

ULTRASONIC WELDING OF ADVANCED THERMOPLASTIC COMPOSITES: AN INVESTIGATION ON ENERGY DIRECTING SURFACES

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SUMMARY

Research on different energy directing surfaces for ultrasonic welding of advanced thermoplastic composites was performed. Special attention was paid to the influence of the orientation of the energy directors with respect to the load direction and to multiple energy directors' configurations.

Keywords: Thermoplastic composites, processing techniques, ultrasonic welding, energy directors, mechanical testing

INTRODUCTION

Fusion bonding, also known as welding, is considered to be a technique ideally suited for joining continuous fibre reinforced thermoplastic composites (CFTPCs). It takes advantage of the main characteristic of thermoplastic resins, which is the possibility of being melted and cooled while retaining their properties. Fusion bonding eliminates the well known drawbacks of the traditional joining techniques, like stress concentration and intense labour (mechanical joining) or extensive surface preparation and long curing cycles (adhesive bonding). As a result, the possibility of assembling structures by welding adds to the numerous advantages of thermoplastic composites over thermosets, like improved toughness, better environmental resistance, shorter processing times, non-flammability and infinite shelf life.

Fusion bonding techniques are usually classified by the type of heating being used. Vast number of means can provide the interface with heat. Hot plates, hot gas, spinning, ultrasonic and radio signal, microwaves, joule effect in a resistor, laser and induction are some of them [1]. From the variety of techniques, three are traditionally regarded as the most promising for CFTPCs: induction, ultrasonic and resistance welding.

Ultrasonic welding, unlike the two other welding techniques, belongs to the group of friction welding techniques. The principle of heat generation is thus based on the conversion of high-frequency mechanical vibrations into heat through combined contact-surface and intermolecular friction. The major advantages offered by ultrasonic welding are extremely short welding times, ease of automation, and excellent quality. Likewise, ultrasonic welding does not require the use of any foreign material in the joint like the

resistive inserts used for resistance welding. However, in order to concentrate ultrasonic heating at the welding interface, energy directors (EDs), i.e. man-made asperities in the form of resin protrusions, are required on the surfaces to be welded. Energy directors play an important role in the welding process and their morphology, size and configuration affect the quality of the resulting welds [2, 3].

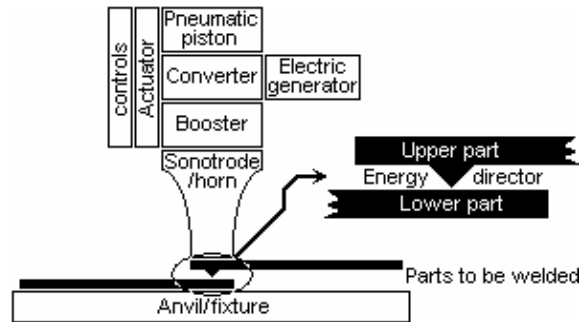


Figure 1. Ultrasonic welding set-up

The process of ultrasonic welding of thermoplastic polymers was extensively investigated in the last decades. Rather large number of mostly experimental studies performed provided good insight into the nature of the process. Comparatively limited research has been performed on ultrasonic welding of CFTPCs. Benatar and Gutowski introduced ultrasonic welding of advanced fibre reinforced thermoplastic composites [4]. They characterized and modelled ultrasonic welding as a complex process consisting of five distinct, highly coupled sub processes: (i) mechanics and vibration of the parts; (ii) viscoelastic heating of the thermoplastic resin; (iii) heat transfer; (iv) flow and wetting and (v) intermolecular diffusion. Due to the difficulties related to applying energy directors on sheet components, the possibility of welding CFTPCs without energy directors was investigated by several researchers [5, 6]. Liu et al. performed an experimental study, based on the Taguchi method, on the factors influencing the weld strength of thermoplastic composites [2]. They also investigated the influence of the shape of the energy director on the performance of the weld.

