PROBADUR : Probabilistic Durability of Structural Laser Assemblies Made of Continuous Fibre Thermoplastic Composite Materials

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1- Introduction

As a result of their advantages, i.e. recyclability, weld-ability, environmental compatibility, long (continuous) fibre thermoplastic composites (LFTPC) are increasingly used in many industrial sectors (automotive, aeronautic, medical devices). Indeed, in the next ten years, the environmental rules (petrol & fuel oil consumption reduction, CO2 reduction, recyclability of materials…) will put the pressure on the use of new structural materials like composites.

A lot of industrial sectors of the mechanical engineering industry should be impacted by this evolution in a positive way. For example, the weight reduction of heavy equipments on wheels, using petrol/fuel oil will be more and more essential. But various industries may use new structural composite parts like civil engineering equipment manufacturers, lifting equipment manufacturers (cranes…), agricultural equipment manufacturers or industrial coachbuilders (truck sub-frames, tubs, tippers, rolling tanks…). This trend gives a good opportunity for the introduction of lighter and more environmental friendly composite materials instead of metals in the structures and will lead to the development of thermoplastic composite instead of thermoset composite materials.
To get structural complex parts, several joining techniques have been developed (induction welding, resistance welding, adhesive bonding, and laser welding) but a real lack of knowledge about the mechanical resistance after welding remain in literature especially for thermoplastic reinforced composites.

A French-German research and development project between Fraunhofer and Carnot Institutes (ENSMP, ENSMD, CETIM), PROBADUR, (Probabilistic Durability of Continuous Fibres reinforced Thermoplastic Composites) was initiated in 2008 in order to build the basement of a mid-term probabilistic approach of the fatigue behaviour of LFTP (continuous fibres) composite materials (PA66/GF) and of welded assemblies by laser of these materials for structural applications. The main objectives and the results of the project lead to :

- master the quality of structural welded assemblies of LFTP parts with an optimized welding process. This step requires to understand and simulate what happens at the interfaces between the parts involved in the assembly during the welding process, but also to evaluate the impact of the assembly process on the long term behaviour of the structural parts under fatigue.

- optimize, the laser welding process both on samples (coupons in PA666/GF) and on a structural part (a stiffener welded on a plane part), to improve the welding processes and the way to assembly the parts among themselves (welding speed, laser seam geometry…)

- evaluate the behaviour of LFTP composites, mainly in terms of mechanical characterization, fatigue loading by performing S/N tests and quasi static tests (Arcan test, lap shear test…)

- introduce in the design offices new design methods of structural LFTP parts based no more on a deterministic approach but on a probabilistic approach in order to take in a better way the specifities of the materials and of their manufacturing and assembly processes.

2- Materials tested

The material is a composite made of a polyamide matrix (PA6) and continuous glass fibers reinforcement. Plates of unidirectional (UD) composite of 300mm x 300 mm x 2.4mm have been investigated (Figure 1).

(a) (b) (c)

Figure 1: a) and b) UD plies, c) materials microstructure seen in the SEM (scanning electron microscope)

These composites are manufactured by thermoforming by superposing UD layers in order to get various stacking sequences of composite materials. Manufacturing conditions : T=300°C, pressure : 5 bars during 3 min.

Plates manufactured : glass/PA66 (40% volume fraction), 300 x300 mm² plates with 5 stacking sequences :

[0°] – 2, 4, 5 and 6 plies; [0°/90°n/0°] with n=2 and 3; [0°/90°]; [0°/±20°n]s with n=2; [0°/±45°/90°]s.

Applicability of the laser welding essentially requires two parts with similar chemical properties (the same polymer matrix and fibers reinforcement). One part has to be optically transparent at the wavelength of the laser beam and the other one is absorbing the laser energy. The transparent part is composed of natural polymer matrix and glass fibers reinforcement, while the absorbent material is the same composite, including black carbon pigments in the matrix (giving a black colour).

3- Laser Welding Process

The laser used is a 70 W diode laser with an articulated robot. The two plates (one transparent to laser and one absorbing the laser energy) are clamped together and the laser moves to create a seam at the interface. The laser power is temperature driven (at the interface) to compensate the material heterogeneity.

