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14. ABSTRACT
The project concerned fatigue testing and numerical evaluation of a steel / composite hybrid girder. The girder was previously built under collaboration between Maglev Inc. and Lehigh University. The girder was instrumented with strain gages and LVDT's to monitor strains and deflections. A test setup with bottom supports and towers for mounting two or three hydraulic actuators was installed in the ATLSS test lab. The girder was fatigue tested for over 300,000 cycles at loads up to 120% of design load. There was extensive cracking in the steel structure, but only minor damage in the composite panels towards the very end of the test. No damage in the adhesive joints was found. All items included in the proposal were fully addressed. Reports have been prepared for publication in scientific journals. The results have been instrumental for the design and manufacturing of an instrumented slamming test facility presently being developed under an ONR grant.

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Project: Fatigue Testing of Maglev-Hybrid Box Beam

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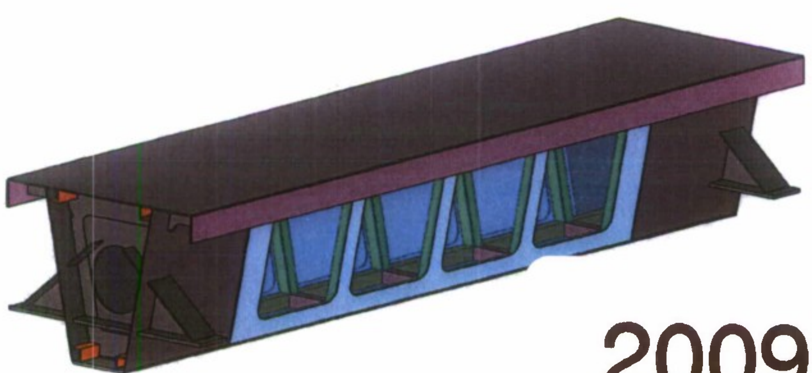
Abstract

This report summarizes the results from the ONR project "Fatigue Testing of Maglev-Hybrid Box Beam". The project concerned fatigue testing and numerical evaluation of a steel / composite hybrid girder. The girder was previously built under collaboration between Maglev Inc. and Lehigh University. The girder was instrumented with strain gages and LVDT's to monitor strains and deflections. A test setup with bottom supports and towers for mounting two or three hydraulic actuators was installed in the ATLSS test lab. The girder was fatigue tested for over 300,000 cycles at loads up to 120% of design load. There was extensive cracking in the steel structure, but only minor damage in the composite panels towards the very end of the test. No damage in the adhesive joints was found. All items included in the proposal were fully addressed. Reports have been prepared for publication in scientific journals. The results have been instrumental for the design and manufacturing of an instrumented slamming test facility presently being developed under an ONR grant.



Introduction

Larger naval vessels are presently mainly made of steel. A few smaller vessels (up to 73m) have been made of composites. There are indications that there may be considerable benefits combining steel and composites in so-called hybrid structures. The benefits include strength-to-weight ratio, fatigue strength, corrosion resistance, moldability, flatness for signature requirements, sound and thermal insulation, etc. from the composites; and strength, ductility, isotropy, weldability, ease of manufacturing, outfitting etc. of the steel. A hybrid structure is also well suited for incorporating blow-out panels to mitigate internal blasts.

Over the past ten years there has been considerable research in joining technologies between steel and composites, and various hybrid coupon specimens as well as a few small scale hybrid hull specimens have been manufactured and tested. There has been little work on fatigue of larger specimens. The present project concentrated on this aspect.

The objective of the study was to fatigue test the steel/composite hybrid girder shown in Figs. 1-2. The eight stainless steel "window openings" were closed out with vacuum infused glass fiber skin / foam core sandwich panels. The panels were bonded to the steel frame with an epoxy paste adhesive. No mechanical fasteners were used. Six of the eight panels were conventional sandwich panels with a uniform core thickness up to near the edges, where the core tapered off and the two skins joined. The last two panels had deeply corrugated inner skins and flat outer skins. The corrugated panels were lighter and presumably stronger than the conventional ones. The two different panel configurations are shown in Fig. 3.

Detailed information of the design and testing of the girder are provided in references 1-3.

Fig. 1. Steel part of the steel/composite hybrid girder.

