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P. Baur, A. Roy, Pascal Casari, Dominique Choqueuse ...+1 more authors

Institutions: University of Nantes, IFREMER

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P Baur[1], **A Roy**[1], **P Casari**[2], **D Choqueuse**[3] and **P Davies**[3]*
[1] CRITT Matériaux, Rochefort Cedex, France
[2] Institut de Recherche en Génie Civil et Mécanique, Université de Nantes, France
[3] Materials and Structures group, IFREMER Brest Centre, Plouzané, France

Abstract: This paper describes the tests performed on a full-size motorboat to demonstrate the potential for adhesive bonding to replace overlaminated connections. Adhesive bonding resulted in a significant reduction in assembly time for bulkhead connections compared with overlamination. Drop tests and sea trials were performed using specially adapted strain gauge instrumentation. These indicated low adhesive joint strain levels, even for severe test conditions. No damage was observed. The data obtained will be used to improve laboratory test procedures to simulate service loading of boat structures.

Keywords: adhesive, structural testing, marine composites, impact, sea trials

1 INTRODUCTION

Composite materials have been extensively used in the pleasure boat industry for many years [**1**–**3**]. The manufacture of small pleasure boats (motorboats and sailing boats from about 5 to 8 m long) involves the assembly of different components, the main ones being the deck–hull and bulkhead–hull connections. These operations are time consuming and can account for up to 30 per cent of the total manufacturing time. In order to reduce this time and the associated labour costs, the use of bonding is now being considered by some boatyards to replace the overlaminating method (which is currently widely used).

To validate this manufacturing option, a research programme including research centres, adhesive manufacturers and boatyards started several years ago. Many of the results from the initial studies, which focused on the mechanical behaviour and durability of adhesively bonded specimens, have been reported [**4**–**7**]. In parallel with tests carried out in the laboratory on subcomponents, an adhesively bonded prototype has been manufactured, instrumented and tested under real conditions. This paper will describe these prototype tests.

The aims of this part of the programme were as follows:

(a) to improve the manufacturing process,
(b) to evaluate the loads applied to the connections at sea,
(c) to verify by a drop test the capability of the structure to support severe loading.

* *Corresponding author: Materials and Structures group, IFREMER Brest Centre, 29280 Plouzané, France.*

2 MANUFACTURING OF THE PROTOTYPE

The structure retained for this study is a 5.75 m long motorboat designed for sea fishing and excursions (Fig. 1a). The characteristics of the boat are shown in Table 1.

This boat is an improved standard boat, and the manufacturing process has been modified in order to replace the overlaminating of the bulkheads onto the hull structure by a bonding operation. Figure 1b shows the interior of the boat before bonding the deck.

The adhesive chosen is a filled vinyl ester based adhesive provided by the Reichhold company. Other

Table 1 Prototype boat characteristics

Length	5.75 m
Width	2.45 m
Draught	0.4 m
Weight without engine	640 kg
Motor	90 hp
Maximum speed	30 knots
Hull and deck construction	Glass/polyester by hand lay-up
Bulkhead construction	10 mm thick plywood

