# Performance Assessment of Composite Structures: An Overview of Activities at the University of Southampton

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**Summary:** The purpose of this extended abstract is to provide an overview of activities relating to performance assessments. The work described is wide ranging and not intended to provide a detailed account of any particular approach.

## Introduction

Understanding the mechanical and physical behaviour of layered orthotropic material is an essential key step in performance assessment of composite structures and sandwich structures. At the University of Southampton, UK, work has been conducted in analytical, numerical and experimental techniques for damage assessment of composite materials and structures. Data-rich experimental mechanics techniques have been developed to assess damage using thermoelastic stress analysis (TSA) [1], vibration-based approaches [2-4] and acoustic emission. Alongside this advanced signal processing procedures have been devised to parameterise the data. Work has also concentrated on extracting the stresses and their distributions from complex structures to establish the failure mechanisms and make predictions of the component life [5-8], in particular adhesive joints, e.g. [9].

A range of composite materials have been studied but the main thrust is in applications relating to the marine industry and therefore the work described in this extended abstract will focus on glass reinforced polymer composites; although some recent work on full scale tests in carbon fibre Nomex honeycomb sandwich structure is also detailed. Multi-scale evaluations are described from the fibre matrix interaction to assessment of full scale structure. A key part of the work has been in devising measurement approaches that permit detailed information to be extracted from experimental data to allow comprehensive assessment of structures and materials: some key examples of this are provided. The work covers examples of experimental stress analysis and its use as a validation tool, fatigue damage assessments and applications to NDE. In evaluating performance a key consideration is the manufacturing process and parts of the extended abstract are devoted to the discussion on the effects of manufacturing and concurrent engineering. Finally some insight into through life assessments is provided. The extended abstract concludes with an overview of what the Southampton team regard as technical and scientific challenges facing the marine industry in the future.

## Thermoelastic stress analysis of composite structures

Thermoelastic Stress Analysis (TSA) [1] is a well established technique for the evaluation of stresses in engineering components. The general layout for TSA is shown in Figure 1. All that is required is an infra-red detector and a means of applying a cyclic load. The only preparation that is required is a single coating of matt black paint to enhance emissivity and data that is directly related to the stress can be collected in a matter of seconds. Hence real time data from structures experiencing damage can be obtained. Essentially an infra-red detector is used to measure the small temperature change associated with the thermoelastic effect and is related to the changes in the sum of the principal stresses on the surface of the material. The thermoelastic response from orthotropic composite laminates differs significantly to that from homogeneous isotropic materials. The stress field associated with a typical fibre/matrix composite is essentially discontinuous and on a micro scale cannot be considered homogeneous. The challenge has been to apply this technique to composite structures and obtain meaningful data related to the stresses.

