THE ROYAL INSTITUTION OF NAVAL ARCHITECTS

SIMULATION BASED DESIGN FOR HIGH PERFORMANCE COMPOSITE SAILING BOATS

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SUMMARY

Composite materials are being used extensively from high-end racing yachts to production yachts. There are three distinct areas where the confidence in the design of the composite structures can be increased through numerical tools developed in the aerospace and automotive industries. These three areas are the as-built properties of the structure, the actual loads experienced by the structure, and the failure mode of the structure.

Draping analysis and resin infusion analysis will be discussed as tools to predict the as-built properties of a composite structure. These as-built properties can then be used in the structural analysis to provide a more confident estimate of the safety margins. Actual loads experienced by slamming events will be demonstrated to be modelled using the Smoothed Particle Hydrodynamic (SPH) feature of the non-linear explicit finite element dynamics code PAM-CRASH (TM). Finally, when the design loads are exceeded, understanding the progress of failure and being able to design for this can lead to designs that contain or limit the failure, thus improving the survivability of a structure, and hence reducing the risk to the sailor(s). Multi-model coupling will also be discussed as a means to conduct such analyses efficiently.

1. INTRODUCTION

The design of racing and cruising yachts is a well-developed activity. There are many tools available, yet we would propose there are significant advances that can be made that are relevant to specific markets.

The two most significant areas for improved design – be it reduced cost for production boats, or reduced risk in a highly optimized raceboat – are a more accurate prediction of the actual properties of the as-built composite material that emerges from the yard, and a more confident prediction of the actual loads the boat is going to experience in its passage over the waves. Knowing these two factors with increased confidence will lead to a more confident and cost-effective design.

An accurate prediction of the as-built material properties relies on measuring or predicting the fibre orientation and resin content of the as-built composite material throughout the entire hull and structure of the yacht. To measure this would be tedious, whereas to predict this with today's computer power is comparable to the numerical analysis already conducted.

The in-service loads on a sailboat have traditionally been difficult to measure, and so rules-of-thumb or guidelines from classification societies or rules are generally adopted. For a 'conventional' yacht in 'conventional' service these may be acceptable, but for a novel form of yacht, or a race boat seeking an advantage, then a better solution from a clean start is preferred.

An equally valuable tool for the in-service loads is to predict the damage that may result from a one-off event, and then assess the survivability of the yacht after the event. To do this requires the ability to predict the load the structure will have to endure, followed by an accurate prediction of the failure of the composite material. This can now be achieved with numerical means developed and proven in the aerospace industry and now available in commercial software packages.

The work presented here utilises the hull geometry of the Grand Soleil 50 (GS50), a performance-cruiser yacht designed by Botin-Carkeek and built by Del Pardo Boatyard. The boat is completely built with the infusion technique using multiaxial reinforcement, vinylester matrix and PVC cores. Hull, deck and internal structures are infused separately and bonded together with methylacrylate adhesives.

2. Existing Design Procedure

The structural design for the GS50 has been conducted by Olivari Composite Engineering, Italy. SYSPLY finite element analysis software [1] has been used by Olivari Composite Engineering since 1989. This FEA tool includes solid elements for the adhesives used for the bonded joints, allowing an enhanced understanding of how the hull, deck and internal structure work together in response to the design loads.

The GS50 employs many manufacturing and structural features that have been optimised through analysis with SYSPLY, such as:

- custom multiaxial fabrics to reduce the number of layers of reinforcement in the hull and deck skins.
- reduced and simplified internal structure.
- assembling by structural bonding only.

Optimised design and manufacturing through careful analysis has enabled this current generation of yacht to be 1500 kg lighter than previously, whilst maintaining high global stiffness and the best safety factors. The design optimisation has also improved the quality in construction and reduced the labour content.

The following sections describe higher-level optimisation techniques that may further refine the design.

3. PREDICTING AS-BUILT PROPERTIES

The "as-built" properties are the local properties that account for the local fibre orientation and resin and void content that develop during the manufacturing processes to produce the composite hull and structure. There will always be some deviation from the 'assumed' properties to the as-built properties, but how much there is, and how it might influence the analysis has to be weighed up for each design case.

3.1 Draping Analysis

The fibres of a reinforcement fabric will shear and deform as they morph from their initially perfect orientations on the roll to the complex curvature of a mould surface. The primary mode of deformation is in-plane shear of the fabric for a no-crimp or woven fabric. The final orientation of the fibres may consequently be different from those assumed by the designer.

