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Alternatives for a hand lay-up composite structure: E-glass/epoxy adhesive joint or tapered laminate

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Open contact molding processes in one-sided molds, such as spray-up or hand lay-up, are still the most commonly used processes for manufacturing fiberglass composite products. In this way, structures with good load-bearing capability are usually obtained, although defects may be also present in the laminate, often including non-uniform impregnation and insufficient dimensional control. In cases when these defects have a reduced impact on the performance of the composite obtained, the low cost of manufacturing justifies the use of an open contact molding process. In adhesive joints, additional factors, such as adhesive characteristics, may also affect load-bearing capability. Some adhesives provide an efficient bonding only when their thickness is small [1], while in some cases joint strength increases only until an optimal adhesive thickness or a limit length is reached [2]. Adhesive defects, often detrimental of the joint performance, may present a varied morphology, including porosity, air trapping and presence of pollutants [3].

The application of a geometry alternative to adhesive joints may also be considered to resolve the discontinuity e.g., the use of tapered laminates, formed by dropping off some of the plies at discrete positions over the laminate. Promising characteristics of tapered laminates are structural tailoring capabilities, damage tolerance, and potential for creating significant weight savings in engineering applications [4]. However, stress concentration at drop-offs may lead to delamination in the resin rich areas present at drop-offs edges, often referred to as "resin pockets". This problem is likely to be even more influential in case of manufacturing using open contact molding processes [5]. As a consequence, design of tapered laminates is usually carried with conservative rules, since the influence of the structural parameters on laminate mechanical performance is not fully known [6]. Among parameters affecting the strength of the laminate are the distance between successive drop-offs (stagger distance) and the lay-up of the dropped sub-laminate [7].

In this paper, two alternative geometries have been initially considered for the manufacture of a 6-mm thick component by hand lay-up stacking of an E-glass-epoxy twill-weave laminate, with 50(±1) wt% glass fiber content (fabric weight 1700 g/m^2). In the first case, two 3-plies laminates were bonded together using modified epoxy adhesive, using sand paper for surface preparation and compressing the adherents at 60 °C during the cure cycle. In the second case, a tapered laminate was produced from a 5-plies laminate, introducing drop-offs on both sides of the outer ply, covering then the laminate with an additional ply. In this way, a slope angle of 7 ° was created between the surface of the laminate and the covering ply, with a stagger distance of approximately 10 mm on each side (see Fig. 1).

A first difficulty arises in comparing the performance of the two different geometries. From a practical point of view, the ultimate strength of the two configurations, when loaded in tension, can provide a first indication for the comparison. Ultimate strength has been determined on the joints by performing lap shear tests, according to ASTM D3163 standard, while on tapered laminates tensile tests have been carried out, according to ASTM D3039 standard, measuring stress in correspondence of maximum section. The obtained ultimate stress was 12.4 (±0.6) MPa for adhesive joints and 13.6 (±0.9) MPa for tapered laminates.

In is worthy also to note that the ultimate strength values obtained yielded only an "apparent" joint strength, albeit useful for structure performance evaluation. The reason for this is that lap-shear failure was in the majority of cases accompanied by extensive plastic deformation in the adherents, which should ideally also accounted for [8]. In addition, 30% of the joints showed cohesive fracture, originated by the cracking of the adhesive layer due to excessive plastic deformation.

In contrast, low-angle tapered laminates are usually less prone to fail by the combined effect of gripping pressure, shear and tensile stress, showing in contrast a quasi-pure tensile fracture [9]. In practice, in the totality of tapered laminates tested, the high stress concentrations, typical of resin-rich areas, originated tensile failure in correspondence of resin pockets. This type of failure was accompanied in 20% of the tapered laminates by fiber cracking in proximity of the covering ply edge.

Three-point bending tests were also carried out on the two configurations, according to ASTM D790 standard, using a span 60 cm on specimens 150 cm long.

