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Joachim L. Grenestedt

Richard Sause

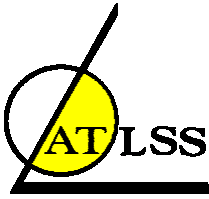
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Vierendeel Steel Truss / Composite Skin Hull Test

Final Report

Project I, ONR Grant No. N00014-01-1-0956

Non-magnetic Stainless Steel for Double Hull Ship Construction

by

Joachim L. Grenestedt, Ph.D.
jog5@lehigh.edu

Richard Sause, Ph.D.
rs0c@lehigh.edu

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**ATLSS is a National Center for Engineering Research
on Advanced Technology for Large Structural Systems**

117 ATLSS Drive
Bethlehem, PA 18015-4728

Phone: (610)758-3525
Fax: (610)758-5902

www.atlss.lehigh.edu
Email: inatl@lehigh.edu



Joachim L. Grenestedt
Associate Professor
Mechanical Engineering



Richard Sause
ATLSS Director and Professor
Civil and Environmental Engineering

ABSTRACT

This report summarizes a project to manufacture and structurally test a hybrid ship-hull girder consisting of a Vierendeel-type steel truss closed out with composite sandwich panels. The Vierendeel truss consisted of a welded AL-6XN stainless steel frame that was designed to provide strength and stiffness to the hull girder, whereas the lightweight vacuum-infused glass-fiber-reinforced vinyl-ester skin / foam-core sandwich panels were designed to take local sea load and shear load. The panels were adhesively bonded to the steel truss. The manufactured girder was 6 meters long and its cross-section was a 1:35 subscale model of that for a 142-meter-long ship-hull girder.

The full-size girder was initially designed, analyzed using finite elements (FE), and structurally optimized. Then the subscale model was manufactured and tested. The test specimen was subjected to a flexural sagging test, essentially through a six-point bending test. In the test setup, loads were applied such that the maximum bending moment and the maximum shear load were achieved simultaneously, but not at the same location. The maximum loads were scaled from the maximum loads for the full-size girder, which were derived from ABS rules.

Numerous strain gages and LVDT's were used during the test to acquire data on the hybrid girder's behavior. Loading was discontinued when the applied load was 140 percent of the design load, to preserve the girder for future study. After the test, there was no indication of any failure in the composite panels or in their bonds to the AL-6XN steel truss. The steel truss had yielded, however, and there was residual post-test deformation of the girder. Overall, the study indicated that the steel-composite concept is a viable concept for further evaluation and design as a strong and lightweight hull system.

An extension of this study is being performed under a separate ONR contract, No. N00014-03-1-0597, "Vierendeel Type Steel Truss/Composite Skin Hybrid Ship Hulls."

Introduction

As new structural materials are developed that have potential uses in naval ships, ship-hull designs incorporating these new materials must be evaluated for their overall suitability, including their strength, stiffness, and fabricability. The current study was initiated as a step in the evaluation of a new hybrid design that combines a high-strength stainless steel hull frame with composite-panel skins.

The objective of the study was to manufacture and structurally test a Vierendeel type steel truss / composite skin hybrid ship-hull section. The hybrid hull consisted of a steel frame that was closed out with composite sandwich panels. The steel frame was designed to provide strength and stiffness to the hull girder, whereas the lightweight composite panels were designed to take the local sea load and shear load. A 142-meter-long ship-hull girder, similar to a destroyer in terms of size, weight and speed, was initially designed, analyzed using finite elements (FE), and structurally optimized. Based on the optimized 142-meter-long full-size ship hull, a subscale model was manufactured and structurally tested. The cross section of the model was obtained by scaling the full-size ship by 1:35 (Fig. 1).

