FATIGUE OF FIBERGLASS GENERIC MATERIALS AND SUBSTRUCTURES

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ABSTRACT

The results on an ongoing study of the fatigue of wind turbine blade materials and substructures are summarized. A new approach to high cycle fatigue testing has been developed, based on small volume critical element tests which can be run at high frequency (100 Hz) to reach high cycles (10^8 cycles) in about eleven days of testing. Initial tensile fatigue S-N data from the first series of tests are presented. Associated fatigue studies on conventional coupon specimens at lower frequency have led to improved triaxially reinforced laminate constructions compared with other triax materials reported earlier. Three-dimensional finite element modelling of damage development helps to explain the behavior of the triax materials. Initial results are also presented for an I-beam substructure fabricated from the generic materials tested as coupons. The initial beam specimens have been subjected to static and fatigue loading, and analyzed using three-dimensional finite elements.

INTRODUCTION

Fatigue results and test methods for standard generic material coupon tests have been summarized in References 1 and 2*.

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Characterization of other generic wind turbine blade composite materials supplied by U.S. blade producers continues, and initial results from three additional experimental components to the fatigue study at Montana State University are reported herein. First, a new testing technique has been developed to achieve high cycles in a shorter time by running small volumes of material at high frequencies. Traditional coupon tests run at a typical frequency of 10 Hz require over one hundred days to reach 10^8 cycles for a single test. The new tests were developed to run at frequencies up to 100 Hz, shortening the time required for 10^8 cycles to eleven days. For the first time, this technique allows the accelerated fatigue characterization of blade materials out to the design lifetime range in a practical time period. The use of small specimens and high frequencies requires validation in terms of applicability to composite structures. These data are intended to represent the material behavior of a layer or two material, failing in one of several possible modes (fiber dominated tension or compression; matrix dominated tension, compression, or shear; and interply delamination). The overall laminate will then experience a sequence of local failure, consequent load redistribution, and final failure. The theoretical context for this approach is the "critical element" modelling being pursued by Reifsnider [4] and others.

The second area of new work is the development of an I-beam substructure test. The I-beam geometry is intended to allow a relatively simple application of the coupon fatigue database to the prediction of lifetime trends for composite structures which are similar in nature to blades, but smaller, simpler, and easier to test. Beams are assembled from flanges, webs, and shear stiffeners, so that flanges of different generic materials can be tested in the beam geometry. The beams are analyzed with 3-D finite elements to obtain a complete stress and strain distribution as a basis for prediction of fatigue life from coupon tensile and compressive S-N data. The I-beam loaded in four-point-bending provides a much improved basis for the interpretation of compressive load carrying capability. There has been considerable difficulty in predicting composite structure lifetime from coupon data in the advanced composites industry [4].

The third new area is processing. Composite plates and beams are now being processed at Montana State University using resin transfer molding (RTM) [4]. In this process, reinforcement fabrics (the same as those used by blade manufactures) are placed in a closed mold, and the polyester resin (again, the same resin as in typical blades) is pumped in to fill the mold. This process yields higher quality than hand layup in terms of higher fiber content (if desired), lower porosity, better fiber alignment, and two flat surfaces. This development has been essential in producing small specimens for the high frequency tests, where we want a baseline material with excellent fiber alignment as discussed later. The in-house molding capability also allows us to produce beam webs and flanges without requiring special molding by blade manufacturers. We continue to test materials supplied by blade manufacturers as an essential part of the program to represent actual industry materials, both for coupon data and beam flanges.

HIGH FREQUENCY, HIGH CYCLE TESTS

Fatigue testing of standard coupons of fiberglass, one to two inches wide and an eighth to a quarter inch thick, is limited to a frequency range of about 20 cycles/second (Hz). This limitation is due to internal hysteretic heating of polymer based materials, coupled with their poor heat transfer characteristics. Depending on the load level and frequency, temperature can increase to a level where failure is thermally induced rather than mechanical in nature. The data then cannot be applied to the lower frequencies of applications such as wind turbine blades [5]. It is difficult or impossible to build a database for fatigue performance at 10^8 cycles as required for wind turbine blades if the frequency is limited to 10 to 20 Hz, since a single test then requires 50 to 100 days or more of a dedicated servohydraulic testing machine.

The objective of this study was to develop special fatigue test for higher frequency, with a goal of 100 Hz. A high response testing machine (Instron Mod. 8511) was obtained for this purpose. A finite element heat transfer study indicated that specimens on the order of 0.06 inches or less in thickness should be able to be tested at 100 Hz and low applied stresses.