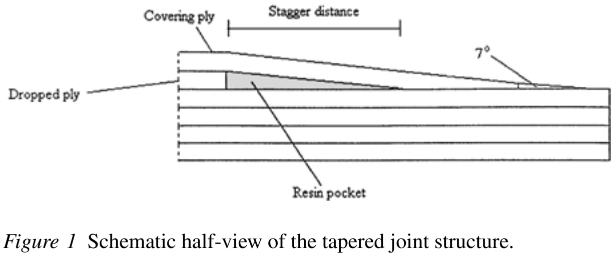

Figure 1 Schematic half-view of the tapered joint structure.

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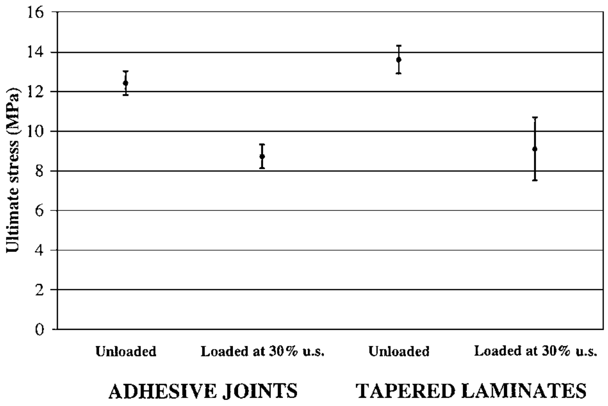


Figure 2 Tensile properties (initial and residual) of both structures.

It has been possible to determine the flexural strength of the structures, because both failed within the 5% strain limit, as prescribed in ASTM D790 standard. The stress was again measured in correspondence to the thicker section of both configurations. In the particular case of the adhesive joints, carrying out flexural tests was only justified by the need to provide a comparison of the two structures, when a load orthogonal to the interfaces is applied. Quite obviously, adhesive joints bending failure occurred by fracture of the composite and not by pure cracking of the adhesive. Values of 720 (±40) MPa and 650 (±50) MPa were obtained for the adhesive joints and the tapered laminates respectively.

The values of tensile ultimate stress obtained for the two configurations were also used to carry out a progressive loading procedure: 30% ultimate stress (u.s.)-zero-50% u.s.-zero-70% u.s.-zero on ten joints per configuration. During this sequence, acoustic emission (AE) was continuously monitored. The AE system employed was a PAC MISTRAS with a pass-band 100–300 kHz filter. An AE sensor was applied in acquisition, positioned on the geometrical center of the structure.

TABLE I Average felicity ratio

Previously attained stress	Adhesive joints	Tapered laminates
30% u.s.	1	0.96
50% u.s.	0.9	0.87
70% u.s.	0.71	0.68

Two guard sensors were also employed and disposed on the grips at a distance of approximately 100 mm at both sides of the joint, so as to exclude signals detected first by the guards.

AE monitoring allowed Felicity ratio measurement to qualify damage accumulation before propagation of delamination [10]. Experimental criteria were used to enable Felicity ratio measurement, stating that acoustic emission was considered to be *active*, whenever a counts rate (counts/second) of more than 15, including more than 10 hits is detected in a continuous period of 10 s [11]. Felicity ratio F was measured by Equation 1:

$$F = \frac{\sigma_{nAE}}{\sigma_o} \tag{1}$$

where F = Felicity ratio, σ_{nAE} = stress for AE resuming during repeated loading, σ_o = stress reached in the previous loading.

A Felicity ratio lower than 0.9 is normally considered an indication of significant damage taking place in the composite [12]. It may be inferred therefore from results in Table I that loading at 70% of ultimate stress generates not negligible degradation of the properties of both structures. However, a significant decrease, not lower than 25%, of residual properties after a first loading at 30% of ultimate stress, can be observed from data in Fig. 2. This may suggest the presence of internal damage in the plies at very low stress, albeit not related to the presence of delamination, shown by Felicity ratio only for loads exceeding 70% of ultimate stress.