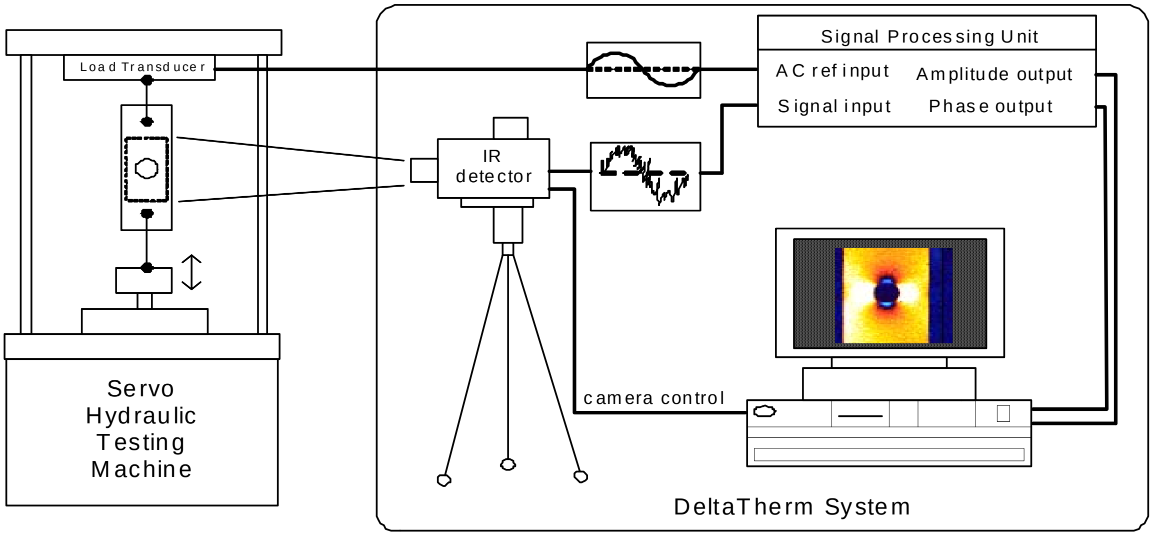


Figure 1 Test set-up for TSA

So far, the application of TSA to composite materials has focused on non-crimp, non-woven fibres, e.g. [10, 11]. In woven material, even under simple loading conditions such as uniaxial tension, the response will be non-uniform and dependent on the orientation of the weave. In general the heterogeneous nature of laminated composite materials produces a non-uniform thermoelastic response. Typically in laminates constructed from layers of unidirectional material, this non-uniformity is only present from lamina to lamina, i.e. through the thickness of the laminate. As the material properties are uniform within a single ply, thermoelastic measurements from the surface may assume orthotropic material properties. Therefore woven materials commonly used in shipbuilding provide an enormous challenge to TSA. Recent work [12] at high magnification on these materials has revealed that the stresses in the woven structure can be obtained using the technique, providing the possibility of identifying damage initiators in structure. A typical data set from a twill type weave is shown in Figure 2. Here the stress concentrations because of the crimp are revealed. It should also be noted that the weave dimension was about 0.5 mm. This means that in this data interaction at the fibre-matrix scale is being revealed, which has not been seen previously, experimentally.

There is significant work being conducted on the load transfer in adhesively bonded joints with specific interest in pultruded composite materials. A numerical model has been developed to represent the through thickness layers in a pultruded material and the materials data for this model was obtained using the TSA technique [13]. Figure 3 shows the stress plots obtained from the TSA and FEA results obtained for an adhesively bonded double lap joint. Figure 4 shows the correlation between the TSA and FEA results. Two FEA results are shown based on assumptions regarding the through thickness thermoelastic constant. The results indicate that the two assumptions, which can be considered to be true upper and lower values, bound the experimental results.

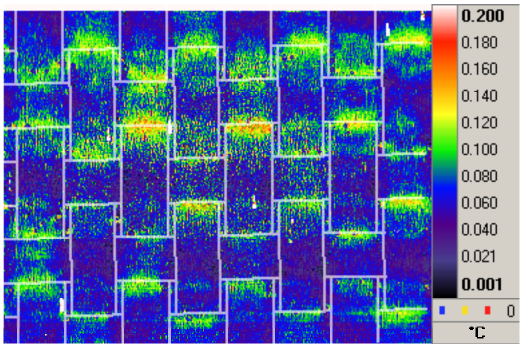
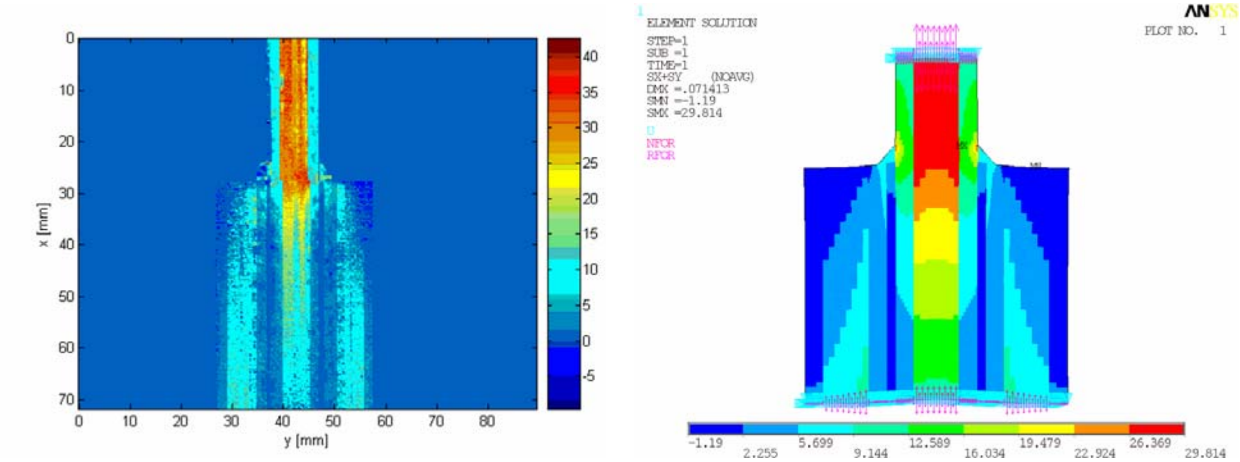


Figure 2 Thermoelastic data from a woven glass epoxy material

Further work is continuing on the determination of through thickness thermoelastic properties for the constituent materials in the pultruded lay-up. This data is essential for the application of the modelling approach for adhesively bonded lap joints where the load transfer is in the through thickness direction. Initial results indicate that the assumptions made as shown in Figure 4 bound the actual results.



(a) TSA (b) FEA

Figure 3 TSA and FEA stress data for a double lap joint in tension

Some recent work on analysis of sandwich structures has included examinations of core junctions [14]. Local effects are caused by the mismatch of the elastic properties of the adjoining materials at the core junctions; local bending of the face sheets is induced, along with local tension or compression of the adjacent cores. This is accompanied by a rise of the in-plane stresses in the sandwich faces and a variation of the shear and through the thickness stresses in the adjacent cores. The effect of such a discontinuity had been studies analytically and numerically. Although some validation work had been carried out using strain gauges, TSA provided a full-field verification of the model as demonstrated by the data shown in Figure 5 for two different face sheet materials.

