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about 6400 words

COMPOSITE MATERIALS FOR MARINE APPLICATIONS – KEY CHALLENGES FOR THE FUTURE

by

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Introduction

Polymeric composite materials have been used in boats, ships, submersibles, offshore structures and other marine structural applications for about fifty years. Considerable progress has been made in this period on understanding the behaviour of these materials and the tailored structures under mechanical, thermal and fire induced load scenarios. Processing and production considerations too have received much attention leading to a capability of constructing quite complex, multi-material, large, three-dimensional assemblies capable of sustaining extreme loads. Nevertheless there is still an air of conservatism and even hesitation in specifying polymer composite based solutions for several applications. This is owed to doubts about new ways to use existing materials or to use new and existing materials in new applications. This implies the need for further work for enhanced application and use of composite materials in marine applications.

The key challenges for the future are two-fold. Firstly, on an economic front, we need to ensure that CAPEX (Capital expenditure) and OPEX (Operating costs) 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. Thus one could argue that these two-fold economic and energy-based outcomes lead to the following five technical 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.

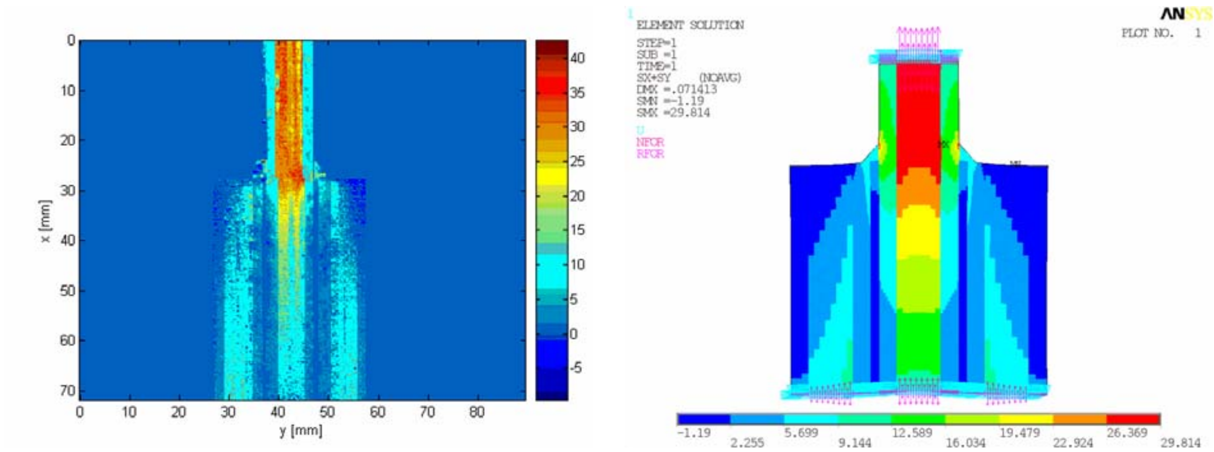
Load Transfer Mechanisms

In recent years there has been an increasing demand for large high-speed marine vehicles such as passenger/vehicle ferries. In these vessels, structural weight is of great importance; lighter weight leads to greater speeds, payloads, and/or fuel economy. Fibre reinforced polymer (FRP) materials offer potential savings in structural weight and have been successfully employed in the construction of a variety of boats and small ships. However the current wet lay-up production techniques have a number of disadvantages; construction of a mould is both expensive and time-consuming, storage of the mould requires substantial space (often at a premium in modern shipyards), whilst emissions from the polymer resins during the curing process can have significant health and safety implications for the workforce. The adoption of a construction technique utilising standard parts based on pre-formed components could reduce or even eliminate some of these disadvantages.

In an effort to simplify the construction of relatively high-speed craft, there has been a move towards the use of extruded aluminium components in substantial parts of their structure. There are now a variety of standard and proprietary extruded planks, which incorporate stiffeners and edge details to allow rapid and economic lightweight construction. Similar concepts have been developed in civil and aerospace engineering applications utilising FRPs in the form of pultruded planks in the construction of lightweight structures such as bridge enclosures and footbridges. However, whilst the planks in these structures are bonded along their edges, structural butt joints are generally not required, either because the structures are sufficiently small that joints are not needed, or because the structure can be built in such a manner that joints are staggered, and longitudinal loads can be carried over a joint by neighbouring planks.

Some interest has developed in the possible use of pultrusions in ship construction. However, transfer of the civil engineering technology to ship construction is not without challenges. Typical ship lengths of interest are much greater than the maximal length of plank that can be economically transported, whilst ship construction practice often requires butt joints to be aligned to allow construction of the ship in discrete “modules”. Finally, present marine design practice requires effective stressed skins in all in-plane directions in order to resist longitudinal and transverse bending of the hull girder. There is thus a requirement for strong and efficient butt joints between plank components if pultrusions are to be used in this context. Initial work on pultruded joints [1] considered butt joint design and the limits of existing materials and joining techniques. Finger joints in glass reinforced plastic (GRP) material, that model pultruded construction, have also been considered [2]. Various joint geometries were examined and the full-field stress distribution over the joint from thermoelastic stress analysis (TSA) was compared with load displacement behaviour. TSA is a well-established full-field, non-contact stress analysis technique based on infra-red thermography. It was shown that by increasing the fingertip angle there is a decrease in load carrying capacity, a decrease in shear stress and an increase in stress concentration factor at the finger joint tip. The results from the experimental work were used to validate a numerical model that provides data for initial joint optimisation.

Continuation of this work considered the load transfer in adhesively bonded joints manufactured from 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 [3]. Figure 1 shows the stress plots obtained from the TSA and finite element analysis (FEA) results obtained for an adhesively bonded double lap joint.