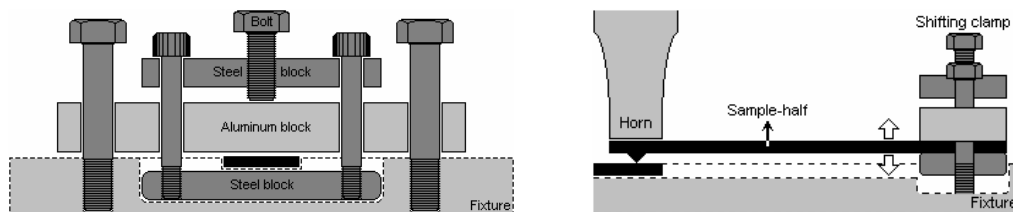


Figure 2. Design of the shifting clamp

This paper presents an experimental study on the influence of several configurations of energy directors in the quality and the mechanical performance of the weld. In first place, the effect of the direction of the energy director with respect to the load direction was investigated. Secondly, attention was paid to the effect of the size and distribution of multiple energy directors.

EQUIPMENT, SAMPLES AND EXPERIMENTAL PROCEDURE

Welding set-up

The welding set-up used in this study is schematically shown in Figure 1. The power supply, denoted as “electric generator” in Figure 1, transforms the main line electric current into controlled high frequency current. The generator output frequency (typically between 20 and 40 kHz) determines the operating frequency of the entire welding system. The piezoelectric converter, or transducer, converts the electrical signal into mechanical vibrations. To transfer the mechanical vibrations (ultrasonic waves) to the work piece, the transducer is connected to the horn (also called sonotrode), which is placed at right angles in contact with the part to be welded. The shape of the horn, i.e. its mass distribution with respect to the nodal plane determines its ratio of amplification. In order to vary the amplitude of vibration without reshaping the horn, a booster is usually placed between the transducer and the horn. The product of the amplification ratios of the booster and the horn provides the amplification ratio of the system.

The support collar of the transducer-booster-horn system is attached to a pneumatic piston that provides the vertical movement of the system along with the static force applied through the horn to the work piece (welding force). Finally, the welding fixture or anvil provides support and positioning of the parts to be welded and avoids unwanted shifting during the welding process.

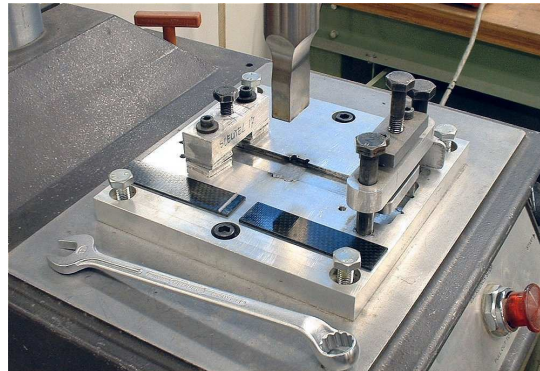


Figure 3. Actual welding fixture and shifting clamp

An enhanced 1000 W Branson 8200 ultrasonic welder with an output frequency of 20 kHz was used in this study. An aluminium booster with 1:1 gain together with a horn specifically designed for welding standard lap shear (LS) specimens provided the required amplitude. The samples were welded in near field.

Welding fixture

A specific aluminium fixture with a so-called shifting clamp was designed for positioning the LS specimens to be welded. The fixture provided perfect positioning and alignment of the specimens and prevented them from shifting during appliance of ultrasonic vibration. The design of the shifting clamp is schematically shown in Figure 2. The upper specimen was clamped between the aluminium and steel blocks using the middle bolt. Any

movement of the specimen on a horizontal plane was thus avoided, while it could still move as a rigid solid in the vertical direction (together with the aluminium and steel blocks). Therefore, the samples could be welded with minimum bending in the upper specimen due to melting of the energy director. The actual fixture with the shifting clamp is shown in Figure 3.

Materials and samples manufacturing

The material used in this study was continuous carbon fibre reinforced polyetherimide (CF/PEI). The prepregged material, supplied by Ten Cate Advanced Composites, the Netherlands, had a 5-harness satin weave configuration and 42.4% wt. resin content. Six-ply laminates, with dimensions of 500 x 500 mm, were consolidated in a hot platen press. The stacks of prepregged material were placed between two aluminium plates, coated with release agent prior to every pressing cycle. The laminates were compression moulded at 320°C and 1.0 MPa. Preheating time was 35 min and consolidation time, 15 min. The laminates were subsequently cooled down to 170°C while the consolidation pressure was maintained. The final thickness of the laminates was 2 mm.