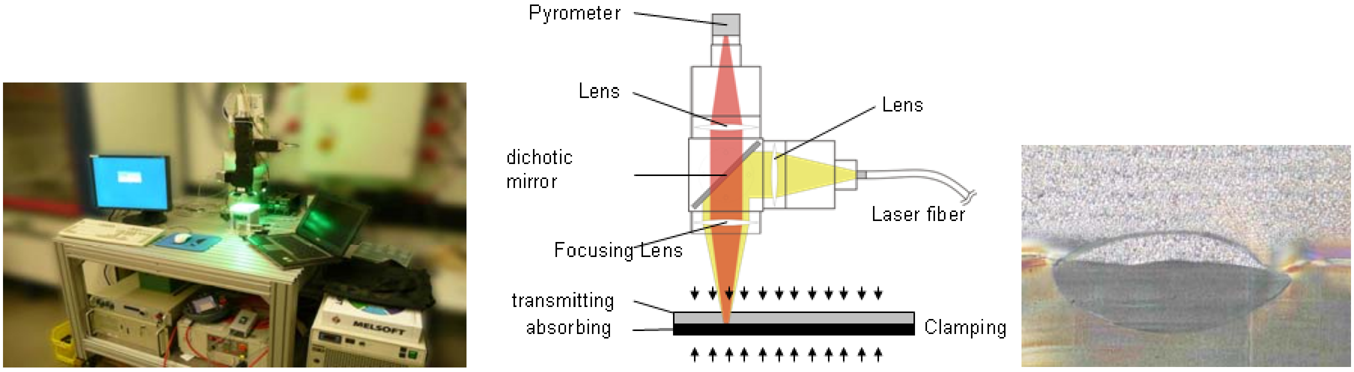


Figure 2 : Diode Laser – principle and cross cut of the seam

The light energy is transformed into heat and the non-absorbent material is heated up indirectly by heat conduction. The melting of their contact interfaces, followed by cooling (consolidation) under pressure, enables the bonding of the two components. Due to the variability of the glass fibre volume fraction, the transmitting energy can range from 27,4% to 39,1% at λ=940 nm, leading to a variation of temperature at the interface from 200°C to 300°C. First conclusions show that there are strong variations on material properties yielding to irregular welding performances. An on-line process control (temperature) is then required. The results show in addition that the material thickness has to be less than 5mm. Finally, the laser welding process is a reliable and reproducible welding tool for GFRP in PA66, provided there is an absorbing part and a transparent one (Figure 3). Moreover, it appears easy to automate the assembly process.

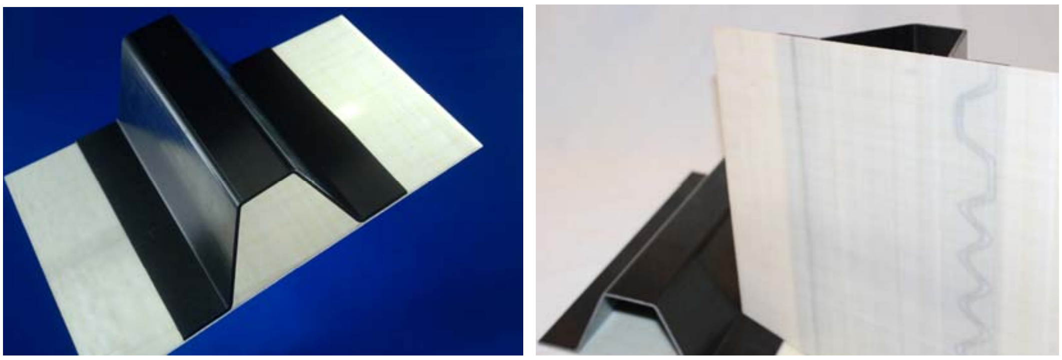


Figure 3 : Example of laser welded part (stiffener)

3- Laser welding modeling

3-1- Microstructural analysis

The propagation of energy provided by the laser beam to the composite structure depends on the materials encountered through the composite thickness. Composite are non homogeneous structure when the micro level is considered. Fibre clusters or resin reached areas can occur, resulting in a change of fibre volume fraction locally. Diffusion of the laser energy is closely dependant on the fibre volume fraction. To evaluate those local changes, microstructural analysis is conducted. Micrographs of the composite plates used as substrate for the laser welding study were taken. An example of micrograph is shown in Figure 4.