(a) TSA (b) FEA

Figure 1: TSA and FEA stress data for a double lap joint in tension

Figure 2 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.

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 2, bound the actual results.

The use of lightweight materials for the construction of the superstructure and other associated structures such as communication masts for marine vehicles and in particular naval vessels has been under investigation since the late 1980's. Initial work naturally focused on the advantages of using GRP such as the weight savings and the lowering of the centre of gravity of the ship, as well as the risk to key operational aspects such as air blast, fire, radar signature and infrared signature. It was not until the late 1990's and early 2000's that the vital topic of how the composite superstructure should be attached to the steel hull began to be investigated.

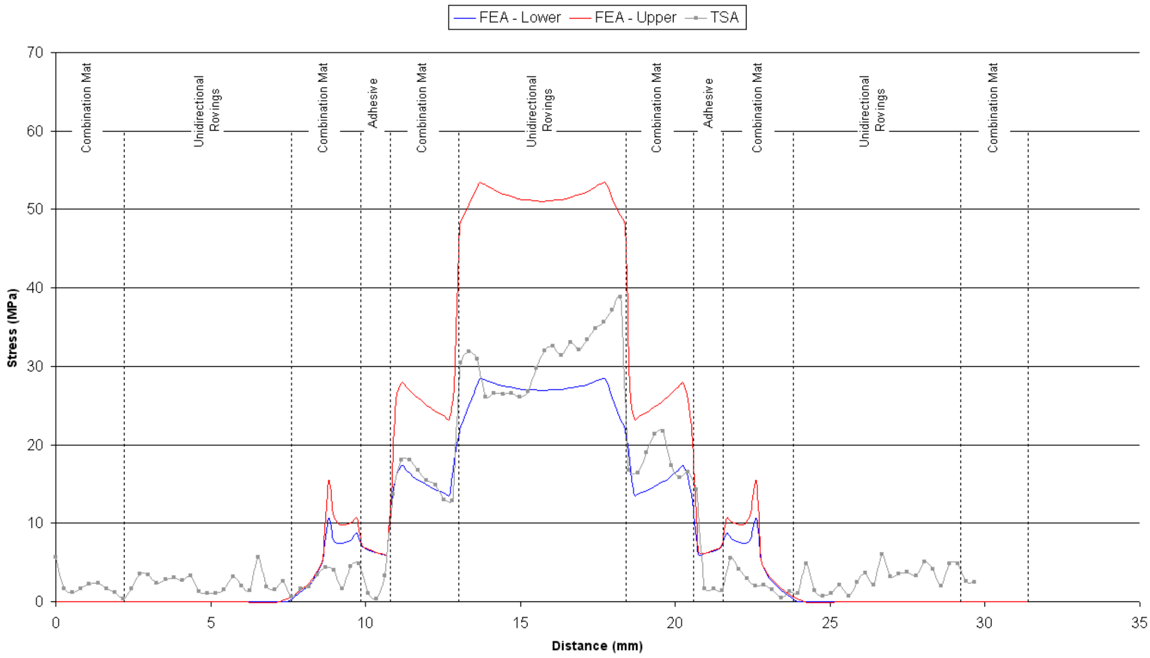
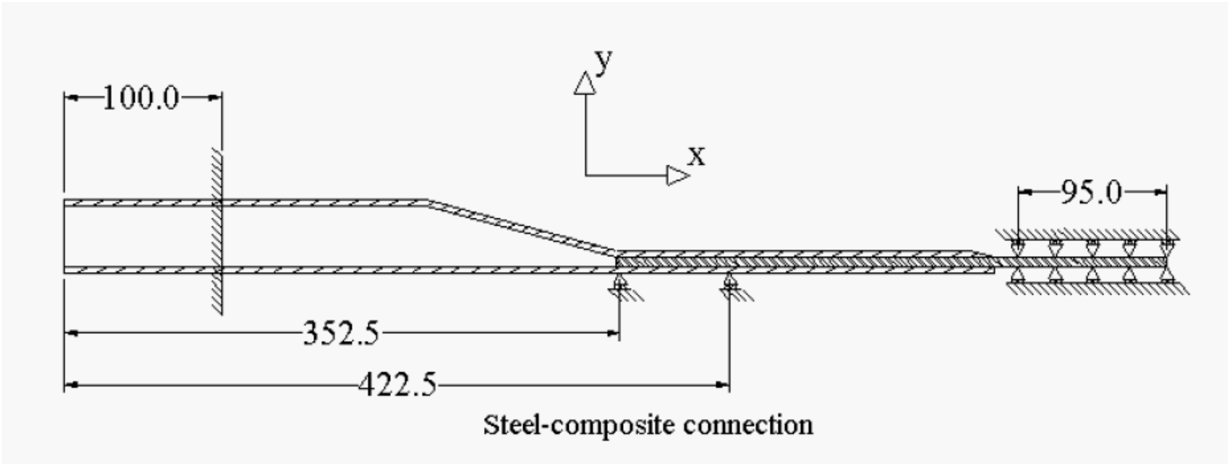
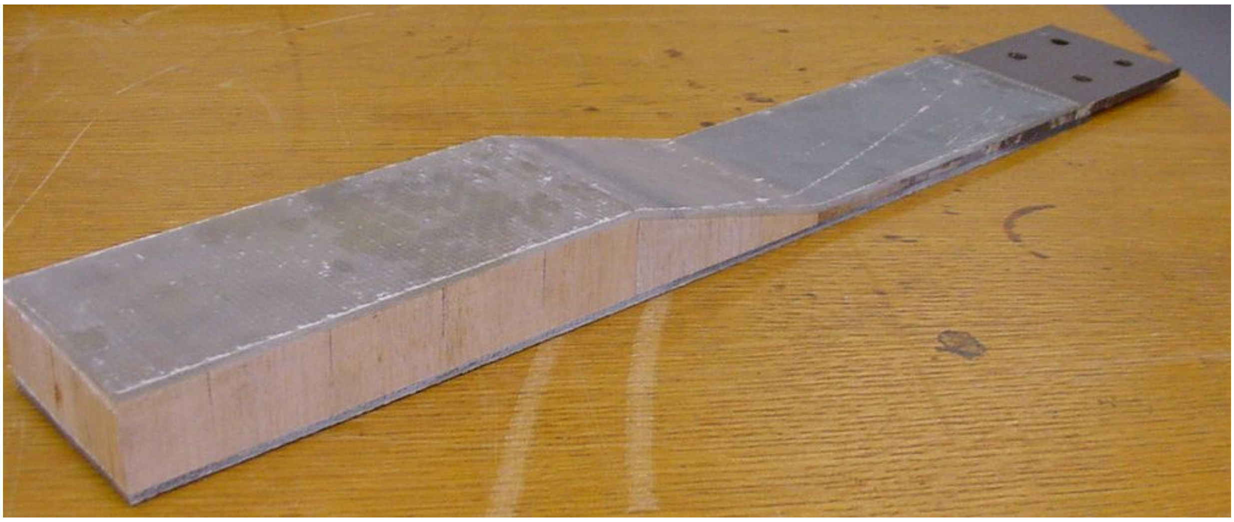