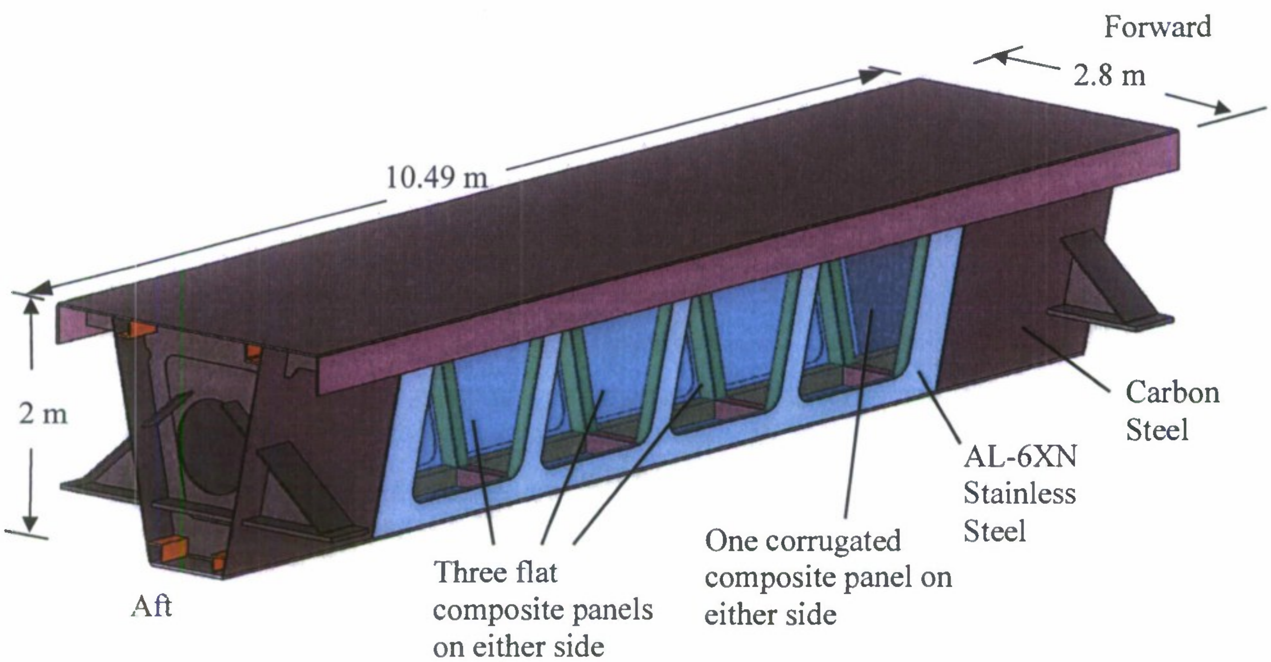


Fig. 2. CAD model of hybrid girder.

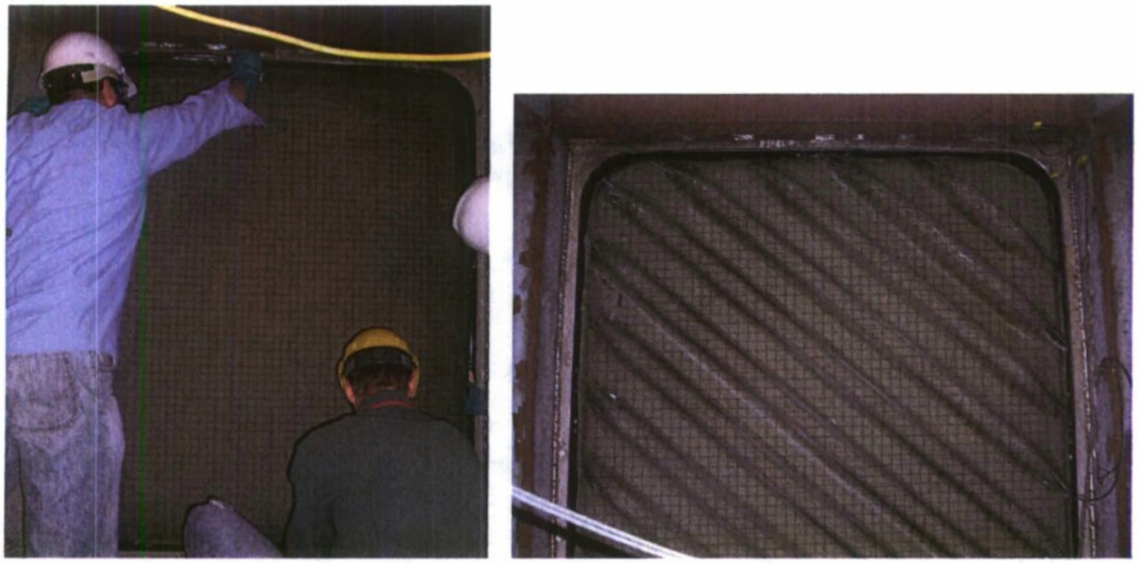


Fig. 3. Photos from the inside of the hybrid girder, showing a conventional sandwich panel (left) and a sandwich panel with deeply corrugated inner skins (right).