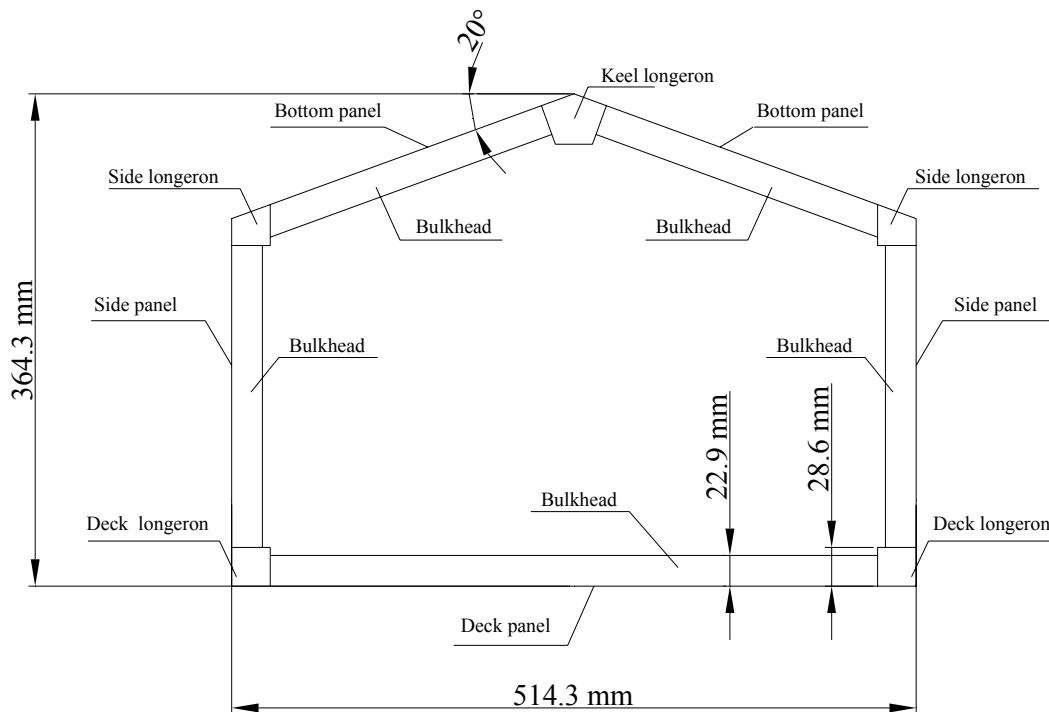


Fig. 1. Cross-section of the 1:35 subscale hull model.
The keel is shown up; the position in which the model was mounted in the test frame during the sagging test.

Manufacturing Procedure

A 6-meter-long steel girder was manufactured by laser- and waterjet-cutting non-magnetic AL-6XN stainless steel and welding a truss, which was then closed out with 60 vacuum-infused glass-fiber-reinforced vinyl-ester skin / foam-core sandwich panels. The thickness of the stainless steel was 2 mm (0.079 in.). The edges of the steel that would surround the sandwich panels were scalloped, in an attempt to reduce elastic stiffness mismatch between the steel and the composite panels. The steel components were tack welded together. The bulkheads were then welded to the longerons and the keel using the Tungsten Inert Gas (TIG) welding process, with 100% Argon shielding gas and Alloy 625 filler wire. The longerons and the keel were welded using the Short Arc Metal Inert Gas (MIG) welding process with a shielding gas consisting of 97% Argon and 3% CO₂ and a 0.023-in.-diameter Alloy 625 welding wire. Fig. 2 shows the scalloped edges on the steel members and Fig. 3 shows the finished steel truss.

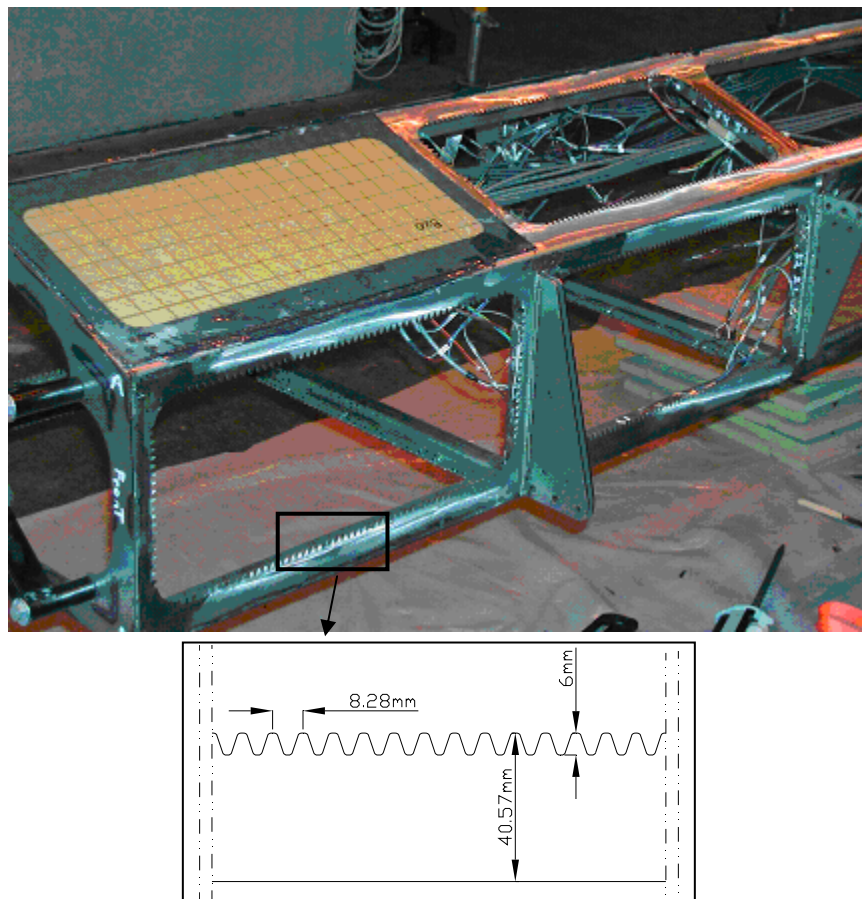


Fig. 2. Stainless steel truss with scallops (fingers) at the edges surrounding the sandwich panels.