Figure 2: Comparison of TSA and upper and lower bound FEA stress data from a line through the joint near to the end of the straps

Joints consisting of an aluminium or steel section laminated into a composite sandwich panel, also know as hybrid joints, have been found to be most suitable. The joint that has been subject to the most attention and is thus the focus of research attention at the University of Southampton is that shown in Figure 3, which is used in the construction of the helicopter hangar on the French La Fayette class frigates. This work was supported by the UK Ministry of Defence (MOD) to gain a better understanding of the strength and durability of the steel to composite connection shown in Figure 3. Some aspects, such as the static compressive strength and fatigue life characterisation of the connection, were investigated through the European project EUCLID RTP3.21 and the results published in Ref. [4]. Further aspects, such as the consideration of the performance of the joint after artificial hygrothermal ageing, the numerical modelling and prediction of failure of the connection, and the optimisation of the connection for the applied loads is provided in Ref. [5]. The results of this work identified the static and fatigue characteristics of the joint to provide information on how the connection behaves under axial loading, as well as the location of initial failure under static loading. In addition, a statistical function was used to correctly represent the fatigue characterisation curve. The long-term accelerated ageing program, to investigate the influence of moisture on the connection, found that the in-plane tensile performance of the joint was unaffected by the accelerated ageing process. The research also investigated the behaviour of the steel-composite joint, providing information vital to the understanding of the mechanisms of stress distribution within the joint and the progression of failure. The progressive damage modelling used a new method of defining the degradation of the material properties post-maximum stress.



(a) Schematic representation and boundary conditions



(b) Photograph

Figure 3: Hybrid steel-composite connection

In addition the model for the degradation was based on a new method of incorporating fracture toughness energy as the variable to describe the mathematical function of property degradation. Genetic algorithms were used to investigate the design space of the steel-composite joint and provided a number of possible improvements to the performance of the joint through geometric changes alone. The main objective of the study was reduced joint weight. This highlighs the importance of optimisation as a tool for the structural engineer in an area where little research has been conducted. A large step change in performance in terms of weight was achieved through the use of this optimisation technique. Overall the research provided valuable information that can be used by the naval architect to better understand the application of steel-composite joints in a marine structure.

Safety

One of the challenges in composites, particularly when products such as ships and boats are made-to-order, with each being of a different design and specification, which militate against extensive testing and prototyping, is the mechanism to manage variability and uncertainty. The variabilities could be related to fabrication-driven, strength-driven and through-life-driven factors.

On the fabrication side one has to consider the following:

- Process type (Spray-up, HLU (Hand Lay-up), VARIM (Vacuum Assisted Resin Infusion Moulding), Prepreg)
- Topology (single skin monocoque, single skin stiffened, sandwich, hybrid)
- Reinforcement type (CSM (Chopped Strand Mat), CFM (Continuous Filament Mat), weaves and stitches)
- Reinforcement material type (Glass, Kevlar, Carbon, hybrid)
- Resin variability (polyester, vinyl ester, epoxy, phenolics) – even from component to component in one structural piece
- Core variability (balsa, PVC (Polyvinyl Chloride), honeycomb) – densities vary from part to part

On the strength side, typically the factors that would need quantifying would be:

- Variation of loads – leads to uncertainties
- Difficulty in prescribing fixity at boundaries – leads to uncertainties
- Variability in material properties – process and operator dependence; affects strength calculations
- Variety of failure limits (e.g. y% of ‘ultimate strength’ as per ABS (American Bureau of Shipping) rules or 30% failure strain implicit in LR (Lloyd’s Register of Shipping) rules)
- Variety of failure models (independent stress/strain or interactive criteria)

On the through-life side, the typical factors are three-fold:

- Fatigue calculations noting variability of loads + load sequence effects and validity of linear Miner’s Rule, S-N response, failure modes
- Durability issues (laminate versus core material versus structure)
- Fracture and life estimation including such issues as consistency of crack initiation locations/causes, crack propagation mechanisms and directions, modelling parameters and validity of Paris equation