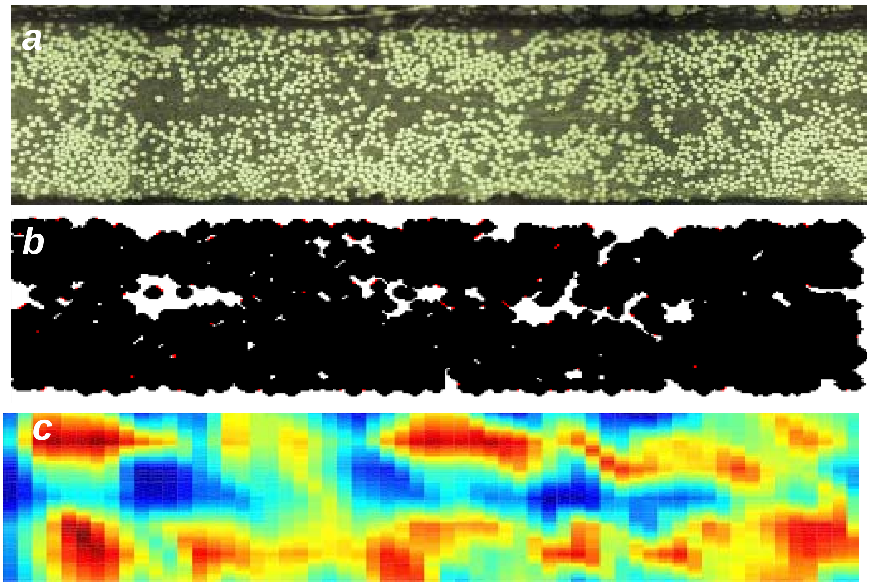


Figure 4 : Image analysis for fibre volume fraction evaluation
a) Micrograph b) Black and white image treatment c) defined pixel fibre volume fraction evaluation

3-2- Energy propagation and heat generation

Laser energy is assumed of a cylindrical shape of 1mm diameter with initial energy of 20W on the section. Due to diffusion through the composite, the laser energy representation at the interface becomes an ellipse when a UD material is considered.

Absorption of the energy is considered only in the second part as the first substrate is considered totally transparent as a first assumption. Energy is thus absorbed by the black material, mostly at the interface, according to Beer Lambert's law for a laser beam that is monochromatic and unidirectional [2]:

$$Q(x) = kI(x_p)e^{-kh} \qquad (1)$$

Where Q is the energy generated, k is the spectral coefficient of the material, I is the incident energy, x is the considered position and h represents the transparent substrate thickness.

Heat then propagates through both substrates by conduction effects evaluated using the heat balance equation :

$$\rho Cp \frac{dT}{dt} = \nabla \cdot (\lambda \nabla T) - Q \qquad (2)$$

With ρ, Cp, λ the composite density, heat capacity and conductivity respectively, T the temperature, and t the time.

