FINAL REPORT

MODIFICATION STUDIES FOR A BRIDGE GIRDER OF REINFORCED PLASTICS

by

Fred C. McCormick
Faculty Research Engineer

and

Professor of Civil Engineering
University of Virginia

Virginia Highway & Transportation Research Council
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SUMMARY

Several modifications were made in the design of a glass-reinforced plastic girder in an effort to improve its load-deflection performance characteristics. The addition of lateral ties between the lower chords of adjacent girders in a trisectional structure significantly reduced the horizontal displacements of the sections due to vertical loads. Considerable improvement was also made in vertical deflections by the replacement of glass strands with Kevlar 49 strands in the tension elements. The replacement of pin-connected stiffener assemblies with rigid stiffeners did not indicate improved performance in a load test. Secondary creep deflections were estimated to increase at a rate of 0.03 inch per year in a trisectional structure loaded to 100 psf. