Effect of structural parameters on mechanical behaviour of stitched sandwiches

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ABSTRACT

An idea already used in the case of monolithics was transposed on sandwich structures: to reinforce transversely the structures, addition of stitches crossing the two skins and the core is performed. The increase of the mechanical performances generated by the introduction of these reinforcements compared to a traditional sandwich is undeniable: modulus and maximum stress under bending, compression and shearing are multiplied by a considerable factor.
Beyond the improvement of the structure stiffness, the stitches reinforce adhesion between the core and the skin and thus reduce inter-laminar delaminating. Even if we consider the increase of the mass of the panels which moderates the mechanical performances (specific properties), the interest of such reinforcements is considerable.
Moreover, in this study, attention is given to the influences of the structural parameters (stitch step and angle) and the characteristics induced by the process with the various requests.
It was clearly highlighted that it is necessary to find a compromise between the structural parameters and the mass to obtain the desired mechanical performances.

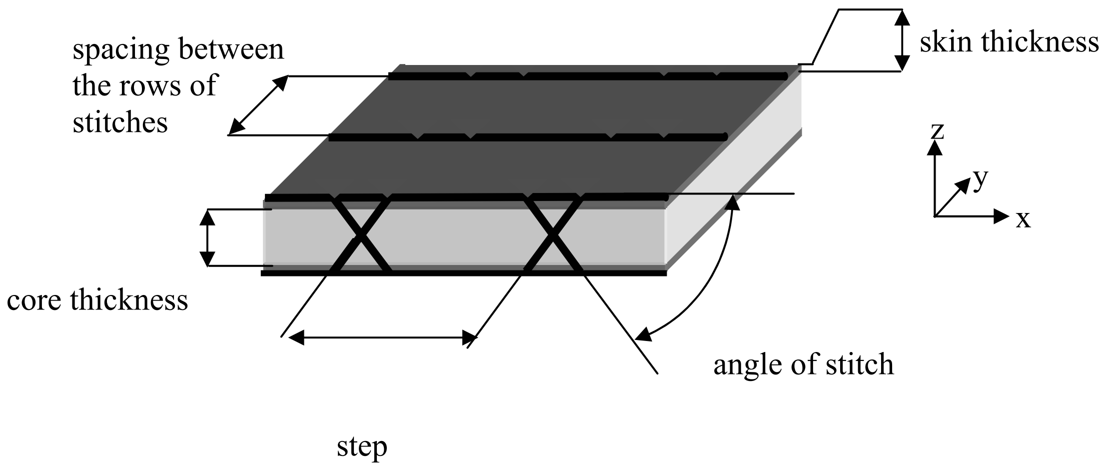
Keywords: sandwich, stitch, mechanical behaviour, structural parameters, 4 points bending, flatwise compression, core shear testing

1. INTRODUCTION

Sandwich structures are a great example of the potential offered by composite materials. The combination of two composite face sheets and a lightweight core allows to obtain a high flexural stiffness with a weak mass.
Two methods can be used to link the core and the skins. The first one, the most basic, consists in gluing skins to the core by a third component. A third entity is then added to the structure. In the second method, by using the resin injection process, the resin impregnates the armature of the skins and at the same time assures the gluing of the core.
The face sheets carry most of the tensile and compressive stress due to axial loading and bending whereas the core carries most of the shear stress. The adherence between core and skins appears therefore as the deciding factor in such a combination, especially for the inter laminar and shearing behavior.
In the case of the monolithic composite materials, the introduction of reinforcement through the thickness showed its own interest and the interest that the scientific community has for such materials [1,2,3]. A priori, the weaving of the sandwich structures should constitute a non negligible value-added for the development of these structures.
Stitching of sandwich structures has received small attention. Currently there are only a few publications [4,5,6] on the stitching of sandwich composites.
This current investigation focus on the effect of structural parameters (stitches step and angle) on mechanical behavior of such materials. A particular attention is given to the dry pre-form manufacturing and the particularities generated by this process.