Fig. 3. Finished AL-6XN stainless steel truss before sandwich panels were mounted. Load-introduction brackets are on the sides of the girder.

The composite panels were made by vacuum infusing vinyl-ester resin into thin glass fiber skins on each side of a PVC foam core (Fig. 4). The resin used throughout was Dow Derakane 8084 vinyl-ester resin. The glass-fiber reinforcement was Hexcel 7725 bi-axial woven glass fiber from Owens Corning. Divinycell PVC foam cores with a 12.7-mm thickness were used for all panels. Four different core densities were used. All deck panels used Divinycell H130 foam, and all bottom panels used Divinycell H250 foam. Divinycell H200 foam was used for the side panels with highest shear load, whereas Divinycell H160 foam was used for panels located in low/no shear load regions. The foam cores were routed to the correct dimension and the edges were beveled 45°. At the edges of the sandwich panels, the two sandwich skins came together to a single skin.

Manufacturing was done as follows: two layers of fiber reinforcement for the outer sandwich skin were placed on a flat steel mold beneath the foam. The foam was placed on the fiber with the beveled side up. One layer of fiber reinforcement was laid on top and the assembly was vacuum bagged. Different infusion schemes, using either grooved cores or resin distribution media, were used. After infusion, the panels were trimmed to design dimensions using a waterjet cutter (Fig. 5).



Fig. 4. Vacuum infusion process for a composite sandwich panel.

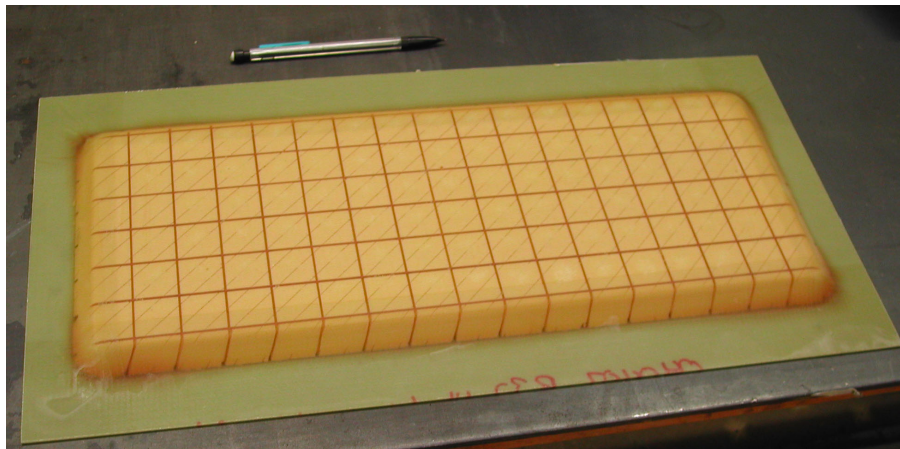


Fig. 5. A finished composite sandwich panel for a bottom panel, ready for bonding to the steel truss.

The sandwich panels were adhesively bonded to the steel truss using SIA E2119A/B adhesive from Sovereign Specialty Chemical. The panels were clamped for at least 8 hours to achieve the handling strength of the adhesive, and left for more than 72 hours at room temperature for full cure. Fig. 6 shows the finished hull girder with the bonded sandwich panels.

