VIBRATION ASSISTED RESIN TRANSFER MOULDING (VIARTM)

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SUMMARY: One of the most promising liquid composite moulding techniques is the Resin Transfer Moulding (RTM) that is the low-pressure injection of resin into a closed cavity filled with fiber preforms. The present paper deals with a new technique developed towards the resin flow enhancement through the fiber preform to reduce voids, bubbles and injection time. The study and the identification of the flow phenomena that emerge during the vibration of the mould and the preform has been revealed some very interesting mechanisms that dominates the resin flow through porous media, the fiber preform at the present case.

KEYWORDS : RTM, flow, Vibrations, Polyester

INTRODUCTION

Resin Transfer Moulding (RTM) is a fairly old manufacturing method for the production of composite materials [9]. Recently, RTM has been rediscovered as low cost production of high quality composite structures is essential and many studies have been focused on the flow phenomena that take place during the resin injection in a closed mould full of fibre preform [10]. The void formation during the filling process of Resin Transfer Moulding is one of the major manufacturing problems especially when the tendency from the producer is to increase the percentage of the fibres into the cavity. Furthermore for polyester resins in order to avoid curing initiation during the filling, the filling stage should be as fast as possible. Many studies have dealt with the mechanisms of void formation as one of the major problems in RTM is that the air (as well as the gases that are produced during the chemical reactions) cannot escape easily from the cavity during the filling process, small or large voids are formed and the quality of the composite is deteriorated significantly. Unfortunately, the variability of preform placement in the cavity and the preform compaction change significantly the theoretically calculated flow paths and without having a standard flow path it is very difficult to design appropriately the filling process in order to reduce void and air-bubbles.

In order to eliminate these major problems, the vibrated resin transfer moulding has been proposed by Pantelelis et al [6]. This technique is based on the external mechanical vibration of the mould and the fibre preform together during and/ or after the filling phase turning the classic RTM process, a static process, to a dynamic one. The mould and the preform are vibrated together so flow velocities of the resin at the flow front are increased instantly and locally. Hence, air traps are very difficult to be maintained as well as wetting is improved considerable. The Darcy law and the numerical simulation of the resin flow through the porous media of the classic RTM still can be used in the case of VIARTM although a new permeability tensor for the vibrating flow is necessary.

For the evaluation of the VIARTM technique and the identification of the flow properties a test apparatus has been developed. A transparent flat mould has been employed in order to track directly the flow front as well as the complete behaviour of the flow. Results indicated that there is an obvious change in the flow of the resin through the fibres and this increases with the volume of fraction indicating that vibrations contribute towards the increase of the capillary pressure and as a result effective resin impregnation through the fibres is attained. However, further studies are essential in order to explore in more details the effects of mould vibrations in the mould filling, the resin curing and the final mechanical properties of the composite part.

VOID FORMATION MECHANISMS

Parnas [7], Kang et al [4], Pearce et al [3], Sadiq et al [2] have dealt with the major problem in Liquid Composite Moulding which is the formation of small (air-bubbles) or large (dry spots) air voids that occur during resin injection through porous media. The task is to eliminate completely dry-spots which destroy the performance of a composite part and to reduce significantly the size of the remaining air-bubbles in the part. Especially in the case of fabrics which are produced from woven or knitted fibre tows or bundles the phenomenon of two different flow paths is evident. The macro flow (or inter-tow flow) is generated through the micro channels that are formed after the compaction of the fabric layers inside the cavity and is dominated by the hydrodynamic pressure whereas the micro flow (or intra-tow flow) is the resin flow through the fibre bundles and is governed by the capillary pressure. Binetruy et al. [5] tried to quantify these flows.

A very interesting point of the study of Patel et al. [8] is the dependence of air traps from the flow front velocity. When the flow rate is high, air bubble generation is observed inside the fibre tows whereas the opposite phenomenon (air-bubbles are generated at the micro-channels) occurs when the flow rate decreases. For the reduction of the void generation the proposed technique is to balance these two flows, the micro- and the macro- flows [8]. However, the problem is that far from the inlet port the flow rate is low as hydrodynamic pressure is vanished (free boundary) and to increase the flow front velocity the pressure at the inlet port should increase considerably.

