# IMPROVED MANUFACTURE AND PRODUCTIVITY OF A HIGH PERFORMANCE COMPOSITE OAR BLADE

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**ABSTRACT**

It is desirable to be able to produce high volumes of quality composite components quickly and at low cost. Autoclave manufacture produces a product of high quality but the production cost is high. Room temperature curing lowers costs but quality and productivity are reduced. The combination of a low temperature curing carbon vinylester prepreg and Quickstep, a manufacturing process that uses fluid as the heat transfer medium, provides both high quality and increased productivity while maintaining low costs.

This paper compares the mechanical performance, productivity and quality of this process to room temperature and autoclave cured laminates and sandwich structures. Quickstep gives increased performance in all areas and produces a product with more consistent properties than the other methods. A rowing oar blade was manufactured by Quickstep, to demonstrate the increase productivity of the process for the manufacture of a curved sandwich component. The length of the cure cycle was not only reduced when manufactured by the Quickstep process, but the total time for manufacture was also reduced because the core was thermoformed while the skins were bonded, making it a one-step cure.

## 1. INTRODUCTION

Carbon Fibre components of high quality, namely high fibre volume fraction and low void content, are typically achieved by the use of prepreg materials and autoclave cure. This requires high manufacturing temperatures and a cycle time of several hours. This method is not suitable for the manufacture of high-grade components where high volumes are also required. Instead, room temperature curing is used but then quality is often compromised when this process is used.

A recently developed Australian manufacturing technique (Quickstep, [1]) has the potential to provide a rapid, low temperature, low-pressure and low cost method for the manufacture of high quality composite components with significantly reduced cycle times in comparison to autoclave manufacture. The suspended laminates are cured in a lightweight two-part mold with elastomer bladders containing a heat transfer liquid that provides controlled and rapid thermal cures. The use of a fluid as the heat transfer medium, and the direct contact with the mold, reduces the curing time of the laminates to minutes as opposed to hours.

A low temperature Carbon fibre Vinylester prepreg, combined with Quickstep, has the potential to increase fibre volume fraction, and decrease void content and cycle time. Furthermore, the low temperatures required to cure the prepreg material and the lower pressures of the Quickstep method provide an opportunity to incorporate polymer foam cores, which often have limited processing temperatures. The combination of factors is ideal for the incorporation of sandwich panel materials, which are usually restricted to room temperature applications.

This paper investigates the potential to make carbon fibre based sandwich components with relatively short processing cycles using Quickstep. A sandwich structure with curved geometry will be used as the prover component, in this case the blade of a sculling oar. Manufacture of this component is usually by hand lay-up using room temperature epoxy resin or a thermal cure using a core material with a higher temperature tolerance. The aim of this study was to determine whether a low temperature prepreg cured in Quickstep would match or improve the mechanical performance of the blade while increasing the quality and productivity of manufacture.

Initially five different carbon fibre laminate systems were compared on the basis of mechanical performance and void content. Hand lay-up room temperature (1) and postcured vinylester systems (2) were used for comparison to the vinylester-based prepreg cured using both an autoclave (3) and Quickstep (4). Room temperature cured epoxy (5) was analysed to compare the performance of the prepreg to materials and manufacturing methods commonly used for oar blades. Flexural properties of sandwich structures were also determined. Finally, the manufacturing of an oar blade in a one-step process was carried out to prove that rapid, high quality production is possible using Quickstep.

## 2. LAMINATE FABRICATION AND TESTING

### 2.1 PLAIN LAMINATES

Four ply laminates were made for flexural testing using a plain weave high strength carbon fibre (195 $g/m^2$, SP Systems) as the reinforcement. The room temperature (RT) and postcured (PC) laminates were all made with the same fabrication technique, wet hand lay-up and vacuum bag evacuation with a caul plate. The room temperature epoxy resin was FGI H180 and the resin for the vinylester laminates was Dow Derakane 411-350 with a curing formulation of 0.2% CoNap and 1% MEKP. Following cure at room temperature, the vinylester postcured laminate was further cured at 80°C for 8 hours.

