63

FINAL REPORT

INITIAL STUDIES OF A FLEXURAL MEMBER COMPOSED OF GLASS-FIBER REINFORCED POLYESTER RESIN

by

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TABLE OF CONTENTS

SUMMARY

An investigation was conducted of the structural behavior of a flexural member composed entirely of glass-fiber reinforced polyester resin. Three experimental girders were fabricated and load-tested in the laboratory. The physical characteristics of the members included a triangular cross section, a top flange built up with preformed shapes, a combination of plates and trussed strands for web elements and a lower chord consisting of multiple strands of resin-impregnated glass fibers.

It was found that experimental deflections and strains were reasonably well predicted for the members by conventional analytical procedure for relatively small loads. Ultimate strength tests were precluded by failures of connections at the top flange joints.

Recommendations are presented for subsequent investigations of reinforced plastic structural members.

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INTRODUCTION AND RESEARCH OBJECTIVES

The applications of reinforced plastics as primary load-bearing structural members have increased in recent years in both the aerospace and building construction industries. Many applications have been made to meet the specialized requirements of a particular service, but all have provided either direct or indirect cost benefits to the user. Among the attractive features of the materials systems thus utilized have been high strengths, low weights and industrialized fabrication capabilities. In light of the paucity of similar applications in the highway industry, and in particular highway structures, an investigation was initiated to explore ways and means to adapt high performance plastic composites to beneficial uses in highway structures. After consideration of the various aspects of the materials utilization question, it was decided to direct the major effort toward the development of a flexural member which would be suitable for a primary load-bearing component in a bridge structure. This report, therefore, deals with the design, fabrication and load testing of a selected flexural member composed entirely of glass-reinforced plastic.

Specific objectives of the research program were as follows:

1. To design a flexural member which would take advantage of the high strength characteristics of glass fibers.

2. To fabricate a test specimen with a size and geometry representative of some in-service structural members.

3. To obtain data relative to the stiffness, strength and stability of the specimen by load testing.

4. To evaluate load performance characteristics and manufacturing feasibility of the flexural member.

These objectives were achieved to varying degrees during the period of investigation from September 1972 to June 1973.

DESIGN OF THE FLEXURAL MEMBER

The approach to the design of the flexural member was dictated by the highly orthotropic characteristics of the composite material used. In order to develop the high tensile strength property of the glass fibers effectively, it was desirable to utilize an arrangement wherein the fibers would be axially aligned with the direction of the tensile stresses in the member. This criterion could be satisfied in the lower chord and diagonal web elements of a Pratt truss configuration, so initial consideration was given to truss geometries. It was also recognized that highest material efficiencies could be achieved by a winding process (i.e., the process of building up a cross-sectional area by repetitive passes of strands of resin-impregnated glass fibers) in which material volumes would be closely matched with strength requirements from point to point throughout the member. However, a filament-wound composite is usually inefficient in resisting compressive (buckling) stresses so the winding process was not considered suitable for the top chord.

With the above limitations and advantageous properties in mind, an initial trial geometric shape was adopted which would combine the features of both an open-web truss and a solid-flange girder. This combination would include built-up elements of filament-wound fiber glass for the web diagonals and lower chord and solid, prefabricated plate and rod shapes for the top chord and vertical web elements. Lateral and torsional stability was provided for the member with a biplanar arrangement of the web elements and a common lower chord, i.e., a triangular cross section. The combination of conventional elements and behavioral concepts from both truss and girder forms with the triangular cross-sectional shape gave rise to the designation of Triangular-Trussed Girder (TTG) for the integrated structural member. A sketch of the initial concept is shown in Figure 1. A solid web plate was also included in the initial concept to provide a form to which the vertical web elements could be attached during the winding operation of the tensile web and chord elements. It was not expected nor intended that the side plates would contribute to the member structurally during loading, the presumption being that the plates would buckle at a relatively low live load. Therefore, no effort was made to bond the side plates to the web elements. However, as will be discussed later, the contribution of the side plates was significant in the performance of the member.

The elements of the eight-foot long member were proportioned to carry a uniformly distributed ultimate load of 10,000 pounds applied to the top plate.

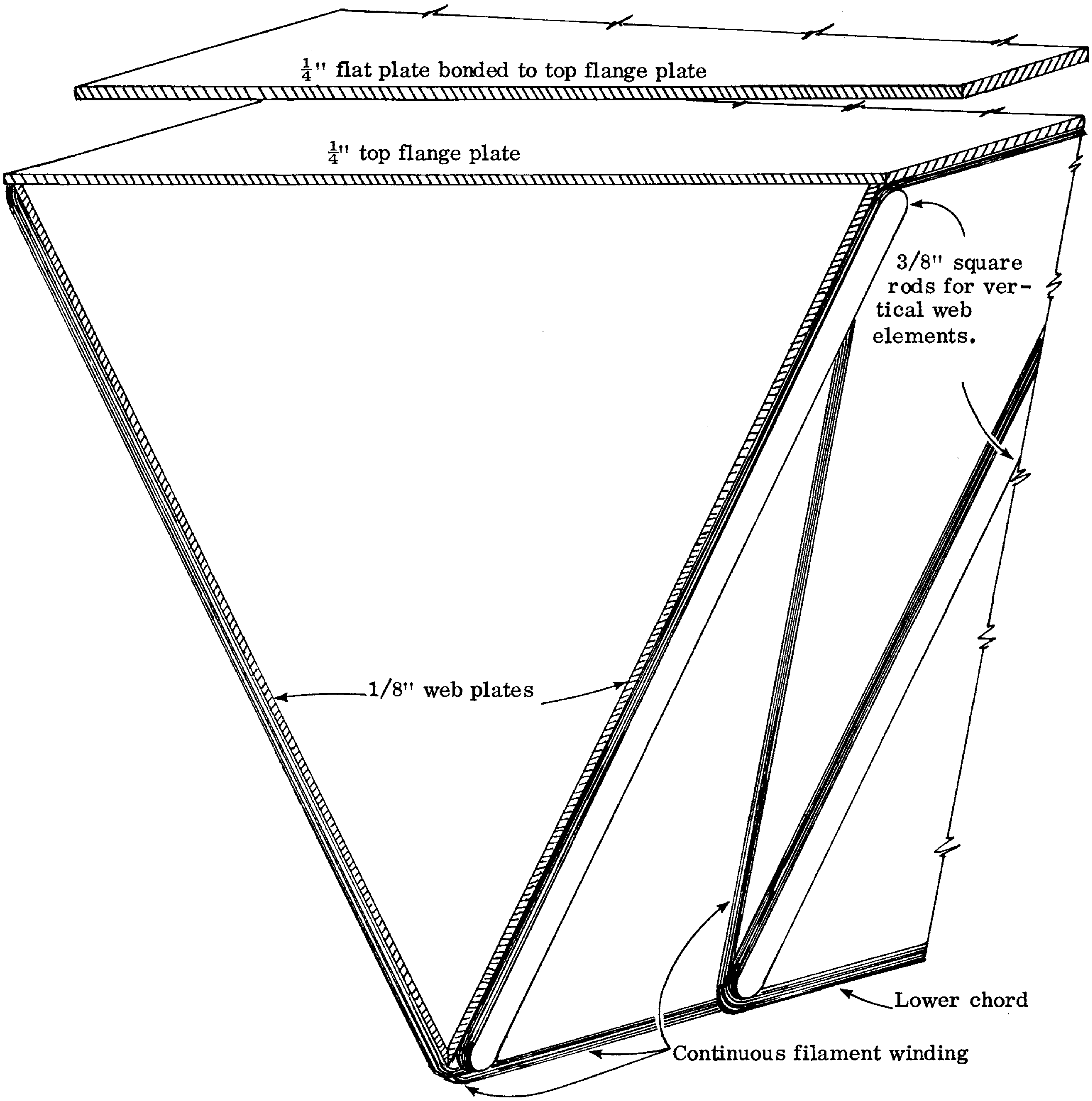


Figure 1. Sketch of TTG structural element after filament winding

Geometric dimensions were established in accordance with the following guidelines.

1. Length to depth ratio for trusses ranges from 6 to 8 for highway structures.

2. Lateral deflections will be resisted by the top plate and the component of the inclined truss projected into a horizontal plane.

3. Resistance to in-plane distortion is inherently high in an equal-angle triangular cross section.

4. The spacing of the vertical web elements required a balance between the unsupported length of the top plate and variation in material volume of the stranded web and lower chord elements.

The above guidelines coupled with intuitive judgment of the interaction of the elements resulted in the adoption of the dimensions shown in Figure 2. The longitudinal spacing of the vertical web elements was based on the parabolic shape of the bending moment diagram for a uniformly loaded beam such that the cross-sectional areas of the chord elements would increase by the same increment in each panel to satisfy the flexural stress requirements. For the uniformly loaded, simply supported member, the moment increase in each panel was $1/32\ wL^2$ from the ends toward the center for a length of L and a uniform load of w. For lack of a better approach, the cross sectional sizes of the individual elements were determined from a simplistic stress analysis of the entire member acting as a pinned-end truss. As will be shown later, this assumed behavior was quite close to experimental observations. From these calculations, the required areas of the elements were as shown in Table 1 when based on ultimate stress values of 100 ksi for tension, 35 ksi for compression and a safety factor of 2. The areas actually provided were somewhat different due to fabrication considerations.

From the detailed sketches of the joints shown in Figure 2, it can be seen that no special efforts were made initially to ensure the integrity of the connection at the top and side plates other than that provided by the resin used in winding. Consequently, it was expected that separation of the plates would occur at low load values. This, in fact, happened and various procedures were investigated subsequently to strengthen the joint.