Loads

The loads for the specimen were derived from hull girder loads on a destroyer, but scaled 1:8 to fit the present specimen. Although the present specimen does not have the shape of a ship hull, there are sufficient similarities to warrant testing under ship hull loads; see Fig. 4. The ship girder loads include a maximum shear force and a maximum bending moment. These could be simultaneously obtained in the test specimen by using a three-point bend setup as shown in Fig. 5.

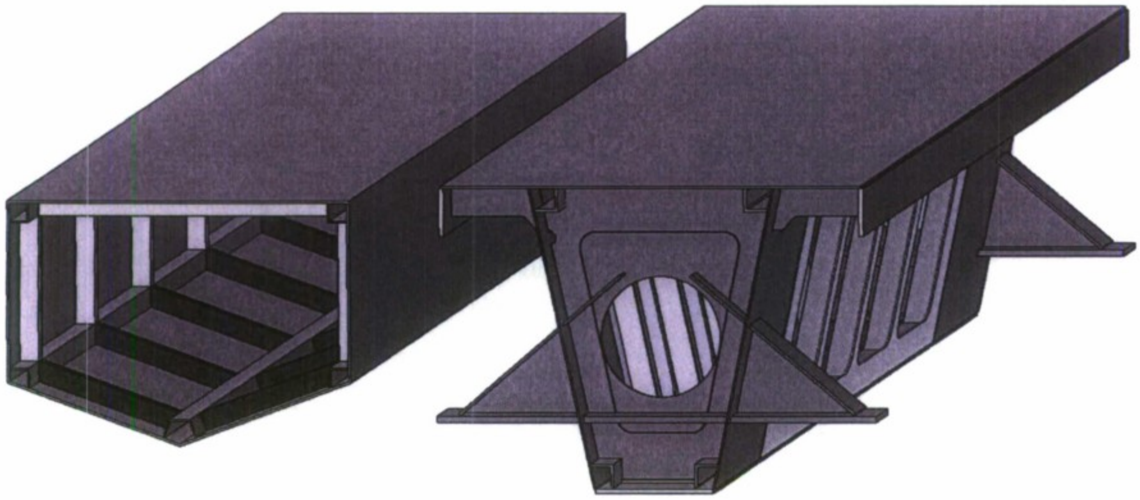


Fig. 4. Scaled down (1:8) destroyer (left) next to the presently studied girder (right).

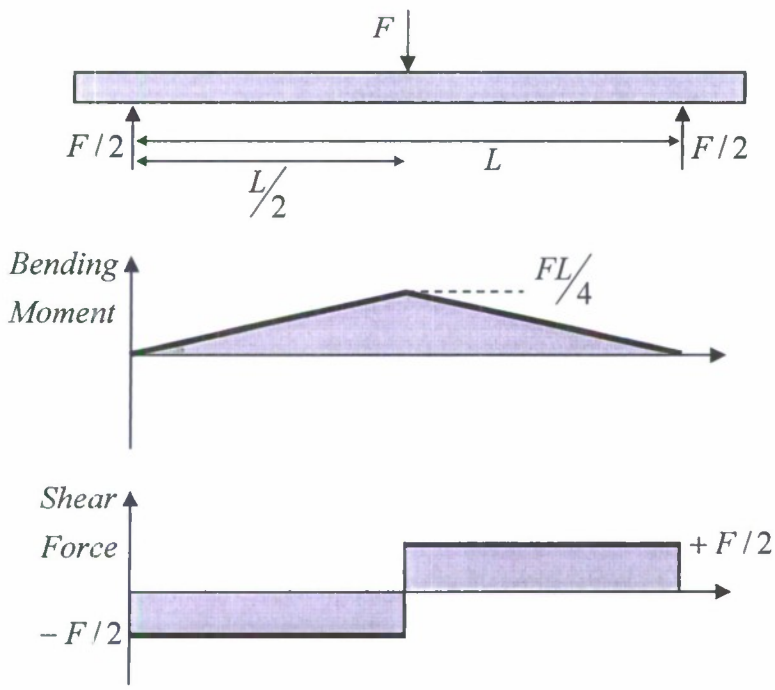


Fig. 5. Schematic of the loads applied on the girder (top) and the resulting bending moment (middle) and transverse shear force (bottom).