2. MATERIALS PRESENTATION

A sandwich structure consists of lightweight core material bonded to two thin face sheets of stronger and stiffer material. The stitched sandwich is produced from a traditional sandwich panel by introducing rows of stitches whose role is to reinforce the link between the two face sheets and eventually increases the mechanical properties in the third direction (fig. 1).
In this paper, the material is constituted of two skins made from 2 plies of woven plain glass (440 g/m^2), a 35 kg/m^3 polyurethane foam core and the stitches composed of two 2400 Tex glass yarns.



"**Fig. 1.** Schematization of a stitched sandwich"

The total thickness of the panels, after injection of polyester resin (RTM process) is 22 mm : 20 mm core thickness and each skin has a thickness of 1 mm.
Due to the stitching process, the spacing between the rows is 25 mm and cannot be changed.
The studied parameters are the angle and the step of stitches. Table 1 shows the different panels used in this work. The stitched panel with 45° angle and 25 mm step will be used as a reference. The other panels differ from this one by only one parameter (angle or stitch density). It is also important to introduce the unstitched sandwich in order to evaluate the contribution of the stitches on mechanical behavior.

"**Table 1.** Configurations of materials"

	Stitches	
	angle	Step
unstitched	None	
stitched ref.	45°	25 mm
stitched 60°	60°	25 mm
stitched 50 mm	45°	50 mm
stitched 12,5 mm	45°	12,5 mm

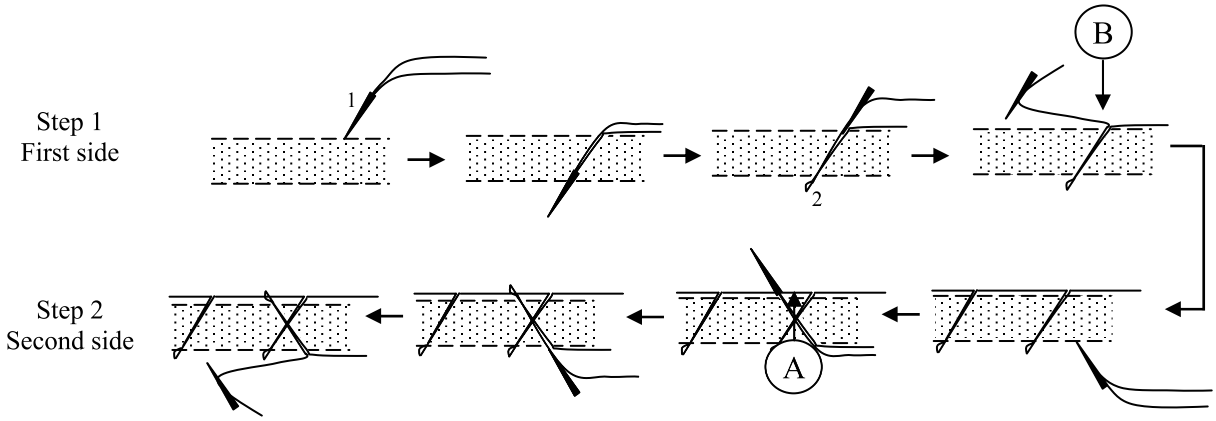
Weight is an important attribute of the sandwich structure. However, introducing stitches increases the weight of the panel as shown in table 2. The 50 mm step stitch rows increase the weight by only 11% whereas the 12,5 mm step stitches increase the weight by 50%. Such weight increase should have an important influence on the specific properties.

“**Table 2.** Areal weight of the panels compared to the unstitched"

	unstitched	**stitched ref.**	**stitched 60°**	**stitched 50 mm**	**stitched 12,5 mm**
Areal weight	100 %	117 %	111 %	111 %	150 %