A "draping analysis" allows the orientation of the fibres of the reinforcement materials to be predicted as they adopt to the curved surfaces of the boat structure and hull. These fibre orientations can then be imported into the structural analysis finite element software to enable an analysis using the predicted fibre orientations may be conducted.

The Figure 1 shows an example of a draping analysis of a specific ply of the hull of the Grand Soleil 50 boat by PAM-FORM [2]. The contour plot visible in the midst of the structure represents the value of the shearing resulting from the draping operation. Based on the computed shearing values, the designer may decide to use the resulting fibre directions in his/her analysis calculations instead of using the theoretical fibre directions defined in the design process.

One can also see on Figure 1 a green curve showing the flat pattern associated to the draped ply. This kind of outcome of a draping analysis enables to specify to a preform supplier what the shipyard is expecting to manufacture, leading to a possible subcontracting of this part of manufacturing and therefore leading to additional potential savings in the boat building.

3.2 Resin Infusion Simulation

A prediction of the resin flow in a resin infusion manufacturing process is a common tool to develop a successful and reliable infusion process for a specific structure. Simulation of the process can greatly reduce the risk associated with an infusion process for a new or large structure.

In its simplest form an infusion simulation will be an isothermal 2.5D (ie shell with curvature) model with constant viscosity resin and simple process parameters like a single inlet and a single outlet operating under vacuum pressure. This will provide a quick approximation to the infusion sequence and highlight areas where problems may arise. This simple approach may be all that is required for the skin of a boat hull.

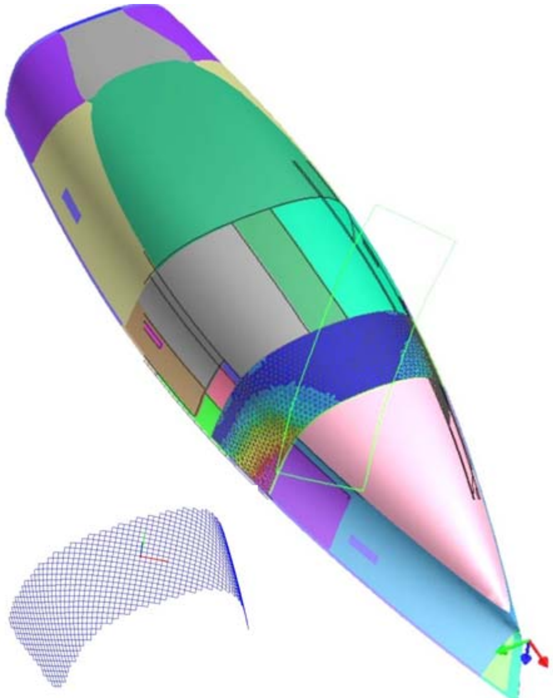

Figure 1. Draping analysis of a ply, fibre directions (blue grid apart) and flat pattern (green curve)

Infusion simulation of more complex components such as the structural keel box of a yacht with a canting keel may require a full 3D simulation with multiple inlets and outlets, to show how the resin flows through the thickness of the laminate and around cores and other inserts. Even more complex simulations may include the influence of temperature on resin viscosity, the thermal effects of mould heating on resin viscosity and the inclusion of resin cure kinetics in the thermal analysis. Thermal effects, particularly from exotherm of the curing resin, can be detrimental to the surface finish of the yacht, hence understanding potential hot-spots through simulation can avoid them in practise.

The shearing of the fabrics that allows the fabric to conform to the mould shape can also affect the local permeability of the laminate, and hence change the flow of resin in an infusion process. For an accurate infusion prediction, the fibre orientations from a draping analysis may be imported into the resin infusion analysis. In this case the shearing that occurs to allow a fabric to conform to a curved surface will cause changes in the local permeability of the laminate, and the infusion analysis can now account for this, leading to a more confident infusion prediction. For a gently curving shape such as hull the changes in permeability due to shear may be small, but for highly sheared laminates around tighter curvatures, the change in permeability can be quite significant.

A 2.5D infusion simulation may also account for compaction of the laminate during infusion, enabling a prediction of the local resin content of the infused laminate. This local resin content can then be used to predict the local strength and stiffness properties of the laminate. Hence a prediction of the as-built laminate properties can be developed from a draping analysis in conjunction with a resin infusion simulation.