The low temperature curing vinylester resin carbon fibre prepreg (Australian composites) used was Dow Derakane 411-350 vinylester resin. The prepreg was cured at a temperature of 80°C for 20 minutes. A vacuum was used on both the autoclave and Quickstep laminates throughout curing. The 80°C processing temperature was chosen to comply with the temperature requirements of the core material, which was incorporated later to form the sandwich structures.

The flexural modulus and strength of each composite was determined using the three-point bend test method, ASTM D790 [2]. Specimens were cut to a length of 50mm and width of 25mm. The specimens were tested using a span-to-thickness ratio of 1-to-32 and a loading rate of 1.7mm/min.

The tensile modulus and ultimate tensile strength of the plain laminates also determined using ASTM D3039 [3]. The specimens were cut to a width of 25.4mm and a minimum gage length of 127mm. The tests were carried out using a loading rate of 2.5mm/min.

### 2.2 SANDWICH LAMINATES

Sandwich laminates containing two plies of carbon fibre in each skin were manufactured for four-point bend tests using the epoxy room temperature hand lay-up system and the prepreg cured in Quickstep. The core used was a closed cell polymer core (Diab Klegecell R200). This core is suitable for use in an oar blade as it has good dimensional stability, a high strength to weight ratio and excellent moisture resistance [4]. The core also has good thermal properties with a maximum processing temperature of 80°C and a heat distortion temperature of 95°C. The four point bend tests were carried out according to ASTM C393 [5]. The span for each material was determined according to Eq. (1).

$$a_1 = \frac{2tF}{S} \quad (1)$$

Where $a_1$ is the support span length in mm, $t$ is the facing thickness in mm, $F$ is the allowable facing stress in $MN/m^2$ and $S$ is the allowable core shear stress in $MN/m^2$. Specimens were cut to a width of 25mm and a length of the span length ($a_1$) plus 50mm. The load span was 1/3 of the support span. The tests were carried out using a loading rate of 2mm/min. Rubber was placed beneath the load points to minimise the localised stresses caused during the bending. The maximum core shear stress ($\tau$) was obtained using the equation Eq.2. [6]

$$\tau_{\max} = \frac{P}{D}\left( E_f \frac{td}{2} + \frac{E_c}{2}\frac{c^2}{4} \right) \quad (2)$$

Where P is the maximum load on the specimen in N, D is the flexural rigidity of the sandwich in $Nm^2$, $c$ is the core thickness in mm, $d$ is the distance between the facing centroids in mm, $E_f$ is the modulus of facings in $MN/m^2$ and $E_c$ is the modulus of core in $MN/m^2$.

The maximum stress in the skin ($\sigma_f$) and the maximum stress in the core ($\sigma_c$) were calculated using Eq. (3) and Eq. (4) respectively. [6]

$$\sigma_f = \frac{Mz}{D} E_f, \text{where} \quad z = \frac{c}{2} + \left( \frac{h/2 - c/2}{2} \right) \quad (3)$$

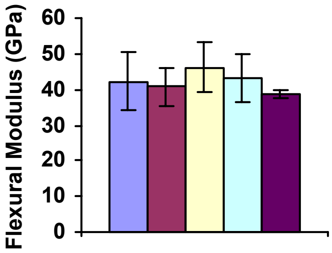
$$\sigma_c = \frac{Mz}{D} E_c, \text{where} \quad z = \frac{c}{2} \quad (4)$$

Where M is the maximum bending moment in Nm and $h$ is the thickness of the sandwich structure in mm.