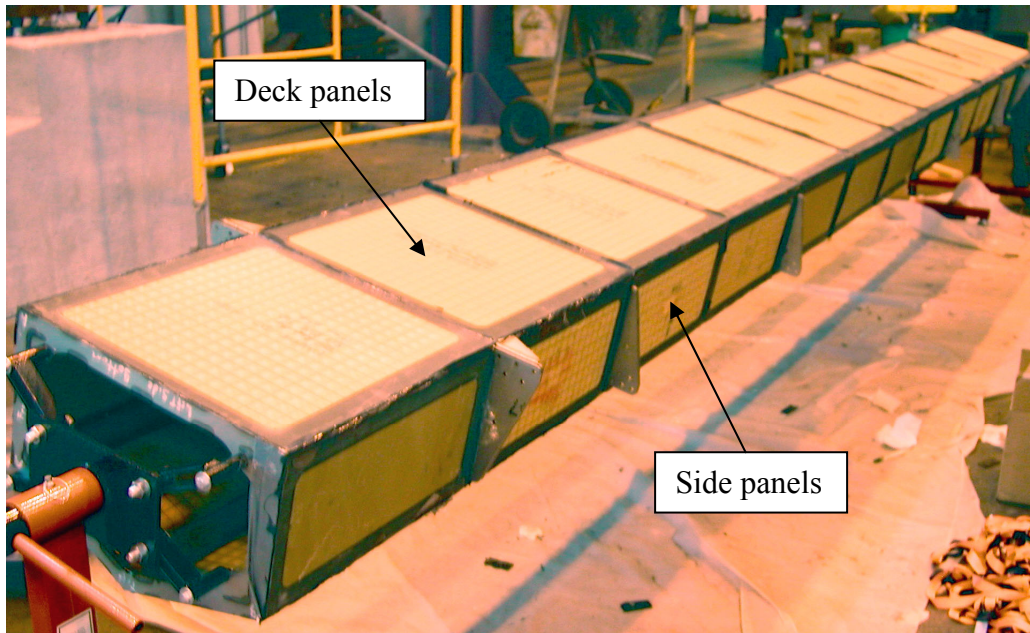


Fig. 6. Finished subscale Vierendeel ship hull girder with composite panels bonded to the steel truss.

Testing Procedure

The specimen was loaded as shown in Fig. 7. In principle, it was a six-point bending test simulating a sagging load, owing to the keel being up in the test frame. To obtain a feasible load distribution using a few discrete loads, the specimen was 6 meters (20 ft) long, which is about 2 meters longer than a true 1:35 scale model.

The loads were laid out such that both the scaled maximum bending moment and the scaled maximum shear load were reached simultaneously, but not at the same location. Maximum loads were derived according to ABS rules [1]. Based on these rules, the estimated design load was $2(F_1+F_2) = 83,300$ N.

The specimen was tested in the ATLSS Laboratory. A single hydraulic jack was used in conjunction with load-spreader beams as shown in Fig 8. Loads were introduced to the specimens through eight steel loading arms, bolted to brackets that were welded to the steel truss. The specimen was supported by an additional four arms mounted to floor mounts. There were eight strain gages mounted on these four supporting arms to monitor load.