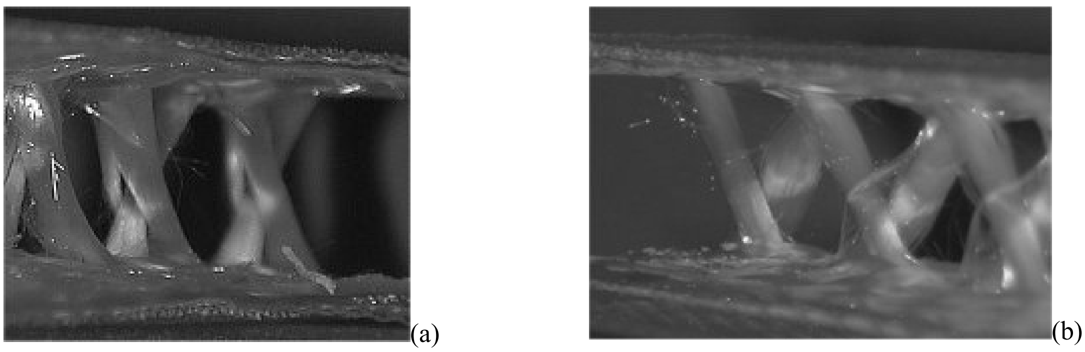
3. MANUFACTURING AND PARTICULARITIES

The stitched sandwich production needs two stages: manufacturing of the dry pre-form and resin injection. Each of this 2 stages involves particularities in the final product.
The dry pre-form is produced by Structiso society. As illustrated in fig. 2, the process needs 2 steps to obtain a good bond between the skins. The first step consists to stitch one row through the panel at the appropriate angle, and in the second step, the next adjacent row is stitched in the opposite direction.



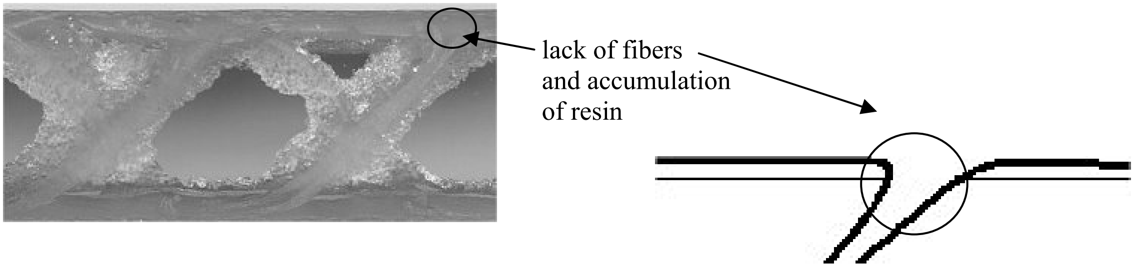
"**Fig. 2.** Stitching process"

This type of process generates a particularity at the stitches intersection (detail A on fig.2). Indeed, as shown in fig. 3, this intersection is sometimes a juxtaposition of the two yarns and sometimes an interpenetration. Note that we don’t use the term *‘defect’* but *‘particularity’* because this phenomenon is very difficult to control. In this study, we will also try to analyze the effect of this first particularity on the mechanical behavior.



"**Fig. 3.** Particularity of the stitches' intersections : interpenetrated (a) and juxtaposed (b)

The dry-pre-form is impregnated by polyester resin by using RTM process. The resin is injected at low pressure (2 bars) on upper face. The stitches act like channels and allow the out-flow of the resin towards the lower face.
As the needle is pushed through the foam core while manufacturing the pre-form, individual cells of the closed cell foam are either pierced. Locally (detail B on fig.2), the trajectory of the wick is curved, leaving free space without fiber.
These damaged cells and the lack of fibers fill with the resin during the injection process, resulting in a accumulation of resin as shown in fig. 4. This extra resin surrounding the stitch is undesirable since it increases the weight of the panel without providing significant additional reinforcement of the foam core.
This second particularity induced by the nature of manufacturing of the stitched sandwich panels, can be a source of damage initiation.



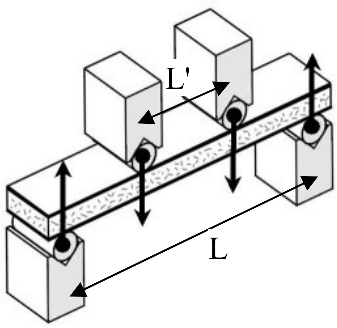
"**Fig. 4.** Zone without fiber but rich in resin within the skin"

4. MECHANICAL TESTING

To determine the effects of structural parameters (angle and step of stitches), typical mechanical tests are performed : 4 points bending test, core shear test and flatwise compression test.