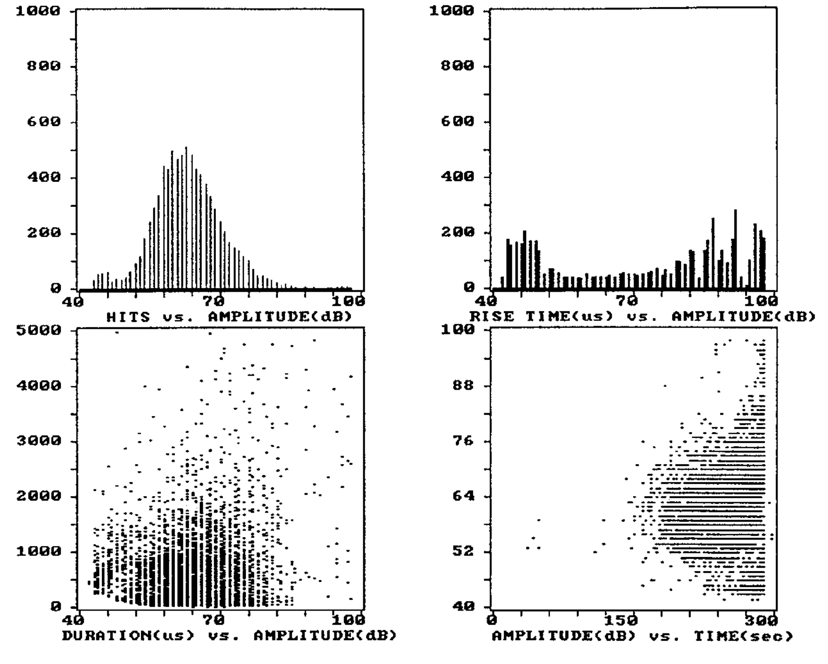


Figure 3 AE diagrams for adhesive joint showing an adhesive fracture.

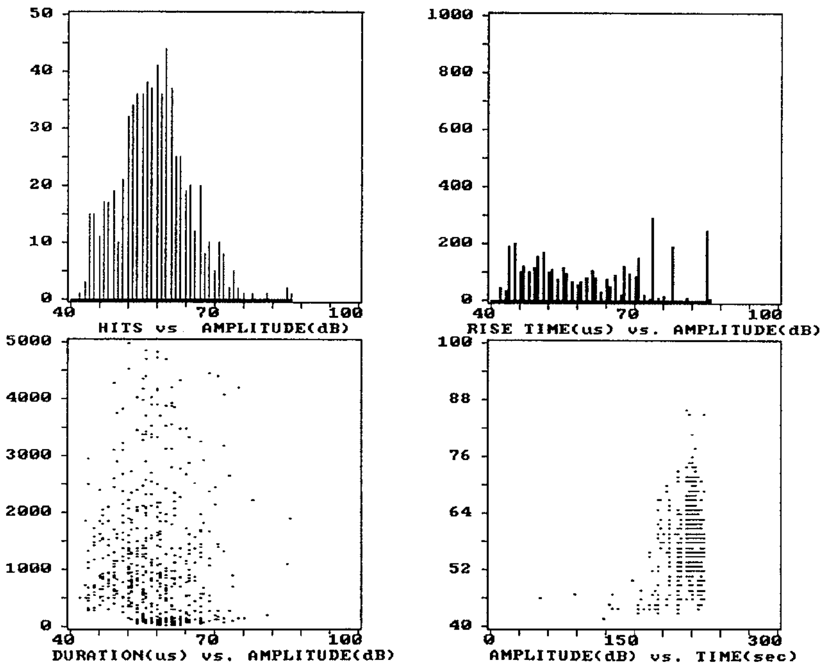


Figure 4 AE diagrams for adhesive joint showing a cohesive fracture.