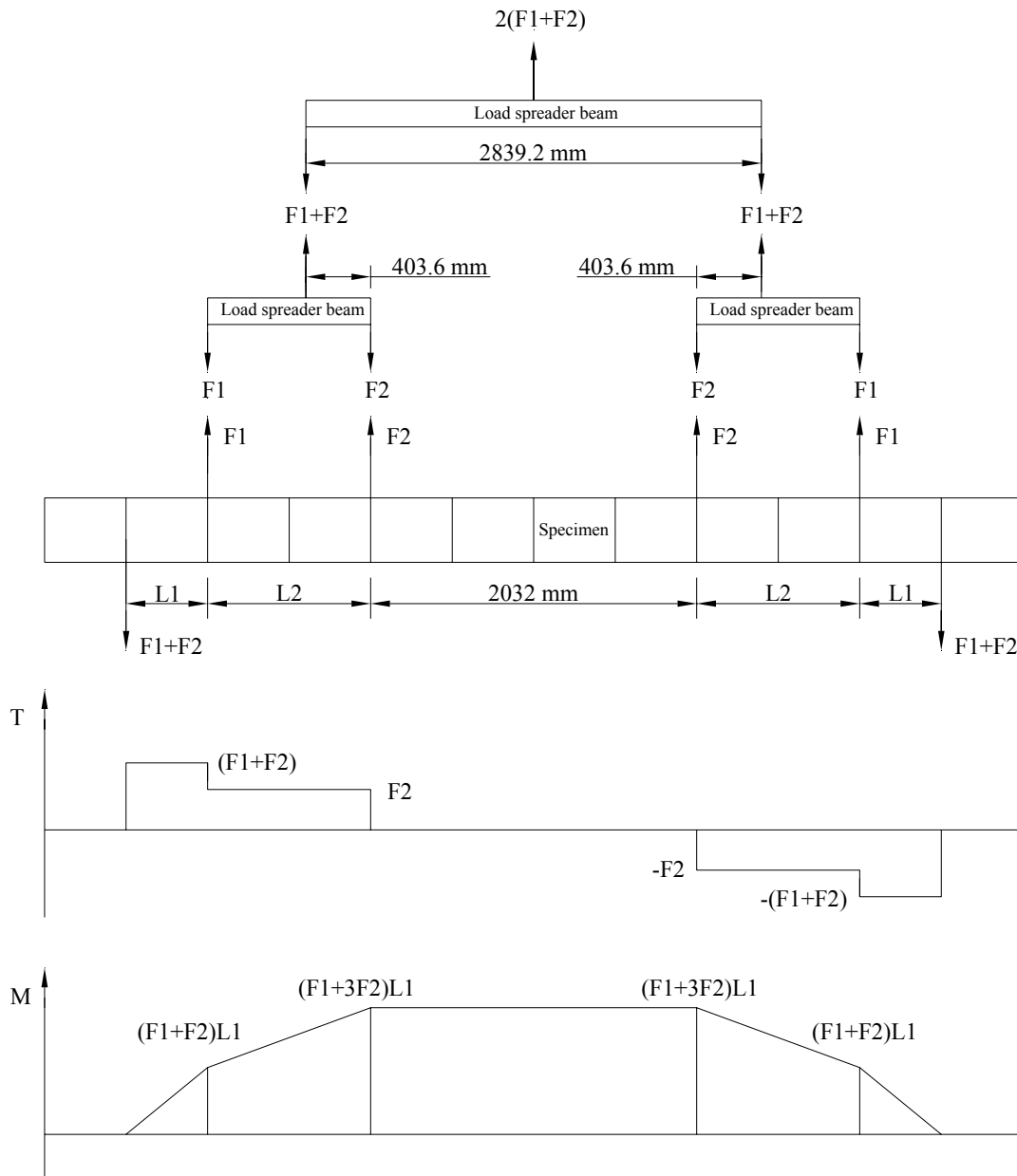


Fig. 7. Schematic of the six-point bending test showing the loading tree (top) and the resulting shear force (middle) and bending moment (bottom).

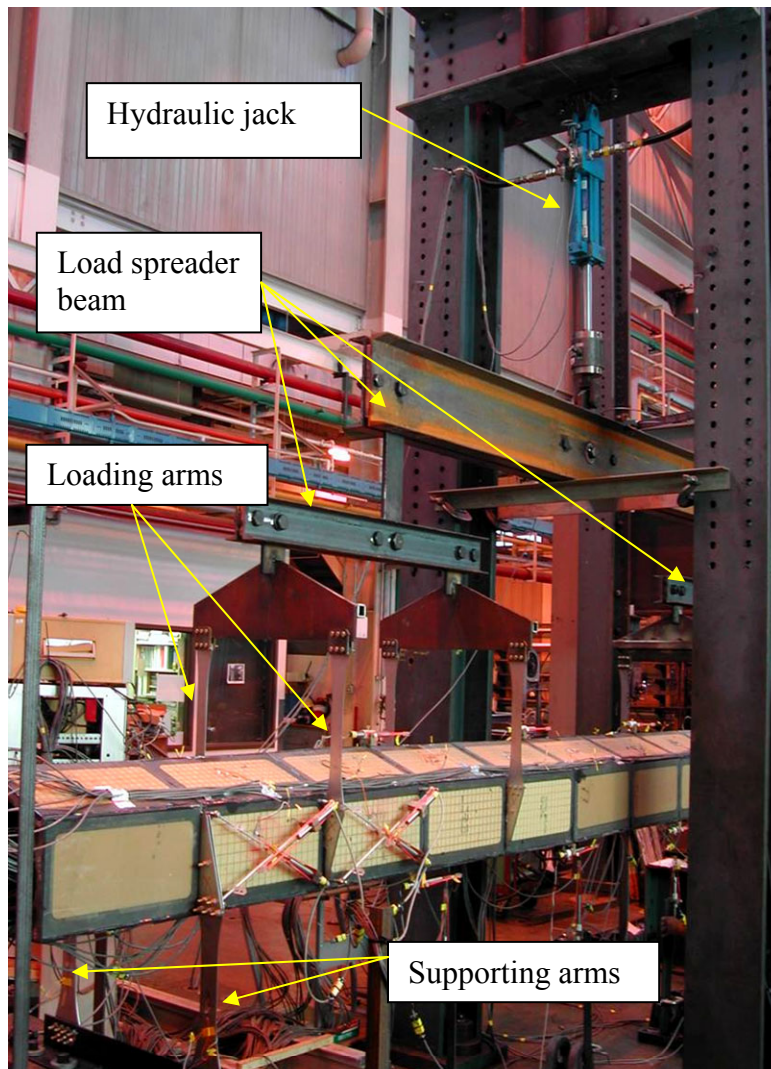


Fig. 8. Six-point bending test fixture with test specimen.