4.1. Flexural testing

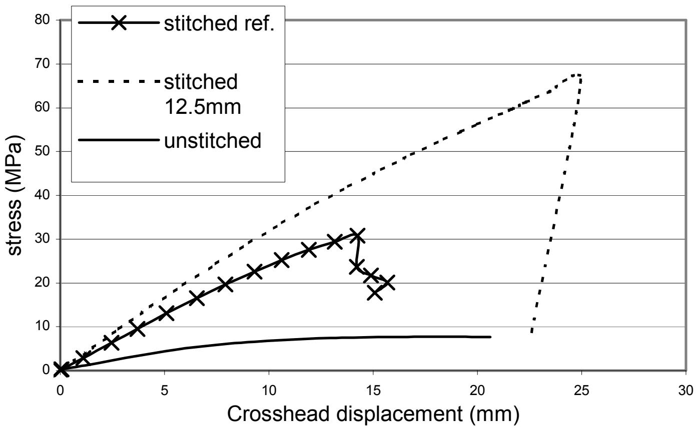
Flexural testing was carried out according to ISO standard EN 14125 shown in fig. 5.
The specimens do not require any particular preparation. Sample deflection is measured by an LVDT transducer attached directly to the specimen. This transducer allows to measure displacement up to 50 mm.



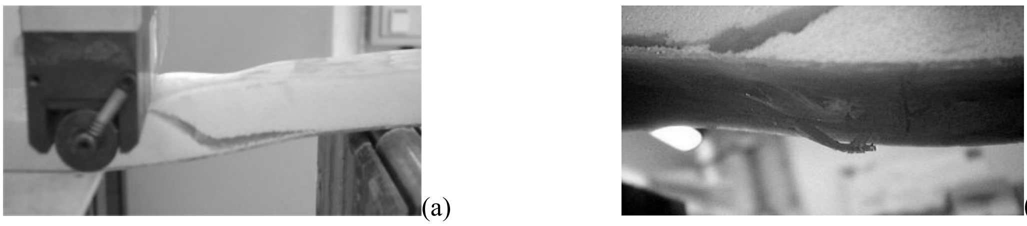
Load nose diameter : 50 mm
Span length L : 440 mm
L' = L/2= 220 mm
Sample length : 550 mm
Sample width : 50 mm
Cross head speed : 2 mm/min

"**Fig. 5.** 4 points bending test and parameters"

Fig. 6 presents a typical 4-point bending behavior. In the unstitched specimen, loading progresses smoothly up to maximum load. Because of the flexibility of the skins, there is not a clear failure. In the stitched specimen, we note a different behavior. The load progresses more quickly. The maximum load depends of the stitch density. Besides, the failure is brutal. The initial failure is located between the inner and outer loading points as shown in fig. 7.a. While the cracks extend through the thickness of the core, the upper skin waves and a local buckling appears between the stitches grappling points. At the final failure the lower skin is pierced by the stitches under the effect of the outer loading point (fig. 7.b).



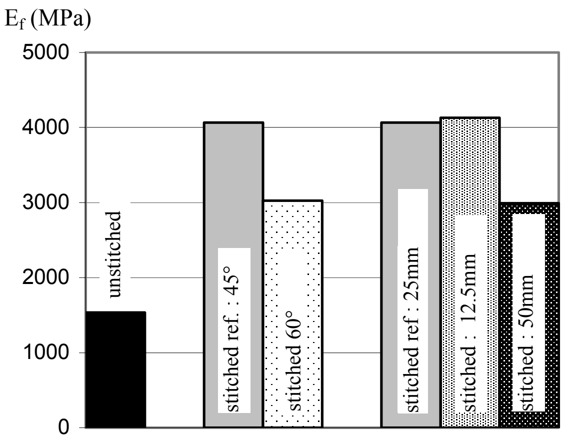
"**Fig. 6.** Typical Four-Point flexure results"