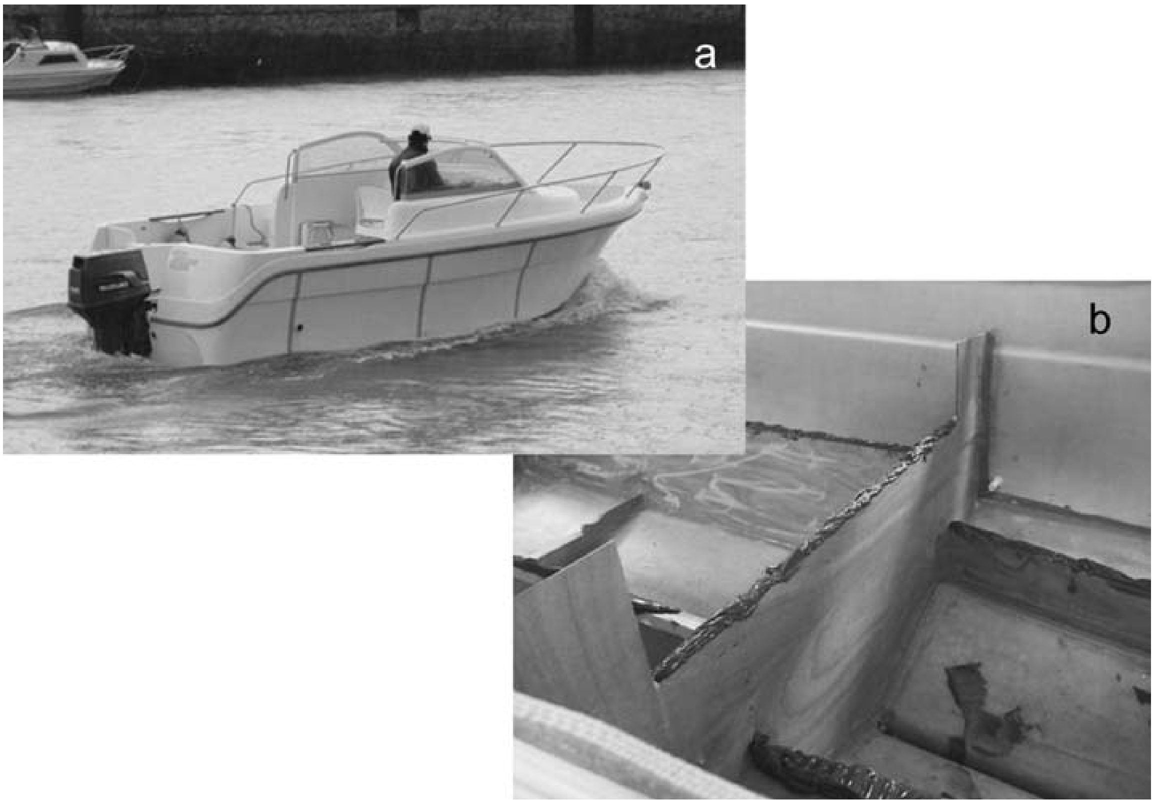

Fig. 1 (a) Prototype motorboat and (b) detail of the bulkhead–hull

structural adhesives including orthophthalic and isophthalic polyesters were also evaluated in a preliminary test programme [**7**], but this vinyl ester was retained on account of its superior long-term behaviour. It should be noted that epoxy-based adhesives were considered to be too expensive for this application. The adhesive is applied in a very simple way, and no surface preparation of either the GRP or the plywood was performed prior to bonding. The gap between the bulkhead and the hull varied from less than 1 mm up to over 10 mm. Such variations are not unusual, but adhesive bondline thickness can have a strong influence on joint strength, and this was one of the parameters examined in the initial test programme. Figure 2 shows an example of results.

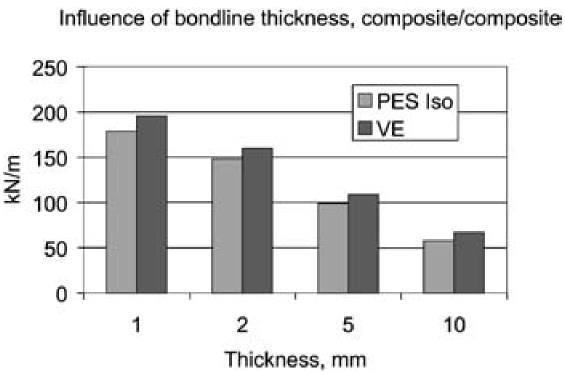

Fig. 2 Assembly strength versus bondline thickness, single-lap shear tests, two adhesives

The drop in measured failure load is related to an increase in peel loading as the bondline gets thicker. There may also be more defects in the thicker joints. Thus, apparent strengths of these adhesives do show a dependence on thickness, and when possible it is preferable to reduce bondline thickness, particularly in highly loaded regions.

For the bulkhead–hull assembly, the bulkheads were placed in position in the boat without fixing, and then a length of adhesive was applied on each side of the bulkhead and manually smoothed. The time needed for this operation is 45 min, whereas the overlaminating operation requires 4 h. For the bulkhead–deck assembly the adhesive was first deposited on the edge of the plywood, and then the deck was put in place without pressure.

In this first phase of the project the bonding process has only been applied to the assembly of the bulkhead with the hull and deck structure. The full bonding including the hull–deck connection will be considered at a later date.

3 INSTRUMENTATION

Few experiments have been performed to measure the strains during navigation of composite pleasure boats, though there is considerable experience of slamming pressures from tests on military craft [**8**]. Baley and

Cailler have described measurements made on an instrumented 7.7 m long prototype composite sailing boat [**9**], while Hentinen and Holm measured slamming loads on a 9.2 m yacht [**10**]. Choqueuse has measured strains on a large composite motor cruiser [**11**]. The anisotropy of the materials, the low strain values on running sections of the structure, the dynamics of the signal (acquisition rates of at least 500 Hz are needed), the limited knowledge of the real geometry (thickness, resin content, ply orientation, etc.) at a given point and the poor stability of strain gauge measurements on low heat dissipation materials (GRP) combine to make this type of measurement very difficult. Taking into account these parameters, and the aim of the study being to determine the loading of the bonded joint, a special instrumentation system was defined.