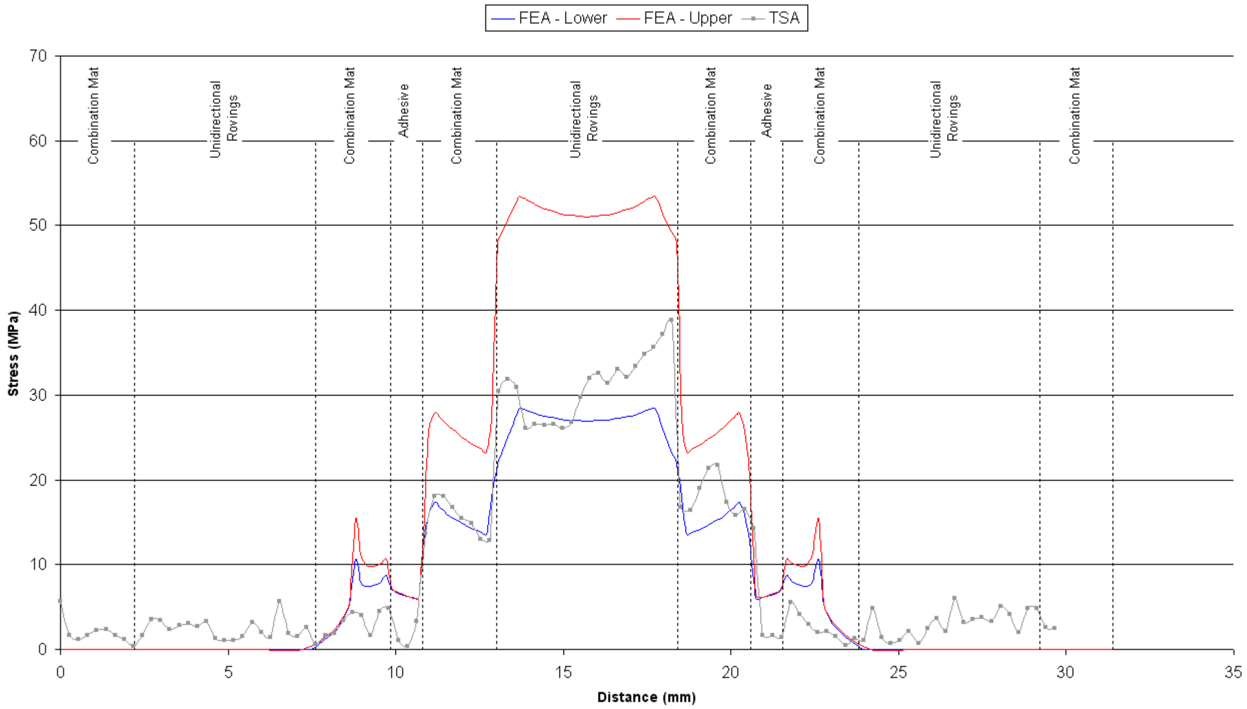


Figure 4 Comparison of TSA and upper and lower bound FEA stress data from a line through the joint near to the end of the straps

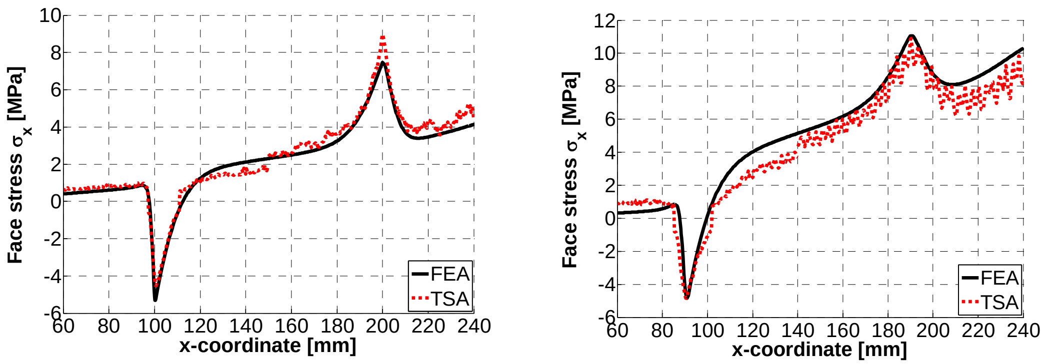


Figure 5 TSA and FEA results obtained for CSM face sheets and NCF face sheets

## Damage evaluation and NDE using infra-red thermography

Figure 6 shows maps of the principal strains around a central circular hole in a glass epoxy plate obtained using TSA subject to progressive damage under fatigue loading. The evolution of the damage is clear. To provide a quantitative damage indicator, Figure 7 shows how the strain metrics obtained from TSA increases with increasing fatigue cycles and how this can be related to stiffness decreases. This demonstrates clearly the strain sum is a useful damage metric as after 11 fatigue ‘packets’ this increases rapidly, indicating that it is necessary to take the component out-of-service and repair. It is noteworthy that the Young’s modulus only shows a steady decrease and does not provide an indicator of when intervention is necessary. The TSA standard set-up requires a cyclic load to achieve the necessary adiabatic conditions to conduct stress/strain analysis, restricting its application to the laboratory. Therefore to full exploit these findings, the challenge is to obtain similar data by applying a transient load to the structure. This would enable the technique to be taken into the field and used to assess damage on in-service structures.