No effort was made to predict elastic deflections in the preliminary calculations because of the behavior of the intersecting joints of the elements and the true value of the elastic moduli of elasticity were unknown.

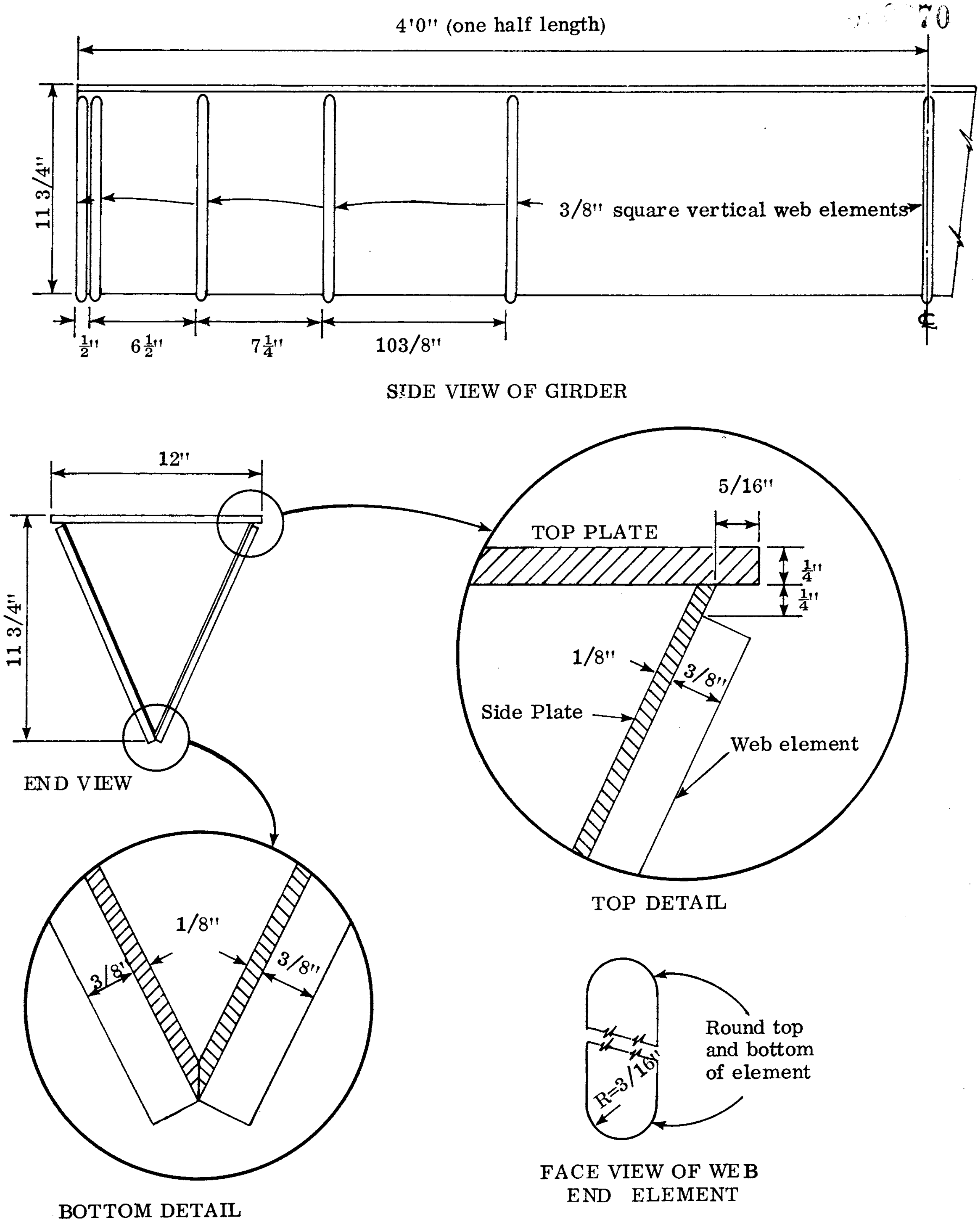
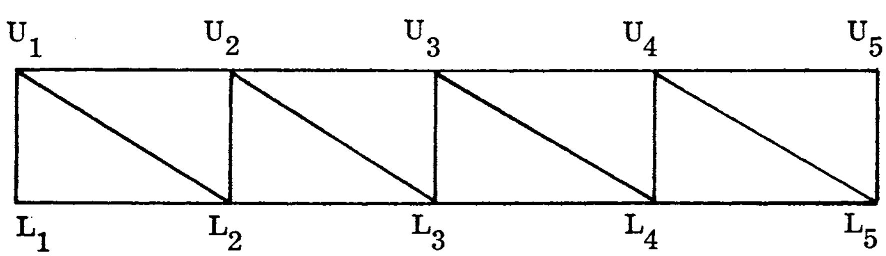


Figure 2. Details of TTG structural element (skeletal frame prior to winding).

TABLE 1

COMPUTED AND SUPPLIED AREAS FOR ELEMENTS OF TTG-1

Element	Required Area (Square Inches)	Supplied Area (Square Inches)
Web, Each Side		
U_1 L_1	0.160	0.28
U_1 L_2	0.064	0.06
U_2 L_2	0.160	0.28
U_2 L_3	0.056	0.06
U_3 L_3	0.137	0.28
U_3 L_4	0.052	0.06
U_4 L_4	0.082	0.28
U_4 L_5	0.063	0.06
U_5 L_5	0.080	0.28
Top (flange plate) Chord		
U_1 U_2	0.144	6.00
U_2 U_3	0.288	6.00
U_3 U_4	0.440	6.00
U_4 U_5	0.532	6.00
Bottom Chord		
L_1 L_2	0.050	0.04
L_2 L_3	0.100	0.15
L_3 L_4	0.150	0.24
L_4 L_5	0.200	0.36



Legend

FABRICATION OF THE TEST SPECIMEN

A. Materials

All of the materials used in the structural members were obtained from Morrison Molded Fiber Glass Company (MMFG) of Bristol, Virginia. These included the following principal items:

1. Glass fiber reinforcing, 30-end equivalent roving of E glass; manufactured by Owens Corning Fiberglass.

2. Polyester resin 1060 (with MEK peroxide catalyst) with a gel time of about 45 minutes and room temperature cure; manufactured by the Koppers Company.

3. Prefabricated plates and shapes of EXTREN 500, composed of the glass-resin system listed above; manufactured by MMFG.

B. Fabrication Procedure

A total of three test specimens were fabricated in the laboratories at the University of Virginia. Specimen 1 (TTG-1) was processed by joining the three plates with tape to form the triangular shape and then attaching the 3/8-inch square rods to the side plates with spots of polyester resin at each end. After curing for at least twenty-four hours, the lower chord and web members were formed by winding the glass roving, impregnated with the liquid polyester resin, around the ends of the rods in a pattern which alternated between the sides of the members. Five different major winding patterns were followed to complete the areas listed in Table 1. The areas of the top plate and vertical web members supplied were excessive and constant because of the fixed minimal dimension of the prefabricated shapes. Because of the thick top plate, no cross stiffeners were used to distribute the test load to the web members at the panel joints. Larger prototype members would permit the variation of these areas to conform better to the calculated stress requirements for the member.

Specimen 2 (TTG-2) was fabricated in the same manner as TTG-1, except that the joints between the plates were strengthened by bonding one-half of a 6-inch wide strip of chopped fiber mat to the face of each of the plates along the length of the joint. The size of the outstanding dimension of the vertical web elements was increased to provide more space for the roving.

Specimen 3 (TTG-3) was fabricated in a manner similar to TTG-2, but with two modifications. First, the mat used to reinforce the plate joints in TTG-2 was replaced with a prefabricated EXTREN angle (1 1/2" x 1 1/2" x 3/16") which was bonded initially to the top plate and subsequently to the top ends of the vertical web elements. Secondly, the side plates were removed from the member after winding to leave an open-web structure which was bonded with polyester resin to the angles on the top plate. Some slight changes were also made in the winding pattern to improve the technique and time requirement for the process. Sequential photographs of the fabrication of the specimen are shown in Figures 3 through 8.

It should be noted that the specimens were fabricated by personnel with no previous experience in fabrication techniques and with no specialized equipment for handling the materials. All bonding and winding procedures were performed manually by two individuals working together. With a little experience, however, the techniques improved rapidly as demonstrated by the fact that the winding operation required two days for TTG-1, three-fourths day for TTG-2 and about three hours for TTG-3.

TEST PROGRAM FOR THE STRUCTUAL MEMBER

Instrumentation

Test specimens were instrumented to obtain data relative to vertical deflections and strains in selected elements during loading. All deflection measurements were made with conventional Tumico dial indicators with least readings of 0.001 inch. Strains were measured in the elements of the member by means of electrical resistance strain gages bonded to the surface. The positions of the strain gages were slightly different in the three test specimens, but in all specimens gages were bonded to the web, lower chord and top plate elements. Gages supplied by the Micro-Measurements Company, types EA-06-250 BF-350 and EA-06-250 TB-350, were bonded with MM A/E-10 epoxy adhesive to TTG-1 and with M-bond 200 adhesive to TTG-2 and TTG-3. In addition, several three-element wire rosette gages were bonded to the side plates of specimens TTG-1 and TTG-2 to monitor the buckling behavior of the plates. Strains were recorded by means of a 50-channel, Model 205 indicator and Model 305 switching system made by William T. Bean, Inc.

Load Testing

All load testing was performed in the structural testing laboratory of the Department of Civil Engineering at the University of Virginia. Test loads were applied with hydraulic cylinders connected to a Riehle/Los pumping console which provided load control to the nearest 80 pounds per cylinder (10 psi uniformly distributed load on the member). An air bag 3-feet by 9-feet by 1-foot deep, made by the Uniroyal Company, was used to spread the hydraulic cylinder force uniformly over the top plate of the member. Support was provided at the ends of the test member by wooden frames built to fit the triangular shape of the cross section.