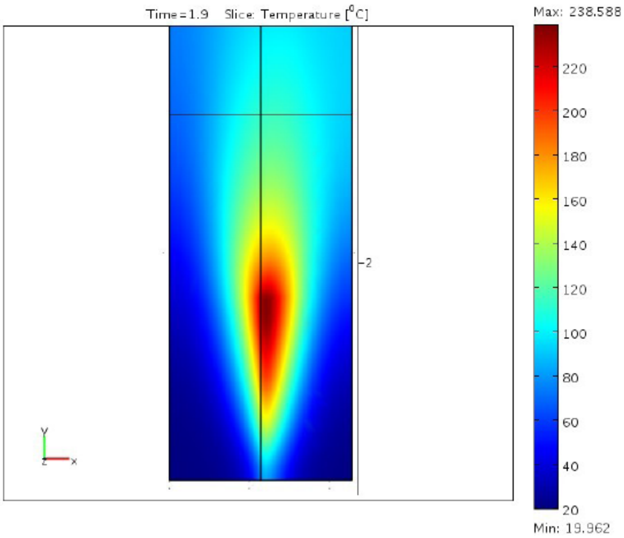


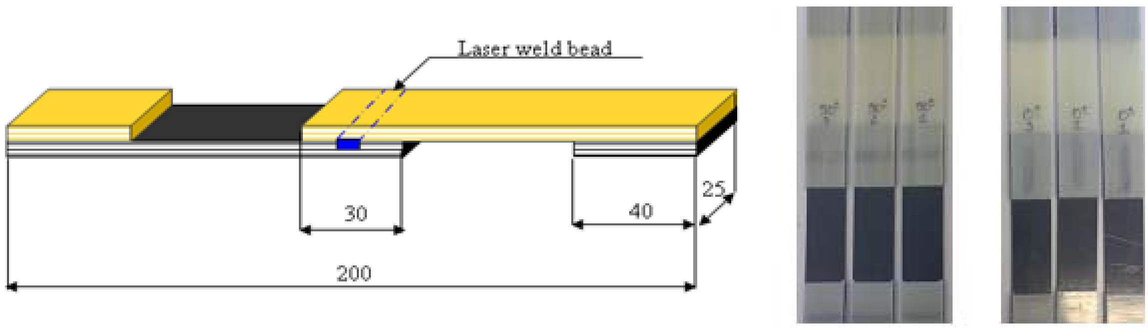
Figure 5 : Temperature profile at the welding interface

Simulation of the resultant temperature through the substrates is obtained by implementation of Equations 1 &2 in a multiphysics code (COMSOL) and taking into account the local substrates properties obtained by applying the rule of mixture using fibre volume fraction mapping issued from the micrographical study [3]. Resultant temperature profile of a moving laser beam with a velocity of 10mm/s is shown in Figure 5. Higher temperatures are reached in the black substrate (on the right) where heat is absorbed. Heating of the transparent substrate (on the left) is only generated through conductive effects. Laser efficiency is shown from this result example as heating and thus polymer melting occurs in a localized zone at the substrates interface, where temperature gets higher than 220°C. The evaluation of the time history temperature of the welding process is necessary to describe the laser welding mechanisms of the composite. Coupling with analytic equations representing the bonding mechanisms (reputation and healing), bonding quality can then be evaluated.

4- Characterization of the behaviour

4-1- Test configuration

After developing the technical basics of the laser based joining process of LFTPCs, lap shear tests results on a laser weld seam under static and fatigue regime are presented. Because of the strong heterogeneity of the microstructure, two configurations of the laser weld seam are analysed: laser beam perpendicular to fibres and parallel to fibres. Acoustic emission test is performed on the first configuration (laser beam perpendicular to fibres) and the damage force is determined to carry out fatigue tests. The lap shear test is the most commonly used to characterize the mechanical behaviour of joined components in the literature (Figure 6).



a) b) LB90 c) LB0

Figure 6 : a) Lap shear test specimen, b) and c) Lap shear test samples in two configurations.

In spite of the complexity of results interpretation, this test gives a first approximation of the mechanical behavior of the welded joint (Figure 7).

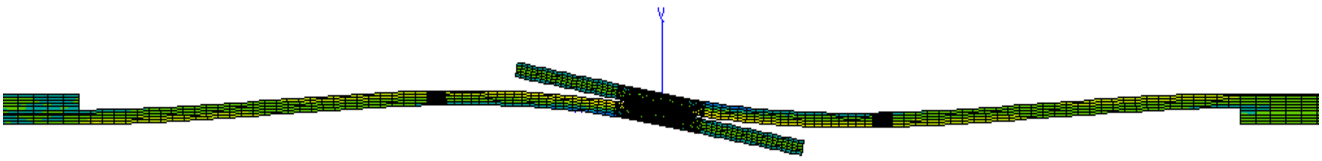


Figure 7 : numerical simulation on lap shear specimen

Two configurations are used: LB90 (for laser beam at 90° to fibres direction) and LB0 (for laser beam at 0° to fibres direction), figure 2-b and 2-c. This enables to highlight the influence of the laser beam orientation on the mechanical behaviour of the weld seam.

To overcome the difficulty in interpreting the results from the lap shear test, ARCAN-Mines tests are performed and the intrinsic mechanical behaviour is determined. This test enables to perform mechanical pure tensile tests, pure shear tests and mixed tests in the aim of characterization of the laser weld seam (Figure 8).