THE EFFECTS OF VIBRATIONS TO THE RESIN FLOW

On the other side, the idea to enhance the intermixing between micro and macro flows using dynamic means is not new. Some very few attempts to develop a Vibration Assisted RTM process have been presented. Two research teams: Baig and Gibson [1] and Song and Ayorinde [11], introduced audio frequency flow vibrations to enhance the productivity and the quality of the process. Both teams developed mechanisms that generated vibrations to the resin that enters the cavity at the inlet port. Advantages of this method were claimed to be a significant decrease of the filling time, the reduction of voids and a more effective resin impregnation of the fibres. However, these advantages were not confirmed in practice as

flow-induced vibrations at the inlet port vanish at the regions were exactly are essential: at the flow front where voids or rich resin areas are formed.
In VIARTM the mould and the preform are vibrated together during the filling process by applying external mechanical vibrations to the mould. The vibrations are generated with a motor coupled with a cam mechanism at a frequency from 15 to 30 Hz and a magnitude of 2 mm.

RESULTS

For the evaluation of the VIARTM technique and the identification of the flow phenomena during the filling phase, a test apparatus has been developed with two flat moulds: A circular flat mould with 340 mm diameter and 3 mm thickness (figure 1) and a rectangular one of 640 X 340 mm with the same thickness (figure 2). The circular mould has a central inlet gate and a single outlet gate at the perimeter of the cavity. An acrylic plate has been used as the upper tool in order to track directly the flow front as well as the complete behaviour of the flow using a digital video camera (figure 1).

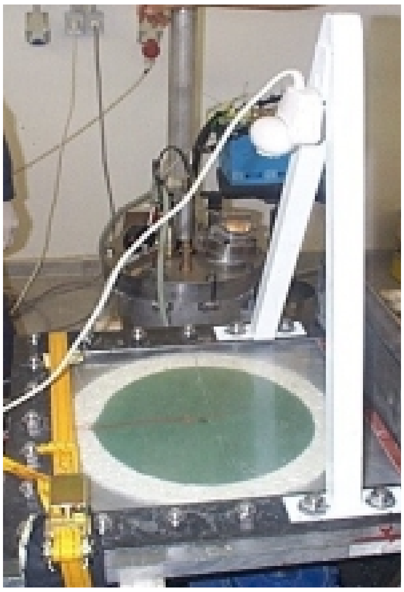


Figure 1. Test apparatus with the circular plate, the acrylic plate and the video camera.

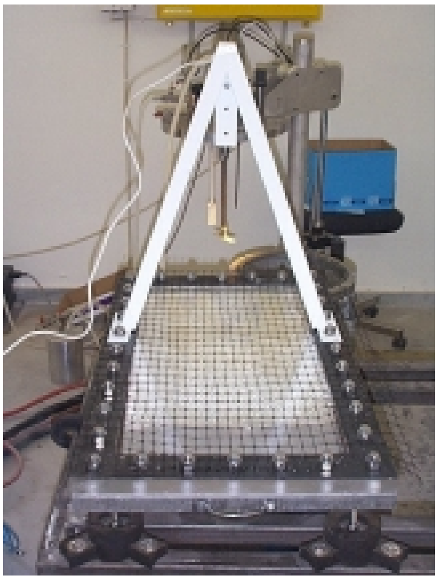


Figure 2. Test apparatus with the rectangular plate, the acrylic plate and the video camera.

In the case of the rectangular cavity the effectiveness of VIARTM can be clearly shown in figure 3 where a polyester part was produced with six layers of plain woven fabric resulting in a 30% approx. volume fraction. The part on the left of figure 3 was produced with VIARTM and 0.2 MPa whereas the part on the right in figure 3 has been produced with the same pressure at the inlet but without vibrations. In order to eliminate he dry-spot on the top of this part with classic RTM the pressure should be increased up to 0.4 MPa.