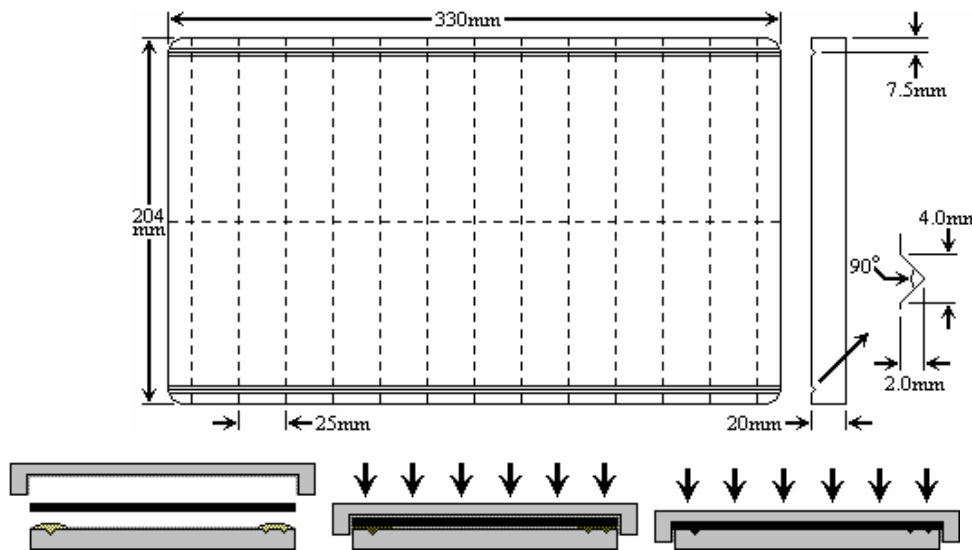


Figure 4. Mould design and procedure for applying the energy directors

In order to apply the energy directors on the contact surfaces of the specimens, specific moulds were designed and manufactured. Laminates with dimensions 320 x 205 mm were cut from the consolidated plates and placed in these moulds. A typical mould design and the procedure for applying the EDs are depicted in Figure 4. The grooves carved in one of the sides of each mould (one different mould for each ED configuration tested) were filled with PEI powder prior to situating the laminate. The closed mould was subsequently placed in the hot platen press and the consolidation procedure was repeated with a consolidation time of 5 minutes. Finally, 25.4 x 101.6 samples were sawed from the resulting laminates.

Experimental procedure

Standardized lap shear specimens with a number of differently sized and oriented energy directors were used in this study. The specimen geometry is schematically shown in Figure 5. Based on previous experience, a basic energy director was defined. The basic energy director (denoted T_1) had a triangular shape with a 90° angle at its top, base of 4 mm, height of 2 mm and length of 25.4 mm, equal to the width of the samples to be welded. As depicted in Figure 5, it is a single energy director placed transversal to the test load and located at the middle of the overlap. The length of the overlap was defined to be 15 mm in this study. All the different configurations of energy directors under investigation were derived from T_1 .

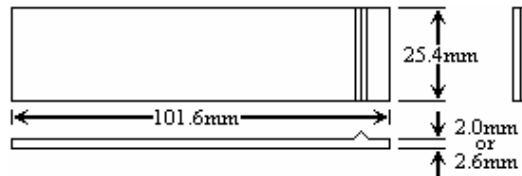


Figure 5. Standard lap shear sample with basic energy director

All the welds were performed under the same welding conditions. The welding time was 3.5 sec, the hold time was set at 3.0 sec and the welding pressure was 4 MPa. The peak-to-peak amplitude of vibration was $50\mu\text{m}$. The influence of the energy director on the strength and the quality of the weld was investigated from two different points of view.

Firstly, the influence of the orientation of the energy director was studied. The standard T_1 energy director was compared with two combinations of energy directors parallel to the direction of the test load, a single parallel energy director, denoted as P_1 , and a double parallel energy director, denoted as $2P_{1/2}$ (Figure 6). The sizes of the parallel energy directors were determined so that the amount of resin available at the welding interface was equal for each configuration.