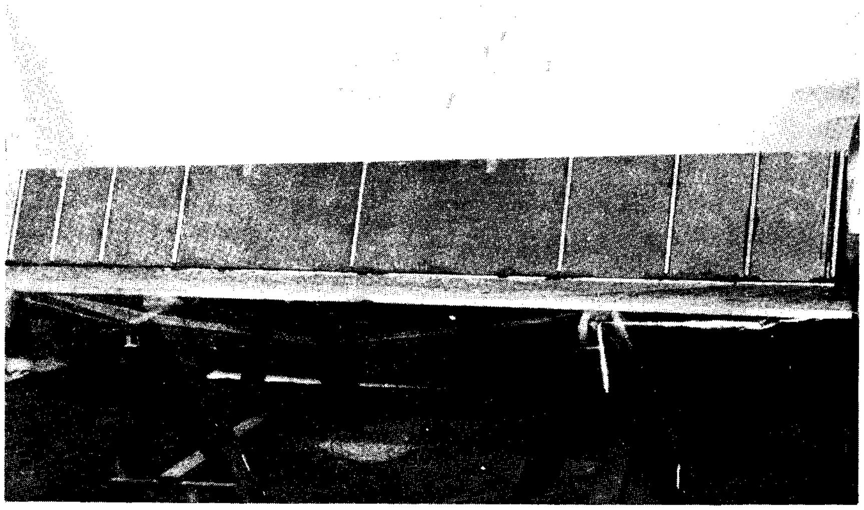


Figure 3. Initial assembly of plates and vertical web elements of TTG-1.

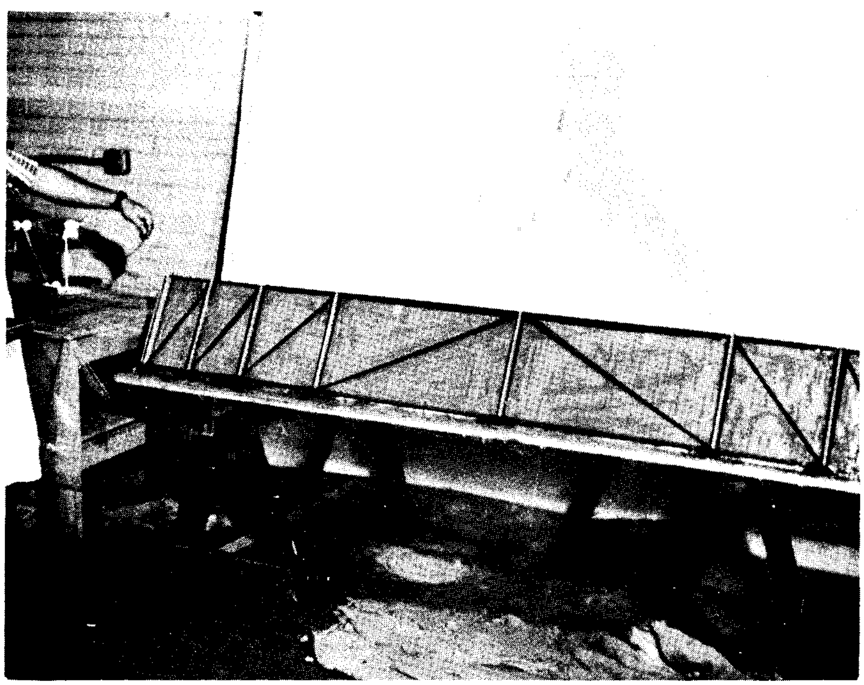


Figure 4. TTG-1 after winding web and chord elements with strands of glass fiber. Note inverted position of member during winding. Operator is holding a strand of roving.

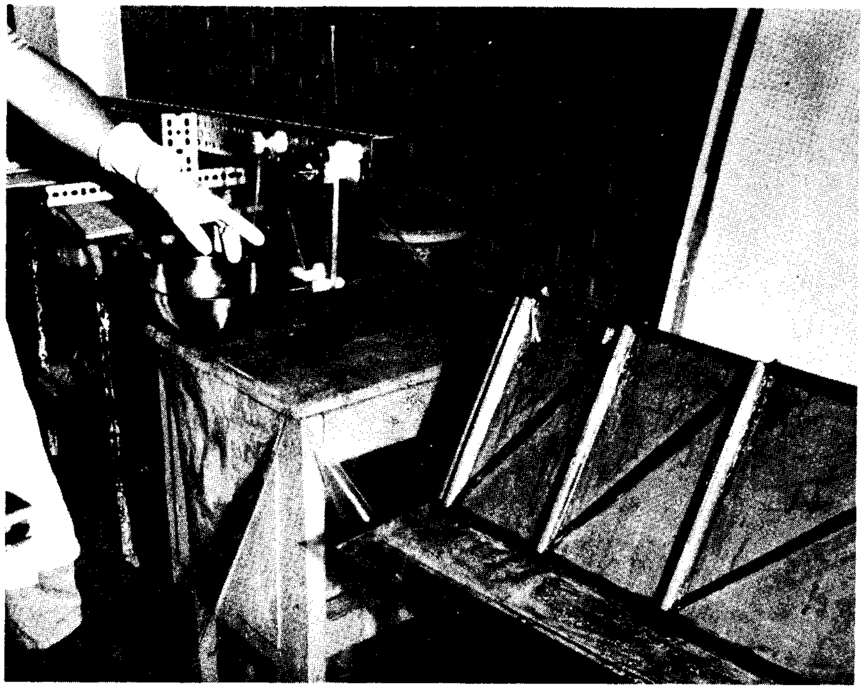


Figure 5. View of TTG-1 and the equipment used for impregnating the glass fibers with resin.

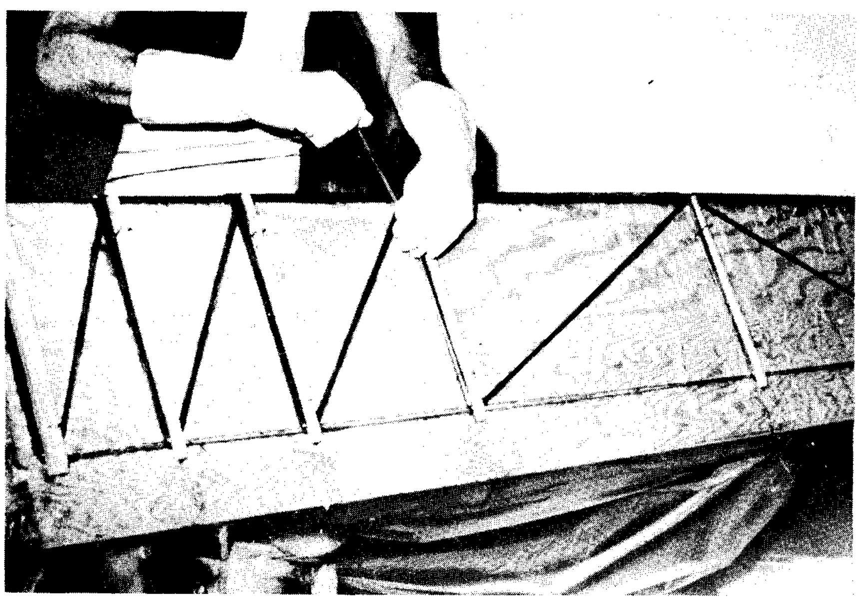


Figure 6. Winding the web and chord elements of TTG-3 on a removable wooden form.

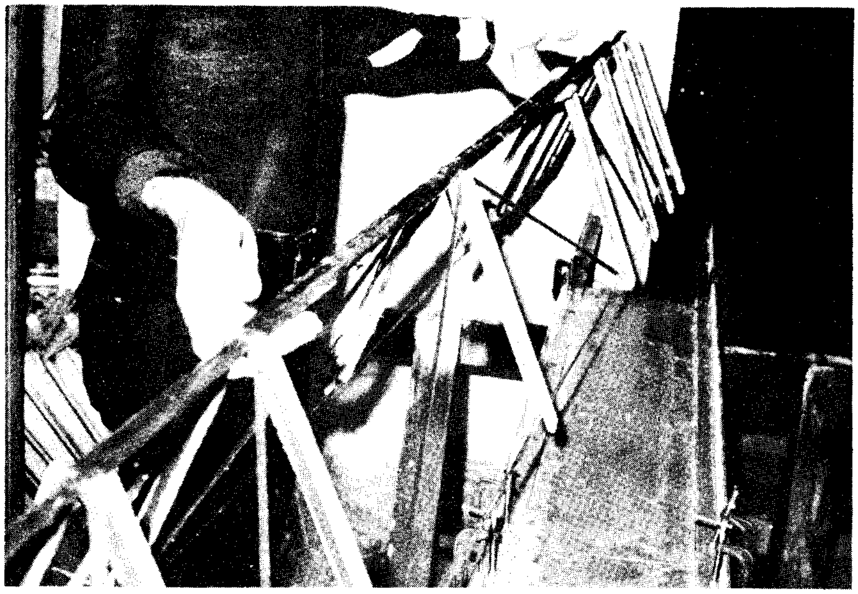


Figure 7. Completed web and chord elements of TTG-3 prior to attaching to the top plate assembly.

Figure 8. Application of resin binder for top cover plate on TTG-3.