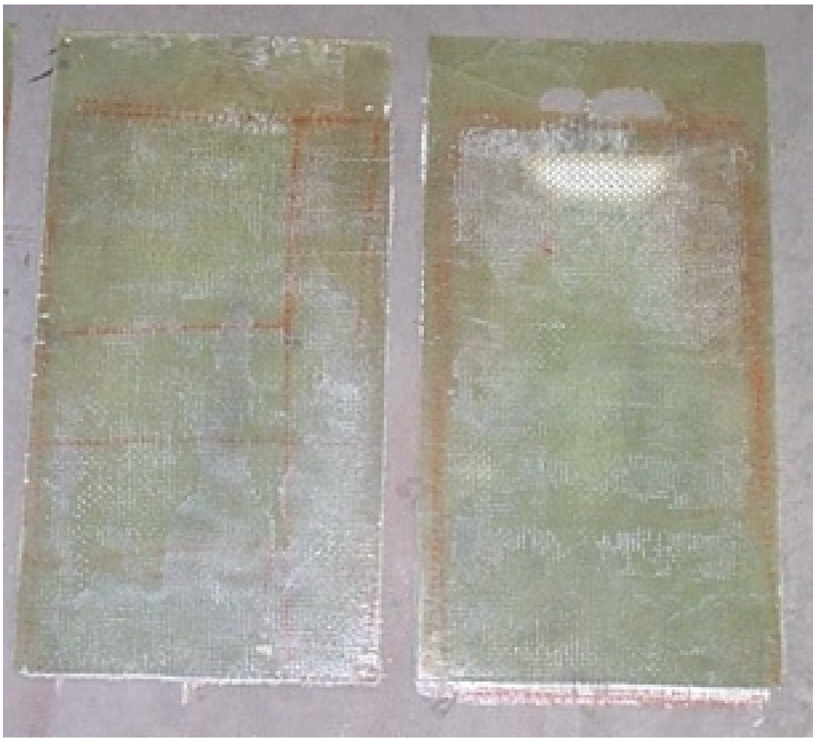


Figure 3. The part on the left was produced with vibrations applied on the mould whereas the part on the right was produced with steady mould.

Case	Reinforcement	Plies	V_f	Pressure (MPa)	Vibration (Hz)	Filling time (s)
1	Random Fiber Mat	3	13,7	0.1	-	202
2	Random Fiber Mat	3	14,1	0.1	15	420
3	Random Fiber Mat	3	14,1	0.1	30	400
4	Random Fiber Mat	3	13,5	0.3	-	45
5	Random Fiber Mat	3	13,4	0.3	15	49
6	0/90 Woven Fabric	6	25,3	0.1	-	100
7	0/90 Woven Fabric	6	27,2	0.1	15	90
8	0/90 Woven Fabric	6	29,6	0.3	-	130
9	0/90 Woven Fabric	6	27,8	0.3	15	80
10	0/90 Woven Fabric	10	43,0	0.3	-	125
11	0/90 Woven Fabric	10	41,0	0.3	15	120

Table 1. Experiments in the circular cavity with various preforms, volume fractions, inlet pressure and vibration frequencies.

Several cases were tested with respect to the different preforms (random strand mat and plain woven fabric), the volume fraction and the inlet pressure as can be seen in table 1.Considering the random chopped strand mat (cases 1-5) a flow uniformity can be clearly observed in most of the snapshots with or without vibrations (figure 4): the resin flows from the centered inlet gate radially without any interaction with the outlet gate at the top of the disk. This flow uniformity is spoiled somewhat in case 4 (0,3 MPa) injection pressure, no-vibration) and this is probably due to the increase injection pressure that raises somewhat the tie bar that fastens the upper acrylic plate at the bottom of the discs). However, uniformity is regained when vibrations are applied to the same configuration (case 5).

