MODELING AND MANUFACTURING THICK CARBON FIBRE COMPOSITES FOR STRUCTURAL SUBSEA APPLICATIONS

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ABSTRACT

The use of thick Carbon Fibre reinforced plastic in primary structural applications is relatively new, even within mature carbon fibre industrial users such as civil aviation. The majority of traditional composites vendors have expertise in designing for secondary structural applications using relatively thin components. Thick composites engineering brings new problems associated with modeling complexity, validation and the importance of manufacturing quality to gain consistent part performance. This understanding is required to retain the high strength to weight ratio of carbon fibre and hence the benefits of using carbon fibre when compared to more traditional engineering materials such as steel. A case study is presented to demonstrate the importance of model validation, manufacturing quality and process control required to retain the benefits of the material properties when designing thick carbon fibre parts.

1. INTRODUCTION

Consider two carbon fibre/resin combinations that were used to make similar but not identical parts. In this example wet filament winding process (fabricated from material Type A) and pre-preg filament winding process (fabricated from Material Type B) were used to manufacture similar but not identical cylindrical parts.

The use of pre-preg material was preferred to a more conventional wet wound system because the latter showed itself to be sensitive to the shop environment and, without adequate environmental controls, could not provide a suitably repeatable process for a product destined to be under high static loads. In addition to the pre-preg being a more stable product it could also be laid down in a more controlled manner because it is tacky. The wet wound product is more likely to slip during fabrication. Other advantages to the pre-preg system include the ability to support higher tow tension than a wet wound system, improving the compaction. Material B was chosen because it is stable at room temperature and does not require special handling such as the use of a freezer to store. Because the components are thick the winding time is long and it is important that the product does not inadvertently cure during fabrication. It is also a low temperature cure product suited to the application and, being a pre-preg, the fibre fraction should be more directly controlled

Both materials possessed similar mechanical properties, however, the fabrication process yields very different results in the performance of the 'as manufactured' component. The 4 point bend test was used to quantify the 'as manufactured' components performance. It was expected that the parts in-service performance could be determined from an artefact of the part using a 4 point bend test. The strength of both materials was known from coupon test data. A virtual 4 point bend model was constructed using a finite element (FE) model and the results compared to the actual test. When both parts were modelled using the material (coupon) strength data with a 100% utilisation of the material properties, the strength of the part undergoing a virtual four point bend was over-predicted. This necessitated alterations to the model using a lower material utilisation factor, which is a multiplier of the material strength, to match the strength of the part. The methodology described in this paper compares different size and strengths of curved artefacts subjected to 4 point bending, the correlation of a failure model with the test data and the application of utilization factors from the correlated model to predict the 4 point bend test results.

2. COUPON DATA COMPARISON

The coupon test data was known for both materials. Figure 1 below compares the as tested coupon data for material A used for the wet wound part and material B used in the pre-preg part. The key feature is that, for both strength and stiffness, the coupon data was lower for the pe-preg material. The fibre volume fraction for material A was 61.9% and for material B it was 59.9%. Void content was negligible for both materials

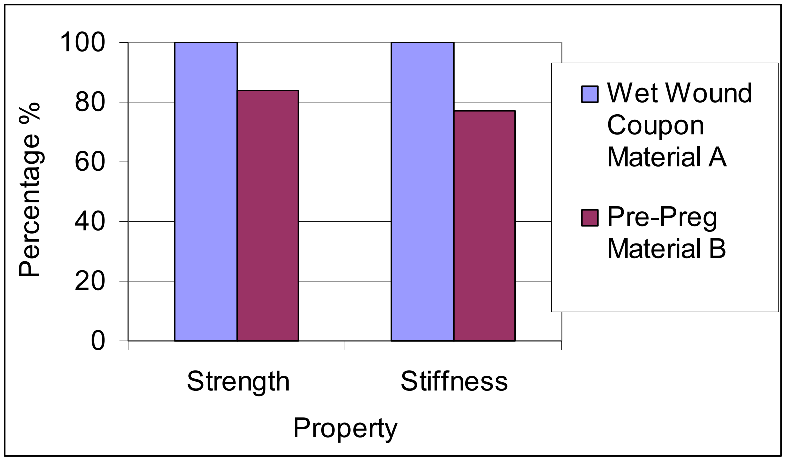

Figure 1 Comparison of Properties from Coupon data

3. ‘AS MANUFACTURED’ PART QUALITY

Figure 2 below compares the void content and fibre volume fraction for the as manufactured parts from materials A and B. Note the tighter control achieved over both the void content and fibre volume fraction using the pre-preg material.