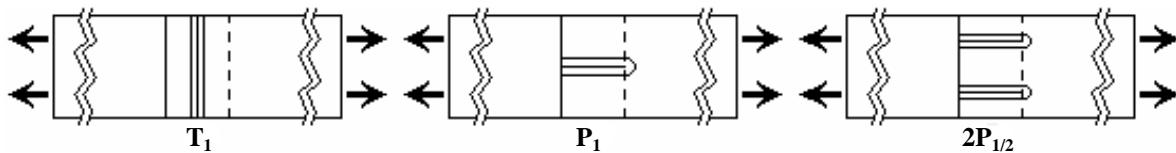


Figure 6. Energy directors with different orientations

Secondly, the influence of multiple transverse energy directors was investigated. Four different types of energy directing surfaces were analyzed and compared to the basic T_1 configuration. The main characteristics of these configurations are displayed in Table 1. Subscripts 1, $\frac{1}{2}$ and $\frac{1}{4}$ are directly related to the size of the basic energy director. Therefore, the cross-section areas of $T_{1/2}$ and $T_{1/4}$ energy directors are, respectively, 0.5 and 0.25 times that of the basic T_1 energy director. As it can be seen in Table 1, the overlap length of the T_1/T_1 configuration was increased to 22.5 mm in order to keep a distance of 7.5 mm between the T_1 upper and lower energy directors.

Mechanical lap-shear strength (LSS) testing, visual and microscope observation were used to evaluate the quality of the welds. In absence of a specific standard test method for

welded specimens, the tests were performed according to ASTM D 3163-01, developed for adhesive bonds in rigid plastics. Eight to fifteen samples were welded per type of energy directing surface. The welds and the tests were performed under standard conditions, i.e. 21°C and 50% relative humidity.

Table 1. Different configurations of transverse energy directors

Configuration	Resin volume (compared to T ₁)	Overlap length (mm)
2T _{1/4} /T _{1/2}	1.0	15.0
2T _{1/4}	0.5	15.0
T _{1/2}	0.5	15.0
T ₁ /T ₁	2.0	22.5

Visual observation of the fracture surfaces provided certain information about the quality of the weld. Two modes of failure were primarily experienced during LS testing: interlaminar and interfacial failure. Failure was considered as interlaminar when it occurred within the bulk structure of the material, with a visible fibre pull-out from the specimens. This type of failure usually leads to the highest LSS values, implying by that the best weld quality. Interfacial failure occurs at the interface between the laminate and the energy director and yields lower LSS values, pointing to insufficient bonding. The amount of welded area was also measured on the fracture surfaces.

RESULTS AND DISCUSSION

Orientation of the energy director

As mentioned earlier, three types of energy directors were tested; the basic transverse energy director, T₁, was compared with the single parallel, P₁, and with the double parallel, 2P_{1/2} (Figure 6). Twelve specimens were welded for each energy director type. Figure 7 shows the results in terms of LSS and amount of welded area. Due to the differences in the welded area, two LSS values were obtained for each type of energy director: LSS1, calculated as the maximum load yielded by the joint divided by the whole overlap area; and LSS2, calculated as the maximum load divided by only the welded area. Therefore, LSS1 quantifies the effectiveness of the overall joint, while LSS2 gives an idea about the local quality of the weld and can be correlated with the failure mode.

Figure 7a shows that the average amount of welded area is around 90% of the total overlap area for configurations T₁ and 2P_{1/2}, while for P₁ decreases to approximately 80%. Therefore, the distribution of molten resin from the energy director to the welding area during the initial stages of the welding process is more effective in the case of the single transverse ED than in the case of the single parallel ED. This result is consistent with the fact that for the single transversal ED the resin needs to flow sideways to cover up to 7.5 mm (half the overlap length) on both sides of its centre line. In the case of the single parallel ED, the

resin needs to flow, however, to cover up to 12.7 mm (half the width of the sample) on both sides of its centre line. Consequently, the distribution of resin within the overlap is enhanced when two parallel EDs are used instead of just one, as indicated by the results in Figure 7a. It is important to notice also in this figure that the scatter in the welded area for the two solutions involving parallel energy directors is quite big as compared to that of the transverse ED. This phenomenon could be explained taking into account that melting of the energy directors results from the combination of the ultrasonic vibration and the pressure (strain) applied to them [6]. When the transverse T_1 energy director is used, the longest side of the quite slender sonotrode completely rests on the ED. That is not the case, however, when using the parallel ED configurations. As a result, differences in the actual pressure applied on the EDs, and thus in their melting scheme, are more likely to occur when a parallel ED configuration, and then a smaller support for the sonotrode, is used.

