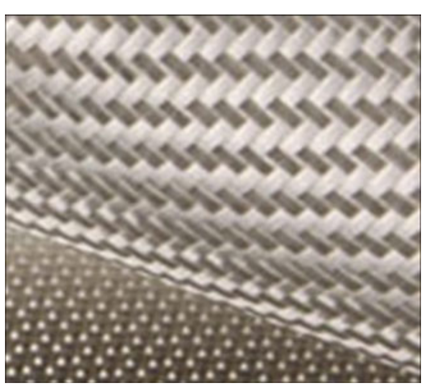

Fig. 2 Carbon fibres type BATAVIA 0°/90°

Table 2 Characteristics of the composite panels

Characteristics	Values
$E_L = E_T$ = Modulus of Elasticity	28.1 GPa
G_{LT} = Shear Modulus	1.12 GPa
ν_{LT} = Poisson's ratio	0.38

Numerical model

An effective suitable numerical model was set up in order to study the deformation of each component and the residual stresses that occur after the riveting process; in particular the same oil pressure (300 bar) and the mechanical properties of the carbon composite panels experimentally obtained, were used.

Numerical simulations of the self-piercing riveting process were carried out using the finite element code DEFORM 2D [13–16]. DEFORM 2D is an implicit finite element commercial code designed to study plastic deformation processes and heat treatments. It is designed for deformation modelling with non-linear deformation.

The numerical investigation could be carried out a 2D model because of its axial symmetrical conditions. In particular, a 2D axisymmetric model was generated including the two sheets to be joined, the rivet and the tool. The movement was set at the punch at the velocity of 1 mm/sec along the direction of -Y. In this way the duration of the process was of 4 s and the chosen iteration method was the Newton–Raphson method. Dies were modelled as rigid contact surfaces, while rivet and sheets as deformable parts.

As far as the composite panel is regarded, a simplifying assumption was made: the panel was considered and modeled as an homogenous equivalent plastic material. The elastic properties indicated in Table 2 were introduced. The elements were imported and positioned in the model as illustrated below in Fig. 4.

As illustrated in the figure an auxiliary rigid element appears. This element prevents both the aluminium and the carbon fibre sheet to move along the Y axis.