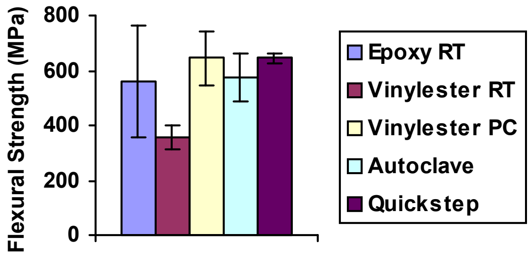
## 3. RESULTS AND DISCUSSION

### 3.1 PLAIN COMPOSITE LAMINATES

The flexural modulus and strength of the five different composites are shown in Figure 1. The plots show that the prepreg cured in Quickstep is comparable to other systems, within experimental scatter, for both the modulus and yield strength. The greater strength of the thermally cured vinylester laminates compared with the room temperature cured laminates suggests the cure is increased using thermal methods. It is also noticeable that the standard deviations on the Quickstep samples for both measurements are much lower than those of the other systems, suggesting greater consistency of cure and material properties for samples made by the Quickstep method.



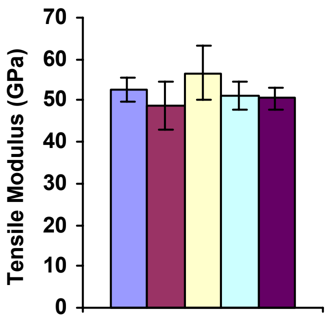

(a)



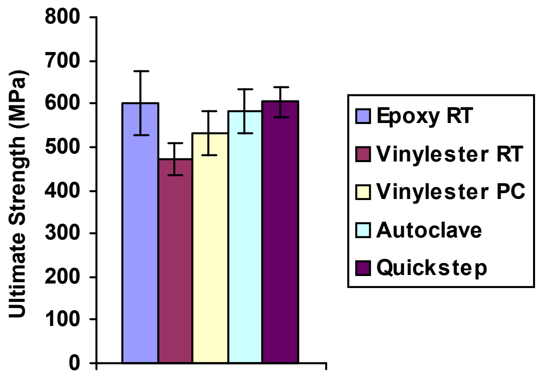

(b)

**Figure 1.** Flexural (a) Modulus, (b) Strength of composites (Error bars signify plus or minus one standard deviation)

The tensile modulus and ultimate strength of the different composites are shown in Figure 2. The tensile modulus, figure 2(a), shows no significant difference between the composites. This is to be expected as the fibres dominate tensile modulus and all of the samples contain the same carbon fabric. Figure 2(b) shows that the ultimate strength of the vinylester laminates increases with the effectiveness of the thermal cure, the best result being for the Quickstep cured laminate.




(a)



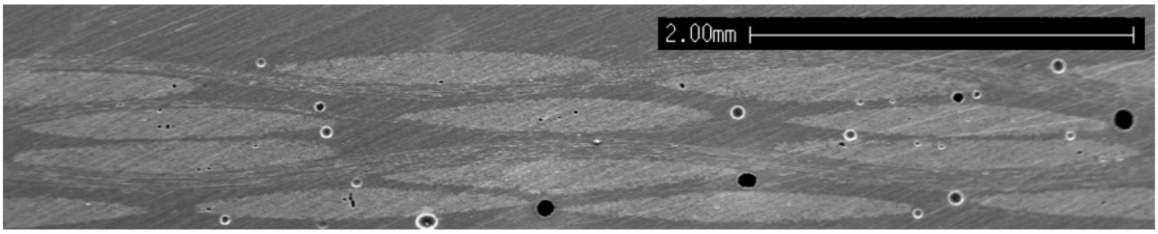

(b)