A 1/4-inch thick strip of elastomeric material was attached to the support frame to assure distributed contact along the sides of the "V" of the support frame and the vertical web elements at the ends of the member. In order to prevent in-plane distortion of the end sections at high loads, 3/4-inch thick wooden diaphragms were fitted inside the test specimen at the points of support. Several reduced span load tests were also conducted by locating the support frames and diaphragms at intermediate panel points. Both distributed and single-point loads were used for these tests. No measurements were made to determine the amount of rotation which occurred at the supports during load applications, i.e., to ascertain the degree of restraint at the support, but visual observations of the member indicated that no obvious end restraint was present. No effort was made to control the environmental conditions during the period of load testing. In general, the temperature ranged from 68 to 75° F and the relative humidity from 45 to 65%.

Several views of the load test arrangement are presented in Figure 9 through 12.

EXPERIMENTAL TEST RESULTS AND DISCUSSIONS

Mechanical Properties of the Composite Material

Mechanical properties used for designing the flexural member were taken from average values recommended by the plastics industry. However, it was necessary to determine the elastic tensile modulus of the as-fabricated composite in order to compute theoretical stresses and deflections for comparison with the load test results. Consequently, upon the completion of testing TTG-2, a portion of the lower chord element was removed from the member and loaded in uniaxial tension in a Baldwin-Lima-Hamilton hydraulic universal testing machine to obtain the stress-strain data shown in Figure 13. The strain data were obtained independently with a bonded electrical resistance gage (MM EA-06-250 BF-350) and a Riehle dial-indicator extensometer at various load increments. The stress-strain relationship appeared to be slightly non-linear with increasing loads, so moduli values were computed at each 500 pound load increment to obtain the secant modulus at the indicated load. The change in the secant modulus with load (axial stress) is indicated in Figure 14. The slope of the modulus-stress curve appears to be constant at -22 psi/psi beyond the 10,000 psi stress value. If extrapolated with this slope to a working stress value of 50,000 psi, the tensile modulus would be 3.94×10^6 psi. This value lies in the range of 2.3 to 6.0×10^6 psi which is quoted for EXTREN products made with the same materials but fabricated by a different process. While the secant modulus may appear lower than expected for oriented glass fibers, some improvement in the value should be possible by changes in fabricating techniques such as better control of strand packing, a reduction in resin and void content and more uniform tensioning of the roving as it is wound. A composition analysis of the lower chord element by an ignition test indicated the element contained 51% glass and 49% resin by weight. When compared with an industry-wide glass weight range of 75 to 85% for filament wound objects, the value of the glass content of the lower chord element was quite low.

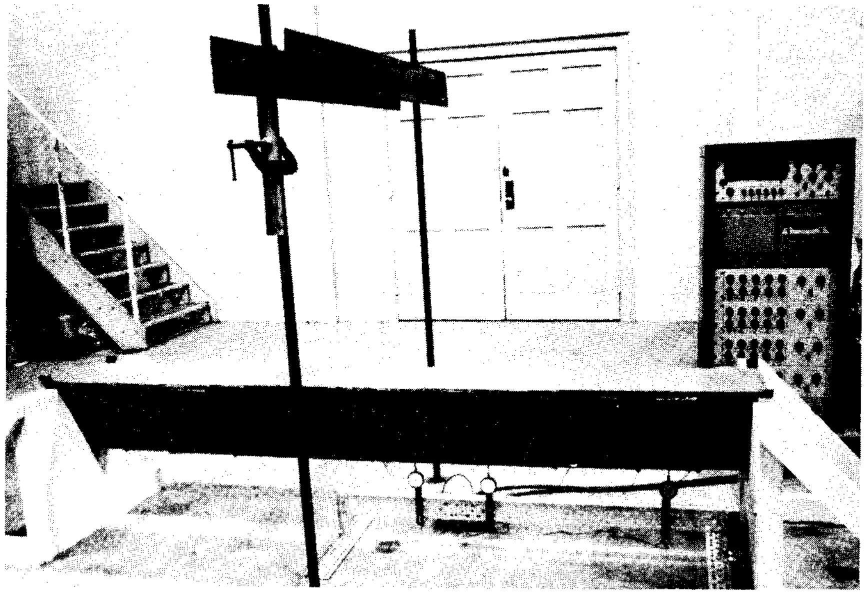


Figure 9. View of TTG-1 prior to loading showing end supports

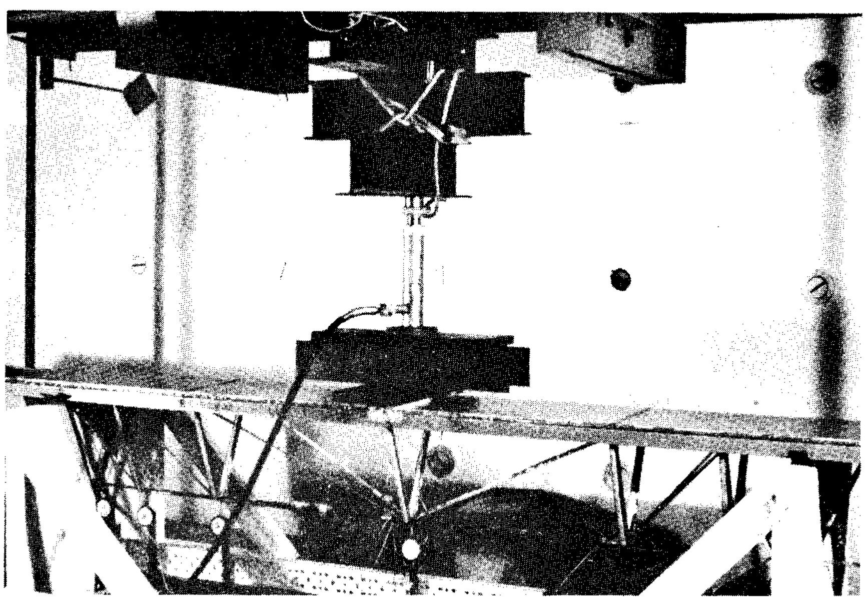


Figure 10. Typical reduced span arrangement with center point load applications.

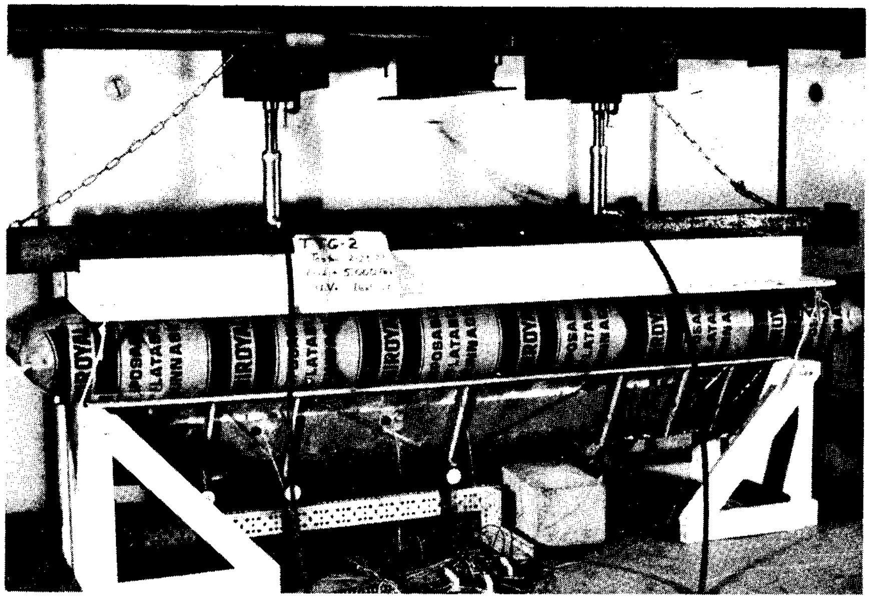


Figure 11. Typical load test in progress on TTG-2.

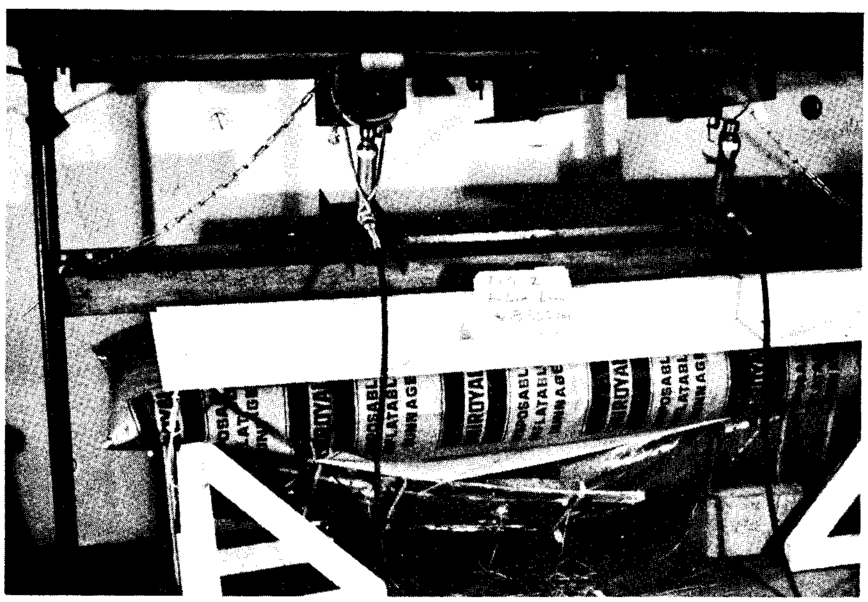


Figure 12. View of TTG-2 at the ultimate load.