From an analysis of the amplitude of the acoustic emission signals detected during final loading to failure, it was also possible to individuate distinctive patterns for the cases of “ideal” failure, not involving cohesive fracture in the joints or damage at covering ply edge in the laminates. Amplitude distribution of the acoustic emission signals is shown in Figs 3 and 4 (adhesive joints) and 5 and 6 (tapered laminates). Fig. 3 is referred to a joint showing adhesive fracture on the whole surface, while Fig. 4 is referred to a mixed adhesive-cohesive fracture case. It is possible to note a prevalence of higher amplitude (even exceeding 90 dB) events in the former case, while in the latter the presence of delamination was suggested by medium amplitude (50–70 dB) and high duration events. In the same way, Fig. 5 is referred to a tapered laminate showing a fracture purely located in the resin pockets, while Fig. 6 is referred to a case involving also damage at covering ply edge. The detection of much higher amplitude events, especially at failure, confirms the marked presence of fiber damage in the latter case [13].

In conclusion, both the structures presented problems related to the hand-lay up manufacturing procedure adopted. This was demonstrated by the presence of internal voids in the laminates, observable in Fig. 7. In the tapered laminate, also some fiber architecture disruption, originated by the drop-off, is apparent from the image. Fig. 8 shows the

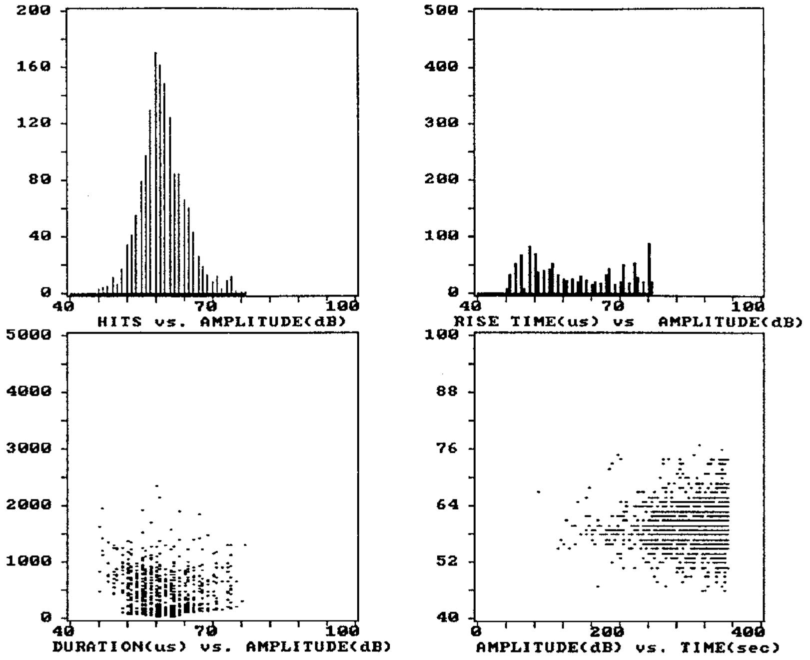


Figure 5 AE diagrams for tapered laminates not showing damage at covering ply edge.