Again with the aid of a finite element analysis, a suitable tab geometry was developed for testing a single strand of unidirectional material 0.017 in. thick, impregnated with a polyester matrix. After a number of attempts, a tabbing arrangement was found which yielded acceptable failure locations away from the tab. The specimen shows minimal heating at 100 Hz as monitored by temperature sensitive paint. Details of this test development are to be published, but can also be found in Ref. 6.

Recent developments have resulted in refinements to the specimen design relative to those shown in Figure 1 for both tension and compression. The original tensile fatigue tests were run on strand materilas which contained significant local waviness that appears to have reduced the properties of the very small test gage sections (Figure 1). The material in these initial tests varied in fiber volume fraction from 0.45 to 0.52, and the average ultimate tensile strength was only 655 MPa with an elastic modulus of 34.5 GPa. This yields a low static failure strain of less than 2%. We have recently switched to a well aligned material based on Hexcel unidirectional fabric which appears to yield better results.

The original strand tests produced the tensile S-N fatigue data in Figure 2 to beyond 10^8 cycles. The test method performed well over the entire range. The frequency was varied from 30 to 100 Hz as the cycles varied up to 10^8, producing a nearly constant load rate. Tests are currently underway with well aligned material to reproduce these tensile fatigue data, and compression tests are currently in progress.

Our experience with the high frequency tests indicates that longitudinal tension and compression fatigue tests can be succesfully conducted at frequencies up to 100 Hz, with cycles to 10^8. Failure modes and lifetime trends are consistent with those from standard coupons, and no significant specimen heating is observed. Generation of a 10^8 cycle database at several R-values is now in progress (R=min. stress/max. stress). Early correlation results indicate that the S-N curves for conventional coupons of industry prepared materials can be obtained simply by normalizing the high frequency S-N results by the static strength.

IMPROVED TRIAXIAL REINFORCED LAMINATES

Several laminates reinforced with $0/\pm45$ triaxial fabrics were shown in Ref. 1 to have poor fatigue resistance. These laminates failed soon after cracking developed in the $\pm45°$ layers, contrary to expectations. Extensive three-dimensional finite element analysis of stress fields around matrix cracks, as well as series of experimental triaxial laminates, have led to an improved understanding of this problem and to laminates with improved tensile fatigue performance.

Table 1

STRESS CONCENTRATION IN 0° PLY DUE TO 90° PLY CRACK

NO MATRIX INTERLAYER	2.46
.01 h INTERLAYER CRACKED	1.71
.01 h INTERLAYER NOT CRACKED	1.39

h= ply thickness

Table 1 gives results from a three dimensional finite element analysis of 0/90 glass epoxy laminates with a crack in the 90° ply. The stress concentration in the 0° (load direction) fibers is much higher when the 0° and 90° layers are packed tightly together, as compared with the case where there is a neat matrix layer between the layers, even if the matrix is cracked. These results, as well as variety of other results for 0/90 and 0/±45 laminates in Ref. 7, show the importance of separating the strands of the reinforcement into distinct layers. Modelling of discrete strands in the 0° layer also showed similar effects. It is notable that similar solutions with carbon rather than glass fiber show much less stress concentration in the 0° material, and this effect has not received widespread attention in the advanced composites literature.

The stitched fabrics used in triax reinforcement show varying degrees of the extent to which the 0° strands are stitched to the ±45° strands. Two quite different patterns are shown in the cross-sections in Fig. 3. The less tightly stitched case, Material W with Hexcel fabric CBD200, shows significantly improved tensile fatigue resistance in Fig. 4 as compared to the tightly stitched case, Material V, reinforced with fabric DBD222 (both materials have a polyester matrix). This is consistent with expectations from the finite element results. The test methods used for coupon testing described in this section are the same as given in Ref.1; specimens were two inches wide, R=0.1.

Even more dramatic results are obtained by using entirely separate 0° and ±45 layers. Material R in Fig. 5 is composed of layers of Hexcel 0° fabric DN105 and ±45° fabric DB120 with a polyester matrix. At high stresses (short lifetimes) the behavior is similar to that of most other triax laminates as described in Figure 5 of Ref. 1. However, at lower stresses a transition occurs, and the S-N data follow the trend line expected for the 0° material alone [1]; the failure strains in fatigue also increased to approximately 0.8% maximum tensile strain at 10^7 cycles. Most other triax laminates fail at strains close to 0.3 to 0.4% at 10^7 cycles, because this is the range where the ±45° plies crack [1]. The behavior of Material R is analogous to that reported for aerospace-type composites of similar ply configurations, constructed of unidirectional prepeg layers [8].