**Figure 2.** Tensile (a) Modulus, (b) Strength of composites (Error bars signify plus or minus one standard deviation)

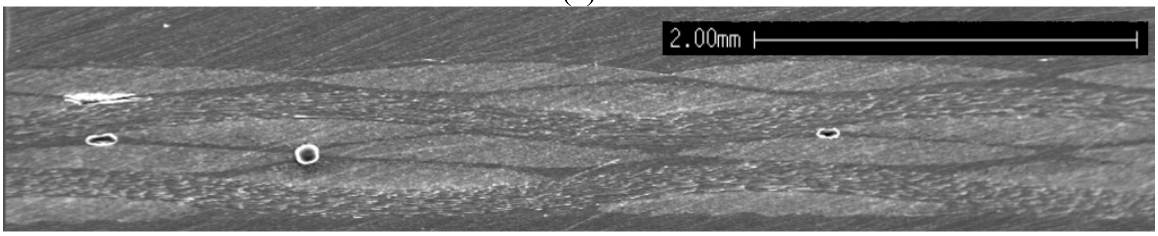
### 3.2. LAMINATE QUALITY

The fibre volume fractions of the composite laminates were between 48% and 60%. As expected the prepreg cured in both the autoclave and Quickstep were found to have increased fibre volume fractions when compared with the room temperature cured laminates.

SEM images of the two room temperature cured laminates and the two prepreg laminates can be seen in Figure 3. The vinylester room temperature cured laminate is representative of the quality of the postcured laminate as it initially underwent room temperature cure in the same conditions. The room temperature cured laminates, 3(a) and 3(b), show a significantly greater number of voids than the Autoclave and Quickstep cured samples. The two prepreg laminates 3(c) and 3(d) are similar in quality and contain very few voids.




(a)

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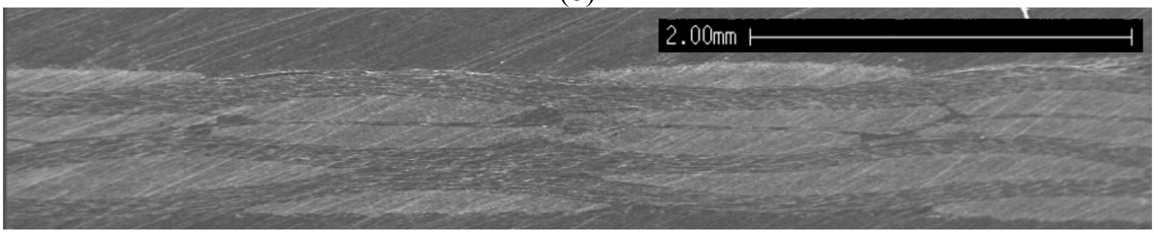
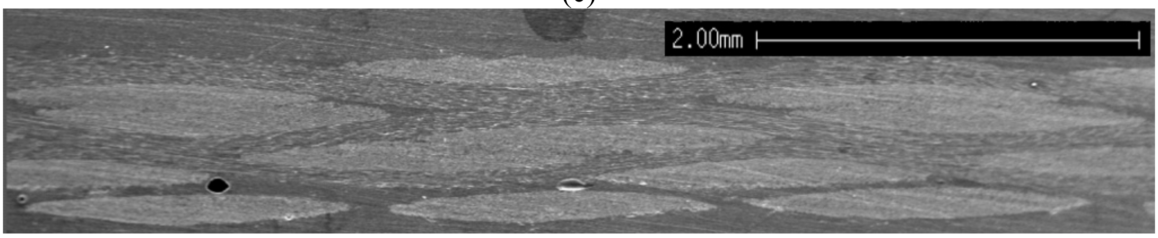



(c)




(d)

**Figure 3.** Cross section of laminates (a) Epoxy room temperature, (b) Vinylester room temperature, (c) Autoclave prepreg, (d) Quickstep prepreg

### 3.3. PRODUCTIVITY

Quickstep's use of a fluid as the heat transfer medium rather than gas and the direct contact with the mold reduces the curing time of the laminates to minutes as opposed to hours in an autoclave, typically cure time is reduced by a factor of five [7]. The time for cure of each system is very important when assessing suitability for high volume production. Table 1 shows the average cure time for each laminate. The thermal curing methods are both significantly faster than the room temperature curing systems, with Quickstep curing four times as fast as the autoclave. This is due to the increased ramp up rate and cool down rates that can be achieved using Quickstep [8]. Baffles within the elastomer bladders ensure the steady flow of the heat transfer fluid past the part not only heating the laminate quickly, but also carrying away any generated heat minimising any exotherm. This allows the laminate to be heated at rates faster than those possible in an autoclave.