The load applied to motor boats differs from that applied to sailing vessels. For the latter the transfer of the wind loading by the mast and the rigging has to be considered, whereas for motor boats the transfer of the power generated by the engine (inboard or outboard) is of prime importance. For all vessels the load induced by slamming (repeated wave loading) has to be considered. However, for the motor boat considered in this study, in order to simplify the mechanical loading applied to the connections, they can be split into (Fig. 3):

(a) tension–compression,
(b) bending,
(c) shear.

Three locations were retained for study, based on the boatbuilder's experience and discussions with a naval architect. These are regions in which joint damage had been observed after severe loading in service, and are shown in Fig. 4.

The measurements are made using sensors composed of strain gauge combinations, which are directly bonded to the adhesive joint of a bulkhead–hull connection. A full Wheatstone bridge is built (four 120 ohm gauges) in order to increase the sensitivity, and the wiring is adapted in order to concentrate on the loading of interest. Thus, each instrumented connection allows the measurement of a particular response by eliminating the other responses. For example, for the tension–compression (T–C) sensor, rosettes of 0–90° gauges are placed on each side of the joint and the wiring is chosen in order to eliminate the bending and temperature effects (Fig. 5).

This sensor is located on the main central perpendicular bulkhead (Fig. 4). For the bending (B) sensor the same positioning of the gauges is performed, but the wiring differs in order to eliminate the tension–compression effect. For the shear (S) sensor the gauges are placed at