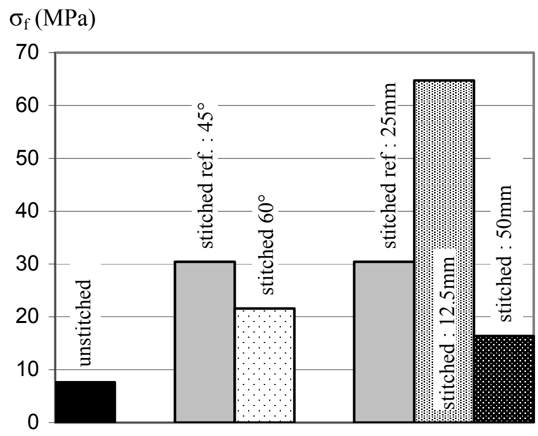


(a) (b)

"**Fig. 7.** Rupture of a stitched sandwich in 4 points bending : local buckling and inter-laminar shear (left) and piercing through the skin

The comparison of the flexural behavior is given by the fig. 8 where the influence of the angle and the step of stitches on the flexural modulus and the maximum stress is illustrated.



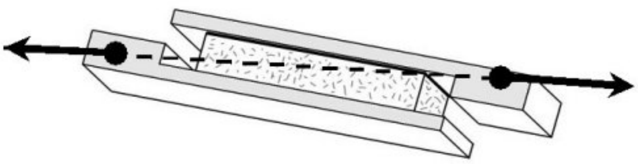


"**Fig. 8.**: influence of structural parameters on flexural properties : modulus Ef (left) and max stress σ_f (right)"

Fig. 8 shows the flexural properties. The benefit brought by the addition of the stitches is undeniable as well as in case of the modulus than in case of maximum stress. Concerning the effect of angle stitches, the 45° angle produces a larger flexural strength and stiffness than the 60° angle. The increase of the angle makes the specimen more sensitive to the inter-laminar shear.
The effect of the stitches step is better observed in the case of the maximal stress. Indeed, the value of the stress is fourth higher for a 12,5 mm stitch step than for a 50 mm stitch step. The gains of performances are less important if we compare the specific properties : a factor 2.5 appears.

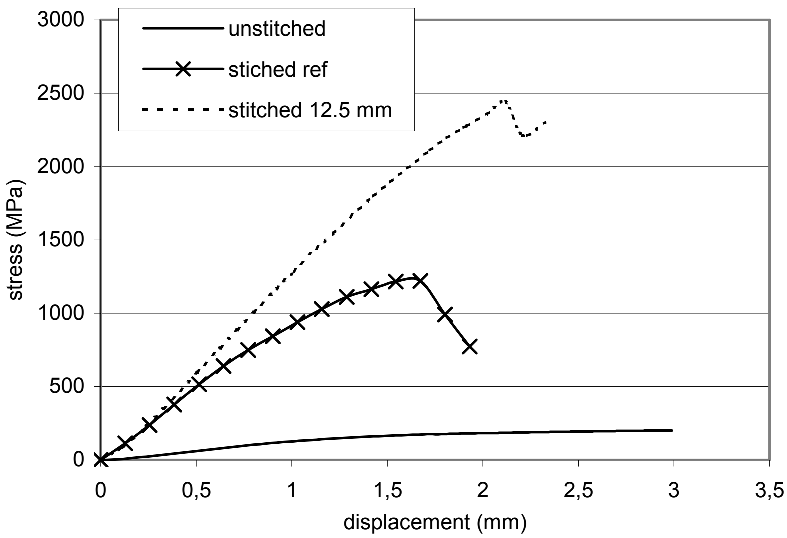
4.2. Core shear testing

The shearing tests represent a suitable manner to determine the equivalent modulus of the transverse shearing G_{xz}. Such tests are carried out according to ASTM 273-61. The specimen is glued to loading blocks with a two-component epoxy glue (araldite) that cures 24 hours at room temperature (fig.9)