The steel truss was instrumented with 110 strain gages (Fig. 9). Of these, 30 gages were mounted on the steel longerons, which are the main load-carrying elements under pure bending loads. The remaining 80 strain gages were mounted on the bulkheads; these sensed local-deformation strains in the steel truss and enabled an understanding of the shear load distribution between the composite side panels and the steel bulkheads. The composite panels were instrumented with 74 strain gages (Fig. 10); these were mounted on both sides of the panels. There were 46 gages mounted on bottom panels, 16 gages on side panels and 12 gages on deck panels. Strain gages on both sides were used since the panels were non-symmetric (in-plane loads coupled with out-of-plane displacements) and enabled monitoring excessive bending as well as panel buckling.

There were 33 linear variable differential transformers (LVDT's) measuring deformations of the specimen (Fig. 11). On the eight side panels with highest shear load, 16 diagonally mounted LVDT's measured the shear deformations. In the length direction of the hull, there were 12

LVDT's mounted to measure horizontal deformations under bending. The remaining 5 LVDT's were mounted vertically from lab floor to the deck surface. Strain and displacement measured from these sensors, as well as the applied loads were recorded by the data acquisition system (Fig. 12).

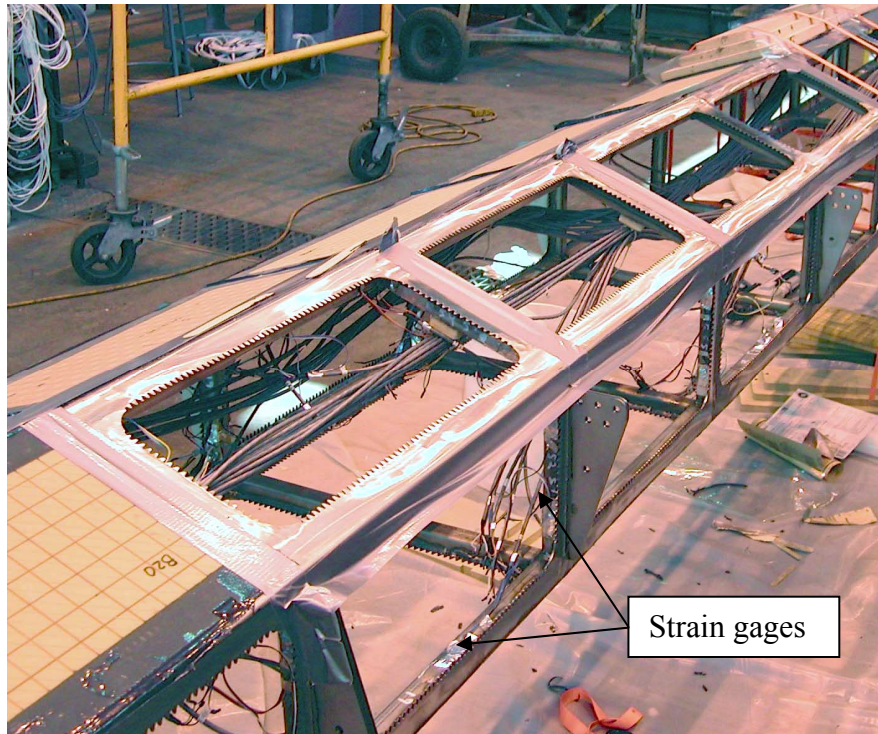


Fig. 9. Some of the strain gages on the AL-6XN steel truss.