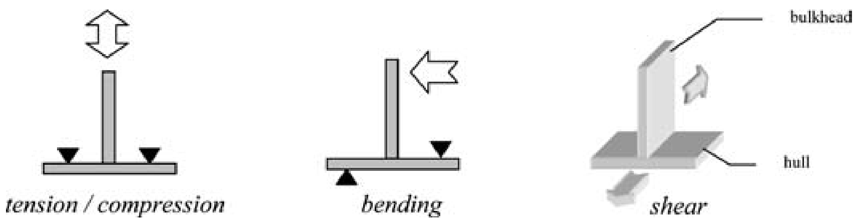

Fig. 3 Mechanical loads on motorboat joints

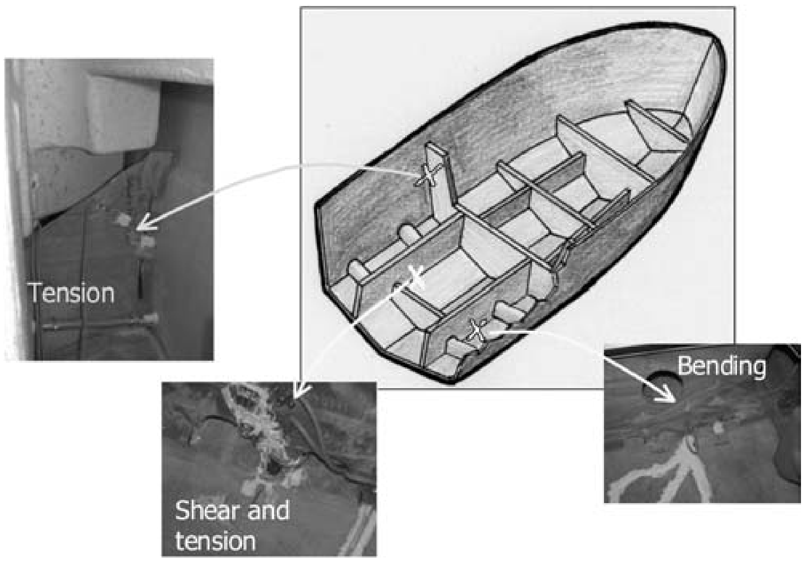

Fig. 4 Sensor positions

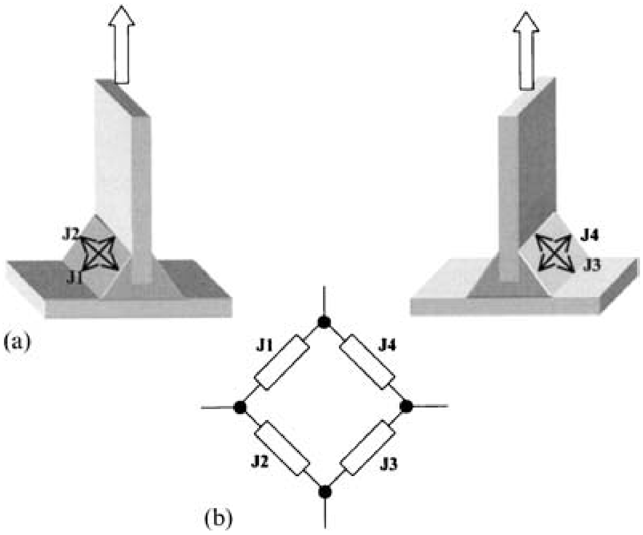

Fig. 5 Tension–compression sensor: (a) gauge positions; (b) wiring diagram. Plane strain assumption: ε_t = tension strain; ε_b = bending strain; k = gauge factor; $\alpha\Delta t$ = response to temperature variation; $J1 = k^*(\varepsilon_t + \varepsilon_b) + \alpha\Delta t$; $J3 = k^*(\varepsilon_t - \varepsilon_b) + \alpha\Delta t$; $J2 = \alpha\Delta t$; $J4 = \alpha\Delta t$; $R = J1 + J3 - J2 - J4 > R = 2^*k^*\varepsilon_t$

45° to the connection axis (Fig. 6). It should also be noted that the wiring of the shear sensors results in a sensitivity twice that of the other sensors.

The bending and shear sensors are placed symmetrically on the back of the two longitudinal bulkheads. An HBM Spider® acquisition data system coupled to a portable computer is used to collect the data. Depending on the type of test, a 2 or 10 s data sequence is recorded. Data recording is triggered by a signal increase.

4 DROP TEST

The first type of test that was performed was a drop test. Similar tests have been used in the past at DNV to study the impact response of boat sections [12]. Here, the boat was lifted by a crane and dropped onto calm water in the 20 m deep section of the IFREMER test basin in Brest. Series of 2 s data recordings were made during the first phase of contact with the water. Figure 7 shows illustrations of the behaviour of the boat during the drop.

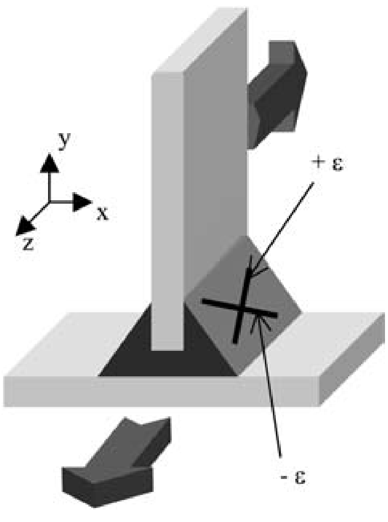

Fig. 6 Shear sensor

Different configurations have been retained for this test. They are reported in Table 2. For the fifth test the sandbags were distributed as follows: 120 kg at the engine position, 400 kg in the cockpit, 80 kg on the aft side of the boat. This distribution simulates the loads in navigation. Some examples of results are presented on the plots in Fig. 8.

The maximum value is obtained during the first 200 ms after the impact with the water, and then the signal is quickly damped to reach a value less than 10 per cent of the maximum value after less than 2 s. A general vibration frequency is noted at about 3.5 Hz which probably corresponds to the first mode shape of the structure. The maximum values observed during the impacts are reported in Table 3. These values are discussed further below.

5 SEA TRIALS

The sea trials were performed in the Atlantic Ocean off the West coast of France. During navigation the boat was loaded with three passengers. The sea conditions were quite good (sea condition level 3–4) with a 30 cm high wave. The measurements were made at a maximum speed of 30 knots and for different vessel orientations with respect to the wave direction (meeting the wave direction head on, at 45°, and with the wave aft) in both straight-on navigation and during turns. Two examples of results are given in Fig. 9.

Table 2 Drop test conditions

Test number	Test configuration
1	Boat empty, 1 m drop, horizontal
2	Boat empty, 2 m drop, horizontal
3	Boat empty, 1 m drop, on port side in order to increase response of tension–compression and bending sensors
4	Boat empty, 1 m drop, on starboard side
5	Boat loaded with 600 kg by sandbag, 1 m drop, horizontal

Table 3 Maximum strains recorded during drop tests

Sensor	Maximum value of $\Delta l/l$ (%)	Drop test number
T–C	−0.27	3–5
B	0.34	4–5
S	0.06	3

Fig. 7 Photos showing boat drop tests

On these curves a general periodic signal with a frequency of around 3–5 Hz is again noted. This frequency is in accordance with the signal observed during the drop test and can be attributed to a general mode shape of the structure.