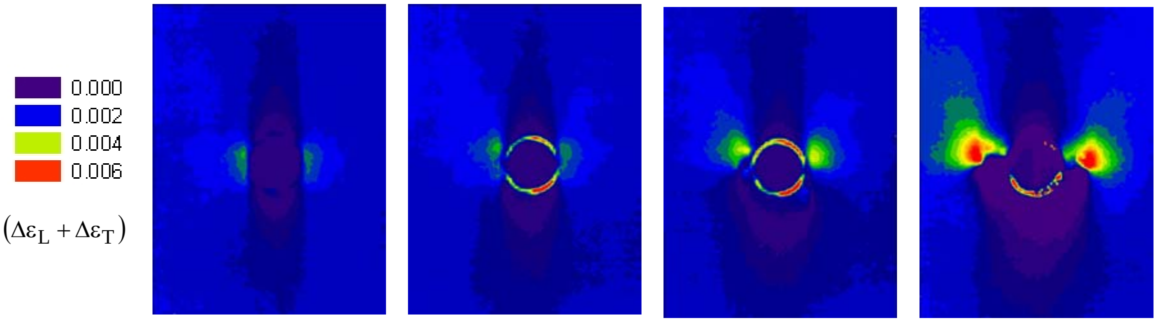


Figure 6 Damage progression around a circular hole

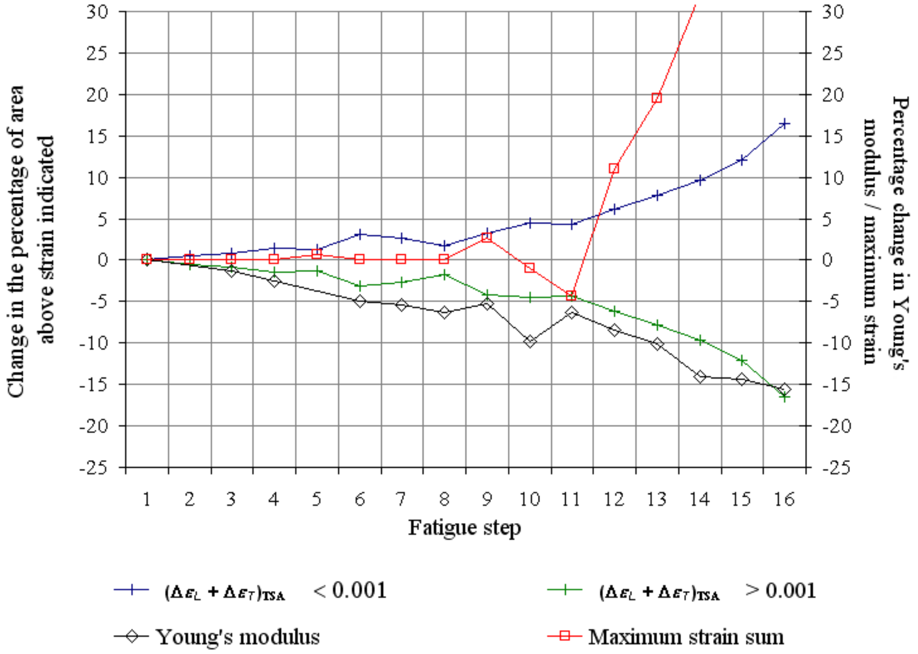


Figure 7 TSA strain metrics and Young's modulus decrease during damaging fatigue

Initial work, using a transient small impact/impulse loading, has shown that a damage detection and quantification NDE methodology based on infra-red thermography is feasible. The technique comprises the use of pulse phased thermography to locate damage and TSA under transient loading to characterise the damage. Some data from a damaged woven structure is shown in Figure 8. Once again the specimen has a circular hole as a stress raiser, however the loading is a single impact. The transient loading approach has been validated using a simple cantilever beam set-up and it has been shown that the stresses obtained correspond with theoretical values. This has provided confidence that heat transfer does not dominate the response and the small temperature change is adiabatic.

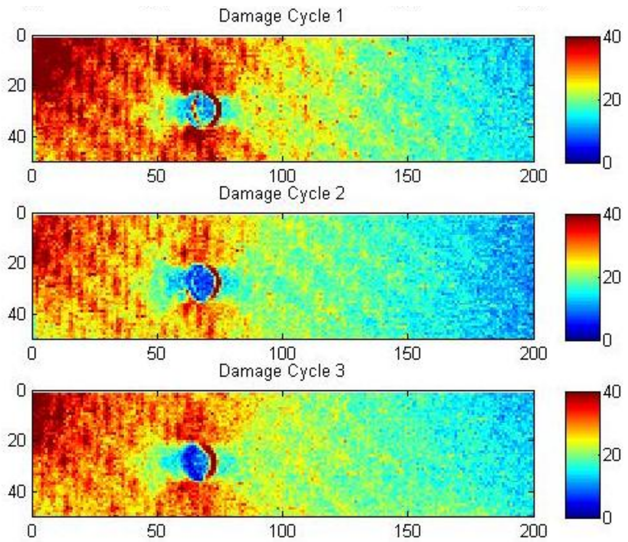


Figure 8 Progression of damage around a hole in a woven GRP specimen – TSA data from an impact load on a cantilever beam