Test Procedure

A three point bending test fixture was erected as shown in Fig. 6. The specimen was supported from underneath at each end by two bearings bolted to floor mounts, at the Center for Advanced Technology for Large Structural Systems (ATLSS) of Lehigh University. At one end was a rounded, fixed bearing which allowed only rotation of the specimen, and at the other end was a rolling bearing which allowed both rotation and axial translation of the specimen. A reaction frame for the load actuators was constructed by placing vertical I-shaped columns to either side of the center of the specimen, and bolting these columns to the lab floor and to transverse connecting channels. Two hydraulic actuators were connected to the top pair of channels, and their load was applied onto two thick steel blocks. Between each of these blocks and the upper deck of the beam were two thin aluminum strips, strategically located above the steel webs beneath the deck. The load jacks were placed in locations which would allow them to only produce loads axial to the vertical box beams of the specimens (i.e. the load jack centerline and the vertical box beam centroidal axis intersected at the location of the upper deck of the specimen). This loading setup was designed to mitigate local fatigue effects around the location of the load.

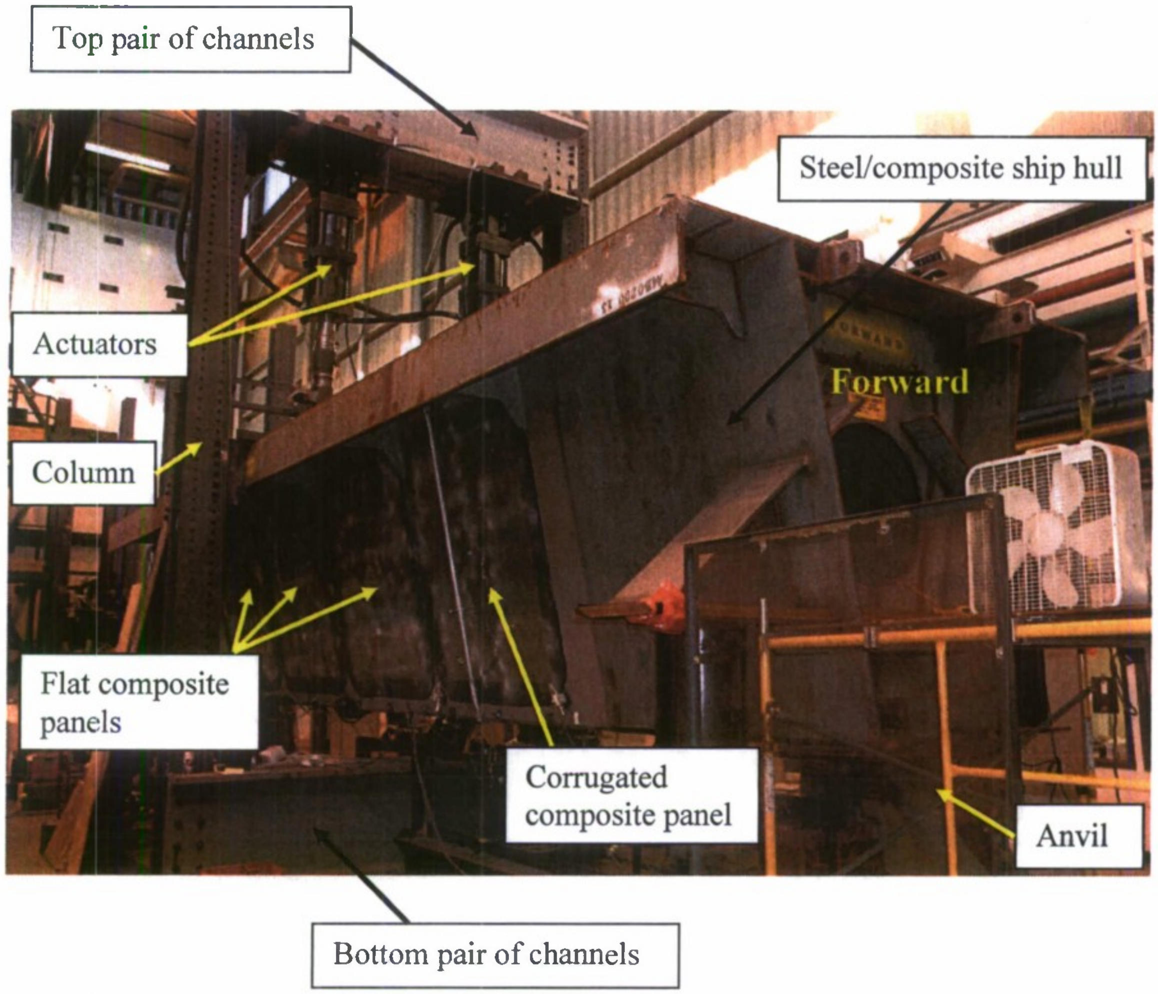


Fig. 6. Test setup for the fatigue testing of the hybrid girder.

Numerical Analysis

A finite element (FE) model of the hybrid ship hull specimen was constructed in ANSYS. The geometry of the model included one quarter of the specimen, and symmetry boundary conditions allowed the model to represent the entire specimen. The model was considerably refined near various stress concentrations due to geometric or material discontinuities. In Fig. 7 the stress state near a longeron-to-bulkhead connection is shown. This is the area where the most severe fatigue cracking occurred.

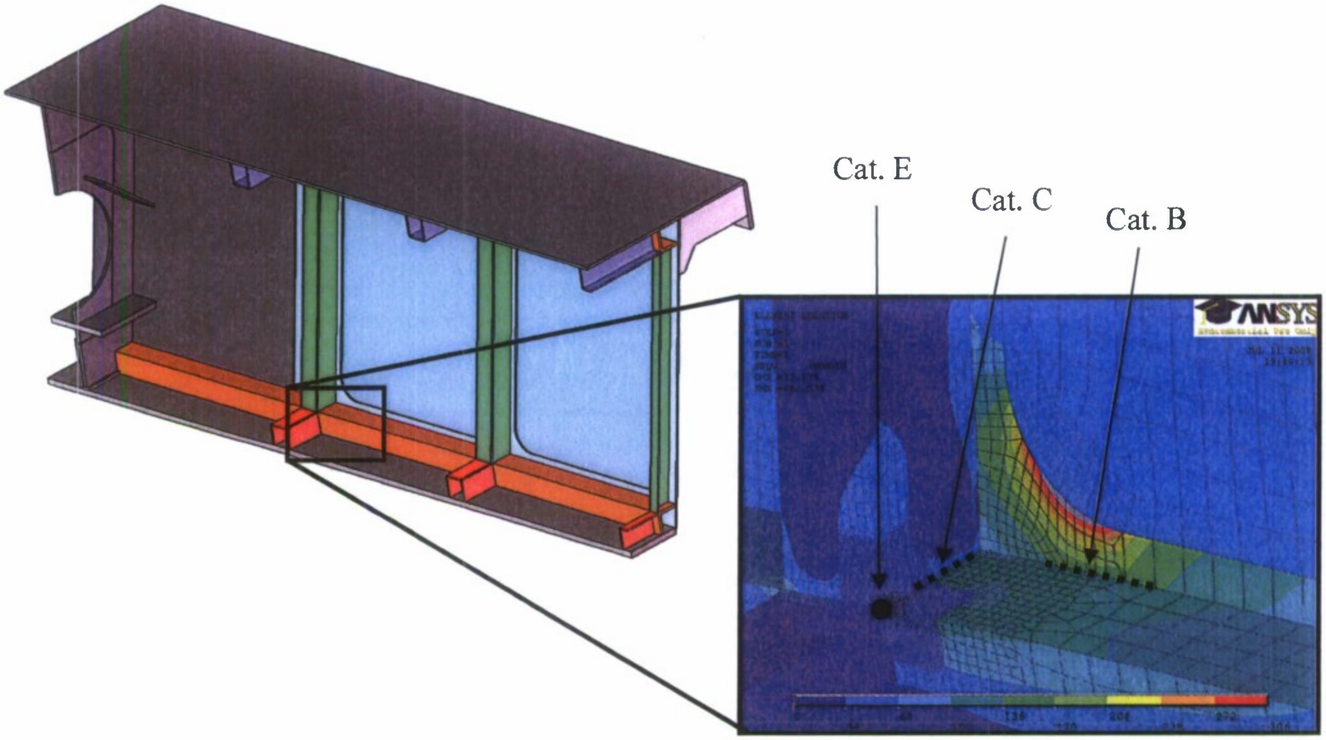


Fig. 7. Finite element analysis of stress state near a joint. Different fatigue categories (B, C, E) are identified.