Figures 2 and 3 are typical results from a resin infusion simulation using PAM-RTM [3]. Figure 2 illustrates the time for resin to fill the Grand Soleil 50 hull mould assuming a uniform laminate. The dark colour (blue) fills first, and the lighter colour (red) fills last. The dark rib-like structure shows the influence of the infusion distribution system that lays over the uniform laminate. An animated 'movie' of the resin filling the mould can provide valuable clues to identify problems and hence make changes to improve the infusion process. Figure 3 shows the variation in fibre content (arbitrary scale) that will result from the combined effects of gravity and vacuum bag pressure on the laminate.

Velocity of the resin flow is an output of the infusion simulation that can be used to predict micro and macro void content in the laminate [4]. This has two implications – a) the infusion process can be tuned to limit the flow velocity and hence limit the void content in a part, and b) the variation in void content prediction may be used to predict the corresponding variation mechanical properties of the infused laminate. These possibilities stem from a recent aerospace industrial project infusing composite blades [5]. The fatigue properties of a laminate can also be shown to be directly related to the porosity content.

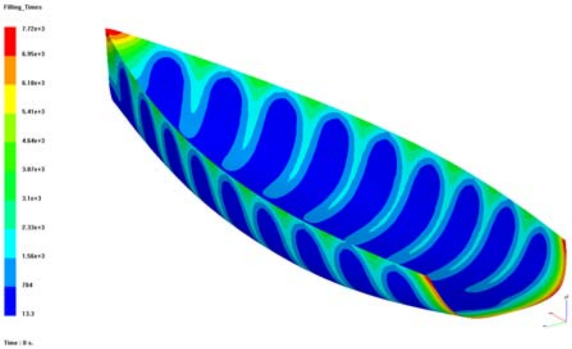

Figure 2. Filling time. Total filling time is around 2 hours 10 minutes.

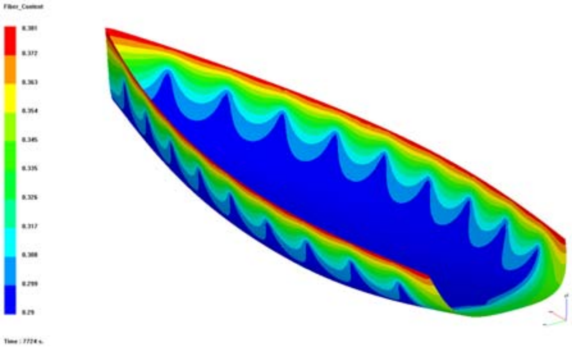

Figure 3. Final fibre content.

4 PREDICTING WAVE LOADS

4.1 Wave Loads

Prediction of the wave-induced loads on the yacht hull is made by simulating the motion of the hull as realistically as possibly. This is achieved by modelling the sea-state of interest and allowing the yacht hull to respond to the waves as the physics of the scenario dictates.

The water is modelled using the mesh-free Smoothed Particle Hydrodynamics (SPH) method. SPH methods, reviewed comprehensively in [6], were proposed some 20 years previously for astrophysics problems [7,8]. SPH is a grid-less, Lagrangian technique in which a set of discrete, interacting, particles is used instead of a solid element mesh. The method is well suited to impact problems such as an object hitting the water because the particles are topologically independent from each other, making splash easily accounted for. Also, SPH can be readily linked to standard FE formulations.

Waves are created in a suitably long numerical wave tank that consists of the water and a mechanism to generate the waves. The waves are created by the efficient process of moving the tank floor in a manner that the water at the depth of the floor would move if it were in an infinitely deep section of ocean. In the case demonstrated here, a single wave frequency is chosen, and so the floor of the tank is moved in orbits according to the wave frequency and diameter according to the surface amplitude required. This is explained thoroughly in [9].

The yacht hull is then allowed to float in the water, and in this simple case, moved forward at a prescribed velocity and yaw defined by a boundary condition. The yacht hull and appendages are defined as a rigid body, with mass and inertia defined on the centre of gravity of the rigid body.

In the case demonstrated here yaw and roll is fixed by a boundary condition acting on the centre of gravity (CG) of the hull, whereas the pitch and heave are unrestrained to allow response to the waves. The forward motion of the hull is controlled by a velocity boundary condition acting on the CG. This is of course not a real sailing attitude, but is adequate to demonstrate the analysis technique for resolving slamming loads. Previous work by some of the current authors [10] demonstrated the ability to apply a force on the centre of effort of the sail plan, and the yacht would move forward in waves with continually changing angles of yaw and heel as happens when a yacht traverses upwind over waves.