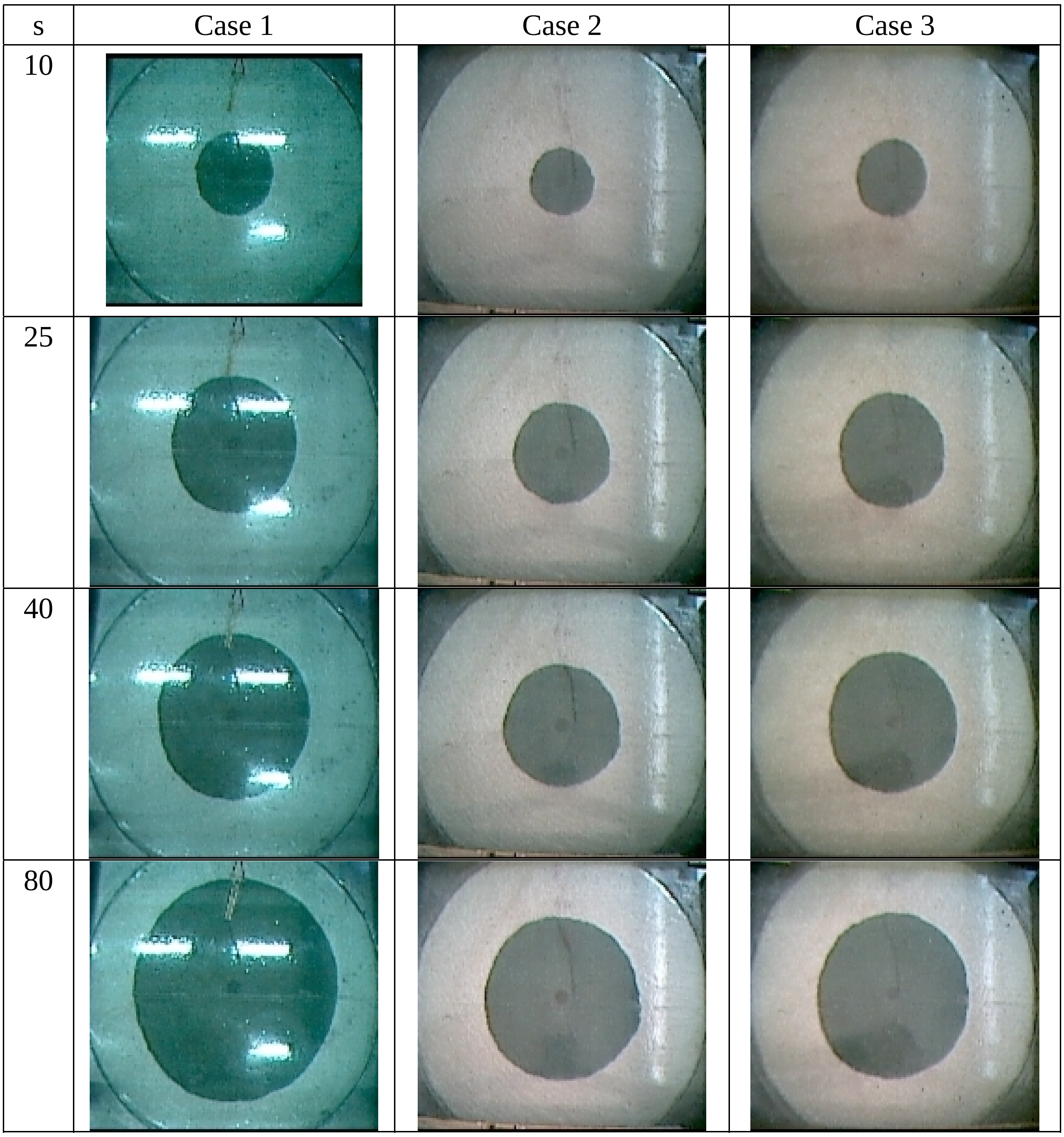


Figure 4. Cases 1, 2, 3: filling patterns of polyester injection (random chopped strand mat, Vf≅ 14 %, injection pressure 0.1 MPa) without (case 1) and with vibrations (case 2: 15Hz and case 3: 30Hz) at 10, 25, 40 and 80 s.

Considering the resin impregnation stage it is obvious that classic RTM (cases 1 and 4) give much faster impregnation than VIARTM (cases 2, 3 and 5). Especially in lower inlet pressures the delay due to vibrations is significant as the filling time has been doubled (from 202 s in case 1 to 420 s or 400 s for cases 2 and 3). However, when the injection pressure is increased to 0.3 MPa the total filling time has been reduced considerably resulting in filling duration of 45 and 49 s for the RTM (case 4) and the VIARTM (case 5), respectively. These experiments can lead us to the conclusion that for low volume fraction composite parts (i.e. from 13.4 % to 14.1 %) and absence of flow paths (random mat) the majority of resin flow is macro flow and vibrations can cause the opposite effect (flow delays).