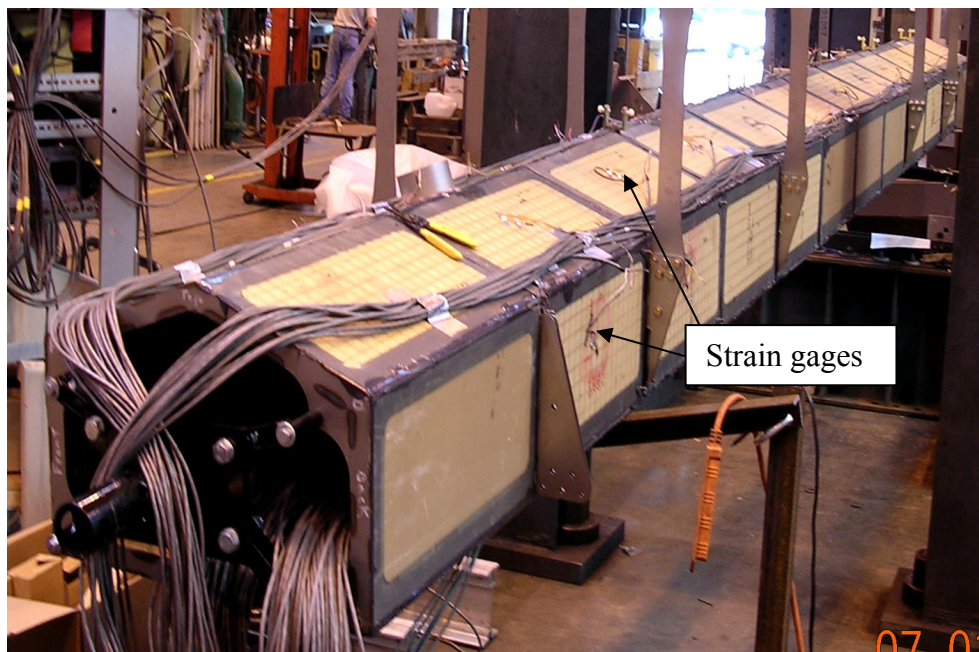


Fig. 10. Some of the strain gages on the composite panels.

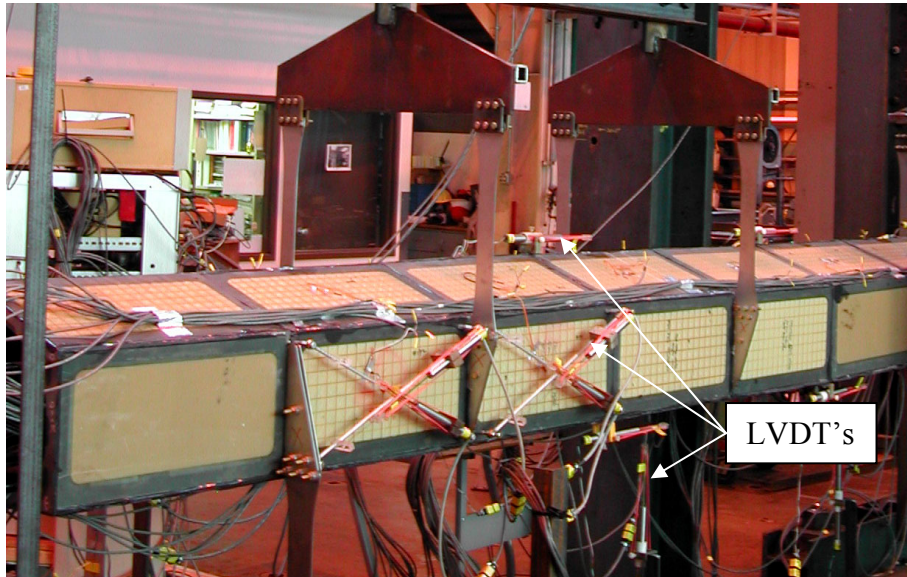


Fig. 11. Some of the LVDT's on the specimen.



Fig. 12. Data acquisition system.

During the test, the ship-hull specimen was repeatedly loaded and unloaded in small increments. The load started from 8,888 N (2000 lbf), and the increment of each load step was also 8,888 N. At each load level, the specimen was loaded and then unloaded three times, before continuing to a higher load level. Both the loading and unloading time periods were two minutes. Each time a higher load level was reached, the specimen was carefully checked for damage. The final load applied was 115.5 kN (26 kips), or 40% higher than the design load. In Fig. 13, the ship hull specimen is seen under the highest load.



Fig. 13. Sagging test with load at 40% above the design load. There is substantial deflection, containing both elastic and plastic parts.

Test Results and Discussions

Throughout the test, there was no indication of any failure in any of the 60 composite panels, or in any bonds between the panels and the steel truss. The test data showed that there was plastic yielding of the steel truss before the load reached the design load. There was substantial yielding and residual deformation of the hull girder, however, when the load increased to 40% above the design load. Fig. 14 shows the compressive strain measured at a strain gage mounted on the steel truss at mid-length of a deck longeron, where the bending moment was the highest. The plot clearly indicates plastic yielding of the steel truss. Fig. 15 shows the strain measured on a composite side panel with the highest shear load. The linear load-strain curve indicates that there was no yielding or damage in the panel.