One approach to address these variabilities and uncertainties is through the use of partial safety factor approaches such as those suggested in some civil engineering codes [6, 7, 8]. These seek to ensure that for any given limit state the calculated effects of destabilising loads (S) are less than the resistance of the structure (R) by a margin commensurate with the required probability of failure. To achieve this, design variables subject to statistical uncertainty are factored by partial safety factors. This can be expressed as:

$$S\left(x_{L,i} \quad \gamma_{fL,i}\right)\gamma_{f3} \prec R\left(a_d \quad x_{M,i} / \gamma_{M,i}\right) \tag{1}$$

where $x_{L,i}$ are the load variables, a_d are the design values of the geometric data and $x_{M,i}$ are the material variables. The partial safety factors can be stated as, $\gamma_{fL,i}$ on the *i*th applied loads, γ_{f3} allows for uncertainty in the design and $\gamma_{M,i}$ on the *i*th material property.

An alternative is a full level 3 probabilistic approach [9, 10] where the reliability of a structure is defined as the probability that the structure will perform its intended function without failing. Defining a performance function, or limit state function, g(x), as the difference between structural "capacity" and "load" then:

- When g(x) > 0 then the structure is safe, "capacity" is greater than "load"
- Conversely, when g(x) < 0 then the structure has failed
- g(x) = 0 defines the boundary between survivability and failure, the limit state itself

The reliability index or safety index is effectively a measure of how far inside the "safe" zone the structure is operating – approaching a zero value, the probability that a structure will fail approaches 100%. As an example, when "capacity" and "load" are normally distributed then Table 1 below describes the decreasing likelihood of failure with increasing safety index:

Safety Index	Probability of Failure
1.28	10^{-1}
2.33	10^{-2}
3.09	10^{-3}
3.71	10^{-4}
4.26	10^{-5}
4.75	10^{-6}
5.19	10^{-7}
5.62	10^{-8}
5.99	10^{-9}

Table 1: Safety index vs. probability of failure (normally distributed variables)

Some work has been done to date in the strength assessment of single skin [11, 12] and sandwich structures [13] as well as fatigue and lifing of composite structures [14, 15, 16]. However, it is clear from these and other current studies that a variety of hypotheses about materials and structural modelling as well as believable materials data sets need to be challenged and new approaches developed.

Other collaborative work has the strategic goal to develop a new stochastic approach to the design of composite structures that is able to account for variations in material properties, geometric indices and processing techniques, from the component level to the full system level. The research focus at the University of Southampton is on the mechanics of composite structures and supplying details of variabilities in composite materials/structures. Other partners focus on stochastic modelling and reliability predictions for use in design. The four phases of the work are:

Phase 1: Identifying the merits of reliability based approaches in composites structures
Phase 2: Application of the reliability approach to stiffened marine composite structures
Phase 3: Use of general purpose FEA coupled with reliability models for stiffened single skin and sandwich panels
Phase 4: General design formulations and recommendations

The first two phases of this work have been completed to date. At the conclusion of Phase 1 various models on time-variant reliability were put forward and an example showing how FE methods can be interfaced with FORM (First Order Reliability Models)/SORM (Second Order Reliability Models) provided. A sensitivity analysis of a laminated plate showed that the influence of load had the greatest influence on the probability of failure, followed by material property.

In Phase 2 the work of Phase 1, modelling of unstiffened composite plates under loading and the subsequent reliability of those plates in withstanding those loads before first ply failure, was extended to the modelling of stiffened composite plates under loading. A practical grillage methodology, using the Energy Method, was identified and extended by the use of equivalent elastic properties for composite modeling. This methodology was applied to the reliability analysis for a composite stiffened plate. Phase 2 demonstrated the importance of accumulating good qualitative data in forming target structural reliability and therefore efficient design. This was revealed by consideration of the effects of the probability density functions, representing the behaviour of the random variables, on the derived structural reliability. As an example load is typically considered to be a subjective uncertainty as often the phenomenological behaviour, such as wave loads, is not wholly understood. Thus during Phase 2 a change was made in the definition of all the variables, from normal distributions to Weibull distributions.

The benefit of using reliability analyses to identify which random variables are more influential on the resulting performance of the finished composite product was also shown. In terms of manufacture or repair this may have the more obvious advantage of allowing the engineer to concentrate on these more important areas – for example, geometry, fibre angle as cloths are stacked, process technique to maximise fibre volume fraction and so forth. The application of a grillage analysis for composite stiffened plates in Phase 2 has led to the definition of subsequent structural reliability that has been applied for the two limit states of stress and deflection. The results from these tests show the versatility in the reliability approach and the ability to better define partial and full safety factors for composite design purposes.

Life Cycle Assessment

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.

There is recognition of such environmental impact issues through, for instance, the issuance of standard procedures (ISO14040) [17]. A typical life cycle comprises sourcing of base materials, processing and production of components that form the ship/boat, manufacturing of the ship/boat, lifetime operations of the ship/boat and disposal or recycling of the ship/boat at the end of its useful life. Life cycle assessment (LCA) approaches can be used for materials selection in which intrinsic properties that may have an impact on how they are implemented in design are considered. While much is being done in many areas of engineering application, it is felt that such approaches could be usefully adapted and extended to marine structure design too, particularly noting the increasing interest in such features by the IMO (International Maritime Organisation), which is currently developing a Convention to provide globally applicable ship recycling regulations for international shipping and for recycling activities [18]. The Marine Environment Protection Committee (MEPC) at its 57th session from 31 March to 4 April 2008, made substantial progress in developing the draft text of the International Convention for the Safe and Environmentally Sound Recycling of Ships, a new convention which will provide globally applicable ship recycling regulations for international shipping and for recycling activities. The new convention will provide regulations for the design, construction, operation and preparation of ships to facilitate safe and environmentally sound recycling, without compromising the safety and operational efficiency of ships; for the operation of ship recycling facilities in a safe and environmentally sound manner; and for the establishment of an appropriate enforcement mechanism for ship recycling, incorporating certification and reporting requirements.