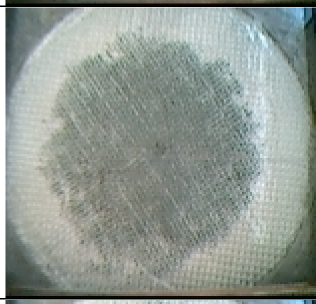
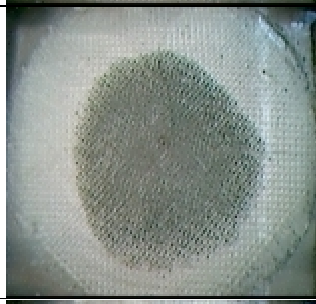
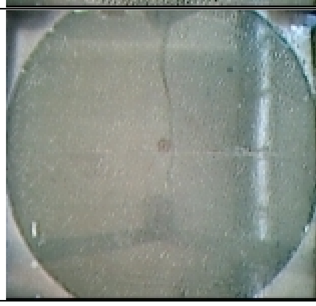
s	Case 6	Case 8	Case 7
10			
25			
40			
80			

Figure 5. Cases 6,7,8: Comparison of filling patterns of polyester with plain woven fabric, injection pressure 0.1- 0.3 MPa) with RTM and VIARTM at 10, 25, 40 and 80 s.

With respect to plain woven fabric we have used six plies at the same mould cavity and the volume of fraction has been increased up to 30% approx. At these cases we can clearly realize that the VIARTM cases (cases 7 and 9) are filled with resin faster than those with the conventional RTM (cases 6 and 8). In the case of low injection pressure of 0.1 MPa (cases 6 and 7) a rather uniform flow front can be depicted with (case 7) or without (case 6) mould vibrations. The filling time in the VIARTM is slightly less (100 s) than the conventional case (100 s) even if in the latter case the volume of fraction was 10% lower due to thickness variations. That is the reason of the increased filling time (130 s) when the injection pressure was increased to 0.3 MPa in case 8, as again for 6 plies of woven fabric the volume of fraction has been increased from 25,3 in case 6 to 29.6 % in case 8. Using the VIARTM with the higher injection pressure (case 9) the filling time has decreased even more to 80 s.

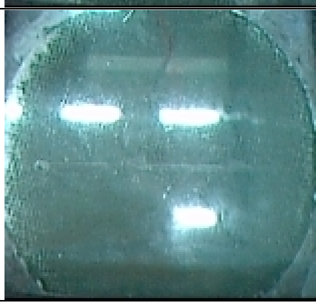
s	Case 10	Case 11
10		
25		
40		
80		

Figure 6. Cases 9,10, 11: Comparison of filling patterns of polyester injection for case 10,11 (plain woven fabric, Vf≅ 43 %, injection pressure 0.3 MPa) without vibrations (left) and with (right) at 10, 25, 40 and 80 s.

However, in the cases of the plain-woven fabric we can easily distinguish the flow unevenness during injection (especially when these flow patterns are compared to those of the random mat). This phenomenon is exaggerated when the pressure is increased to 0.3 MPa as can be seen in flow snapshots and can be the nightmare of every RTM producer air bubbles and in the worst case dry spots can be formatted deteriorating the strength of the part significantly.

Increasing the volume of fraction up to 43% by increasing the number of woven plies from 6 to 10 the non-uniform flow phenomenon has been exaggerated more in case of VIARTM where the initial dry spots are more than evident (case 11, figure 6). However, at the end of the filling phase these dry spots have been eliminated. However we should highlight that the formatted dry spots are not real through thickness dry spots but they are skin-deep air-traps mainly because the resin flow cannot wet instantly in those fiber tows that are compressed considerably towards the face of the acrylic mould. The significant contribution of the vibrations during the filling phase can be depicted in fig. where the flow front at the first 10 s has reached almost the perimeter of the disc.