**Table 1.** Cure time for the different resin systems

| Resin System | Cure time | Postcure | Total |
|---|---|---|---|
| Epoxy Room Temperature | 24 hours | - | 24 hours |
| Vinylester Room Temperature | 24 hours | 8 hours | 32 hours |
| Vinylester Postcured | 24 hours | - | 24 hours |
| Autoclave Prepreg | 2 hours | - | 2 hours |
| Quickstep Prepreg | 0.5 hours | - | 0.5 hours |

## 3.4 SANDWICH STRUCTURES

The four-point bend tests provided the maximum shear stress in the core and the maximum stress within the core and the skins of the sandwich structure. Figure 4 shows a typical load deformation curve for each structure tested. For both systems, catastrophic failure of the skin was observed in compression, usually occurring beneath the loading rollers due to localisation of stress. Importantly, there was no evidence of skin-core delamination in the carbon fibre vinylester system, indicating that a good bond can be achieved using Quickstep.

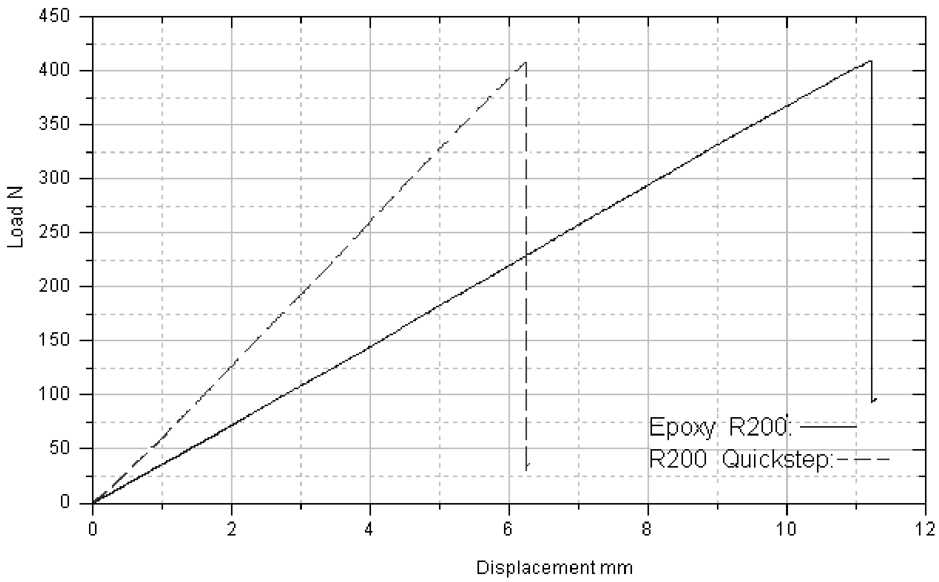
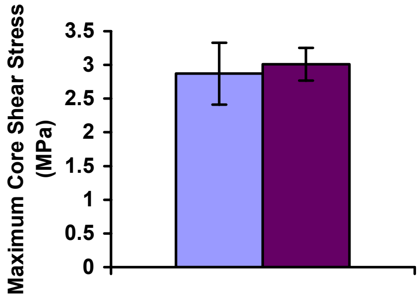


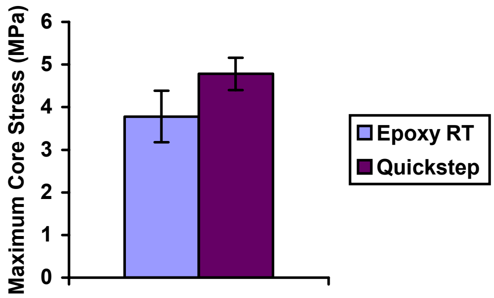

**Figure 4.** Force Deformation Curve for the Four-Point Bend Tests

Figure 5 shows the flexural properties of the sandwich structures. Each plot shows that the prepreg cured in Quickstep achieved higher results than the epoxy and the error bars indicate less variation in the prepreg structures. The prepreg sandwich manufactured in Quickstep achieved a maximum shear stress (see Figure 5(a)) equal to the cores maximum strength of 3 MPa as provided in the manufacturer's data [4], the strength of the epoxy being slightly less.