Current work is investigating the life cycle of a marine structure from raw material to full disposal using an embodied energy approach [19]. 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 4. 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 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.

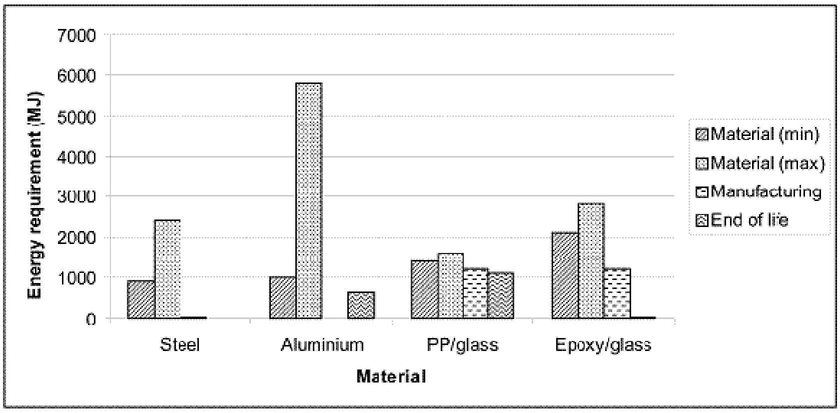


Figure 4: Results of embodied energy analysis for candidate materials

Concurrent Engineering

In the ship and boat design process, appraisal of alternatives plays a key role in obtaining a successful result. An incorrect decision at the initial appraisal stage can have a significant effect on the costs of building a boat or ship. This is compounded in the marine industry by a number of of commercial factors.

- The margins between a profitable and non-profitable design and build are small
- The competition between yards in different countries is very high
- There is a need to get out new models on a regular basis
- It is important to be seen to market products having 'high tech' credentials
- There is a good availability of new materials with potential for better performance
- There is growing commercial and regulatory pressure to introduce new processing techniques

There is intense competition in the boat and ship building market. This requires companies and yards to be innovative and capable of adapting new materials, structures and production technologies in order to generate new, market-leading designs that are cost-efficient to manufacture. There is a long history of approaches applied to steel ship structure design from the 1960s [20] through to the 1980s [21].

There is a need to try and address such issues from a composites viewpoint. Possible approaches will need to be comprehensive in addressing all pertinent facets. Figure 5 shows such a relationship.

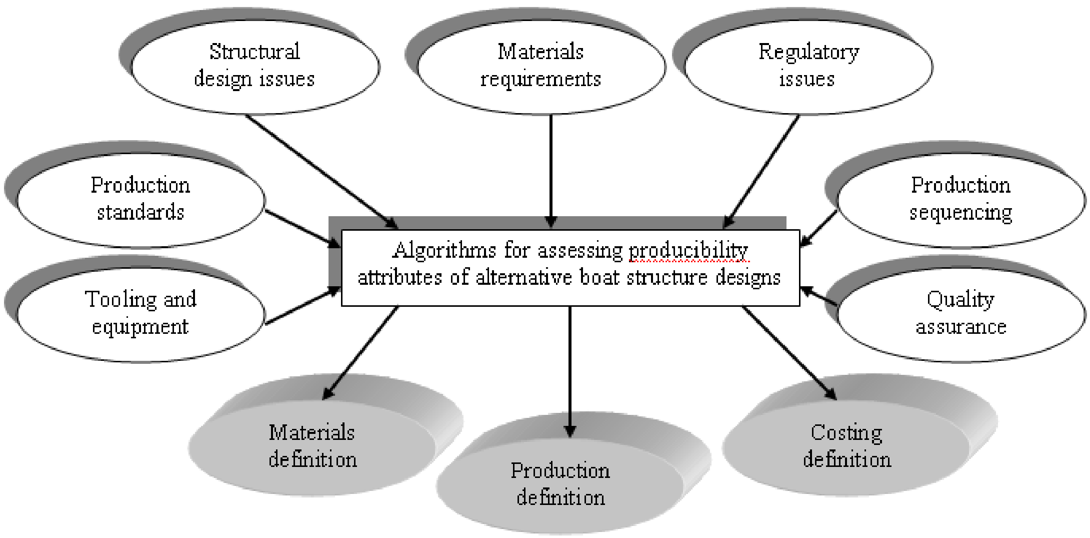


Figure 5: Issues to be considered in concurrent engineering approaches

Some of the key specific objectives could be argued as below.

- To assess materials data base requirements on the basis of existing, validated publicly available literature and to compile this into a standard and accessible format
- To examine availability of design codes (e.g. classification societies, ISO (International Organisation for Standardisation), RCD (Recreational Craft Directive)) and develop linking modules from these into structural analysis software and FEA codes, materials databases, processing information etc., perhaps through a novel web-based procedure for wider application by boat and ship builders and other composites structures fabricators at different sites
- To formulate producibility parameters relevant to new processes such as vacuum assisted resin infusion moulding and develop production models for linking to design suites
- To identify and incorporate parameters affecting variability in materials properties that affect design and processing considerations
- To encourage innovation and evolution by reducing risks associated with new processes/materials

A possible way ahead is to deploy analytical/numerical codes for structural synthesis that are coupled with simulations of the production process that include tooling selection, consumables and the manual/machine interventions in fabrication and which together are linked to optimisation tools which, in the case of composites, are best based on genetic algorithm (GA) based approaches. An example of early work in this regard deals with stiffened, single skin structures [22].