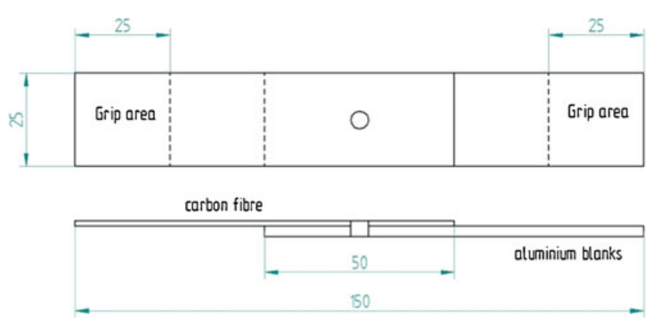

Fig. 3 Specimen geometry for tensile test

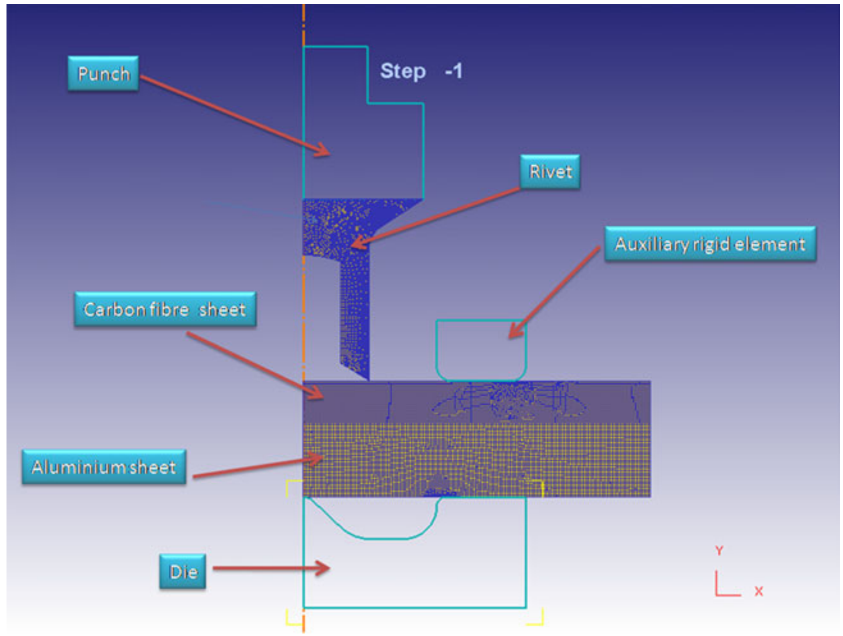

Fig. 4 The initial configuration of the 2D model

The used elements of the mesh were 4-nodes elements. The material properties of the AISI-D2 and the AL-2024COLD for the rivet and for the aluminium sheet were loaded from the materials library of the finite element code DEFORM 2D. As far as the materials modelling is regarded the AA2024-T6 aluminium alloy was modelled through an elasto-plastic work piece and the following flow rule was used:

$$\overline{\sigma} = 385,79 + 1,104\overline{\varepsilon} \tag{2}$$

The mechanical properties of carbon laminate, obtained experimentally, were included in the FEM code. The fracture criterion for the carbon fibre laminate was the normalized Cockcroft & Latham based on a critical value of the tensile strain energy per unit of volume [17]:

$$\int \frac{\sigma^*}{\overline{\sigma}} d\overline{\varepsilon} = c \tag{3}$$

where σ^* is the maximum principal stress, $\overline{\sigma}$ is the equivalent plastic stress and c is a material constant here considered equal to 0.4 for the composite panel on the basis of some literature results and some preliminary tests. After the geometrical configuration and the position of each object was been defined, the mesh was created and the material properties from the library were imported (Table 3).

A particular study has been done to find appropriate friction factors between the different contact surfaces. A constant friction factor law was used and the correct values of friction were identified by inverse modeling, comparing the resultant geometry of the simulation with the section of the experimental joint.

The optimal values identified after several testing are: punch-rivet 0.2, rivet-sheets 0.25, carbon laminate-aluminum sheet 0.12 and aluminum sheet-die 0.7.

Obtained results

The self piercing riveting (SPR) of aluminum blanks and carbon fiber composite panels was investigated carrying a total of 25 different tests at the varying of the oil pressure of the riveting system, in other words, at the varying of the riveting load. In particular five repetitions of each test were developed to verify the repeatability of the obtained results.

Table 3 Defined mesh and material of each object

Element	Type of object	Number of elements	Number of nodes	Material
Punch	Rigid			
Rivet	Plastic	5162	5384	AISI-D2 (E=207 GPa, σ_s=1321 MPa, σ_r=1392 MPa)
Carbon panel	Plastic	3916	4122	Carbon fiber (E_L=E_T=28.1 GPa, σ_r=352 MPa)
Aluminium sheet	Elasto-Plastic	4050	3882	AL-2024COLD (E=65.8 GPa, σ_s=350 MPa, σ_r=440 MPa)
Die	Rigid			

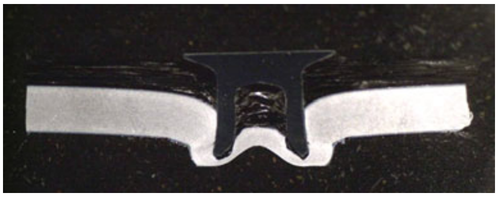

Fig. 5 The transverse section of riveted joints

First of all the SPR process mechanics and the effective fastening mechanics occurring during the process was investigated through a detailed analysis of the transverse section of the obtained joints. In the next Fig. 5 the macro image of the transverse section of a riveted joint obtained with an oil pressure of 300 bar is shown. It can be observed that the rivet penetrates the carbon fiber composite panel and then deforms the aluminum blank against the die. It should be noted that the composite material is blocked inside the rivet, and such material does not plastically deform, limiting as a consequence the plastic deformation of the rivet itself. Overall the typical process mechanics of the SPR process for metal to metal case studies is obtained determining an effective fastening between the two parts to be joined.

Furthermore static tensile tests were carried out in order to investigate the mechanical performances of the obtained joints. In the next Fig. 6 the typical load vs. displacement curve of tensile tests is reported. In the figure it is shown an increase of the carrying load up to a maximum value, such value, of course, depends on the used process parameters. Then the maximum load is reached, the bearing mechanics starts and the failure of the joint starts.

The measured load then decreases up to a plateau which is maintained for all the tensile test, observing the growing of the fracture cracks in the carbon fiber composite panels. In the end a sudden fracture is observed and the capacity to transfer load of the joint is completely lost.