I-BEAM SUBSTRUCTURE TESTS

I-beams are fabricated from resin transfer molded (RTM) webs with either mat or ±45° fabric reinforcement, bonded to flanges which are strips cut from sheets either supplied by blade manufacturers or molded by RTM at Montana State University. All RTM materials used E-glass fabrics and polyester resin identical to those currently in use by blade manufacturers. Current beams are three-inches-deep, with three-inch-wide flanges. They are loaded in four point bending as shown, with an inner span of 15 inches and an outer span of 24 inches. Figures 6 and 7 show the beam geometry, finite element mesh, and test fixture. The beams were designed using 3-D finite elements to provide the stiffest possible geometry while avoiding web and load point failures. The objective of the design was to provide maximum flange stresses relative to load-point deflection, since frequency is limited by the flow capacity of the hydraulic system. Shear stiffeners were added between the outer and inner supports to prevent web failure and to reduce deflections; load introduction pads are also incorporated.

The first exploratory beam tests have been run using the loading fixture shown in Fig. 7. The fixture has performed well, but failures have occurred near the load points, requiring design modifications. Figure 8 gives the flange strain at the center-span. The finite element prediction is in good agreement with the experimental values measured with strain gages. More details of the beam will be provided in the future, when a final geometry is identified. We plan to pursue several methods of NDE in conjunction with the beam fatigue tests, including enhanced radiography of damage, acoustic emission (with Sandia National Laboratories), stiffness changes and possibly modal analysis.

CONCLUSIONS

The results presented have extended earlier findings [1] in three areas. First, specialized high frequency tests have been developed which allow fatigue testing at 100 Hz, and have provided the first fatigue data to beyond 10^8 cycles, the expected range for wind turbine blades. Second, laminates with improved fatigue resistance have been identified for triaxial (0/±45) reinforcement commonly used in blades. Finally, small I-beams have been designed, fabricated and tested with a new fatigue apparatus. The beams allow the use of different flange materials for exploring predictive models for composite structure lifetime based on coupon data, and for developing NDE methods. These developments have been in conjunction with new capabilities in 3-D finite element analysis and resin transfer molding.

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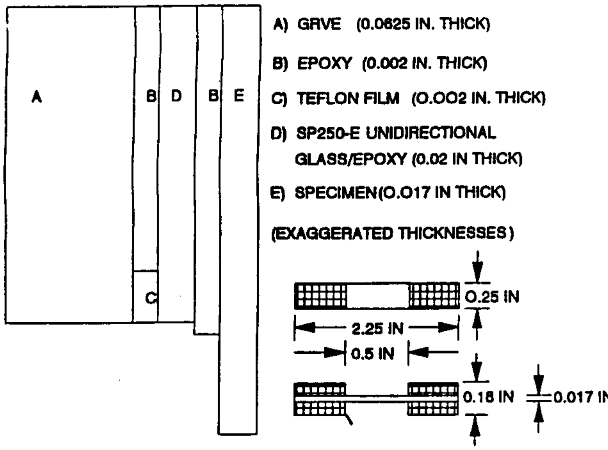