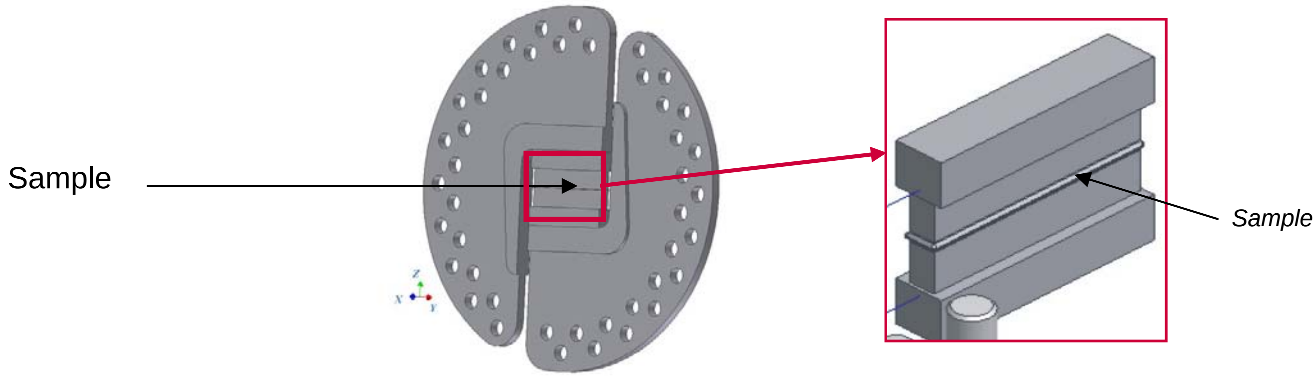
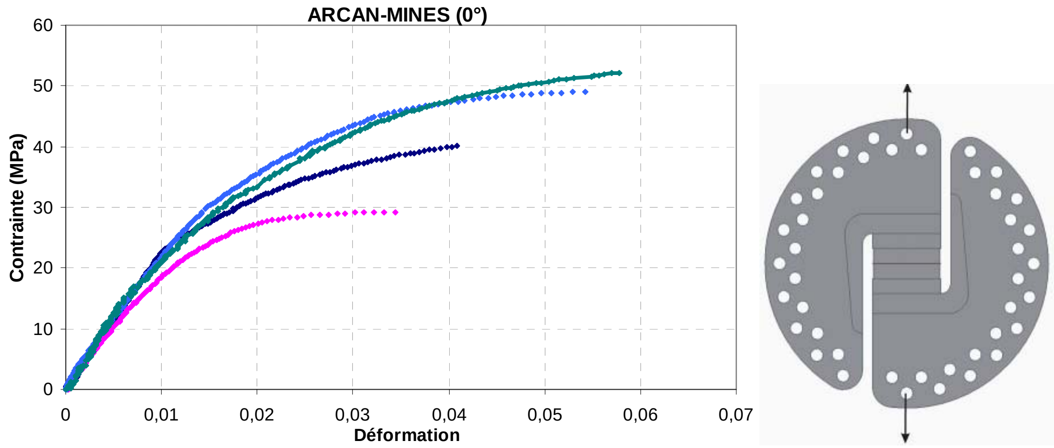