As far as the obtained results in terms of maximum transmitted load are regarded, in Fig. 7, both the obtained

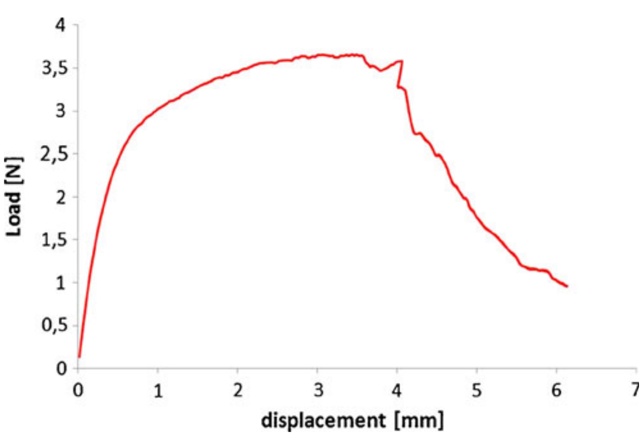

Fig. 6 Load vs. Displacement curve

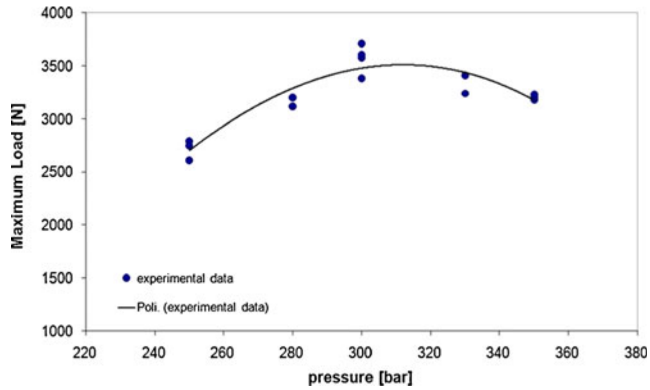

Fig. 7 The maximum load vs. the oil pressure

loads and their dispersions are shown. It should be observed that a maximum load is obtained for the intermediate value of the oil pressure of the riveting system (Table 4).

Specifically the maximum transmitted load is obtained with an oil pressure of 300 bar and what is more, the minimum scattering is also observed.

As it was expected the mechanical behaviour of the joint is strictly influenced by the riveter oil pressure. This fact it is attributable by the different force in the riveting process which determines a different deformation of both the rivet and the aluminium alloy sheet within the die.

The carried out tensile tests showed for all the tested specimens the bearing failure mechanism which, as shown in Fig. 8, is given by the compression and folding of the composite material at the back of the rivet.

The insurgence of the bearing failure mechanism depends on the ratio between the rivet diameter and the specimen's width; in the case of the composite materials, the insurgence of such failure mechanism cannot be predicted on the basis of heuristics rules and depends also on the fibers orientation of the laminate material.

Finally a total number of 20 fatigue tests were carried out on the series of joints obtained with an oil pressure equal to 300 bar, i.e. the one corresponding to the best static resistance of the investigated joint. In particular four repetitions for each of the investigated load level were made. For the fatigue behaviour investigation a

Table 4 Peak load for each type of specimen examined

Oil pressure [bar]	Peak Load [N]	Displacement at peak load [mm]
250	3045,2	1,93
280	3209,6	1,19
300	3719,6	4,62
330	3556,5	3
350	3516,8	3,74

Fig. 8 The bearing failure mechanism

MTS (Material Test System) machinery was used, the movement and the grip was carried out by an hydraulic system which is characterized by high precision and high response time. The fatigue tests were made under load control. The specimens were loaded with a dynamic load with a frequency of 10 Hz. The ratio between the maximum load and the minimum load was equal to 0.1. In the next Fig. 9 the obtained results of the fatigue tests are reported.

The obtained results showed large values of the fatigue resistance even for load amplitudes close to the joint maximum static resistance; in turn a quite large scattering of the results was observed. Two types of cracks can be distinguished in the developed tests. The tests until a number of 200000 cycles the joint present a similar crack as the static tests in which the carbon fibre pulls out determining the failure of the joint (bearing phenomenon, see again Fig. 9).

For the tests carried out with a lower load level the crack behaviour substantially changed. In particular, for tests with a number of cycles superior than 200000, the composite remains undamaged and the crack grows on the aluminium alloy. The crack in the aluminium alloy blank grows along the direction of a transverse section near the hole of the rivet as illustrated in Fig. 10.