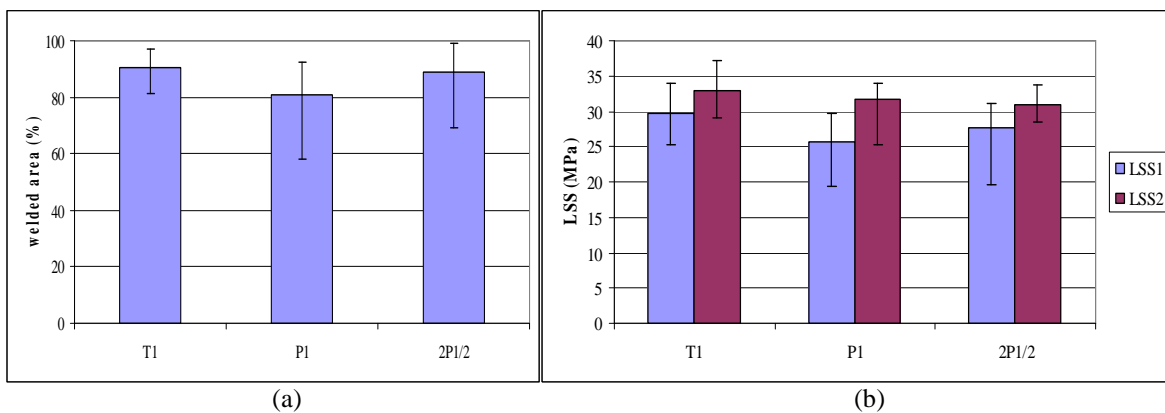


Figure 7. Results for T_1 , P_1 and $2P_{1/2}$ configurations in terms of (a) welded area and (b) lap shear strength

Figure 7b shows quite similar LSS2 values for the three configurations, which indicate comparable quality of the welds. Fracture surfaces also support this observation showing interlaminar failure in the majority of the samples. However, the relatively high scatter of the LSS2 values (around 8% of the average value in all the three configurations) does not allow concluding that parallel and transverse EDs result in welds with the exact same nature. In particular, these results do not confront nor prove the findings of other researchers about a molecular alignment transverse to the direction of the test load (parallel EDs) resulting in decreased strength of the joint [6]. As for the LSS1 values also depicted in Figure 7b, a decrease in the lap shear strength of the P_1 joints caused by a decreased welded area can be observed. Due to the also high scatter in the amount of welded area, the scatter of the LSS1 values is even higher than that of the LSS2 values (9% of average LSS1 for the T_1 configuration and 14% for the P_1 and $2P_{1/2}$ configuration).

Multiple energy directors

Four different configurations with transverse energy directors were tested: $2T_{1/4}/T_{1/2}$, $T_{1/2}$, $2T_{1/4}$, and T_1/T_1 . The first one had the same volume of resin as T_1 configuration, the second and the third had half that volume and the fourth had twice the volume of T_1 . Fifteen samples

were welded and tested for the first configuration, while 8 samples were welded and tested for each of the second, third and fourth configurations.

Figure 8 summarizes the results obtained for these samples. Figure 8a shows again how multiple energy directors contribute to increase the amount of welded area. This stands clear from the fact that the $T_{1/2}$ configuration yields a welded area of only 77% of the whole overlap area, while by splitting that single ED in two ($2T_{1/4}$) the coverage of the overlap area rises up to 90%. Such an effect is not observed, though, when comparing the T_1 and $2T_{1/4}/T_{1/2}$ configurations, which is believed to be caused by the fact that, in order to maintain an overlap length of 15 mm, the distance between the multiple energy directors in the $2T_{1/4}/T_{1/2}$ configuration was so small that hindered the flow of the molten material.