The distribution of forces on the underside of the hull was resolved by dividing the hull into numerous panels, each of which the local force due to interaction with the water was derived. Figure 4 shows the subdivision of the hull into various panels. Each area of different colour is a unique panel. Of specific interest were the panels below the waterline and between each frame of the structure. The panels were aligned with the structural features inside the hull, as identified from an FE mesh of the hull provided by the yacht designer/engineer.

The forces between the water and the hull were developed through sliding contact interfaces. Sliding contact interfaces are numerical algorithms that enable finite elements that are not connected by element connectivity (ie not part of the same structure) to slide over elements from another structure without becoming tangled. The algorithms are well developed for contact based finite element analysis such as car-crash and metal-stamping analyses [11].

Contact interfaces were defined for each underwater panel of the hull, and the SPH elements of the water.

In the analysis of the hull in waves, the yacht hull is slowly immersed into the water and allowed to find an equilibrium attitude (ie float freely) before being accelerated to a constant velocity into the oncoming waves. The waves commence at zero waveheight and increase linearly over the duration of the simulation to various waveheights, the most extreme of which can become quite non-linear with breaking tendencies.

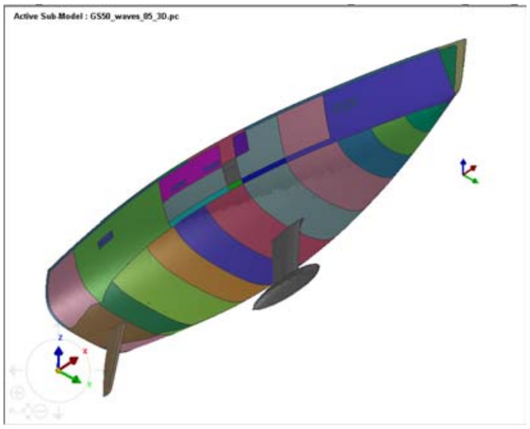

Figure 4. Subdivision of the underwater sections of the hull into individual panels for contact force definitions.

In the case presented here rig loads were not applied, although the inertia and mass of the rig was included in the overall properties of the hull. The inertial effects of rig would be quite significant for the hull motions created here, and so it is correct to include these in the inertia of the hull for the study of hull slamming loads. If loads within the hull were of interest, the mast and rigging could be modelled separately and attached to the hull at the appropriate locations. This would then account for the wave-induced rig loads into the hull at the correct points.

Confidence in the sliding contact interfaces for developing the local forces on the hull was achieved by demonstrating that the total vertical force on the hull at rest and at constant forward speed in calm water are equal to the weight of the boat. An image of the hull moving forward in calmwater is shown in Figure 5.

The forces acting on the underwater sections of the hull are shown in Figure 6. For this trial the horizontal velocity of the hull was zero up until 10 seconds, accelerates to 5m/s at 15 seconds, and is then constant until the end of the simulation at 40 seconds. The mass of the yacht was 15,000 kg (147.15e3 N). The total vertical force between 10 and 30 seconds where the hull is supported in the water, and waves have not yet developed, is within 0.1% of the actual weight of the boat.

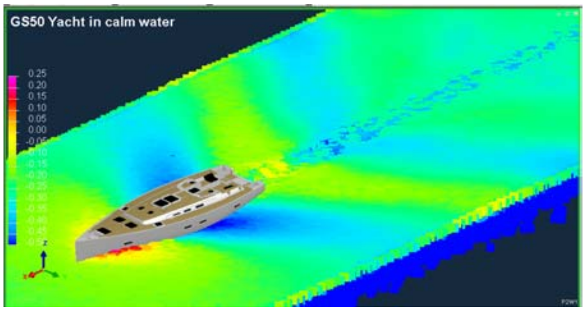

Figure 5 Wave pattern developed by the hull moving forward in calmwater using the SPH technique.