Figure 3 & Figure 4 underline the improvements in the ‘as manufactured part quality. The micrographs clearly show the high void content of the wet wound part compared to the pre-preg part.

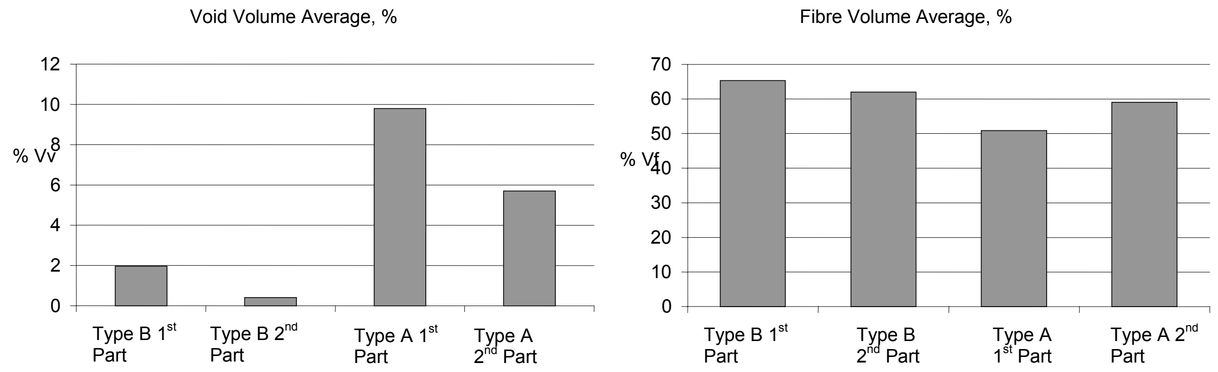

Figure 2 Comparison of Void Content and Fibre Volume Fraction for Type A and Type B 1st and 2nd Parts

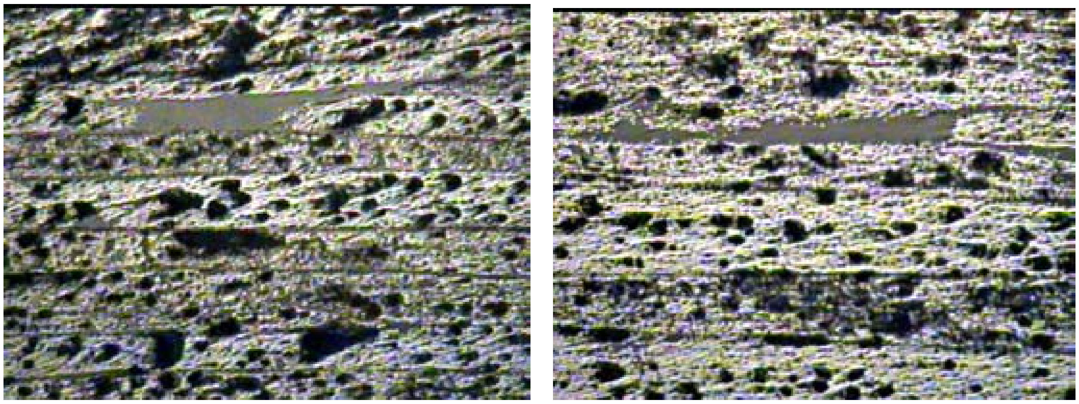

Figure 3 Type A – likened to Swiss cheese

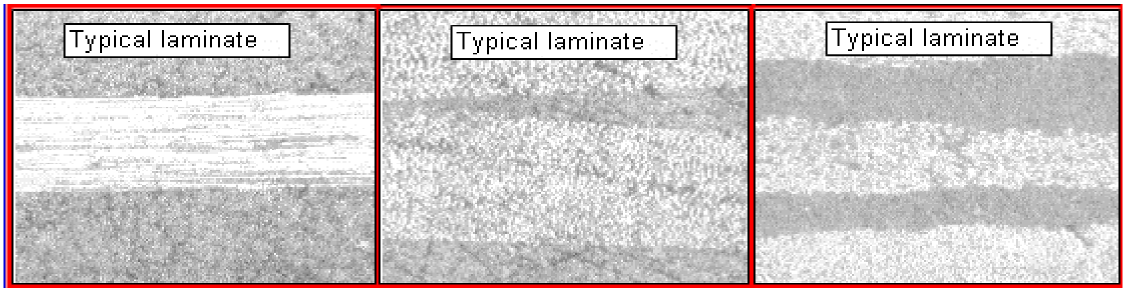

Figure 4 Type B Micrographs

4. FOUR POINT BEND TEST

This section describes the test set-up [1]. The 4 point bend test was selected for three reasons;

1) It was a sensible physical size for direct comparison with FE such that the FE model would not become onerously time consuming to run. The FE model was built in ABAQUS (version 6.4). Each layer's thickness and orientation was represented.