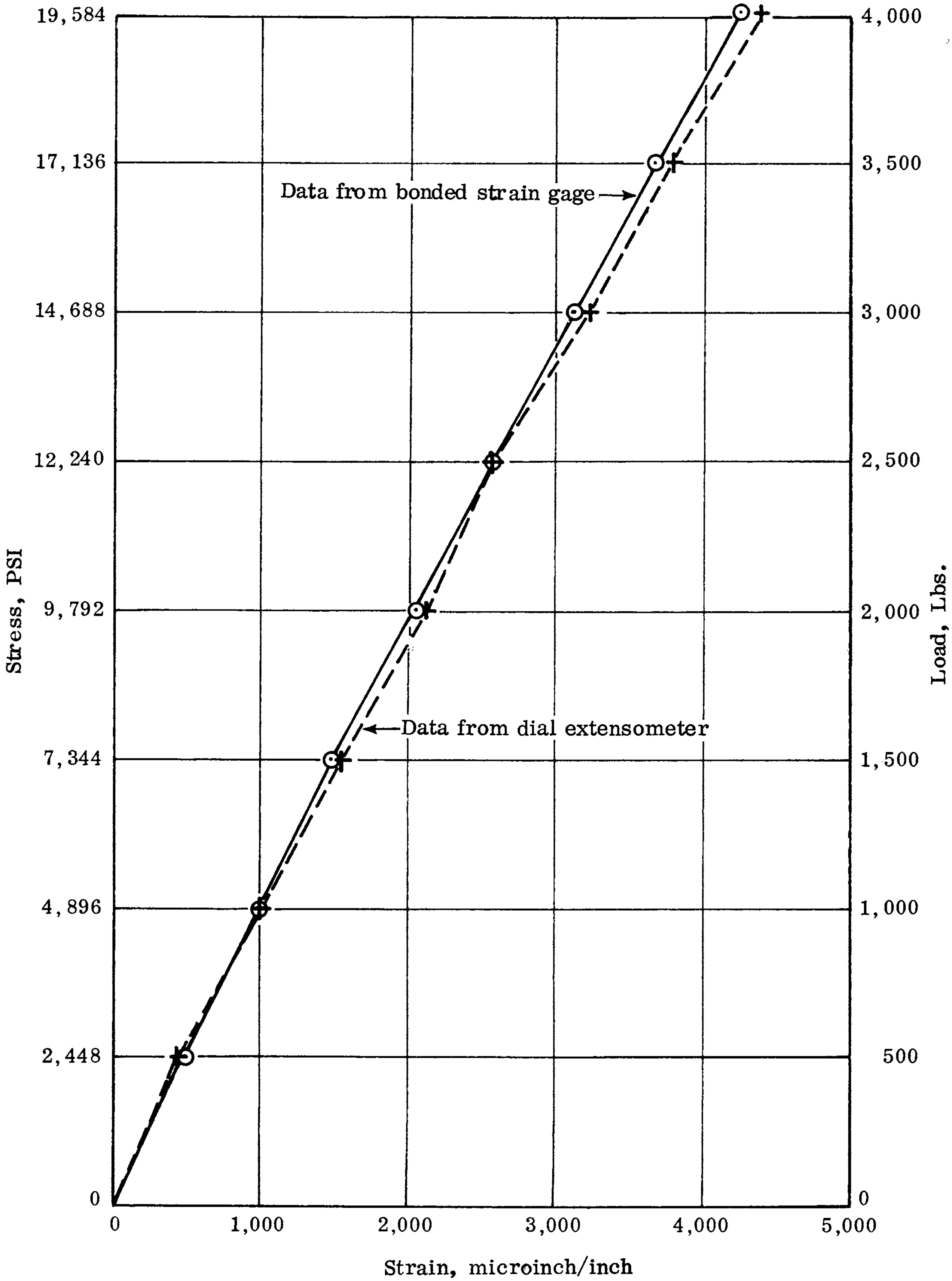


Figure 13. Stress-strain data for lower chord member of TTG-2 un uniaxial tension.

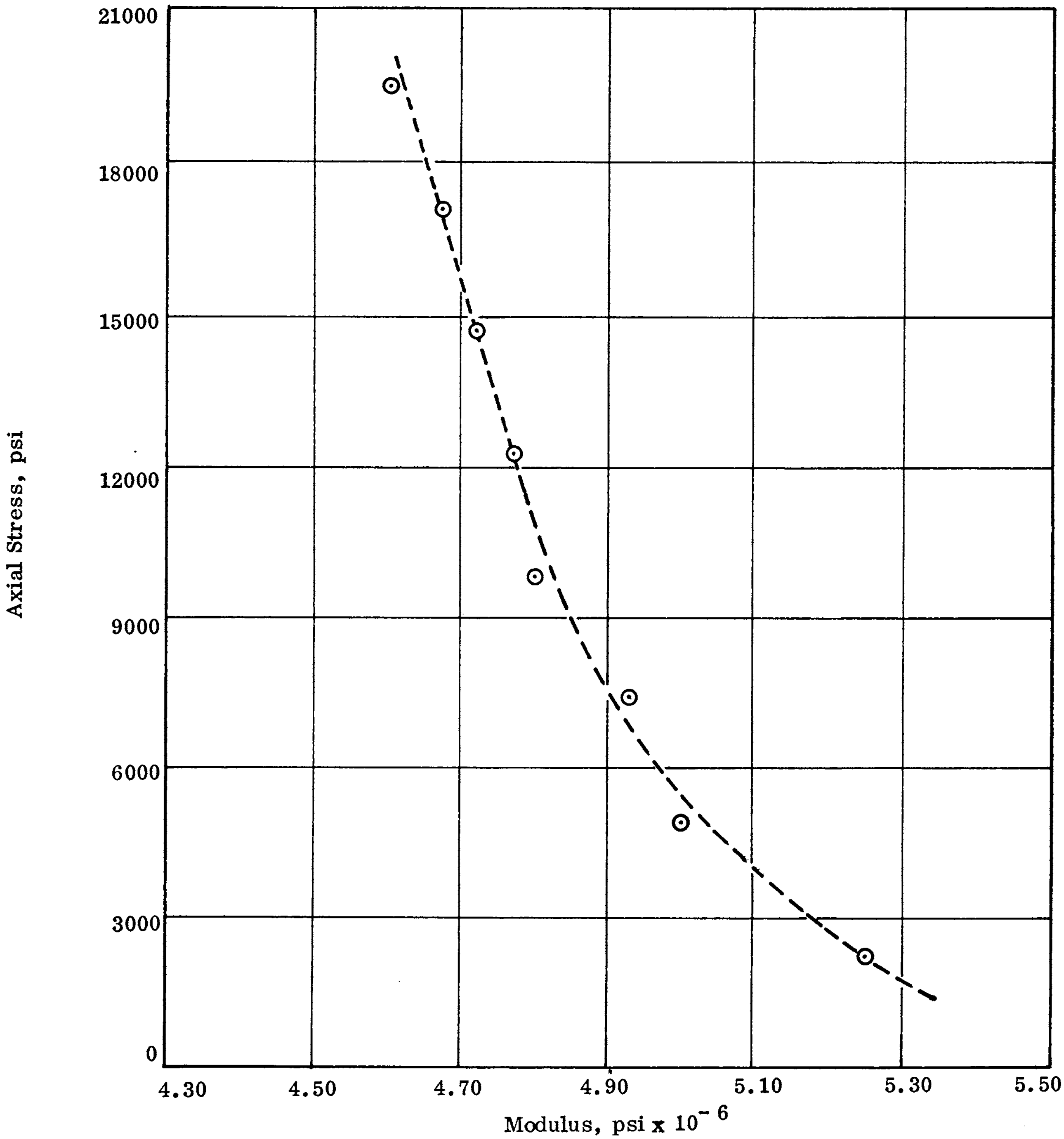


Figure 14. Axial tensile stress vs. elastic modulus of lower chord element of TTG-2.

Failure Modes

Failure of the test specimens was characterized by a sudden change in the load carrying capability due to either rupture of an element or excessive displacement of an element. All three members failed due to inadequate strength or integrity of the joint between the web elements and the top plates.

In the case of TTG-1, initial failure occurred at relatively low vertical loads (1,000 lb.) in the end panels when the adhesive bond at the joint ruptured and permitted a lateral translation of the web plates. Upon removal of the test load, the member regained its shape with no apparent damage to other elements. Therefore, the joint was repaired by winding five strands of resin-impregnated roving circumferentially around the entire member at panel points L_2, L_3, and L_4. A second load test reached approximately 3,000 lb. before the joint in the center panel debonded and the web plates moved outward on both sides. A view of the displaced plates may be seen in Figure 15. Subsequent repair of the joint at the center panel joint by winding impregnated glass roving circumferentially around the member permitted a third load test. Failure occurred finally at a load of approximately 2,400 lb. when the web plates buckled between panel points and the top plate displaced longitudinally. The panel-point connections remained intact.

As mentioned previously, the web top-plate joint of TTG-2 was reinforced with a strip of chopped-glass mat bonded across the joint. Failure of the member was sudden at a load of 8,900 lb. It appeared to initiate with a bond rupture along the mat-web plate interface and the center joint in the web plates opened and ripped the mat as shown in Figure 16. The two top plates were separated with a bond failure at the interface. Several of the lower chord panel points had been overloaded, but none of them ruptured completely.

Specimen TTG-3 failed at 2,400 lb. due to movement of one of the vertical web elements in a longitudinal direction. The resin provided insufficient restraint at the top of the web element to resist the force component transmitted to it from the tension element in the adjacent panel. None of the elements were damaged so provisions have been made to strengthen the connections and retest the specimen.