Figure 1. Tensile specimen for high frequency tests

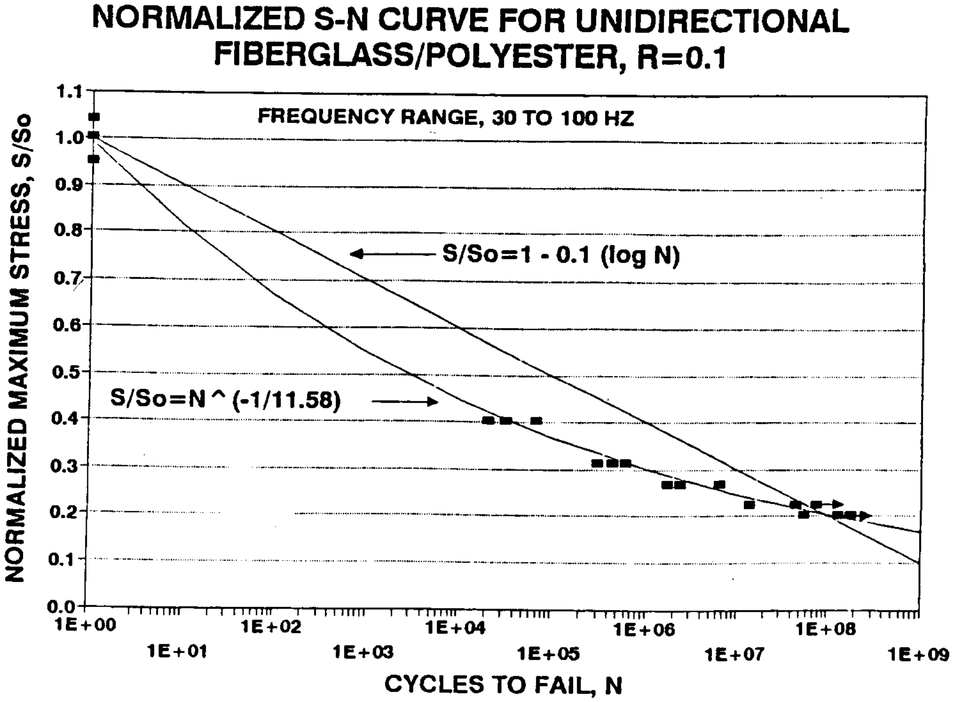

Figure 2. S-N Fatigue Data from High Frequency Tests, Longitudinal Tension Fatigue, R=0.1, 30 to 100 Hz.

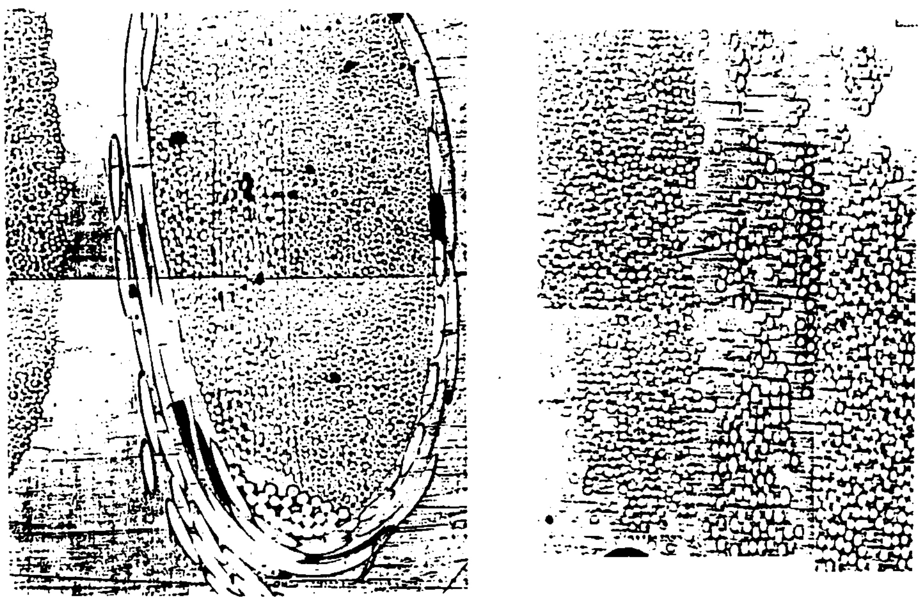

Figure 3. Cross-sectional structure of Materials V (Left) and W (Right).