Small FRP boat design and production in the leisure industry has also been considered. This 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 [23, 24, 25] 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 6.

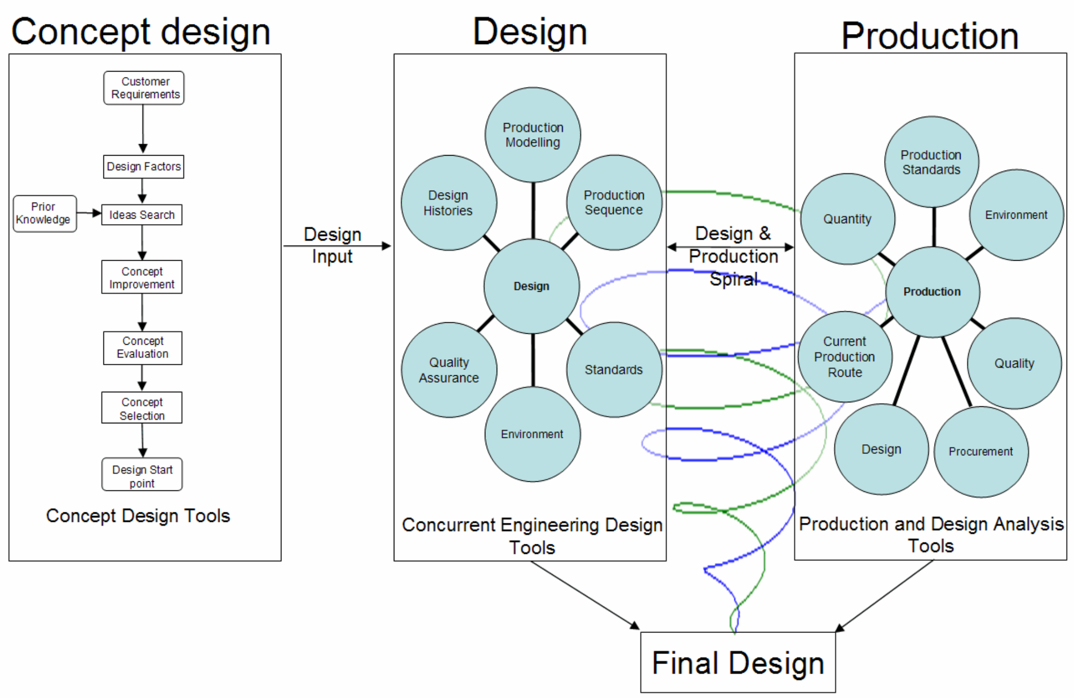


Figure 6: Diagrammatic representation of concurrent engineering environment for FRP boat design and production

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 2 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 3, 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	$\delta_{max}(mm) <$	∞	10.0	10.0	1.0	Input constraints
	$FI_{max} <$	∞	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	Calculated deflection
FI-US1		1.19808	0.2236	0.0468	0.0468	Calculated FI's (3 locations)
FI-US2		0.2558	0.0023	0.0345	0.0345	
FI-US3		1.1865	0.0166	0.0780	0.0780	

Table 2: 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 3: Effect of limit state constraints on stiffened FRP panel weight and cost

Structural Health Monitoring

In the increasingly competitive world, most engineering decisions are governed by commercial considerations. These are related to capital costs (CAPEX) and operating costs (OPEX). The previous section focused on CAPEX. Structural health monitoring (SHM) and any resulting intervention for repair and maintenance of the structure directly affects OPEX. The techniques commonly utilised for SHM purposes are non-destructive inspection (NDI), e.g. acoustic emission [26], visual [27] and vibration based techniques [28, 29]. Visual based techniques have proved useful over the past fifty years or so for thin single skin, unpainted structures. However, with increasing use of sandwich topology in marine construction and the higher plate thicknesses for larger load bearing structures, it is becoming incumbent to examine alternative vibration based approaches. This requires answers to three primary questions:

(a) Does damage exist in a structure?
(b) What is the location and extent of such damage?
(c) What is the severity of this damage?

Once these are answered then one can use continuum damage or fracture mechanics approaches to answer a fourth question:

(d) How much residual life exists in this damaged structure?

One example of work on vibration based damage identification approaches revolved around passive smart concepts with embedded transducers and strain gauges in sandwich structures [30]. Figure 7 illustrates the siting of the Fibre Bragg Grating (FBG) optical strain sensors along skin-core interfaces or in the cores of sandwich structures. The strain measurements were then used in conjunction with a damage detection algorithm which uses vibration-based data to locate and quantify damage using artificial neural network (ANN) approaches. The inputs and corresponding outputs required to train the neural networks were obtained from finite element analyses for different vibration modes for the structural components. Multilayer feed-forward and back-propagation neural networks were designed and trained by using different damage scenarios. After validation, new damage cases were investigated using both experimental and numerical analyses [31, 32] and successful application of the trained ANN's confirmed. Such approaches have the potential for extension to more complex structural components from a practical, boat viewpoint.

Ref. [29] has described a coherent strategy for intelligent fault detection that considers all of the features in detail, i.e. fault definition, operational evaluation (utilising a hiearchical damage identification scheme), sensor prescription and optimisation and a data processing methodology based on a data fusion model. More recent work presents a case study of damage detection in a curved carbon-fibre reinforced panel investigated using ultrasonic Lamb waves [33]. This study showed that multilayer perceptron (MLP) neural networks can efficiently locate damage in a stiffened composite panel, for both classification and regression networks. It was also demonstrated that outlier analysis makes an effective pre-processor of experimental Lamb wave response data for a neural network, and that prior wavelet decompositions of experimental Lamb wave data can facilitate damage detection.