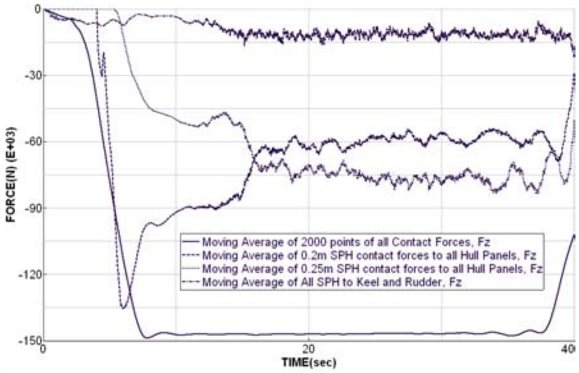

Figure 6. Vertical forces acting on the hull in calmwater.

4.2 Numerical Wave Tank Results

A numerical wave tank (NWT) is a term to describe the numerical representation of the wave environment through which the yacht will travel. For this model the NWT consisted of 708,630 SPH elements, ranging in size from 0.2m diameter on the surface up to 0.4m diameter at the lower depths. The NWT was nominally 150m long, 25m wide and 4.2m deep. The yacht hull finite element model consisted of approximately 74,000 shell elements.

A wavelength of 30m was used. The waveheight increased from zero to a maximum of about 2m.

Figure 7 shows the heave and pitch (z coordinate of the CG of the vessel, and y angle rotation) of the yacht as it moves forward into waves of steadily increasing waveheight. The first ten seconds of the simulation is used to find a static equilibrium before the yacht is accelerated forward to a speed of 5 m/s (9.8 knots). The pitch and heave are seen to increase as the wave height increases.

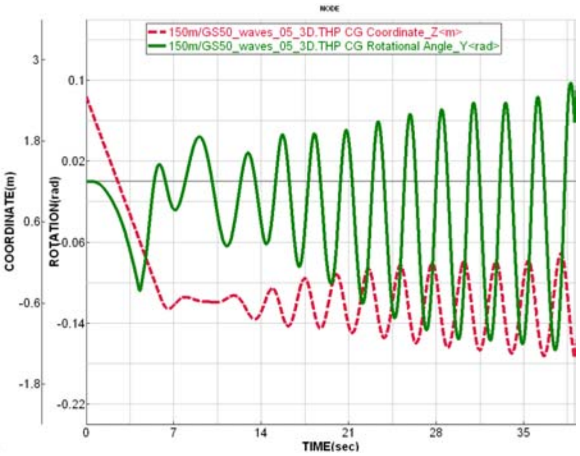

Figure 7. Heave and Pitch of the yacht as it moves forward into waves of increasing height.

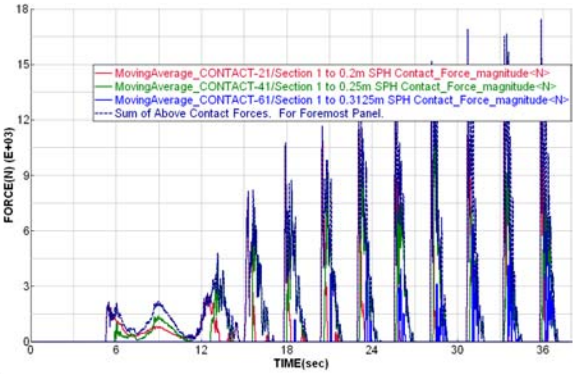

Figure 8. Forces on the foremost panel below the waterline, showing increasing force with wave height.

Figure 8 shows the contact forces between the water and a forward panel on the underfoot of the bow. There are four curves shown in Figure 8, the lower three are the force between the hull and each of the three different SPH sizes, and the fourth is the sum of these three forces. The sum is the net force acting on that panel due to the water. Dividing the force by the panel area will provide the designer with a slamming pressure for design purposes.

5 FAILURE of COMPOSITE STRUCTURES

5.1 Designing for Failure

The idea of designing for failure is a new concept for many composite design engineers. Typically, the designer is tasked with ensuring the structure does not fail under design loads. When the design loads are exceeded, human life is often at risk. Understanding the response of the structure beyond the design loads is the key to improving the survivability of the yacht, and thus making a safer yacht.

Design for the unexpected is becoming mandatory for many vehicles – it is called crash analysis, or design for safety and survivability. It is now common place in the design of cars and for most public mass-transit vehicle types. What does it offer for yacht design?

Principally, it is about making a safer yacht, and reducing the risk for the sailor. This is achieved through understanding how a structure will fail, and then modifying the design to fail in a way that either contains or reduces the extent of damage. If we consider a yacht hitting a submerged object, then the design for failure might try to contain the damage within a section of the keelbox that could be easily repaired or replaced, without incurring damage to the surrounding hull, and hopefully retaining water integrity.