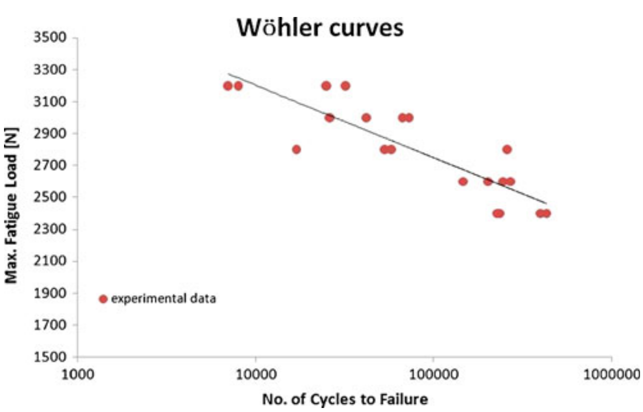

Fig. 9 Fatigue tests results

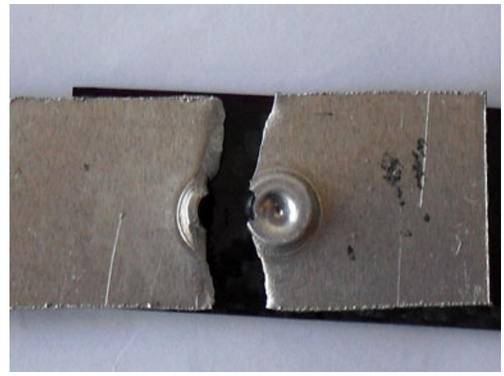

Fig. 10 Particular of the crack in the aluminium alloy

It should be then observed that, unlike static tests, in fatigue tests the fracture occurred also in the lower sheet (aluminium) and not just in the upper sheet (composite panels).

As far as numerical results are regarded, the typical obtained configuration at the end of the SPR process is shown in the following Fig. 11. It should be observed that the mechanical fastening mechanics determined by the SPR process is clearly discernable.

As far as the numerical simulation is regarded, Fig. 12 shows the critical area of plastic strain before the fracture of upper sheet and after its complete separation.

What is more, Fig. 13 shows the stress state in the aluminium sheet at the end of the riveting process when the punch applies the maximum load and residual stresses after the riveting process when the punch back. The maximum