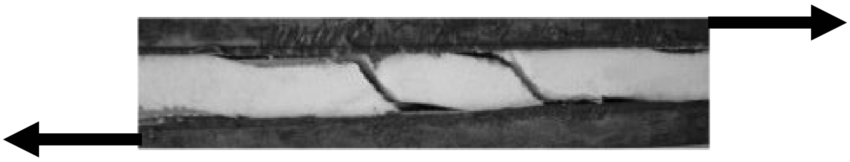
sample length : 270 mm
sample width : 75 mm
cross head speed: 2 mm/min

"**Fig. 9.** Core shear test and parameters"



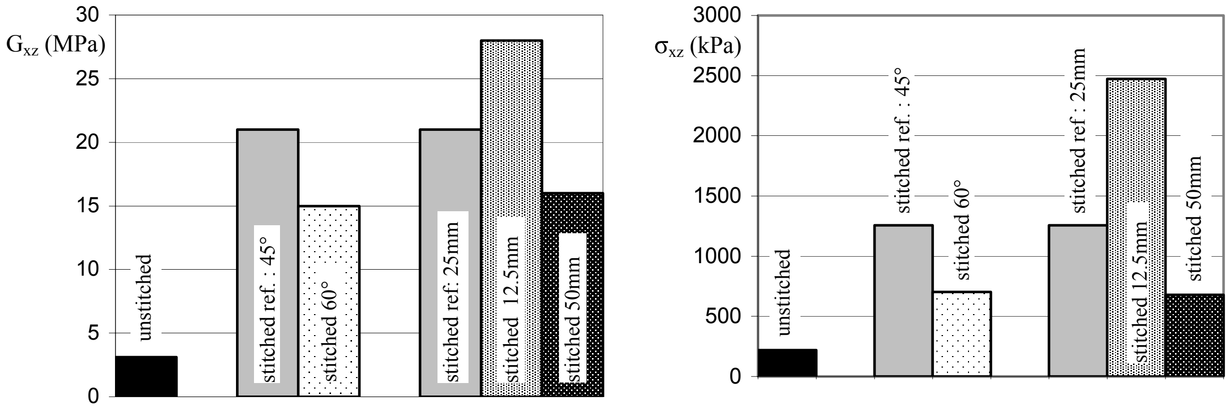
"**Fig. 10.** Typical core shear test results

Plots of stress versus cross head displacement obtained from unstitched and stitched specimens are shown on fig. 10. The effect of stitch is very perceptible. Concerning the mode of failure, there is no notable difference between the specimens. The initial failure corresponds with the occurrence of angled cracks through the foam core (fig. 11). An inspection of the failed specimens showed the failure occurred at the skin/core interface for the unstitched specimen and in the stitch thread at the core-face sheet interface in the case of the stitched specimens.



"**Fig. 11.** shear rupture for a sandwich"

In case of the Gxz modulus as in case of maximum stress, fig.12 shows the improvement and the influence of stitch angle and stitch step.

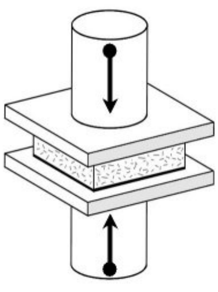


"**Fig. 12.** Influence of structural parameters on shear properties : modulus G_{xz}(left) and max stress σ_{xz} (right)"

It seems that the shear resistance is increased by stitch angle which is stretched towards the horizontal. Thus, the 45° angle specimen presents the best properties according to the effect of angle stitches on the shear properties.
Moreover, the density of stitches (step) is the major parameter : more the skins are linked, better is the behavior. Comparing the "unstitched" and the "stitched 12.5mm", the modulus is increased by a ratio of 8 and the maximum stress by a ratio of 10.

4.3. Flatwise compression testing

Flatwise compression testing was carried out according to ASTM C365 shown in fig. 13.