In contrast to conventional elastic-limit design, designing for survivability necessitates predicting the material behaviour beyond the point of elastic response. The analysis is non-linear and tracks the progress of the failure as it propagates. To achieve this requires an understanding of the material behaviour beyond the elastic design strain.

There are circumstances where the design of the structure into the failure region is necessary. Such applications are the energy-absorbing structures of racing cars [12] and helicopter under-floor structures [13]. In these cases the composite material is designed to fail progressively such that large amounts of energy are absorbed, thereby reducing the likelihood of injury for the occupant(s).

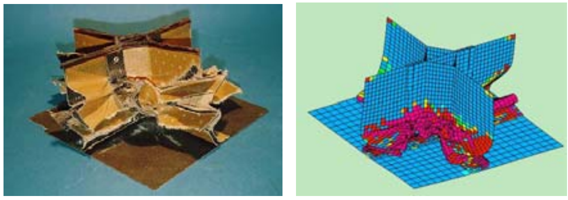

Figure 9. A failed composite cruciform energy absorbing structure (left) and PAM-CRASH model (right) [12].

5.2 Damage Survivability

Damage survivability is another area where knowledge about the development of failure of a structure is required. In this case the *extent* of damage is required to be known, and with this an indication of the residual strength of the structure. An example of this is bird-strike on the leading edge of an aircraft wing or control surfaces, where structural integrity after impact is mandatory to ensure control of the aircraft during critical take-off and landing manoeuvres [14]. Figure 10 illustrates the correlation of PAM-CRASH bird-strike simulation to a physical test.

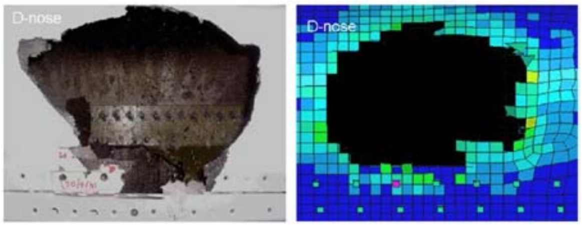

Figure 10. Simulation of a bird-strike on a composite wing component (right) is compared to the test article (left) [13].

Characterising failure of composite materials is complex and not without challenges, the least being that composite materials have many failure modes, not all of which are apparent from a single failure. Consequently, a danger is that conducting a single type of test and calibrating for that failure on a global scale may completely ignore other modes of failure that may develop when the loading scenario is changed. Being aware of this, and when calibration of the failures is comprehensive, the ability to predict the failure progression of a structure provides unrivalled opportunity for the designer to develop structures with improved damage tolerance.

These capabilities have been developed in pioneering research work carried out in the aerospace industry and are now available in commercial software packages such as PAM-CRASH [11].

One of the laminate degradation models available is based on the work of ‘Ladeveze’ and co-workers [15], and has been extended to include fabrics and strain rate effects. The fabric is treated as a homogeneous orthotropic elastic material whose properties may be degraded (damaged) if matrix microcracking and fibre rupture occur due to excessive loading. Criteria are available to account for interaction of the various composite failure modes (interply shear, intraply shear, micro-cracking of the resin, and fibre failure) and also to specify complete failure.

The laminate is modelled as a stack of shell elements, with each element layer representing one ply. Adjacent plies are tied together using a mechanical law which characterises resin inter-ply stiffness and failure behaviour. This approach does give the correct laminate stiffness and can permit delamination by damaging the interface law and allowing ply separation. The computational cost of this approach is acceptable and moderately large structural parts may be tackled using a high performance workstation.

The following example [16] considers a 50mm diameter rigid ball (mass 21kg, velocity 6.28m/sec) striking a flat, simply supported, Carbon Fibre Reinforced (CFRP) plate, Figure 11. The plate is 300mm square and has 16 plies of quasi-isotropic layup [0/45]4S (thickness ca. 4.6mm). A comparison of a conventional multi-layered shell and the new modelling methods shows that proper representation of delamination leads to a better agreement with test measurements. Delamination initially occurs under the impact point at the centre of the laminate, where the shear is a maximum, causing it to separate into two sub-laminates. These sub-laminates will also delaminate at their mid-plane as the punch intrudes further into the plate. This sequence continues until, possibly, all plies are delaminated. The prediction of extensive delamination is valuable information that agrees well with test C-scan results. At this velocity the simulation correctly calculates penetration of the plate by the impactor; for a lower velocity of 2.33m/sec (not shown) the simulation and test both find that the punch rebounds, albeit with significant ply and delamination damage.