Figure 8 : Arcan Mines Test

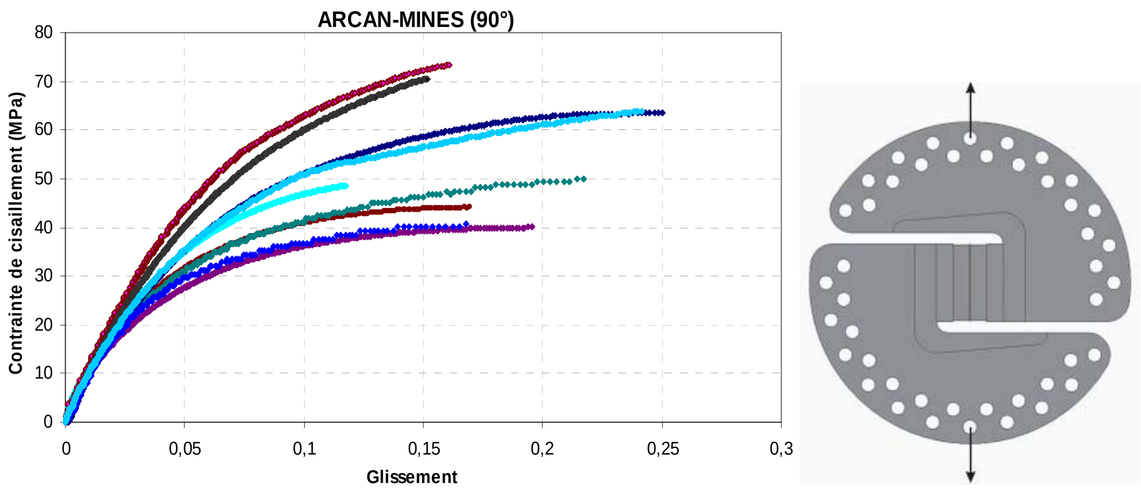
Once ARCAN tests are performed, the stiffness matrix is then obtained, provided by generalized Hooke's Law . The results are presented in Figure 9 and Figure 10.



Traction

Modules	Moyenne	Ecart type	Coefficient de variation	Intervalle de confiance à 95%
E_{33} (GPa)	1.715	0.172	10.05 %	[1.516 – 1.914]
σ_{33}^{R} (MPa)	42.61	10.29	24.15 %	[30.73 – 54.50]
ε_{33}^{R} (%)	0.0467	0.011	24.15 %	[0.034 – 0.060]

Figure 9 : Pure Tensile Test



Cisaillement

Modules	Moyenne	Ecart type	Coefficient de variation	Intervalle de confiance à 95%
G_{13} (GPa)	0.919	0.071	7.71 %	[0.878 – 0.960]
σ_{13}^{R} (MPa)	51.91	12.98	25 %	[44.42 - 59.40]
γ_{13}^{R}	0.17	0.049	28.87 %	[0.14 – 0.20]

Figure 10 : Shear Test

4-2- Fatigue Tests

The main objectives of these tests are :

- to characterize fatigue behaviour of the material and the assemblies
- to Understand the damages and failure processes
- to model the behaviour

In addition, another parameter is taken into account for the fatigue behaviour tests performed: due to the high dispersion of the results for one seam, various configurations of welding were performed and the welded samples tested in fatigue (Figure 11).

Parameters : R=0,1; frequency : 1Hz to 5 Hz

Coupons with 1, 2 or 3 weld lines : 1 line, 2 lines (2P), 3 lines (3P) – 5 mm width
Coupons with medium seam (CM 10 mm width) or large (CL 15 mm width)