Test Results and Discussions

Static test results at the design load (1600kN) were compared with finite element analysis predictions. At the design load, the measured vertical displacement at the center of the beam (VLVDT-3) was 9.7mm, which is slightly smaller than FE prediction of 10.6mm. Other results also showed that the FE predictions were generally slightly larger than actual measurements. A possible reason for the difference is that the material properties (stiffnesses) of the composites used in FE analysis were slightly lower than those of the real material.

Test results from strain gages near the most critical welds matched well with the FE predictions. At the design load, the strains measured were 450-480 micro-strain, which is approximately 10% lower than FE results at corresponding locations. The strains measured near the top center transverse box beam were slightly higher, presumably because these gages were relatively close to where the load was applied.

In addition to the sensors applied on the composite panels, an optical measuring system, Aramis 3D Image Correlation, was used to measure the strain and displacement distributions of a corrugated panel when loaded to the design load. A random marking pattern was applied to the panel's surface and the Aramis system captured pictures of this pattern using two CCD cameras simultaneously. Using image correlation and photogrammetric principles, 3D coordinates of the surface of the panel were tracked at each stage of load and the resulting deformations at every point on the surface were calculated. Fig. 8 shows the out-of-plane deformation of the corrugated panel under the design load. The results from the Aramis 3D Image Correlation System matched well with LVDT measurements and FE analysis.

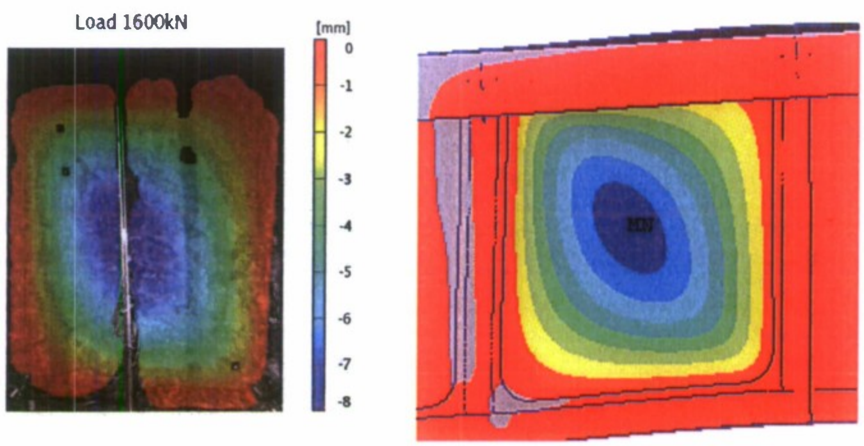


Fig. 8. Comparison between measured (left) and calculated (right) out-of-plane deformations.

Throughout the fatigue tests, there was no indication of any damage in the adhesive bonds between the composite panels and the steel truss. Cracks were found in the corrugated composite panel at a very late stage of the test, after the specimen had been tested for 193,000 cycles at 120% of design load. By using a corrugated design, a 15% weight reduction was accomplished in comparison with the traditional flat panels. Although the corrugated panels showed larger out-of-plane deformation, the in-plane stiffness of these lighter panels matched that of the traditional flat panel. The large out-of-plane deformation did not cause any significant damage during either the fatigue tests or the final static test to 77% above the design load.

The whole specimen performed well when loaded statically to 177% of the design load. No cracks were found in any of the flat composite panels. There was no indication of any damage in the adhesive bonds between the composite panels and the steel truss.

Conclusions

A ten meter long hybrid ship hull specimen was designed, manufactured, and tested under fatigue loads. The specimen was fatigue tested at 70% of design load for 100,000 cycles, 100% of design load for 25,000cycles, and 120% of design load for 200,000 cycles. The specimen performed well when loaded statically to 2840kN, which is 77% above the design load. Cracks were found in the category E detail steel welds during fatigue testing at 120% of design load. Many of the cracks in the steel were ground and re-welded, or the crack tips were drilled, in order to continue the fatigue test. Two corrugated composite panels had some cracks in the inside glass fiber skin near the end of the fatigue tests, while there were no cracks found in any flat composite panels. There was no indication of any damage in the adhesive bonds between the composite panels and the steel truss. The success in testing this large scale hybrid ship hull specimen further supports that a strong and lightweight ship hull could be made using this steel/composite hybrid concept.

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