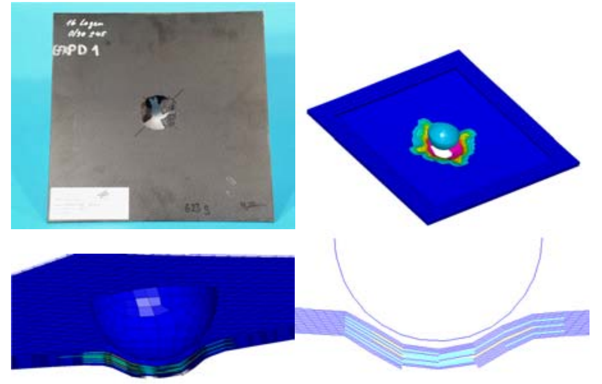

Figure 11. Composite failure predictions of a ball hitting a composite plate – (clockwise from top right) the test panel, the FE model of the panel after damage, the impactor striking the panel, and a section through the impact region.

Usually the weak link in a sailing boat and much more in a powerboat is the core of a sandwhich laminate. Typically the overall structure is designed to be adequately stiff under the sailing loads and the resulting stress safety factors for the core are relatively high. Fatigue of the core might occur occurring only in the extreme sailing conditions experienced by the VOR 70 [17] or the ORMA trimarans where non linear deformations of the panels and of the structure must be considered. For these applications, the laminate including the core could be modelled and the progressive development of fatigue damage could be studied. The key then would be to similar studies on alternate construction methods – say including rip-stop tie-layers through the core (ref multihull world) – to investigate if more robust laminates can be developed.

In the production boats the quality control during the construction is still the main problem and most rupture and damage are caused by the construction defects. A calibration of the severity of construction defects could also be studied by this type of numerical failure analysis.

6. MULTI-MODEL COUPLING

Multi-model coupling (MMC) is a unique feature integral to the explicit, non-linear, FE code PAM-CRASH [11] which allows two independent FE models to be joined and run as one model [18]. Specifically, this modelling feature unifies two FE models where the cycle time-step of one is much smaller than the other. In other words, MMC allows the incorporation of components requiring a very fine mesh without affecting the larger time-step of the more coarsely meshed global model. It does this by allocating different CPUs to each of the two models, running them independently and effectively allowing the joined model to run at two different time-steps.

The algorithm which is used internally within the implementation exploits a mathematical technique called sub-cycling. It allows each model to run using its own time-step while simultaneously accounting for any interactions between the two models via an interface. The two distinct models are linked numerically by either a defined tied interface (which stipulates how the models are joined) or by a defined contact interface (which describes how they physically interact).

In the case here of a yacht hull in waves, one model may include the waves and the necessary wave generation components, and the other model the fully structural model of the yacht with composite laminate damage. The time-step of the yacht hull with its necessarily fine mesh and stiff material properties will inherently have a smaller time-step than the numerical wave tank containing the SPH elements for the water.

Without MMC the only options are to conduct calculations for the SPH for every time-step of the composite structure, or, to grossly simplify the composite structure to enable a large time-step as required by the SPH elements.

The MMC method provides the engineer with the option of avoiding such simplifications by allowing very finely meshed components to be incorporated into a more coarsely meshed global model without greatly impinging on computational requirements.

7. CONLUSIONS

Checks on the structural strength of a yacht hull through use of the as-built material properties can provide an increased confidence in the safety factor on the design. Numerical tools such as draping analysis and resin infusion simulation can provide a prediction of the as-built properties.

Wave-induced loads on the hull can be predicted by use of a finite element model of the yacht coupled with a Smoothed Particle Hydrodynamics representation of the ocean waves. Local panel pressures on the underside of the hull due to slamming are able to be resolved. Use of multi-model coupling of the finite element model of the hull with non-linear material properties, and a second FE model of the waves, can provide a prediction of local composite failure.

Using a complete value chain of numerical tools from the manufacture to the end-use-severe-event simulation can lead to designs that will have a greater damage threshold and hence provide increased survivability for the sailor and yacht in extreme conditions.

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9. AUTHORS BIOGRAPHY

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