The maximum values are observed for peaks which have a value 5 times higher than the general value observed during navigation. This peak level must occur at the moment when the boat motion is out of phase with the sea surface.

During tacking, a significant increase in signal is observed in the bending sensor. However, the level obtained appears to be much lower than the peak observed during the full-speed navigation. The maximum values observed on each sensor are reported in Table 4.

It is apparent that these values are considerably lower than the maximum values recorded in the drop tests. Their significance is discussed further below.

Table 4 Sea trial maximum values recorded

Sensor	Maximum value of signal (mV/V)	Maximum value of $\Delta l/l$ (%)	Test
T–C	−1.2	−0.12	+45°/sea
B	1.1	0.1	Facing the waves
S	0.6	0.015	+45°/sea

6 DISCUSSION OF RESULTS

The first point to highlight is that no damage has been observed on the boat after these two series of tests. This confirms the potential for adhesive bonding to manufacture the joints in motorboats of this type, though of course a final judgement will only be possible when information on long-term behaviour of the structure is available after many years of in-service navigation of the boat.

In order to establish how close the adhesive is to damage and failure, the values recorded by the sensors during the trials (Tables 3 and 4) should be related to the corresponding material properties. Unfortunately, this is not simple. The values of strain, $\Delta l/l$, in percentages, have been indicated in these tables. These values take into account the gauge factor and the type of bridge wiring. However, as the loading conditions cannot be clearly defined, and the joint geometry is not perfect (variable shape and symmetry), it is very hard to make this correlation, so the values noted must be considered as indicative only. In addition, the values provided by the sensors correspond to the surface strains of the joint. The strain within the joint is quite complex, as can be shown by a simple finite element analysis, and the value will strongly depend on the exact geometry. Modelling of the whole vessel with the detail necessary to study the hot spots, which are to be expected at the stress