2) It was expected that the results from the 4 point bend test could be applied to other models in order to predict the performance of the part.

3) The 4 point bend test was undertaken on artifacts from the parts themselves so it was expected that manufacturing quality would be included in the test data. Note that void volume, fibre volume fraction and Tg test were also carried out to establish manufacturing quality and provided a mechanism for quantifying the effects of manufacturing quality on part performance.

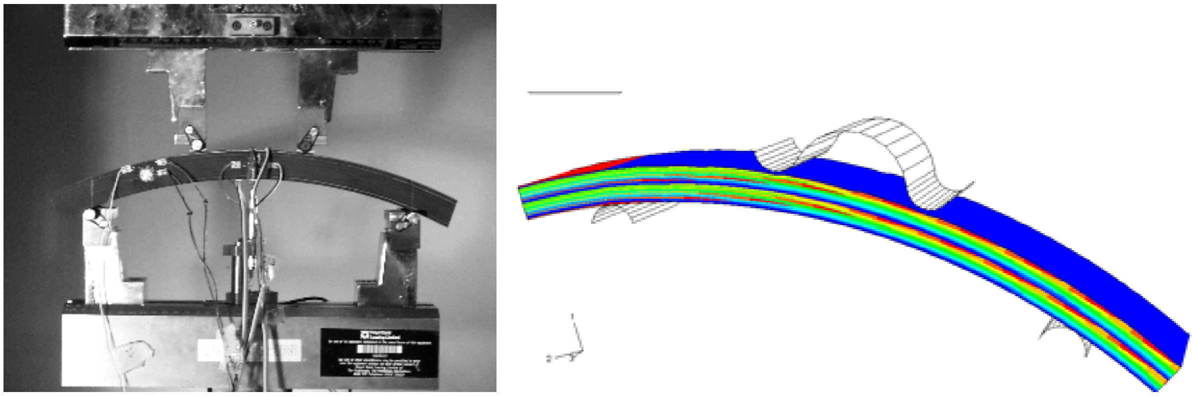

Figure 5 Left, Example of the test set-up. Right, FE model of the test set-up

Figure 5 left, illustrates the artifact and the test set-up used by the National Physical Laboratory in the UK. Figure 5 right, shows the test set-up replicated in FE.

5. COMPARISON OF THE TEST AND FE PREDICTION

This section presents the results of two different material types and geometries. Type A was a wet filament wound process with thickness ‘a’ and Type B was a pre-preg, filament wound process of thickness ‘b’. The laminate orientation and layer thicknesses were also different for each type. The analysis of the results of the two models is presented below.

Figure 6 illustrates the failure obtained during the test of type A, failure propagations in beams from the virtual FE tests and the load displacement curve of the test and the FEA model respectively. The failure propagation of the virtual test of type A is shown in Figure 6 top right & bottom left and it can clearly be seen to correlate well with the actual test shown in Figure 6 top left. The delaminations at the mid point of the test piece and around 1/3rd of the thickness are clearly identified as is the relative severity of the delaminations. Figure 6, bottom right, illustrates the difference between the predicted load displacement curve and that of the actual test using 100% materials utilization. While the displacement to failure correlates well, the actual load seen in the virtual test is much higher.