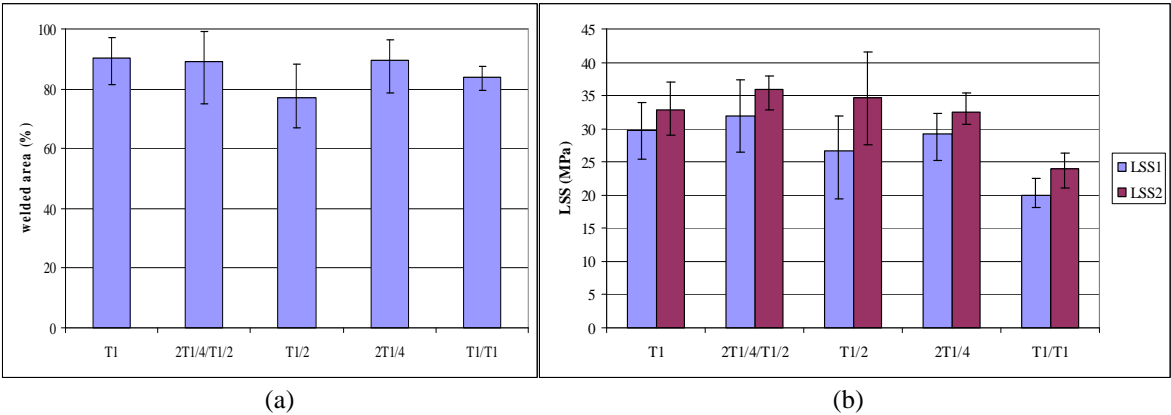


Figure 8. Results for T_1 , $2T_{1/4}/T_{1/2}$, $T_{1/2}$, $2T_{1/4}$, and T_1/T_1 ED configurations in terms of (a) welded area and (b) lap shear strength

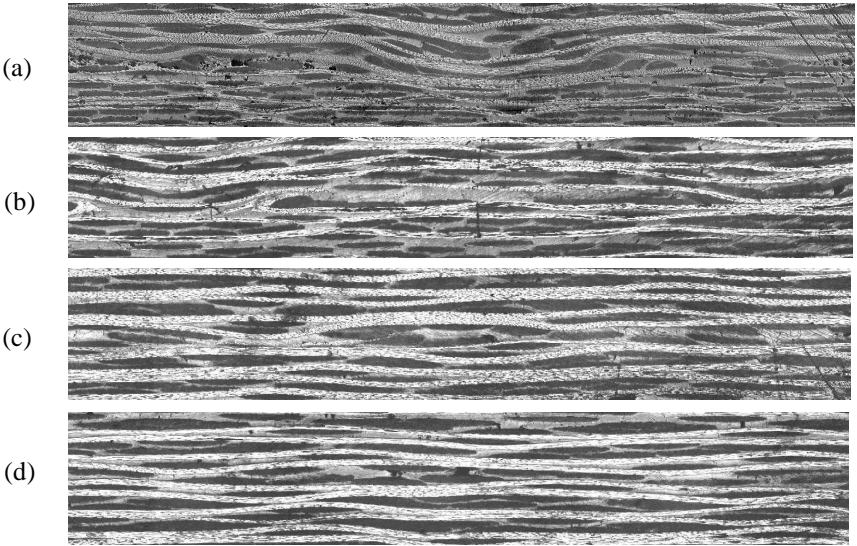


Figure 9. Cross-sections of welds with different ED configurations (from top to bottom): P_1 , $2P_{1/2}$, $T_{1/2}/T_{1/2}$ and $2T_{1/4}/T_{1/2}$

The LSS2 values for all the configurations tested are between 32 and 36 MPa except that of the T_1/T_1 configuration, which is only 23.90 MPa. An explanation for this can be found in

the failure mode of the samples. Most of the samples of the T_1/T_1 configuration showed an interfacial fracture mode and extensive flash of molten resin, indicating that the amount of resin material to form the joint was excessive. The majority of the samples belonging to the rest of the groups showed, however, an interlaminar type of failure. The highest LSS1 and LSS2 values were yielded by $2T_{1/4}/T_{1/2}$ EDs, although the relatively high scatter in all the results does not allow drawing any general conclusions about this behaviour.