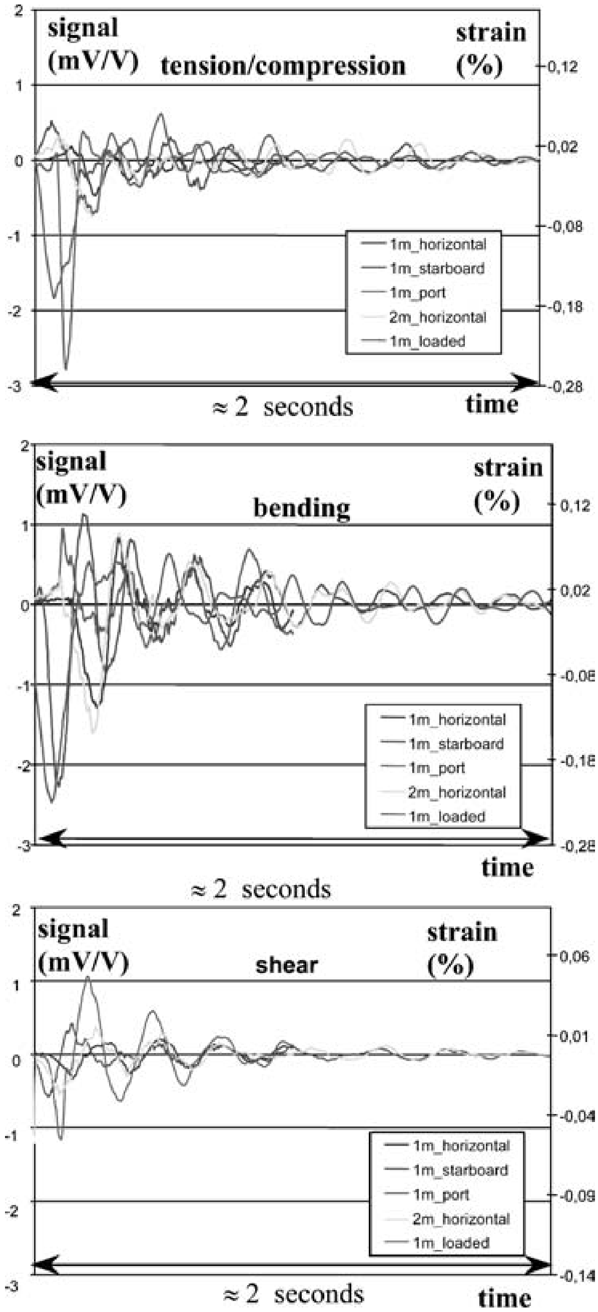

Fig. 8 Examples of recorded data from sensors during drop tests

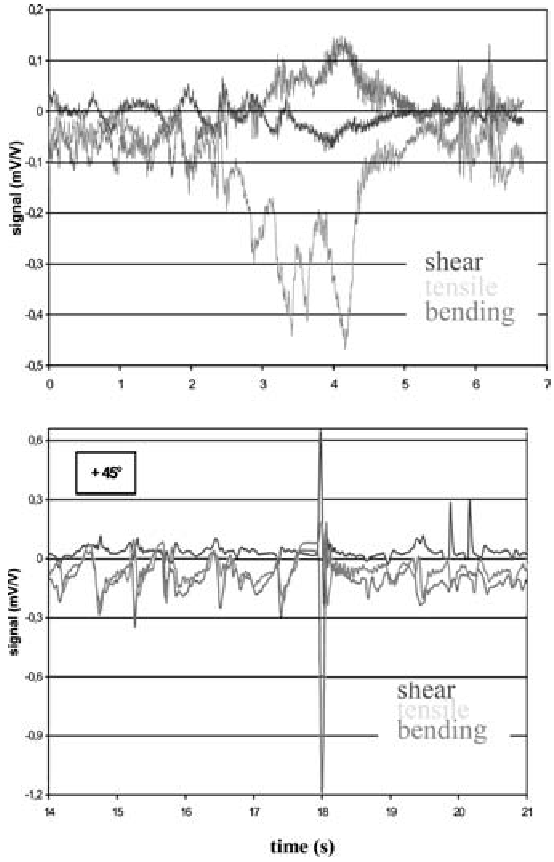

Fig. 9 Sea trial recordings during changes in direction

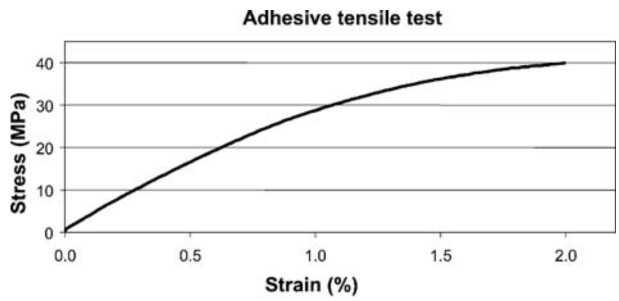

Fig. 10 Tensile stress–strain data, quasi-static test, filled vinyl ester bulk adhesive

concentrations near the joint ends, requires very large models, and the strains in these regions are impossible to measure. Nevertheless, some comments may be made.

The data usually available for an adhesive are quasi-static tensile stress–strain plots. An example is shown in Fig. 10 for the filled vinyl ester adhesive used here. The strain at failure is considerably higher than those measured during prototype tests, even taking into account that the strains recorded by each individual loading sensor may be summed in the worst case. Also, prototype measurements from the tension–compression sensor indicate that peak values are compressive rather than tensile, and the maximum tensile strain was even lower.

Loading rate effects may affect material properties. The highest strain rates during the prototype tests are around $0.05\ s^{-1}$. At hot spots (the ends of the joints) these could be even higher. Strain rates in tensile tests are typically 50 times slower than this value, so higher strain rate data may also be needed to assess adhesive performance.

Further studies now underway are focusing on developing design criteria for adhesive connections.

Particular emphasis is being placed on rate effects and the influence of cyclic loading. Finally, it should be noted that drop tests are now being considered by ISO [**13**] as a means of qualifying small boat structures.

7 CONCLUSION

This study has demonstrated the strong potential for adhesive bonding of bulkhead assemblies in small motorboats. Large savings in assembly time were achieved compared with the traditional overlamination method. Drop tests and sea trials, using specially adapted strain gauge instrumentation, have indicated low strain levels in the adhesive joint, lower during sea trials than during drop tests. The latter may prove to be useful in qualifying the connections, but further tests are needed to validate this. No damage was observed after any of the tests. This suggests that further optimization of the assembly design may be possible, and studies are continuing. Fatigue and ageing studies are also under way, as these will govern long-term performance.

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