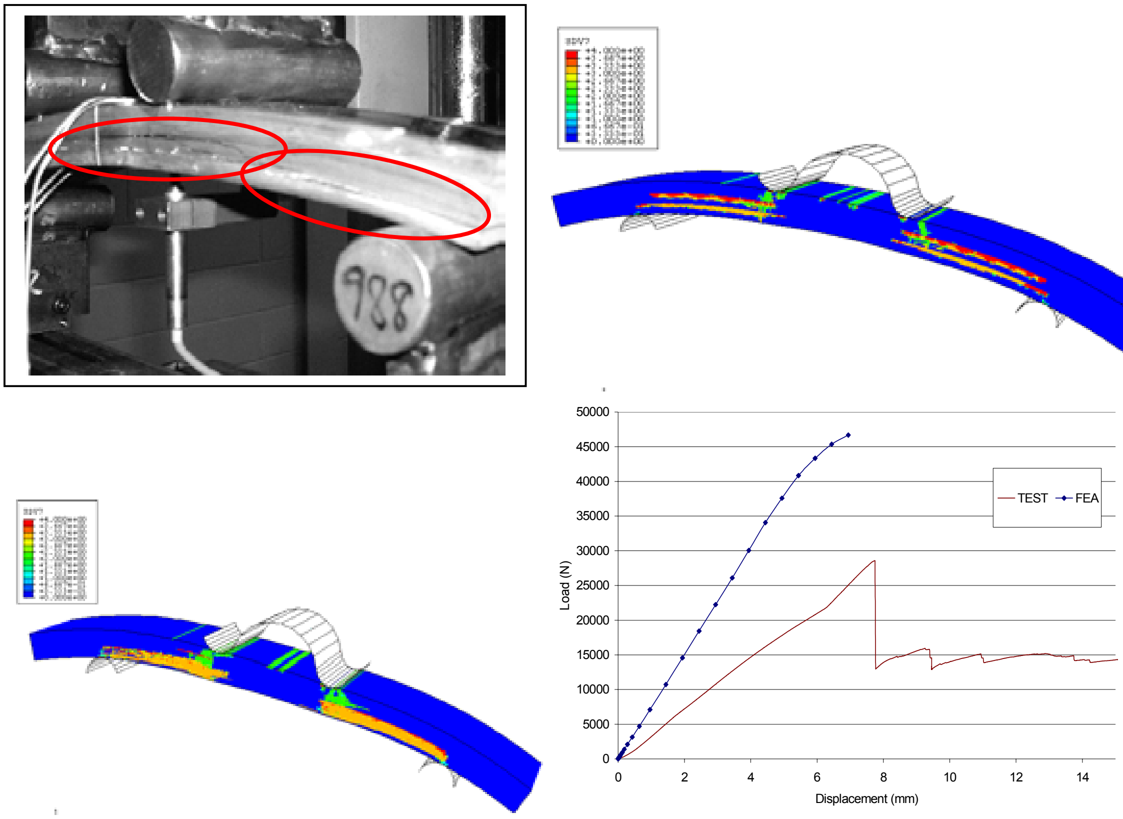

Figure 6 Top Left, Image of failure in Type A, Top Right and Bottom Left, Predicted failure propagation in type A. Bottom Right, Load displacement curve for Type A

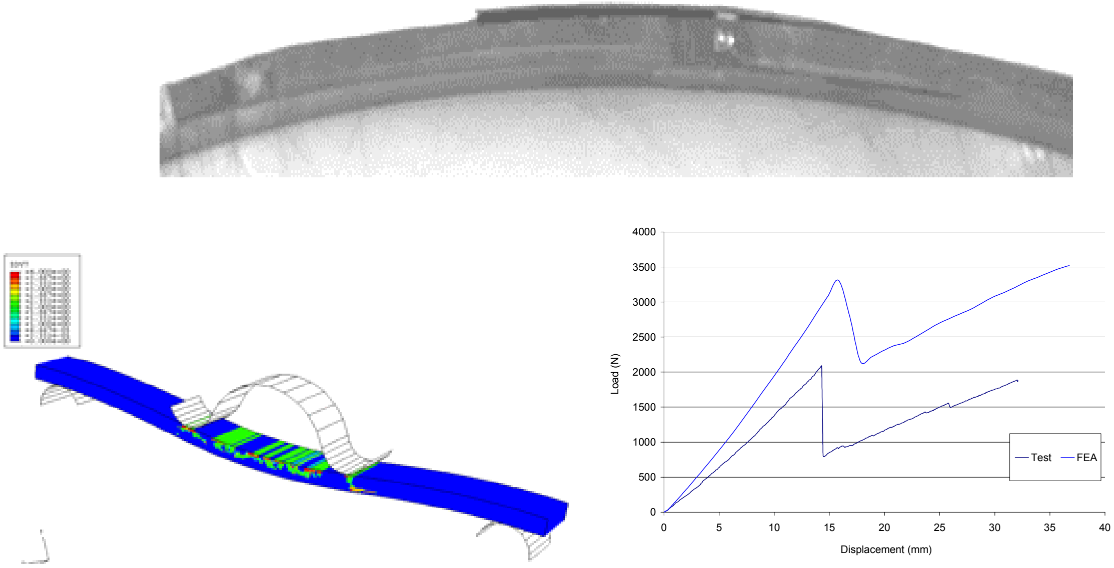

Figure 7 Top, Image of failure in Type B. Left, Predicted failure propagation in type B. Right, Load displacement curve for Type B.