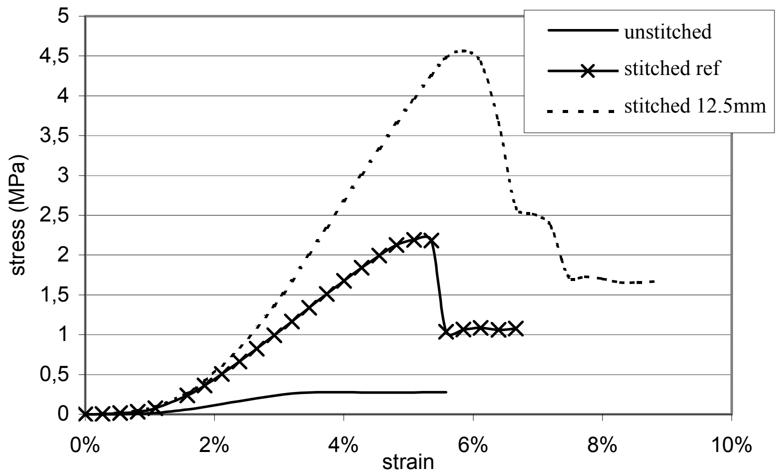


sample length : 100 mm
sample width : 100 mm
cross head speed : 2 mm/min

displacement of the plates is measured by 2 sensors diametrically opposite.

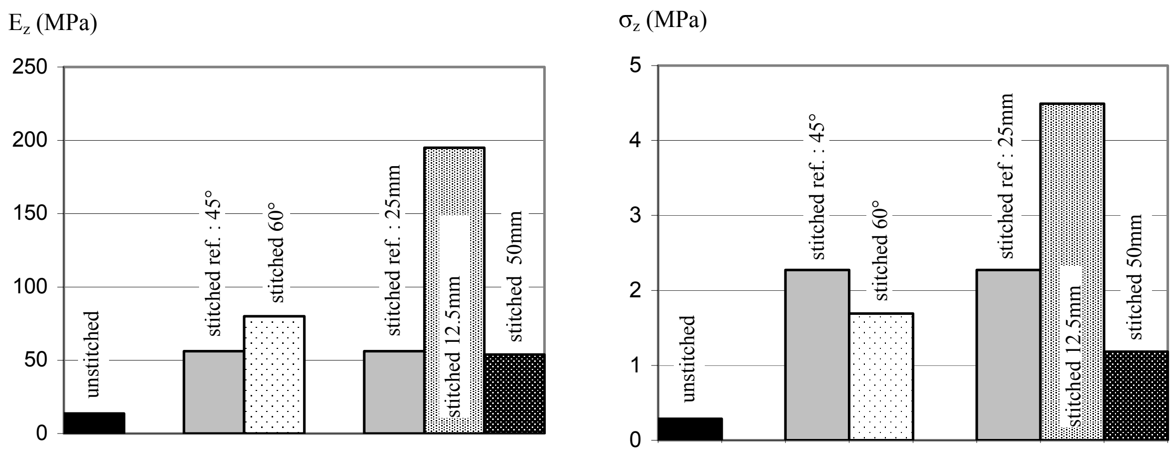
"**Fig. 13.** Flatwise compression test and parameters"

In this test, the core of the sandwich undergoes all the stresses. The skins do not undergo the effect of compression. Typical stress-strain curves are shown in fig. 14.



"**Fig. 14.** Comparison between compression behaviour in flatwise compression test"

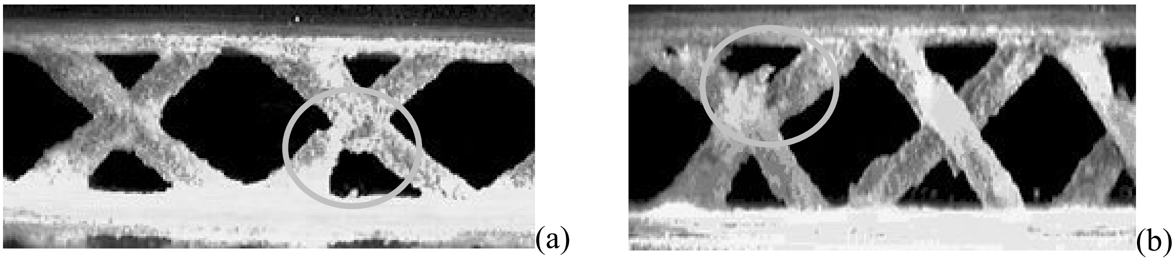
Here again, the effect of stitches is very perceptible. The mechanical properties in the third direction are improved appreciably. Fig. 15 confirms this fact and shows that the increase of the stitches density provides the best performances.
Concerning the effect of the angle stitches, the stiffness and ultimate stress are more important for the stitched specimen with the 60° angle than with the 45° angle. This result was expected considering the configuration of the test. Contrary to the previous test, the best performances are obtained when the stitches have the tendency to be vertical..
One of particularity of this test is the absence of external signs of deterioration of the sandwich after failure. All damages are internal.