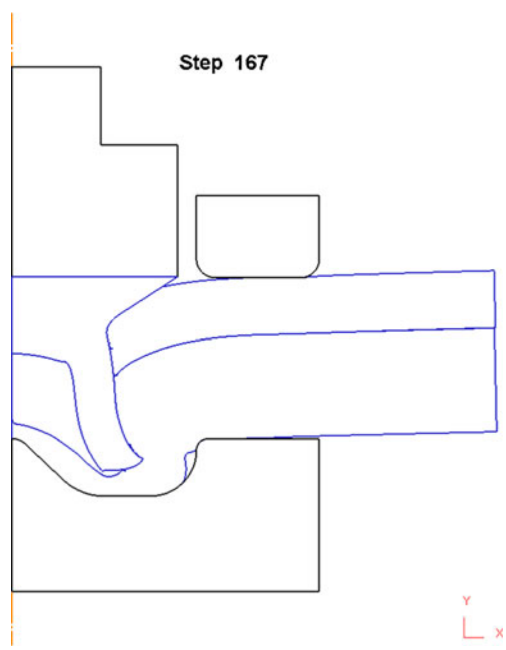

Fig. 11 Deformed shape of the objects in the 2D model at the end of the process

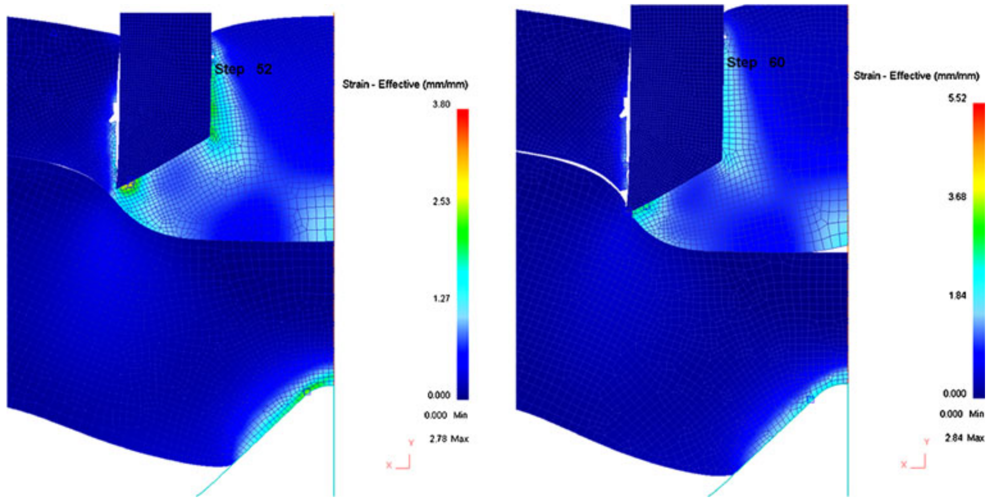

Fig. 12 Zoom view of the plastic strain state before and after the fracture of carbon sheet

principal stresses is changed from 299 MPa to 196 MPa while the minimum ranges from -1090 MPa to -303 MPa. The tensile residual stress has a negative effect on the fatigue life of the joint, because the stress state at the apex of the crack increases favoring the propagation of the defect. In contrast, the residual stresses of compression tend to close the apex of the crack by increasing the fatigue life of the component.

The numerical study has been done to study the stresses that occur during the riveting process and the stress concentrations o caused by the same joint in order to better understand the failure modes of the joint.

Conclusions

The present paper had the purpose to evaluate the possibility to join two different materials such as carbon fibre laminate and an aluminium alloy using self-piercing riveting operation. In short it can be concluded that self-piercing riveting can be effectively used to join carbon fibers composite panels and aluminum blanks, so the self piercing riveting can be applied to join not just aluminum sheets but also hybrid parts.

In self pierce riveting, a very important process parameter is the oil pressure of the riveting system that must be carefully chosen in order to get effective mechanical performances of the obtained joints.

The failure mechanism in the static tests observed for the investigated hybrid joints was fundamental the bearing one occurring in the composite panel, highlighting the good interaction and clamping mechanics between the rivet itself and the two parts to be joined namely the aluminum blank and the composite panel. In turn in fatigue test both bearing in the composite panel and crack growth in the aluminum blank were observed depending on the load level used in the fatigue tests.

Finally, the riveting process was examined through a FEM analysis which offered convergent result to the experimental process highlighting the mechanical fastening obtained through the SPR process. In this, FEM analysis can be considered as a valid tool to understand the phenomenon concerning the process.

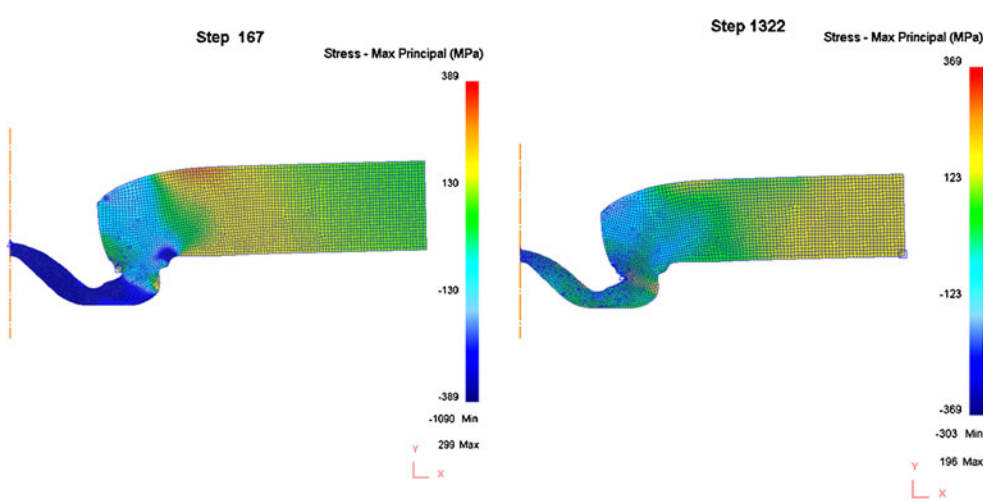

Fig. 13 Residual stresses after the riveting process in the aluminium sheet

The numerical study has shown a high stress concentration that can motivate the fatigue failure of aluminum sheet for tests with a number of cycles superior than 200000. Such information is definitively useful for the design of the joining technique especially as the joint has to be used under fatigue load conditions.

It can be concluded that this joining technique will be able to find lots of application in all the industrial fields which need to use innovative materials and a cheap and fast joining technique such as aerospace and aeronautical and automotive industry which have the need to combine lightweight structures and effective joining techniques.

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