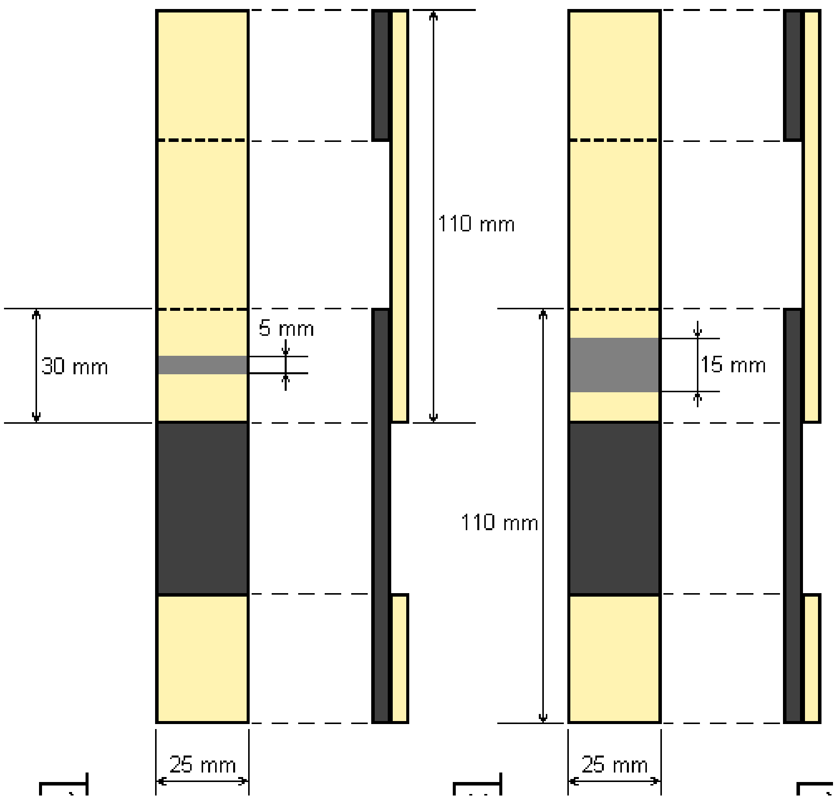


Figure 11 : various configurations of welding

a : (1, 2 3 lines 5 mm width

b: medium or large seam 10mm to 15 mmwidth

The results of fatigue tests are displayed in the following graphs.