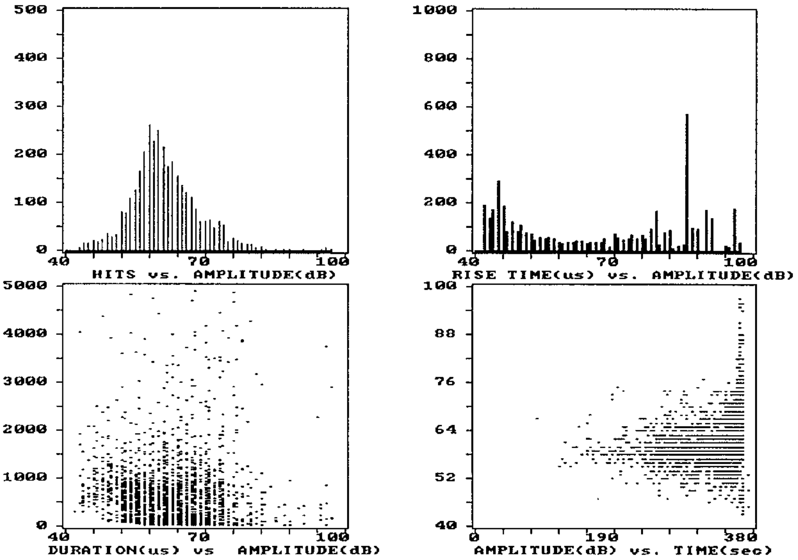
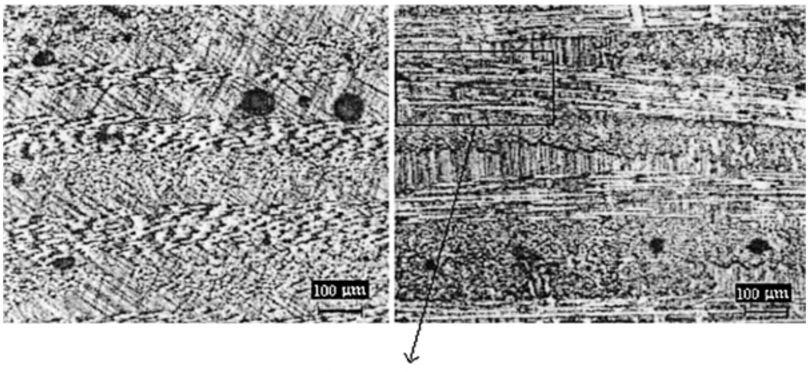


Figure 6 AE diagrams for tapered laminates showing damage at covering ply edge.



Region with fibre architecture disruption

Figure 7 Fiber architecture of the bonded composite (left) and of the tapered laminate (right).

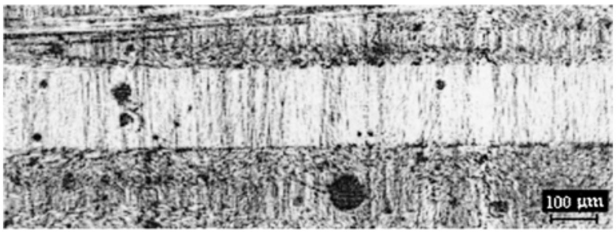


Figure 8 Voids in the proximity and inside the adhesive layer.

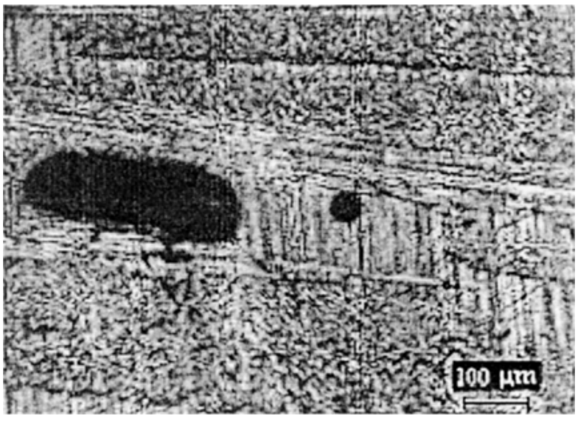


Figure 9 Large void in the resin pocket in tapered laminate.

presence of a substantial amount of air-trapped voids inside the adhesive layer, while in Fig. 9 larger voids (exceeding a length of 300 μm) are apparent in the resin pocket, where the fracture of tapered laminates originated.

As a whole, the tapered laminate showed higher properties than the adhesive joint, although, for a substantial improvement of properties, porosity in resin pockets should be reduced, which is unlikely to be possible with a hand lay-up molding procedure. In addition, tri-dimensional stress field present in resin pockets was demonstrated to be detrimental for the residual strength of tapered laminates, which showed post-loading degradation comparable to that observed on single-lap adhesive joints. Ideally, these preliminary considerations should be confirmed by tensile fatigue testing on the specimens. However, an improvement of manufacturing procedure would be of paramount importance for both geometries at this stage.

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