## Full scale assessments of sandwich structure: linking cost and performance

This study provides a detailed consideration of five manufacturing options (MO) that are used to produce aerospace sandwich panels. The structural performance of full-scale panels manufactured from each process was considered and linked with cost analysis. Figure 9 shows an overview of the strategy. By considering the traditional prepreg, autoclave cured process, the sources of cost have been investigated and it has been shown that by removing a portion of the large labour content and the autoclave cure, in favour of an oven only cure, it would be possible to make significant savings. Monitoring the time to manufacture representative full-scale sandwich panels using the five manufacturing options has shown that by using a Resin Film Infusion (RFI) with an oven cure a 30% reduction in time to production is possible. To make an assessment of the comparative structural performance of the face sheets, laminates were produced using the five manufacturing options material quality and mechanical characterisation tests are required. The results of the tests showed that the laminates produced using RFI are comparable in quality and performance. A full-scale test rig has been designed to replicate the in-service load, shown in Figure 10. In service the panels are subjected to a pressure load across the mould side face sheet, which is constrained by bolts on three sides. To experimentally model the pressure load, a water filled cushion is used to impart the load into the panel in a uniform fashion. The design is such that it is suitable for full-field measurement techniques (TSA and digital image correlation) to assess the stresses and deformations in the panels and identify regions of weakness resulting from the manufacture. A full description of the test rig is given in [15] and preliminary work on the full-field experimental analysis is given in [16].