Strength Characteristics

The ultimate strength of the primary elements (top plate, web and lower chord) was not fully tested in any of the three specimens, because of the failure of the top joints between plates. Whereas the anticipated ultimate stress of the stranded tensile member was around 100,000 psi, the maximum experimental stress value computed from strain measurements was approximately 24,000 psi. Compressive stresses in the vertical web elements were quite low because of the excessive cross-sectional areas required for fabrication. Strain gages were mounted on the top plates, but no accurate data were obtained due to the bi-directional bending of the plates that developed when the distributed load was applied to the top plate. However, readings obtained from the concentrated load tests of TTG-3 indicated

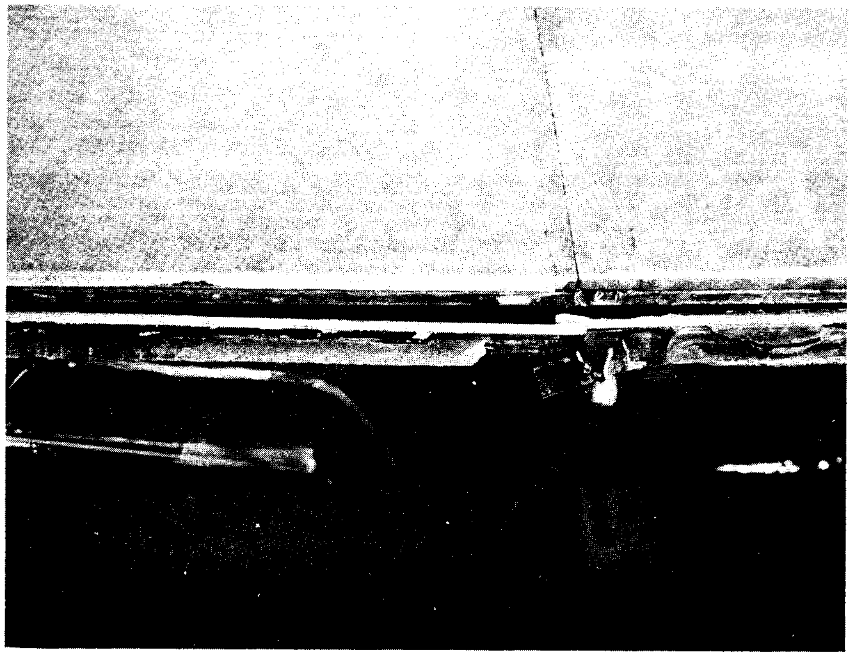


Figure 15. View of top and web plates of TTG-1 showing open joint after failure of the center panel.

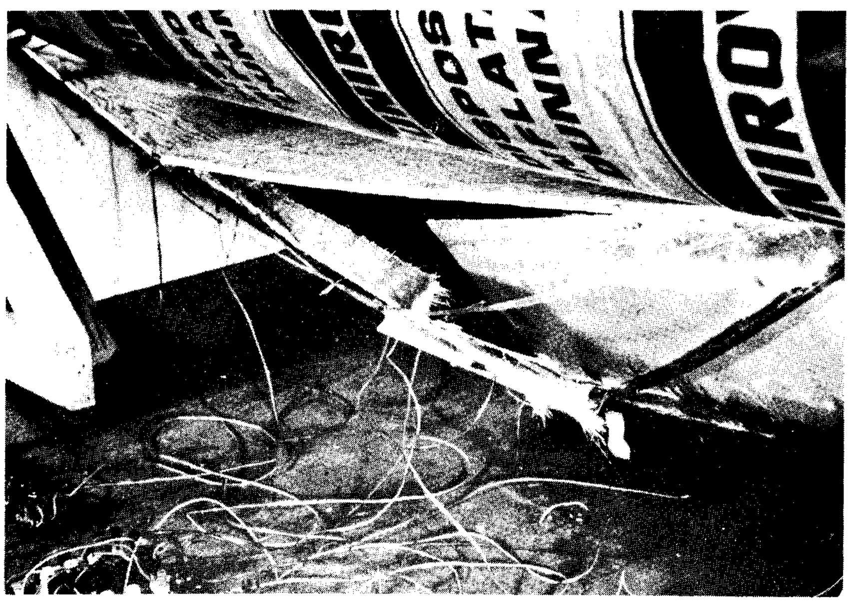


Figure 16. View of ruptured joint of TTG-2 showing torn mat and displaced plates.

that compressive strains in the upper plate were about one tenth of those in the lower chord for the same load values. The excessive material supplied in the top plates undoubtedly accounted for the low strain readings. The several rosette strain gages mounted on the web plates of TTG-1 and TTG-2 gave no indication of measurable buckling of the plates prior to failure of the member. The data from these gages did provide principal strain values of anticipated sense and direction.

Figure 17 shows typical load-strain data from some of the elements of TTG-3. Of particular interest was the linear or near-linear relationship of the parameters. However, it should be noted that the loads were applied over relatively short periods of time, e.g., approximately one hour, so creep effects were not reflected in the data.

Figure 18 presents comparative strain data in several elements of each member and for all three test specimens. These data may be observed as a measure of the efficiency of the material distribution among the several elements of the member. Ideally, for optimum distribution wherein all elements of a given member would be strained equally (and thereby stressed equally in the uniaxial loading situation) for a given load application, the bars would all be the same height on the chart. It can be seen from the comparison that the configuration of TTG-3 more nearly satisfies this condition than do those of TTG-1 and TTG-2. Refinement of the design of the members to provide more or less cross-sectional area as needed in the tensile elements would provide a balanced structural system throughout. Specified incremental changes in the areas may be achieved without difficulty by altering the winding procedures for the glass roving.

Stiffness Characteristics

The stiffness of the flexural member is characterized herein by the deflection of the member under load. Some of the features which affected the deflections included (a) the mechanical and geometric properties of the member, (b) the web plates and (c) the joints at interconnecting elements. These features are discussed below.

Effects of Mechanical and Geometric Properties

Elastic deformation and, in this case, the deflections of a structural member are affected directly by the elastic modulus of the material. As described in a previous section, the tensile modulus was determined experimentally for a section of specimen TTG-2. Values for both tensile and compressive moduli were taken from the curve shown in Figure 14 for deflection calculations.

Table 2 presents results of theoretical and experimental values for deflections of the midspan of the three test specimens. The theoretical values were computed by a strain-energy analysis which treated the member as a simply-supported, pinned-end truss. Cross-sectional areas of the wound truss elements were computed by multiplying the known number of strands of impregnated roving in an element by the cross-sectional area of one strand of impregnated roving.

Note: Load was applied uniformly distributed on top plate of TTG-3 with full span length of 94 inches.

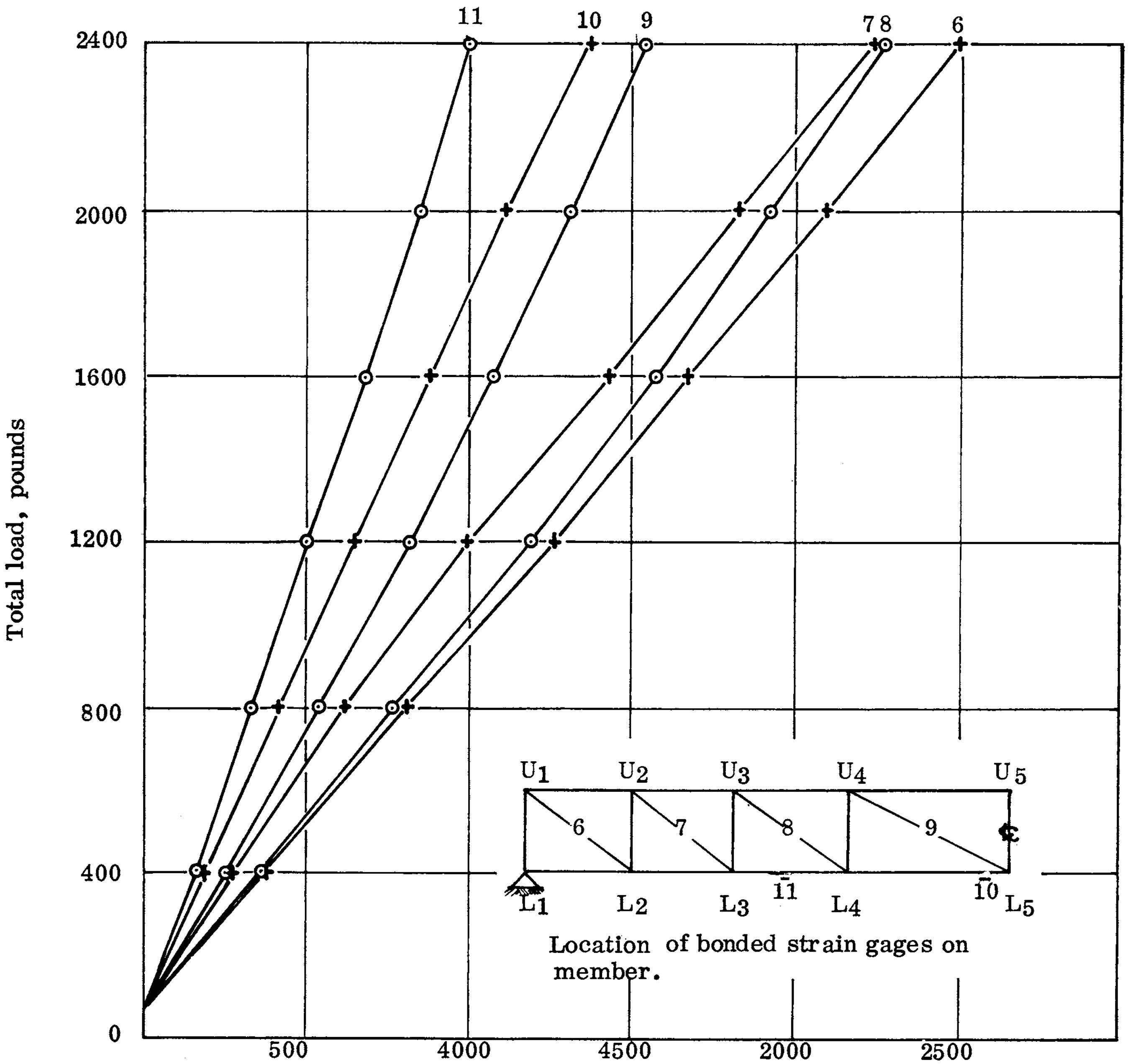


Figure 17. Typical stress-strain data of selected elements from TTG-3.