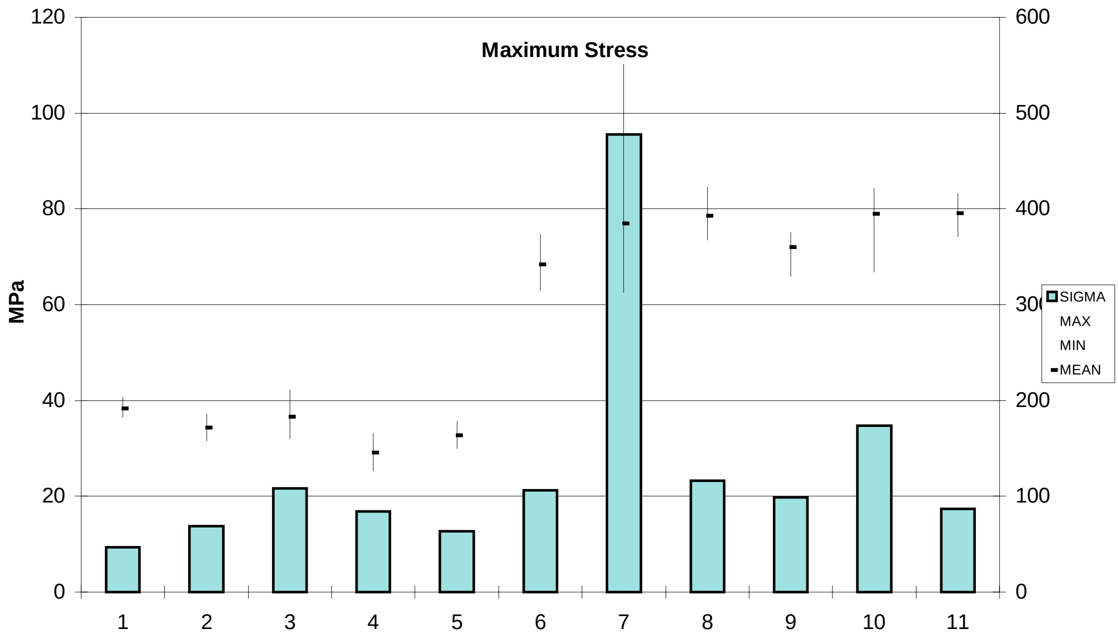


Figure 7. Maximum flexural stress for the circular plates produced during the experiments of cases 1 to 11. On the left scale of the y-axis is the sigma variable and on the right scale of the y-axis the maximum flexural stress.

In order to explore the effects of vibrations during the filling phase test specimens were produced and tested in accordance with the ASTM D790 at sizes of 25X80 to 13X100 according to the final thickness of the specimen. As can be seen in figure 7, there is a clear difference between the random mat with V_f at 14% (cases 1 to 5) and plain woven fabric with V_f at 25 to 41 % (cases 6 to 11). With respect to the random mat, there is not a clear difference between specimens produced with RTM and with VIARTM. However there is a significant advantage of 30 % higher maximum stresses for specimens produced with lower inlet pressure (cases 1, 2 and 3) with respect to the 0.3 MPa cases 4 and 5. In the cases of plain-woven fabric results are rather confusing indicating that there is not a clear conclusion on the way vibrations affect the strength of the composite part. In cases 6 and 7 (six plies, 1 MPa pressure) a very large dispersion of the results in the case of VIARTM is evident, with the maximum stress rising above 550 MPa in some specimens. In the case of higher injection pressure (cases 8 and 9) no significant differences are observed although the mean maximum flexural stress of the specimens are at the same level as those of the lower injection pressure. Finally, in the case of the highest volume fraction (cases 10 and 11) a much homogeneous strength behaviour is achieved especially in the VIARTM case and the mean values for RTM and VIARTM produced specimens are equal. This last observation confirms our flow observations that although voids seem to be formatted during injection in the VIARTM case (figure 6) finally there is no strength deterioration with respect to the classic RTM.

CONCLUSIONS

An alternative technique was presented for the enhancement of resin impregnation through the fibre preforms in RTM. Applying vibrations at the mould and the preform resin impregnation is improved especially in the case of high volume of fraction (V_f) and woven fabrics where problems with the classic RTM occur. However, further experiments are essential in order to study the resin impregnation in higher V_f (up to 65%) as well as to introduce measurements techniques to get a better insight of the effects of vibrations at the inter and intra fibre tow resin impregnation.

ACKNOWLEDGEMENTS

This work was partially supported by the Greek Secretary for Research and Technology and the European Union under the EPET II project No 88. The authors wish to thank Dionysios Asvestas, Achillios Karamitsos, Thomas Vrouvakis and Kostas Kalimeris for their great support on the construction of test apparatus and the execution of experiments.

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