The results of the mechanical testing and analysis of laminate quality have proven that the vinylester carbon fibre prepreg, cured in Quickstep, achieved improved mechanical performance and productivity as well as increased laminate quality when compared to room temperature cured epoxy systems. This shows that the Quickstep manufacturing technique and vinylester prepreg material are suitable for the manufacture of high volume quality composite sandwich structures.




(a)

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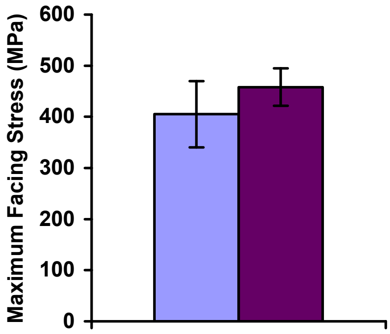


(c)

**Figure 5.** Sandwich Properties (a) Core Shear Stress, (b) Core Stress, (c) Facing Stress (Error bars signify plus or minus one standard deviation)

## 4. BLADE MANUFACTURE

In all types of rowing, blades are used in pairs. For the oar to perform well it is important that the blades are consistent in weight and dimensions. Other blade requirements affected by the choice of materials include high stiffness and strength. It is also important that the manufacturing technique be capable of efficiently producing a quality product at low cost.

Testing of the materials has shown improvement in the mechanical properties, quality, consistency and processing time of the vinylester prepreg cured in Quickstep when compared to a room temperature cured epoxy system. Bader [9] compares several materials and manufacturing techniques on the basis of cost for performance equating a lower mass for equivalent stiffness or strength with superior performance. Other factor such as cost of production, material cost, tool life and achieved dimensional tolerance, were also taken into account. A similar comparison, based on the requirements for the blade can be used here. For this component performance can be compared equating a blade that has high quality, consistency and a low production time, for equivalent mechanical properties, as a superior product. The Quickstep cured prepreg is preferred over epoxy room temperature for better performance by this measure.

There are several other possible advantages to manufacturing sandwich structures using Quickstep. The direct contact of the heat transfer medium has the potential to reduce the manufacturing time for curved sandwich laminates. The polymer core for such components is usually thermoformed prior to the bonding of the skins. To thermoform the core an even temperature distribution is required, which is not easy to achieve using hot air ovens or infrared heaters. The direct and even application of heat provided in Quickstep allows a thin core, such as that in the blade, to form over the curved surface in the same application as the skin bonding at 80°C. This makes the manufacture of the blade a one-step process.

The low pressure generated by the fluid filled bladders is around 12 kPa allowing for the use of low cost tooling such as a thin composite or sheet metal part [7]. The mold requires no reinforcement structure but does need to be able transfer heat to the part. These two factors mean that the blade can be manufactured in Quickstep quickly and at lower cost.

To prove the advantages of Quickstep a prototype oar blade was manufactured. The part was a simplified version with a curved shape, similar to that of popular commercial sculling blades but did not include the shaft insert point and had no surface coatings. The low cost thin mold was made from glass fibre and vinylester resin. The manufacture of this component offered the opportunity to see if it is possible to thermoform a thin core to shallow curvature and bind skins in one step so as to reduce the manufacturing time.