Note: Total load of 2000 lbs. was distributed uniformly along the top plate.

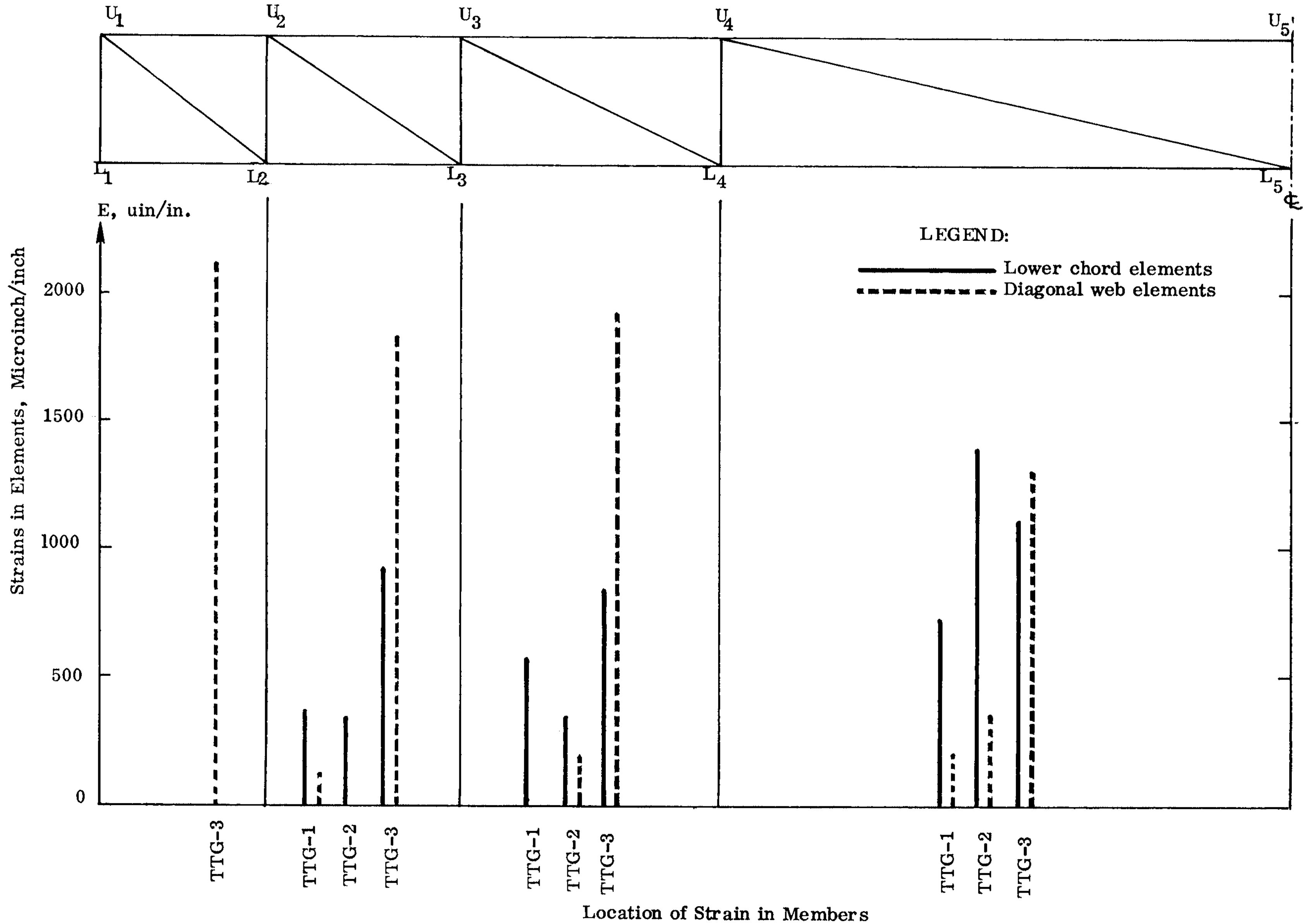


Figure 18. Comparison of strains between elements at selected locations in test member

TABLE 2

LOAD-DEFLECTION VALUES FOR TEST SPECIMENS

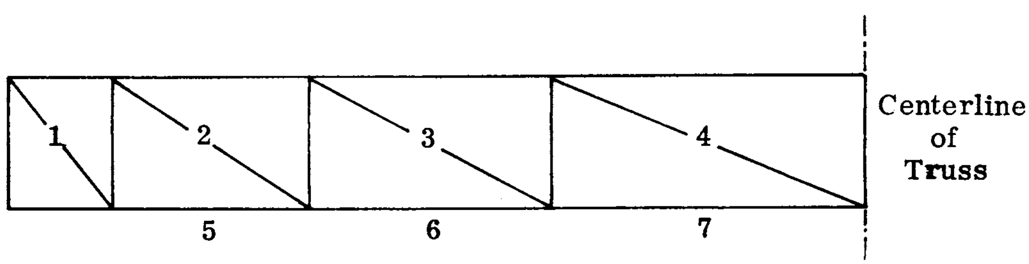
Total Load Pounds	Experimental Centerline Deflections TTG-1, Inches	TTG-2, Inches	TTG-3, Inches	Theoretical Deflection, Inches	Difference for TTG-3, Percent
400	0.019	0.015	0.044	0.046	3.4
800	0.038	0.031	0.095	0.093	2.3
1,200	0.058	0.047	0.147	0.146	0.7
1,600	0.077	0.063	0.203	0.194	4.7
2,000	0.098	0.078	0.268	0.246	4.3
2,400	0.167	0.100	0.331	0.300	9.4

TABLE 3

STRAIN DISTRIBUTION IN TEST SPECIMENS FOR LOAD OF 1,200 POUNDS

Element Location	Experimental Strains TTG-1, u"/inch	TTG-2, u"/inch	TTG-3, u"/inch	Theoretical Strains, u"/inch	Difference for TTG-3, Percent
1	*	*	1,310	1,249	4.9
2	78	*	1,125	991	13.5
3	*	105	963	1,178	18.3
4	120	200	658	798	17.5
5	237	200	554	633	12.5
6	377	200	525	490	7.2
7	433	775	424	591	28.3

*Values not measured



Location of Strain Gages on Truss

Effect of Web Plates

Inspection of Table 2 indicates reasonably close agreement between theory and experiment for TTG-3 but poor agreement for members TTG-1 and TTG-2. In addition to the full span, uniformly distributed load data shown in Table 2, similar data were obtained for concentrated, center point loads at both full and reduced spans for TTG-3. In general, these data provided the same information with approximately the same percent difference between theoretical and experimental values as those shown in Table 2. Comparisons of strains for several of the elements at a load of 1,200 lb. are shown in Table 3. Closer agreement of the experimental with the theoretical values is again noted for TTG-3 than for the other two test specimens. It seems apparent from these data that without the web plates, the behavior of the member may be predicted reasonably well by a conventional strain-energy truss analysis.

Limited success was achieved in analyzing the role of the web plates in contributing to the strength of the member. The force interaction of the web plates and the stranded truss elements along with dissimilar deformation characteristics of each component made it difficult to separate the behavior of each component during a load test. Specifically, it was not clear whether the member (TTG-1 or TTG-2 in this case) should be considered as basically a hybrid girder reinforced with web stiffeners or a psuedo truss reinforced with web plates. Several experimental and computational efforts were made to resolve this question.

Series of relatively low load tests were conducted on TTG-1 with a single, 1/4 inch thick top plate and then with the second 1/4 inch thick top plate bonded to the member (refer back to Figure 1). The change in the behavior of the member was as expected when an additional cover plate is added to the top flange of a girder, i.e., the neutral axis moves toward the top flange; the flexural strains in the lower flange increase; and the deflections of the girder decrease. From this test series it therefore appeared that the characteristics of a conventional girder predominated. A second series of loads were applied with reduced span lengths by moving the end supports to the interior panel points. Using measured deflections, "effective" stiffness values, EI, were computed for the various span lengths. Very poor correlation resulted from these calculations; partially due to poor test procedure. From this investigation, the predominating influence of girder behavior did not appear valid. Theoretical computations also were made for the critical buckling load of the thin web plates in the girder disregarding the action of the trussed strand elements. These computations were based on simplistic behavior of the plates by assuming edge loading due to bending of the girder only. A buckling load of 2,496 lb. was predicted,which was slightly higher than the test load (2,400 lb.) reached before the joint failure of TTG-1. At best, the above information provided only clues relative to the role of the web plates.

A better indicator was deduced from an analysis of the deflection of the different members. In this analysis, it seemed reasonable to assume that the superposition of forces from the conceptually independent structural systems, pure truss and pure girder, could be applied to the combined member in view of the linear elastic properties of the materials. An estimate of the amount of total load carried by the truss component and the girder component was made as follows:

1. Curves for the theoretical load-deflection value of the girder and the truss were plotted separately in Figure 19. (Note that the experimental values for TTG-3 are shown for comparison with the theoretical values.)

2. From these curves, a deflection value for the truss, δ_t, was selected for a given truss load, w_t. For example, a value of $\delta_t = 0.100$ inch was selected for $w_t = 800$ lb.