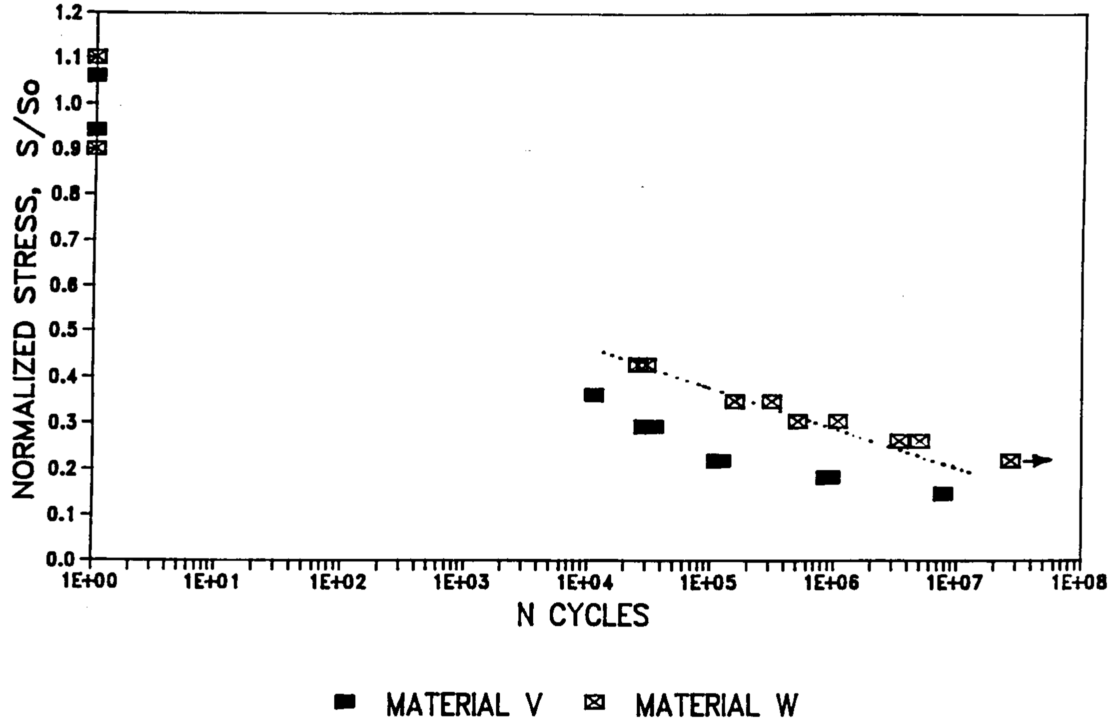

Figure 4. Coupon S-N Fatigue Data for Two Triax Materials, R=0.1.

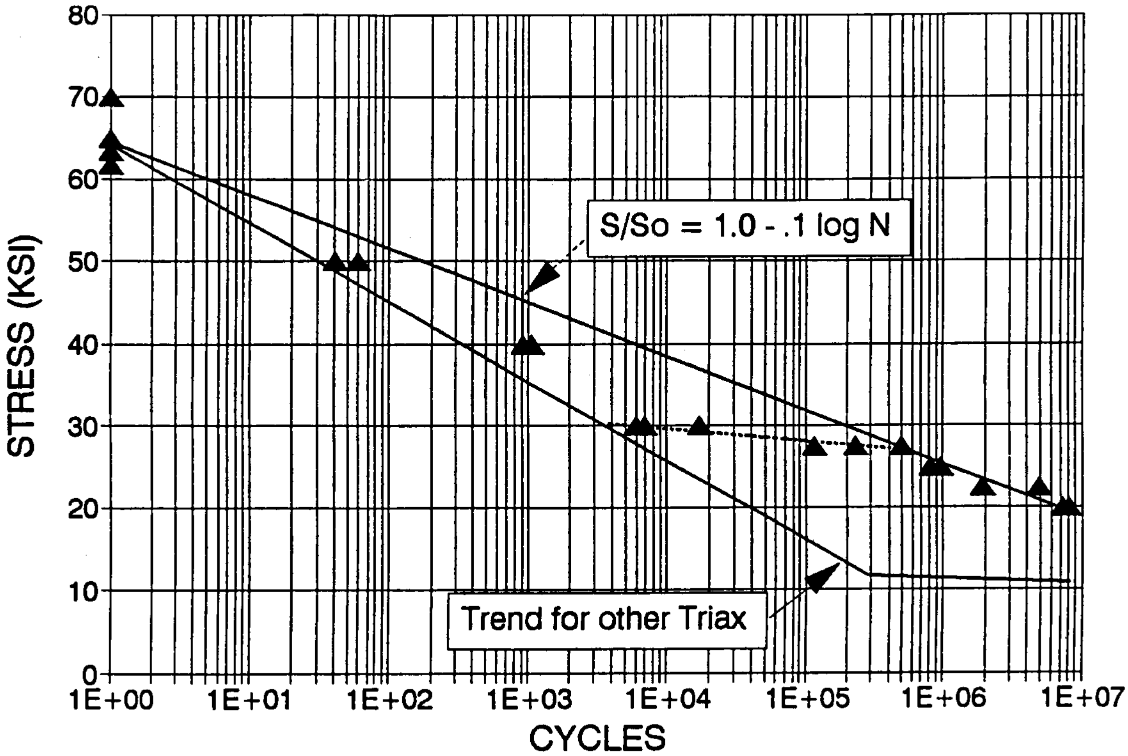

Figure 5. Coupon S-N Fatigue Data for Material R. with 0° Layers separated from ±45 layers, R=0.1.