Apart from a potential improvement of the coverage of the overlap area, there is a clear advantage in using multiple energy directors that derives from the decreased pressure at their tips and leads to reduced disturbance of the fibres in the outermost layers of the welded parts. This effect is clearly visible in Figure 9, where microscopic images of four samples welded with different ED configurations are shown. Fibres are clearly disrupted when using a single ED (Figure 9a for P_1 configuration) and the result is undoubtedly improved when gradually increasing the number of EDs (Figures 9b and c for a two-ED configuration and Figure 9d for a three-ED configuration).

Table 2. Recent results on ultrasonic welding of C/PEI samples

Apparent fibre orientation	Welded area (%)	Average LSS1 (MPa)	Standard deviation (MPa) [%]
Parallel to load direction	100	40.10	0.57 [1.43]
Transverse to load direction --	100	31.14	1.24 [3.97]

Recent work carried out at the TU Delft on multiple ED configurations has shown that by further increasing the number of EDs it is possible to weld the whole overlap area in a highly repeatable fashion. Likewise, it has been shown that the scatter of the LSS values can be drastically reduced by taking into account the apparent orientation of the fibres on the surfaces to be welded. Five-harness satin is not a plain weave fabric, which means that, although the distribution of the fibres in the 0° and 90° directions is balanced (50:50), the apparent primary orientation of the fibres is 0° on one of the sides and 90° on the other side of a single ply. Due to the type of fracture experienced by the strongest welds (part of the surface layers being ripped off and getting stuck to the other sample), the apparent orientation of the fibres on the surfaces to be welded plays a key role because determines the number of fibre bundles that need to be severed as a result of the fracture process, as shown in Figure 10. The results obtained are listed in Table 2.

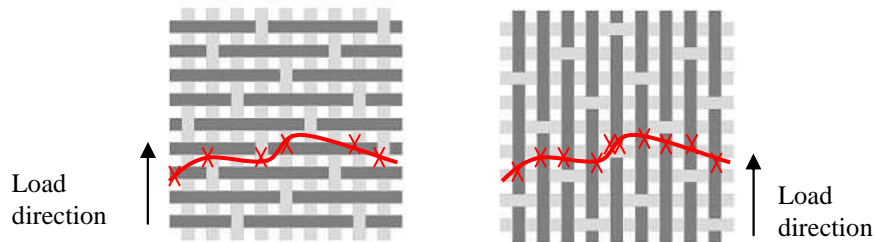


Figure 10. Fibre bundles that need to be severed (X) to rip off a certain patch of material when the apparent orientation of the fibres is transverse (left) and parallel (right) to the load direction

The values listed in Table 2 and the fact that the samples used for obtaining the results displayed in Figures 7 and 8 were cut with the surface apparent fibre orientation either parallel or transverse to the load direction, and used randomly for constructing the LS

samples, explains the generalized big scatter in the LSS2 values. Likewise, the also high scatter in the welding area also accounts for the elevated scatter in the LSS1 values.

CONCLUSIONS

An experimental study on the influence of the geometry and configuration of the energy director(s) in the quality of the weld was presented in this paper. Its impact was investigated from two different points of view: the orientation of the energy director(s) with respect to the direction of the load and the size and distribution of multiple energy directors.

The main conclusions that can be drawn from this study are the following:

- The coverage of the overlap area can be enhanced when using multiple energy directors, provided that their location and size do not hinder the flow of resin.
- Multiple energy directors significantly reduce the disturbance of the fibres in the outermost layers of the welded parts.
- Transverse energy directors provide less scatter in the amount of welded area than parallel energy director configurations.
- An excessive amount of resin at the welding interface leads to decreased strength of the weld. There is, however, a wide range of resin volumes for which welds with a satisfactory strength level can be obtained.

Very few conclusions could be obtained about the effect of the different configurations of energy directors in the mechanical properties of the welds due to a generalized high scatter in the results. Recent results indicate a direct relation of such a lack of consistency with a random usage of samples with 0° and 90° apparent surface fibre orientations to produce the welded samples.

ACKNOWLEDGEMENTS

The authors would like to thank Ten Cate Advanced Composites, Airtech International and INTA for their support in this research work. They would also like to thank F.P. Bouwman, B.J. Weteringe and V. Palardy for their valuable contributions to this work.

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