3. Recognizing that the girder deflection, δ_g, equals δ_t and also equals the deflection of the composite test member, δ_c, the load on the girder, w_g, could be determined from the curve for the girder. For example, $w_g = 860$ lb. for $\delta_g = 0.100$ inch.

4. Since $w_g + w_t = w_c$, the total load on the member to produce δ_c, then w_c may be found. For example, $w_c = 1,660$ lb.

Figure 19 also indicates that the load on the member was fairly equally divided between the truss and girder components. This circumstance was by chance rather than design, so no inference should be made about the generalized behavior of a combined truss-girder system based on this analysis. It is probable that the contribution of each component could be varied over a large range. Figure 20 compares the experimental load-deflection data from TTG-1 and TTG-2 with the predicted relationship based on superposition principles. The sharp break in the curve for TTG-1 at 2,000 lb. of load may have been due to initial buckling of the web plates, but this was not detected with the rosette strain gages. However, it should be noted that the superposition analysis precludes any instability whatsoever of the web plates and would therefore be applicable only to the lower load values shown.

A final consideration of the data of Figures 19 and 20 demonstrates the strong influence by the web plate on the midspan deflection of the test member. For example, at comparable loads of 2,000 lb. the deflection of TTG-3 was 0.27 inch compared with 0.08 inch and 0.10 inch for TTG-2 and TTG-1, respectively. This effect would undoubtedly disappear, or certainly be reduced substantially, at higher loads or for different plate sizes.

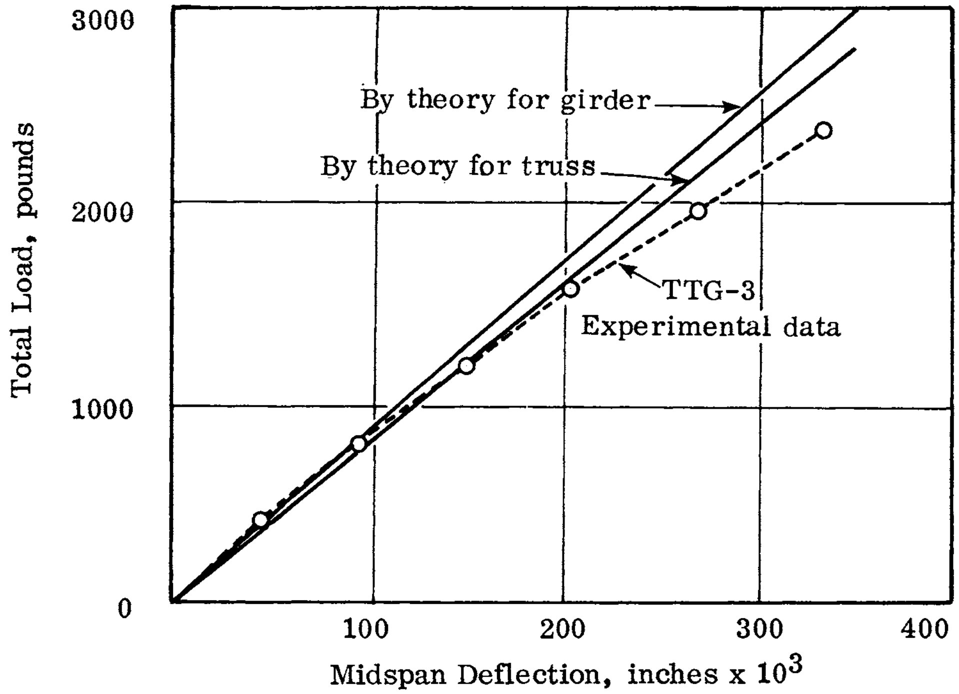


Figure 19. Comparison of experimental and theoretical deflections at midspan for uniformly distributed loads on top plate.

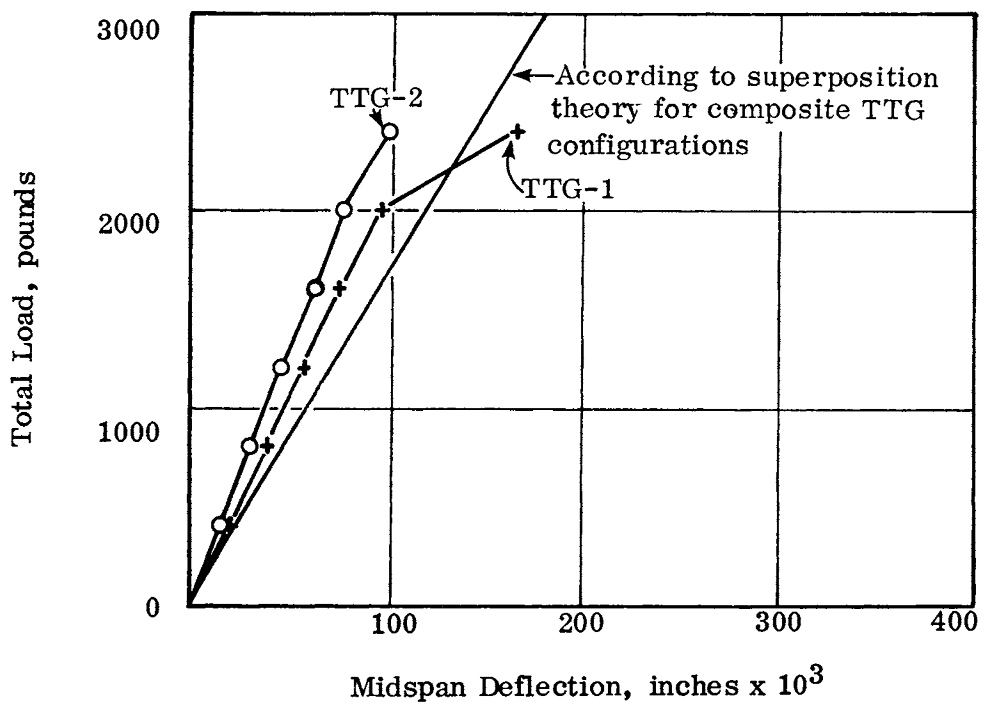


Figure 20. Comparison of experimental and theoretical deflections at midspan for uniformly distributed loads on top plate.

Effect of Joints

The effect of the joints upon the stiffness of the members may be deduced from Figures 19 and 20. As may be recalled, specimen TTG-1 and TTG-2 were essentially identical except for the addition of the glass fiber mat used to connect the top and web plates. The deflection curves for these two members clearly indicate that the web joints had very little effect upon the magnitude of the displacements. The data for TTG-3 cannot be compared with those for TTG-1 and TTG-2 because of the totally different construction of the member. However, it was apparent that the joints at the intersecting elements of TTG-3 provided very little moment resistance in view of the close agreement between the theoretical and experimental data of Figure 19.

MANUFACTURING FEASIBILITY

Throughout the development and fabrication of the test member, consideration was given to the feasibility of manufacturing similar members by automated machines with mass production techniques. The development of the member did not reach a stage where it was considered worthwhile to obtain detailed estimates from manufacturers relative to tooling cost, production schedules and other topics. However, two consultations were held, one in January 1973 and one in April 1973, with principals in the firm of Goldsworthy Engineering of Los Angeles, California. These conferences resulted in preliminary assurances, without any estimate of cost involved, that the geometrics and assembly sequences of the flexural member would not present insurmountable manufacturing difficulties. Much of the fabricating equipment produced by Goldsworthy Engineering in the past has performed more complex tasks than those required by the proposed TTG structural concept. Based upon these communications, it appears that the currently conceived configuration of the TTG member would lend itself to industrialized manufacturing procedures.

CONCLUSIONS

The preliminary nature of the studies provided few comprehensive conclusions relative to the overall consideration of adaptation of high-performance plastics to highway structures. However, within the scope of the investigations conducted, data were obtained which demonstrated or suggested the following conditions or relationships.

1. Classical design and analytical procedures based on a pinned-end truss configuration were in reasonably close agreement with the experimental strains and deflections measured during load testing of the open-web member (TTG-3).

2. Experimental midspan deflections of the combined plate and stranded web member (TTG-1 and TTG-2) were predicted fairly well by superposition theory for low loads and small deflections.

3. Measured strains and deflections in the members varied linearly with load over the test range. However, the elastic tensile modulus of the stranded material appeared to decrease with increased load.

4. Initial failure of all three specimens occurred in the joint between the top plate and web elements and thereby precluded the determination of the ultimate strength values of the elements or the behavior of the member at high loads.

5. The presence of the web plates increased the deflection stiffness of the test member substantially when compared with the open-web member without the web plates.

RECOMMENDATIONS FOR CONTINUING STUDY

It is recommended that the work begun in the initial phase of the research investigation be continued to obtain information relative to short-and long-range goals as follows.

Short-Range Goals

A. Devise a suitable connecting configuration for the top and web plates which will permit the ultimate strength determination of the web and chord elements.

B. Examine the winding patterns used in fabricating the test specimens to effect modifications leading toward improved material efficiencies.

Long-Range Goals

A. Investigate the behavior characteristics of multisectional TTG members jointed laterally with top cover plates and web diaphragms as may be required for stability. These investigations should be both analytical and experimental with possible extension of laboratory work to field studies.

B. Ascertain the validity of the findings of the initial phase by varying the geometric dimensions and proportions of the TTG structural form. Considerable use could be made of computer models to study shape variations that would improve material efficiencies and performance characteristics.

C. Expand contacts and discussions with manufacturing representatives relative to production costs and techniques.

D. Conduct pertinent investigations related to natural environmental conditions, in-service traffic hazards and load applications, extended maintenance considerations and performance criteria, including serviceability and safety requirements.