"**Fig. 15.** Influence of structural parameters on compression properties : modulus E_z(left) and max stress σ_z (right)"

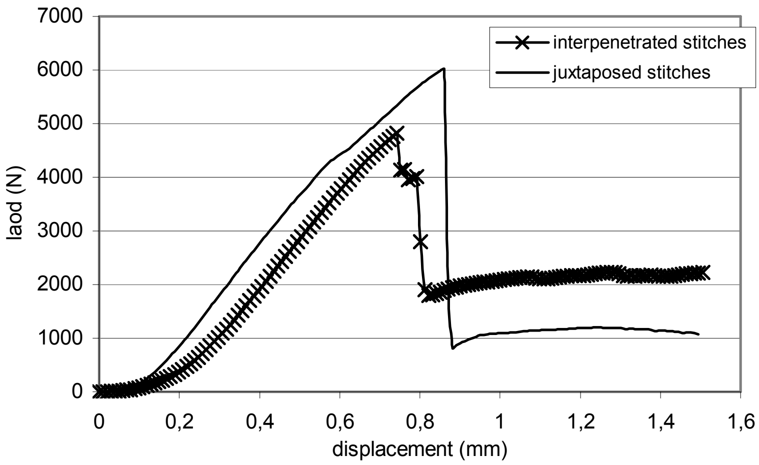
5. INFLUENCE OF A MANUFACTURING'S DEFECT

The stitching process introduces particularities as explained previously. An example of the effect of the yarn interpenetration is illustrated by the test of compression



"**Fig. 16.** Mode of rupture in compression: interpenetrated stitches (a) and juxtaposed stitches (b)"

In the juxtaposed stitches, both of the two yarns break simultaneously as shown in fig.16.b whereas in the interpenetrated stitches, the yarn which is interpenetrated is mechanically weakened, therefore it breaks precociously transferring the load on the second yarn that breaks on its turn.
This phenomenon has a consequence on the load displacement curves as shown on fig.17. Thus, even if this particularity has no effect on the stiffness, the maximum loading is 20% lower in case of interpenetrated stitches than in the other case.



"**Fig. 17.** Influence of the interpenetration of the stitches on compression behaviour"

For the study of damage initiation, a particular attention should be given to these particularities.

6. CONCLUSION

Comparatively to the unstitched sandwich panels, stitching increases significantly the stiffness and ultimate stress under bending, core shear and flatwise compression. The percentage of gain depends on the structural parameters (angle and step stitches) of the stitched sandwiches. Thus, for the high stitch density (step of 12.5 mm) the improvement of the performances can reach 250% for bending rigidity and 1000% for the shear failure stress.
It is obvious that the increase of the stitches density improves the mechanical properties considerably. On the other hand this increase leads to an increase of the mass and consequently a loss of specific properties. A compromise must be found. Such a compromise should be also found concerning the effect of the stitch angle on the mechanical properties. Thus, the 45° angle offers the best performances on the bending and shear behavior whereas the 60° angle presents the best properties on the compression behavior. The choice of structural parameters will depend on the specification of the structure. It seems therefore necessary to develop a predictive tool with the aim of helping in the decision of the choice of the materials. This topic constitutes one of the future axes of development. It will be associated to the study of damage mechanisms of the stitched sandwiches with correlation of the effect of structural parameters.

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