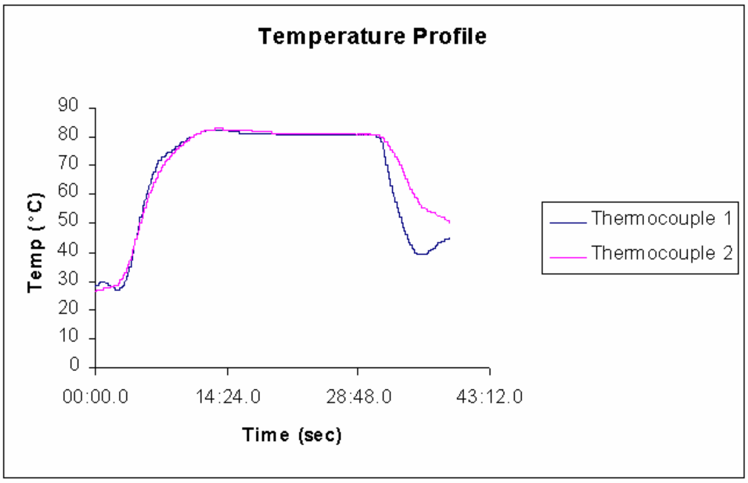


**Figure 6.** Cure temperature profile

Three blades were manufactured using a 5mm foam core and three plies of carbon for each skin. The use of the glass fibre mold had a small effect on the cure time due to the longer time required to ramp the temperature up and down, caused by the absorption of heat by the mold. The temperature profile for a cure can be seen in Figure 6. The cure time averaged 42 minutes with a 20-minute dwell time. The core was formed to the blade shape at 80°C during the curing process. Figure 7 shows the final product.

(a) (b)

**Figure 7.** (a) Front view (b) Side view of an oar blade

The standard deviation on blade thickness was 1.2% as opposed to range of 2-6% in the commercially manufactured blades measured. The average weight of the blades was 252g with a standard deviation of 2.2%. These low deviations indicate that the blades manufactured by the quickstep process are more consistent than room temperature cured blades.

## 5. CONCLUSION

The Quickstep cured prepreg has matched or exceeded the mechanical performance and had more consistent results than all of the other laminates with which it was compared. The quality of the thermally cured prepreg, and the cure cycle time, was also better than the room temperature laminates. The use of a fluid as the heat transfer medium in Quickstep decreased the cure time for the carbon vinylester prepreg by a factor of four when compared with air induced heat transfer in an autoclave which is comparable to previous results [7].

The manufacture of the oar blade, a sandwich structure with curved geometry, demonstrated that the Quickstep process can be used for the manufacture of real components. The component manufacture time was further reduced by thermoforming the core at the same time as bonding the skins, making the oar blade manufacture a one-step process. The reduced curing time, shorter processing time and lower cost mold, combined with the high quality of components that can be produced, shows that Quickstep is a promising method for the rapid production of high quality composite sandwich components.

## ACKNOWLEDGEMENTS

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References

1. Quickstep Technologies, http://www.quickstep.com.au
2. "ASTM D 790M - Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials [Metric]"
3. "ASTM D 3039 – Standard Test Methods for Tensile Properties of Fiber-Resin Composites"
4. "DIAB Klegecell – R Grade Technical Data", http://www.diabgroup.com/aao/a_literature/a_pdf_files/R_Grade_E.pdf
5. "ASTM C 393 – Standard Test Method for Flexural Properties of Flat Sandwich Constructions"
6. "DIAB Sandwich Handbook", http://diabgroup.com/aao/a_literature/a_pdf_files/sandwich_hb.pdf
7. **Griffiths, B. and Noble, N.,** "Process and Tooling for Low Cost, Rapid Curing of Composite Structures", *SAMPE J*, **40**/1 (2004), 41-46.
8. **Hodgkin, J.H, Nadine, R.,** "A New Development in High-Speed Composite Fabrication – For Aerospace, Automotive, and Marine Applications", *International SAMPE Symposium and Exhibition (Proceedings)*, **45**/11 (2000), 2274 –2282.
9. **Bader, M.,** "Selection of composite materials and manufacturing routes for cost-effective performance", *Compos Part A-Appl S*, **33** (2002), 913-934.