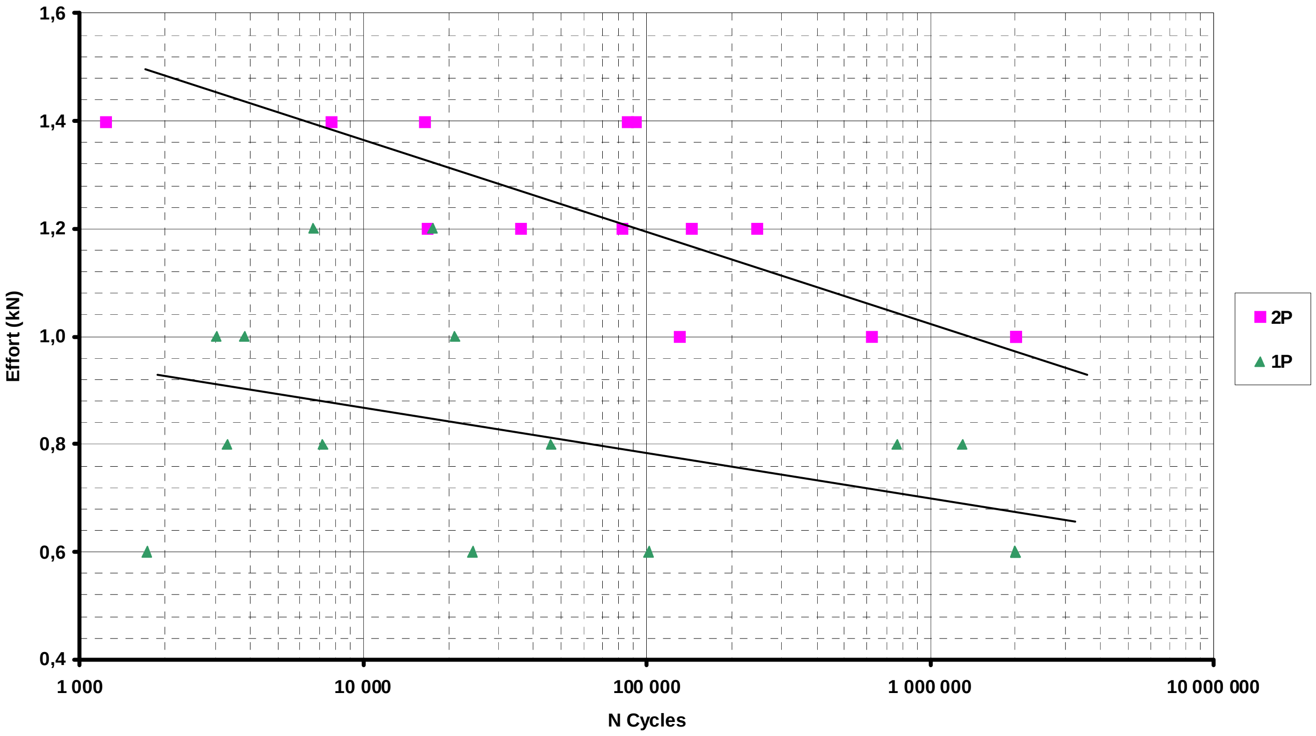


Figure 12 : S/N curves on lap shear coupons for one line and two lines

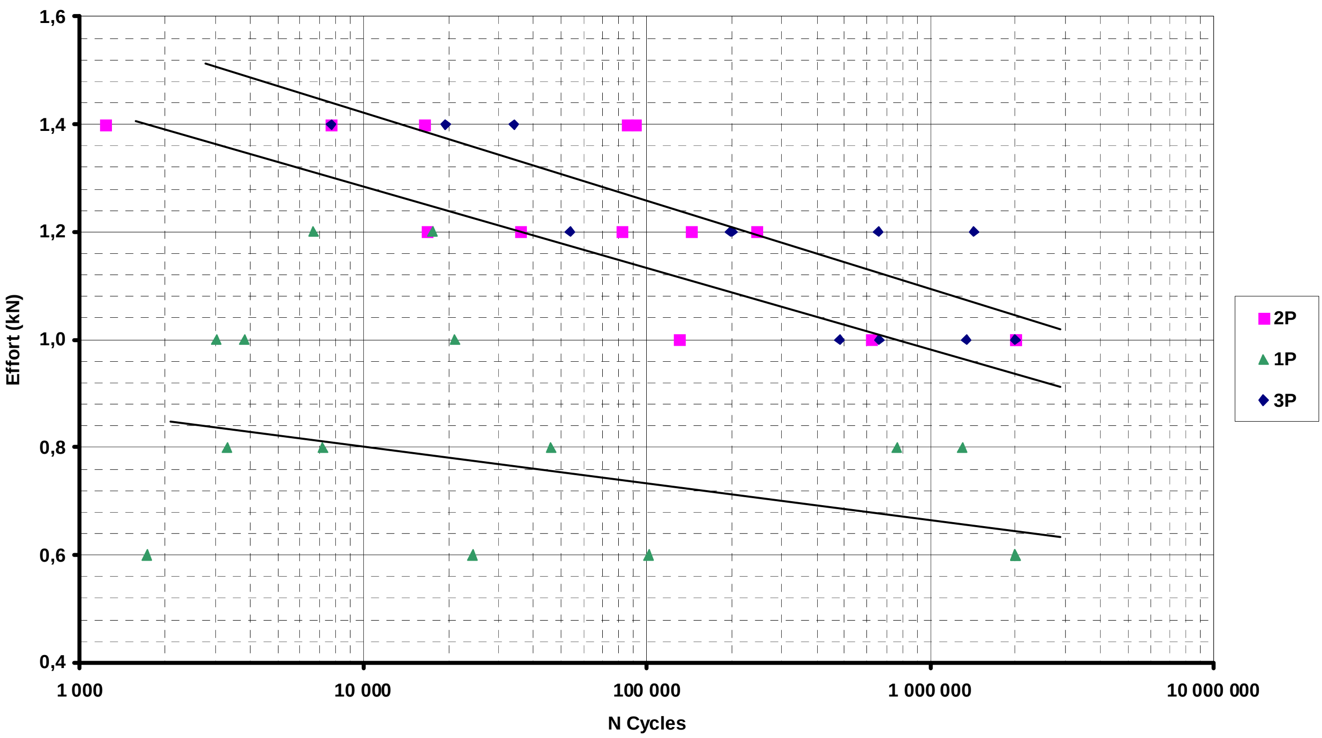


Figure 13 : S/N curves on lap shear coupons for medium and large seam compared to one line

5- CONCLUSION

First conclusions show that there are strong variations on material properties yielding to irregular welding performances. An on-line process control (temperature) is then required. The results show in addition that the material thickness has to be less than 5mm. Finally, the laser welding process is a reliable and reproducible welding tool for GFRP in PA66, provided there is an absorbing part and a transparent one. Moreover, it appears easy to automate the assembly process, the laser welding is then a very convenient process for polyamide.

Laser efficiency is confirmed from modelling as heating and thus polymer melting occurs in a localized zone at the substrates interface, where temperature gets higher than 220°C. The evaluation of the time history temperature of the welding process was made and is necessary to describe the laser welding mechanisms of the composite. Coupling with analytic equations representing the bonding mechanisms (reputation and healing), bonding quality can then be evaluated.

Regarding the mechanical behaviour, the quasi static test (Arcan Mines) show very good performances of the welded assembly, which are confirmed by fatigue tests on various welding configurations. Indeed, if a great scatter is observed in the results for one line, better performances are obtained for various lines or larger seam lines in fatigue.

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