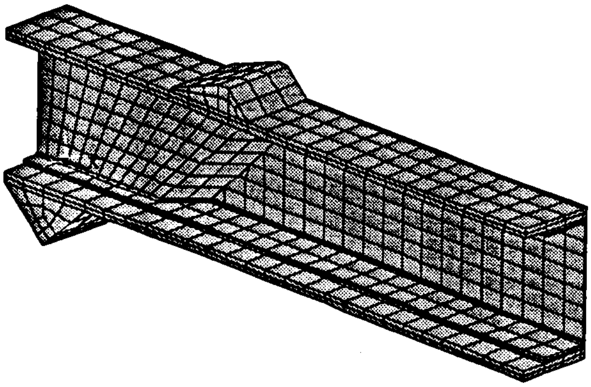

Figure 6. I-beam structure and Finite Element Mesh.

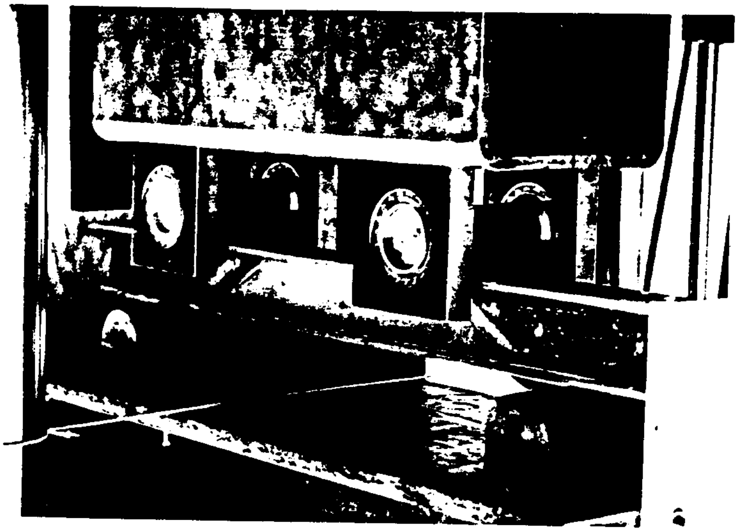

Figure 7. Photograph of I-Beam in loading Apparatus Incorporated into MTS 880 Testing Machine.

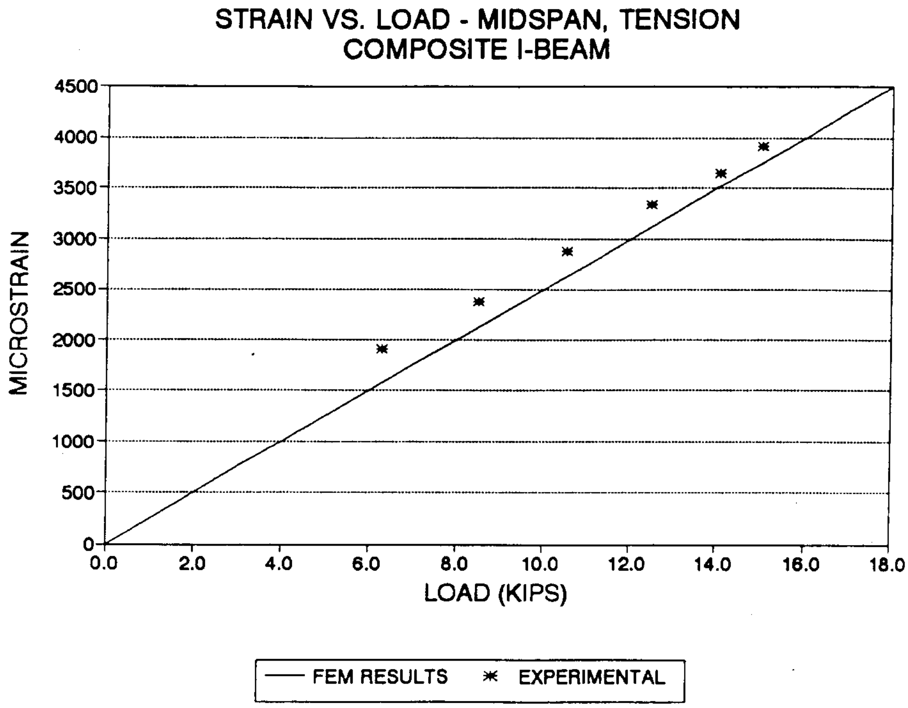

Figure 8. Predicted (FEM) and Experimental Flange Strain at Mid-Span vs. Load for I-beam.