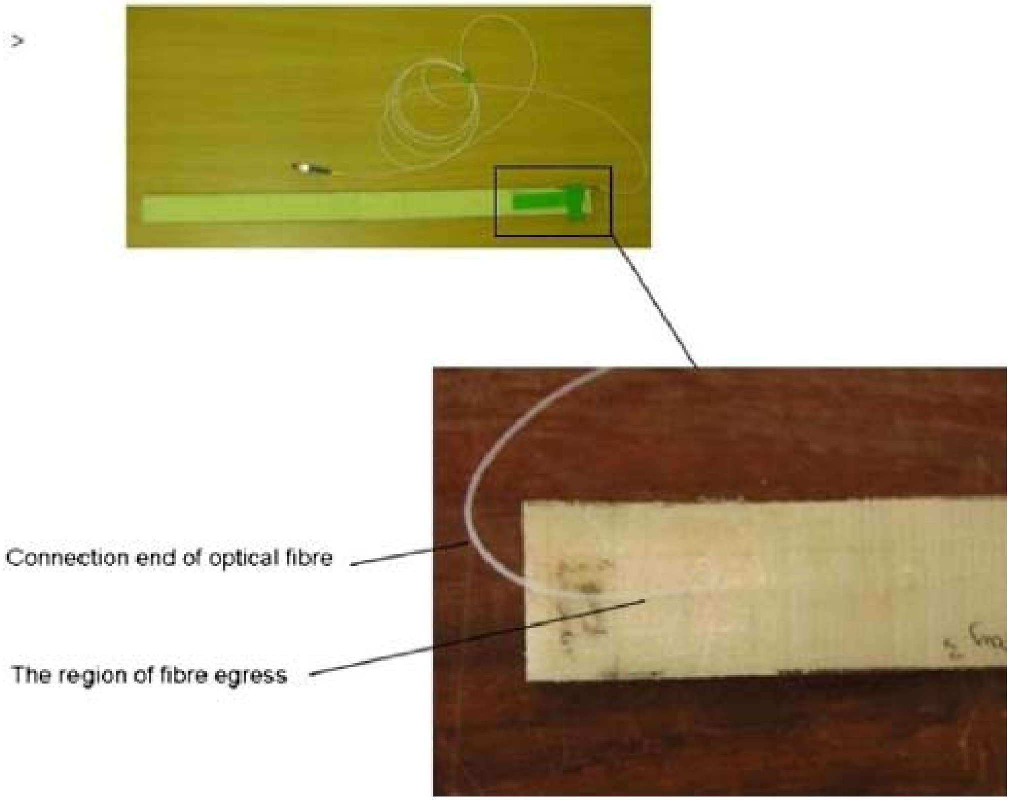


Figure 7: Embedding FBG sensors in sandwich structures

In addition to these vibration based approaches other data-rich experimental mechanics techniques have been developed at the University of Southampton for damage assessment of composite materials and structures, such as acoustic emission, thermography and TSA. These are focused on question (d), i.e. how much remnant life is there in a structure? TSA uses an infra-red detector 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 stress data can be collected in a matter of seconds, from cyclically loaded components, and hence real time data from structures experiencing damage can be obtained.

As the thermoelastic signal is dependent on both the surface stresses and the surface temperature of the component decoupling these effects, particularly in composite materials which have an inherently low value of thermal conductivity, is crucial as there will be viscoelastic and frictional heating at any damage sites. A methodology to decouple the response is provided in Ref. [34] that involves making corrections for increases in surface temperature so that the thermoelastic signal is dependent only on the stresses. 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 therefore been to apply this technique to composite structures and obtain meaningful data related to the stresses. A procedure based on the laminate strains rather than the surface ply stresses enables a calibration approach that accounts simultaneously for the laminate mechanical response and the surface thermoelastic response has recently been developed [35].

In the area of damage evaluation and NDE (Non-destructive evaluation) using infra-red thermography progressive damage under fatigue loading has been considered [36, 37]. Figure 8 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 [37]. The evolution of the damage is clear. To provide a quantitative damage indicator, Figure 9 shows how the strain metrics obtained from TSA increases with increasing fatigue cycles and how this can be related to stiffness decreases [37].