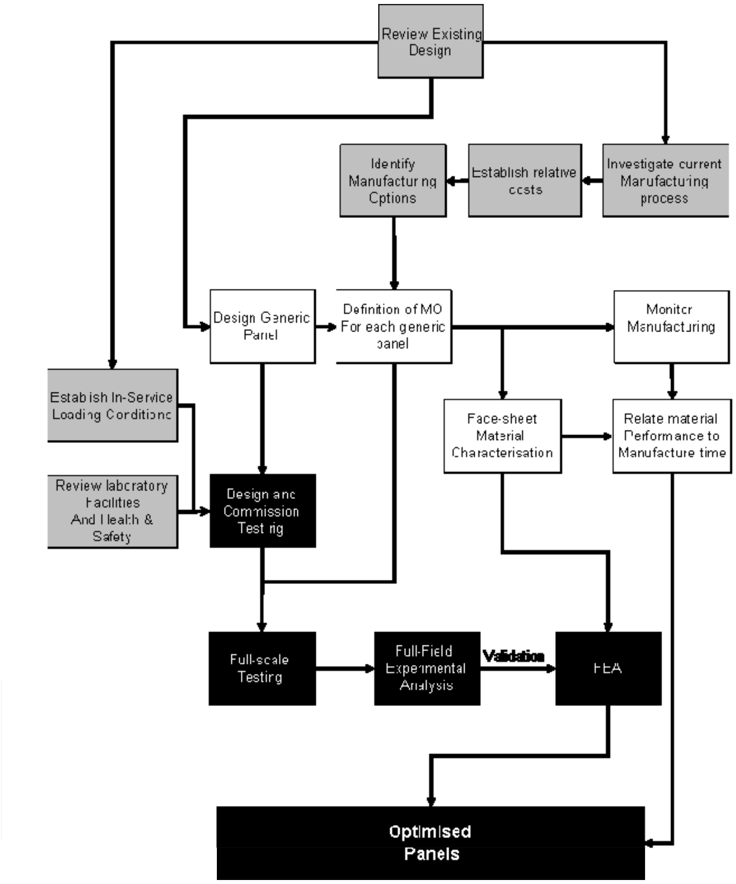


Figure 9 Linking cost of manufacture with performance

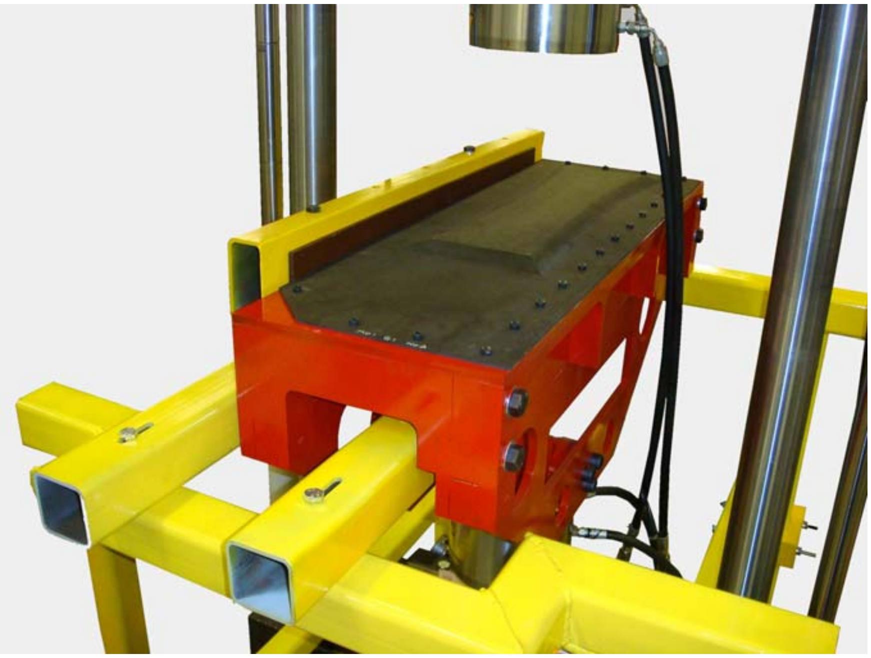


Figure 10 Full-scale test rig in servo-hydraulic test machine

## Concurrent Engineering

Commonly, small FRP boat design and production in the leisure industry is inefficient by being sequential in practice and in a highly competitive market attention has been turned to alternative successful design and production techniques employed in other sectors. Improving the design process can have a significant impact on the cost of the final product – whilst around 5% of the final product cost comes from design costs, design value can affect the final product cost by up to 80%. In the aerospace and automotive industries, concurrent engineering uses parallel instead of sequential design processes, thereby allowing simultaneous changes necessitated by inputs from, for example, production engineers, quality assurance, structural engineers, outfitters and classification societies to lead to a rapid optimal design, reducing design and production times and increasing quality with little penalty in cost. The aim of current work is to assist the UK boat building industry to embrace modern integrated design and production techniques to help maintain and improve its competitive position and speed up new product introduction.

The work undertaken to date [17-19] has concentrated on four main areas, namely materials database issues, design codes and standards, production process modelling and concurrent engineering principles. Using a web-based environment with easily accessible Microsoft Access™ and Excel™ facilities, concept design, detailed design and production can be fully integrated, as shown in Figure 11.

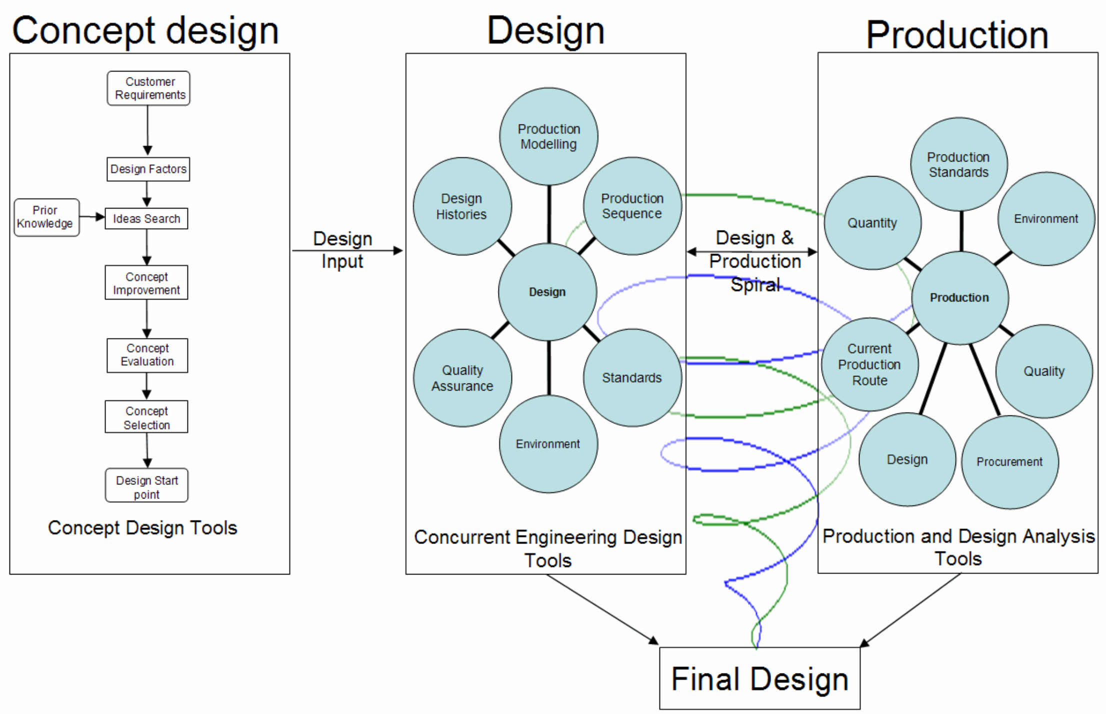
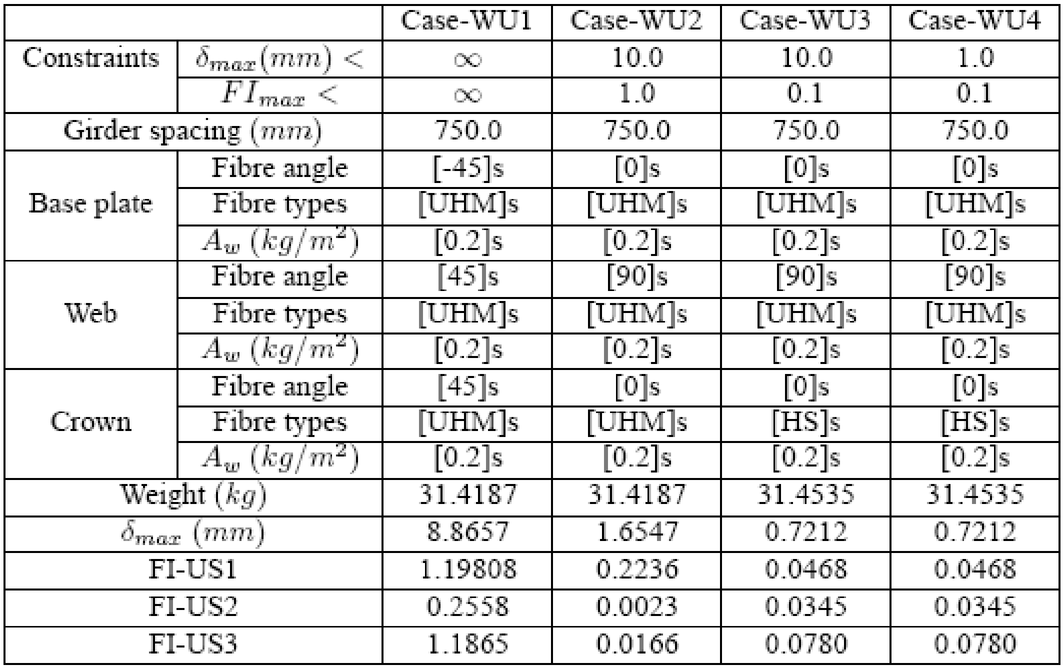