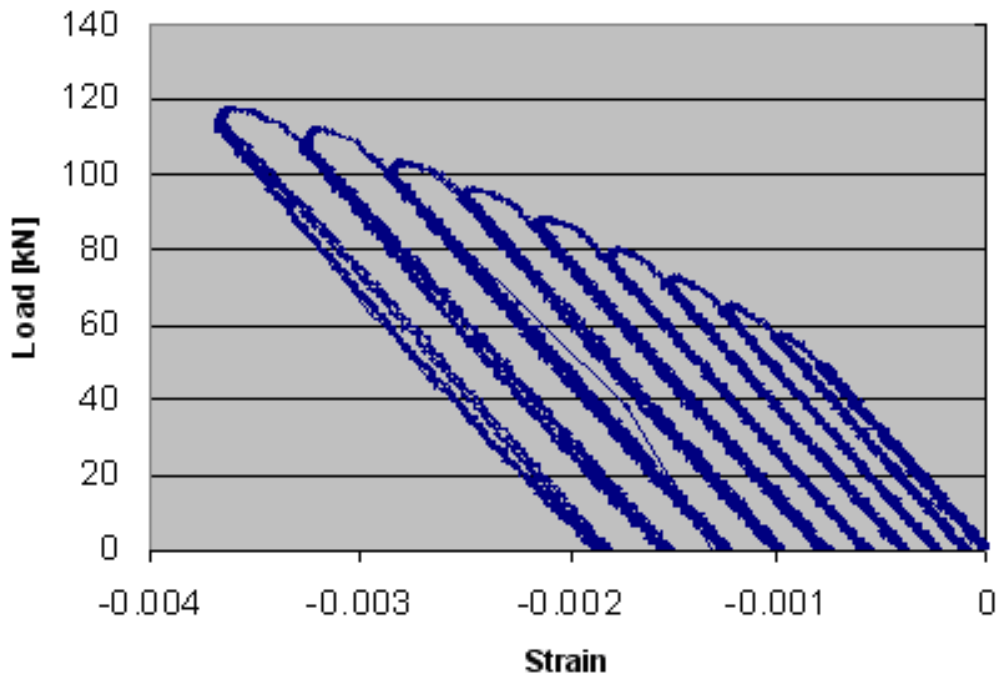


Fig. 14. Load-strain plot from a strain gage on a deck longeron in the lengthwise center of the specimen, where the bending moment was the highest.

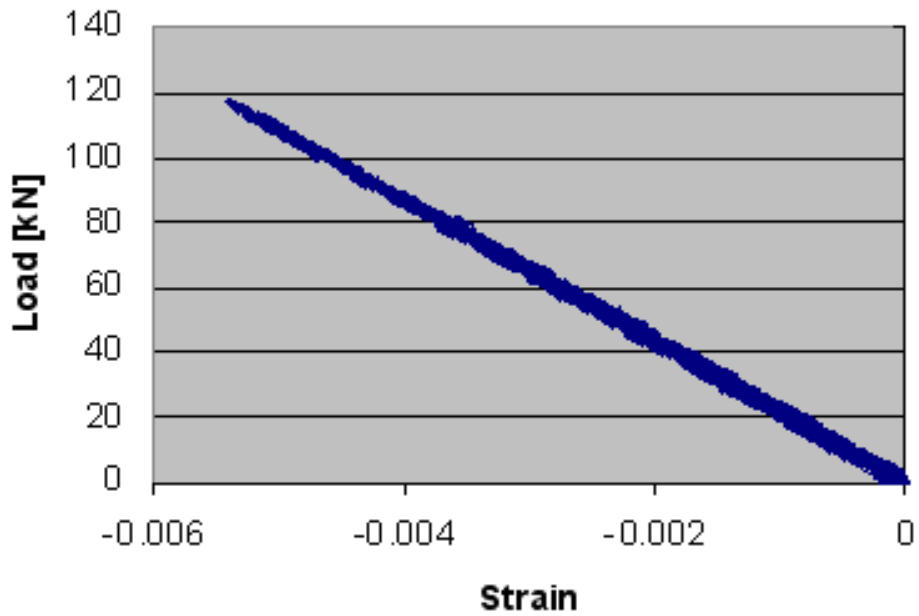


Fig. 15. Load-strain plot from a strain gage mounted on one of the highest shear loaded composite sandwich panels.

Conclusions

A Vierendeel-type AL-6XN steel truss / composite skin ship-hull girder specimen was manufactured and structurally tested under sagging loads derived from ABS regulations. The cross-section of the 6-m-long specimen was designed as a 1:35 subscale specimen of a 142-m-long ship-hull girder. Structural loading was discontinued at 40% above the design load, at which point there was substantial yielding and residual deformation of the hull girder. However, there was no indication of failure in any of the 60 composite sandwich panels, nor in the bonds between the panels and the steel truss. The test indicated that this steel-composite hybrid concept is a viable concept for further evaluation and design as a strong and lightweight hull.

Related Work

A journal paper on the current study is being prepared for submission to a scientific journal. Under a separate ONR contract, N00014-03-1-0597, a study of the Vierendeel hull has continued with a hogging test and a damage tolerance test and is leading to two additional papers.

Reference

1. *ABS Guide for Building and Classing High Speed Naval Craft* ▪ 2003, Part 3 – Hull Construction and Equipment, American Bureau of Shipping, Houston, TX, 2002.