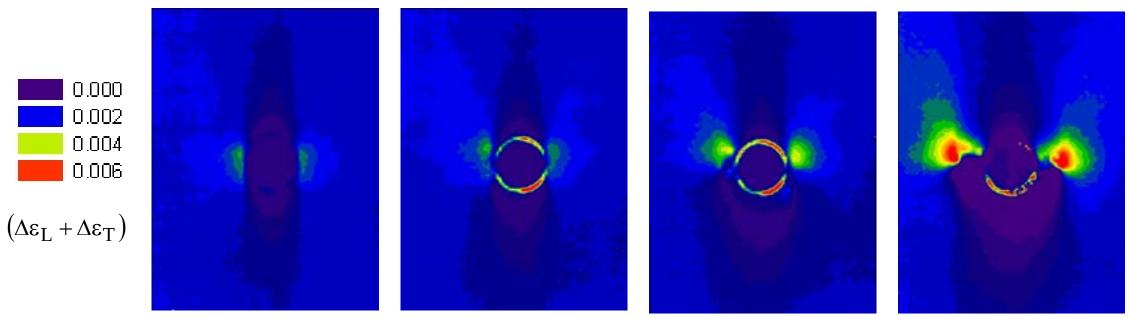


Figure 8: Damage progression around a circular hole

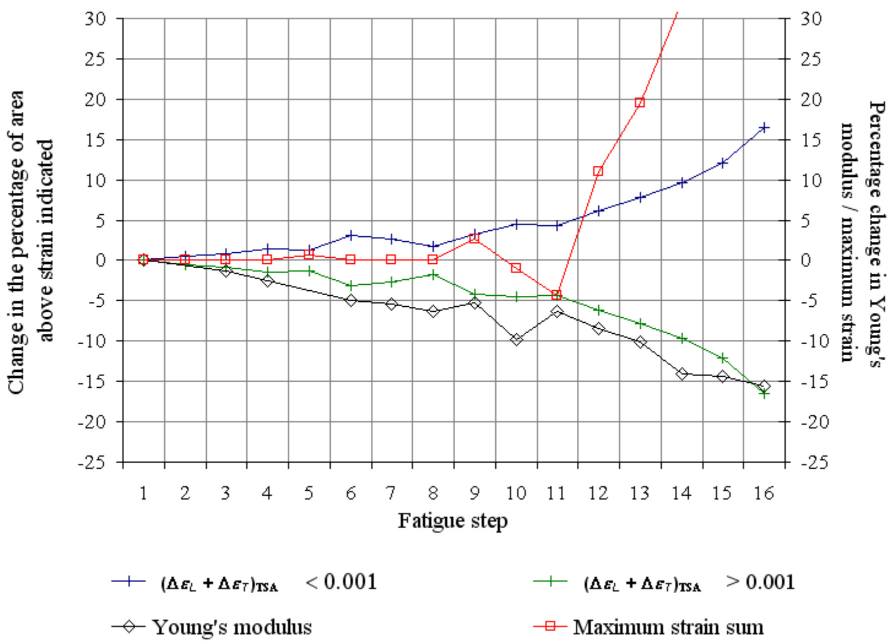


Figure 9: TSA strain metrics and Young's modulus decrease during damaging fatigue

This demonstrates that 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.

So far, the application of TSA to composite materials has focused on non-crimp, non-woven fibres, e.g. [35]. 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 [38] 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 10. 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.

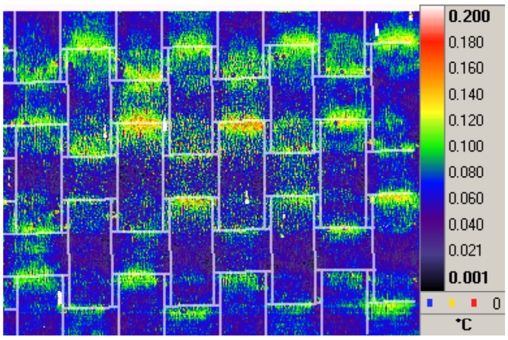


Figure 10: Thermoelastic data from a woven glass epoxy material

The standard set-up for TSA requires a cyclic load to achieve the necessary adiabatic conditions to conduct stress/strain analysis, which has traditionally restricting its application to the laboratory. Therefore to fully 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. Initial work, using a transient small impact/impulse loading [39], 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 11. 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.

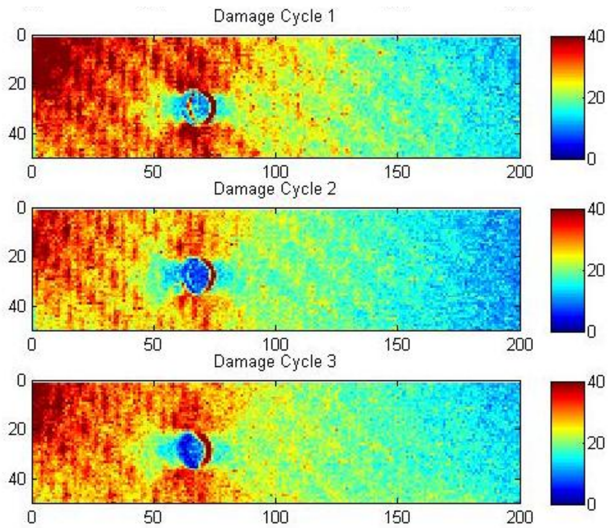


Figure 11: Progression of damage around a hole in a woven GRP specimen – TSA data from an impact load on a cantilever beam

A study that considered intervention for repair has also been completed [40]. In this work a generic methodology was developed that enables vessel owners to apply a systematic procedure to make decisions regarding damaged vessels. The methodology is based on the RNLI's experience of composite vessels. From the first report of damage to the return to service a series of prompts enable the vessel owner/operator to address each stage of the repair and identify the repair procedure, yard and if applicable assessment routine. The methodology has been applied successfully to steel construction and composite construction using HMS Nottingham and an RNLI lifeboat as illustrative examples. It is intended that the procedure be made available through computer software and the potential implementation of this is also discussed in Ref. [40].

Conclusions

In conclusion it can be clearly stated that there is a future for the continued and increasing use of polymeric composite materials for structural marine applications. There is a great deal of interest from industry in new ways to use existing materials and in using new and existing materials in new applications. The performance of structures in marine craft need regular and constant improvement, which will be driven by safety and quality issues. Economic constraints will also play an increasing role in the future, hence the requirement for development of concurrent engineering approaches. Life cycle assessment of composite structures, in order to better understand and appreciate the environmental impact of their use, is also required. Structural health monitoring and its associated inspection, intervention and repair strategies will become increasingly important to both ensure the safe operation of marine composites and to maximise and extend the life of these components.

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