Figure 11 Diagrammatic representation of concurrent engineering environment for FRP boat design and production

One aspect of the concurrent engineering tool being developed is the optimisation of stiffened FRP panels typically found in small boat construction. Using a materials database, an analytical grillage analysis, production cost modelling and Lloyds Register Special Service Craft Rules and ISO 12215-5 rules, candidate design solutions can be rapidly assessed for reduced cost and weight using a genetic algorithm. Table 1 gives an example of optimised layup schedules for unidirectional stiffened panels under 4 different stiffness and strength criteria. Alternative panel limit states can be incorporated using relevant failure criteria for differing modes of loading: Table 2, for example, shows the influence of including the constraints of 4 failure models including buckling on the weight and cost of a stiffened panel in the boat's sideshell (6m$^2$).

To incorporate the importance of design histories in optimised design, the application of neural networks to facilitate self learning within the concurrent engineering environment is envisaged; thereby lessons can be learnt for new designs from records of previous design successes and failures, helping to make concurrent engineering philosophies and practice a step change in the UK small FRP boat production sector and an injection for international competitiveness.



| | | Case-WU1 | Case-WU2 | Case-WU3 | Case-WU4 |
|---|---|---|---|---|---|
| Constraints | $\delta_{max}(mm) <$ | $\infty$ | 10.0 | 10.0 | 1.0 |
| | $FI_{max} <$ | $\infty$ | 1.0 | 0.1 | 0.1 |
| Girder spacing $(mm)$ | | 750.0 | 750.0 | 750.0 | 750.0 |
| Base plate | Fibre angle | [-45]s | [0]s | [0]s | [0]s |
| | Fibre types | [UHM]s | [UHM]s | [UHM]s | [UHM]s |
| | $A_w\ (kg/m^2)$ | [0.2]s | [0.2]s | [0.2]s | [0.2]s |
| Web | Fibre angle | [45]s | [90]s | [90]s | [90]s |
| | Fibre types | [UHM]s | [UHM]s | [UHM]s | [UHM]s |
| | $A_w\ (kg/m^2)$ | [0.2]s | [0.2]s | [0.2]s | [0.2]s |
| Crown | Fibre angle | [45]s | [0]s | [0]s | [0]s |
| | Fibre types | [UHM]s | [UHM]s | [HS]s | [HS]s |
| | $A_w\ (kg/m^2)$ | [0.2]s | [0.2]s | [0.2]s | [0.2]s |
| Weight $(kg)$ | | 31.4187 | 31.4187 | 31.4535 | 31.4535 |
| $\delta_{max}\ (mm)$ | | 8.8657 | 1.6547 | 0.7212 | 0.7212 |
| FI-US1 | | 1.19808 | 0.2236 | 0.0468 | 0.0468 |
| FI-US2 | | 0.2558 | 0.0023 | 0.0345 | 0.0345 |
| FI-US3 | | 1.1865 | 0.0166 | 0.0780 | 0.0780 |

Input constraints

Calculated deflection

Calculated FI's (3 locations)