Failure of type B was concentrated in the top layers as can be seen in the top image in Figure 7. This is the scenario predicted by FEA as the virtual test also shows failure dominant along the top layers, seen in Figure 7 bottom left. The load displacement curves of the tests and the FE models for the beams for type B using 100% stiffness and strength utilisation factors are shown in Figure 7 bottom right. It can be seen that even though the response of the test section was captured qualitatively, particularly the deflection at first failures, the magnitudes of the stiffness and the strength are over predicted.

Figure 7 shows images of the failure obtained during the test of type B, failure propagations in the beam sample from the virtual FE tests and the load displacement curve of the test and the FEA model respectively.

6. CORRECTION FACTORS

In order to compare the two samples, the models were tuned to match the stiffness and strength obtained from the experiment. This was achieved by using lamina property utilisation factors on stiffness and strength, k_E and k_F respectively. The material properties used in the model were then obtained by multiplying elastic modulus and strength properties of lamina by appropriate utilisation factors. Figure 8 shows the load-displacement curves for the artefacts where the finite element model was adjusted to incorporate the material property utilisation factors. It can be seen that the use of simple coefficient on the material properties brings the prediction in to line with the actual test results.

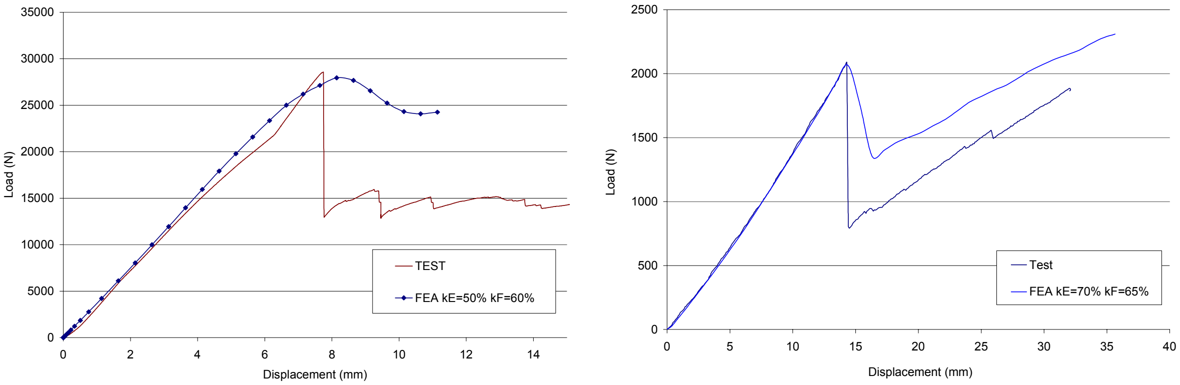

Figure 8 Left, displacement curves for the type A. FEA model uses degraded properties. Right, Load displacement curves for the type B. FEA model uses degraded properties.

The utilisation factors for the cases presented here varied between 50% and 95% depending on the type of material from which they were made. Table 1 shows the improvement of utilisation factor, hence the quality, of the components when comparing Material A with Material B.

Material Property	**Component quality improvement (%)**		
	Type A 1^{st}	**Type B 1^{st} Part**	**Type B 2^{nd} Part**
Stiffness	100	140	150
Strength	100	108	158

Table 1: Component quality improvement

7. CONCLUDING DISCUSSION

It can be seen that improvement in manufacturing process results in significant increase in material utilisation factors. The coupon test data suggested that the pre-preg material exhibited circa 80% of the mechanical properties of the wet wound material. When fabrication and processing conditions are considered it was found that material utilization factors were significantly higher for the pre-preg material, resulting in improved part quality. It clearly demonstrates that process controls contribute significantly to a composite materials ability to perform consistently to its potential. Without proper process controls the material will be under-utilised, a component's performance will not be reliably predicted nor will it perform to a consistent standard. In addition, poor process control leads to higher material costs for a given component since utilization of its properties will be low thus requiring more material than is necessary as well as higher factors of safety. However, while this paper compared wet wound products to pre-preg fabricated products it is not suggested that wet wound process should not be used, merely that such processes require high quality facilities that enable proper control in order to produce consistent, repeatable and known product quality. Pre-preg can have an advantage when proper environmental control can not be achieved, for example if the fabrication shop is subject to seasonal temperature variations.

8. ACKNOWLEDGEMENTS

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