Table 1 Weight minimisation of unidirectional stiffened FRP plate subject to stiffness and strength constraints (FI is failure index)

| | Mass (kg) | Cost (£) |
|---|---|---|
| **Lloyds Register SSC Rules:** | 151.42 | 371.92 |
| **Analytical approach:** | | |
| *Strength limit state* | 88.11 | 338.56 |
| *Strength, Deflection & Buckling limit states* | 104.12 | 315.60 |

Table 2 Effect of limit state constraints on stiffened FRP panel weight and cost

## Life Cycle Assessment: thermoplastic matrix composites

The understanding of the environmental impact of a product will encourage better industrial practice and be more adaptable in order to exceed current legislation which is becoming increasingly strict and requires the manufacturer to take more responsibility for their production and products. The marine industry has been investigating the use of thermoplastic matrix composites (TMCs) as an alternative to thermoset composites for a number of years. The marine industry cannot use costly high-performance materials which require specialised curing cycles. Therefore there has been increasing interest in the use of cheaper and lower performance polypropylene thermoplastics and glass reinforcements as a recyclable and durable structural material. Current work is investigating the life cycle of a marine structure from raw material to full disposal using an embodied energy approach [20].

A grillage structure is used to highlight the issues concerned. Four materials were considered, steel, aluminium, glass reinforced epoxy (GRE) and TMC. Plate thickness and stiffener dimensions were determined in order to ensure that the stress in the grillage did not exceed 60% of the yield stress of the material and that the mid-point deflection of the panel did not exceed 1% of the panel width. The dimensioning was conducted using Vedeler’s analytical model for grillage structures. The initial results were presented as a weight value and showed that steel (107 kg) and aluminium (38 kg) were the heaviest options. Both GRE and TMC were lighter at 28 kg and 23 kg respectively. Data was collected regarding the energy required to manufacture the raw materials for all four material choices. Manufacturing methods were explored and the associated energy consumption calculated for cutting and joining. Post life disposal methods were examined, recycling as the option for both steel and aluminium and mechanical and incineration options explored for the composite materials. The results of the energy analysis are shown in Figure 12. Two results are provided for the energy required to produce the raw materials, the high value is for virgin material the low value is for material is obtained using recycling. The results show a large difference between virgin and recycled metallic materials, most possibly due to the process maturity of recycling metals. This is not reflected in the composite results. However, one cannot specify only recycled steel for construction and so the question remains - How much energy does steel manufacture consume? This will vary depending on the amount of recycled scrap is used in the process and the type of furnace that is used for steel manufacture. For the composite results there is little difference between virgin and recycled materials. In general recycling in this study was the generation of energy through incineration of the used composite which can offset the energy required to manufacture new material.

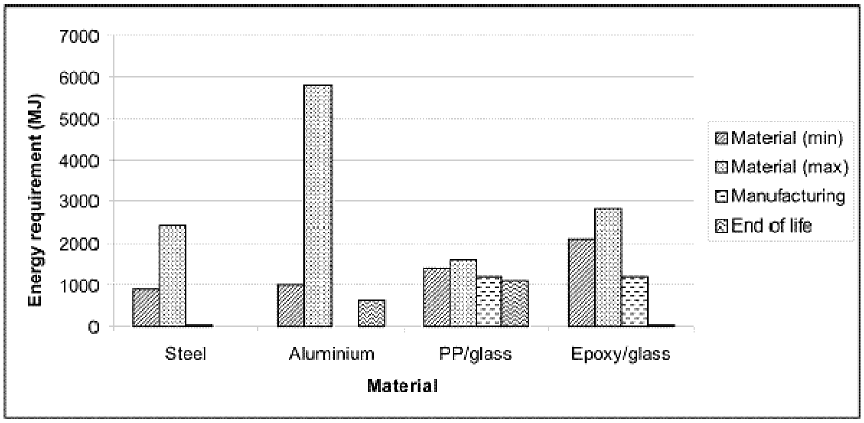


Figure 12 Results of embodied energy analysis for candidate materials

## Conclusions

An overview of activities at the University of Southampton has been presented in the paper leading to the following five technical and scientific challenges:

1. Enhanced levels of fundamental understanding of the load transfer mechanisms in layered orthotropic structures using empirical, physical means to ensure enhanced confidence in theoretical modelling capabilities.
2. Better appreciation of the modelling of safety concerns that account for potential variabilities and uncertainties in material and structural behaviour.
3. Life cycle assessment of composite structures, leading to cradle to grave design concepts, that are better able to account for environmental impact based on energy considerations.
4. Development of concurrent engineering approaches that account for design-production interaction leading to specification of optimal design choices from a costings viewpoint.
5. Identification of apt inspection, intervention and repair strategies for ensuring continued structural health of the artefact through its life.

Underpinning these key challenges for the future are two larger societal concerns. Firstly, on an economic front, we need to ensure that CAPEX and OPEX of ships, boats and other marine artefacts, are optimised and the materials specification leads to such a goal. Secondly, with ever growing concern for sustainability, it is important to appreciate and understand life cycle issues from an environmental impact viewpoint.

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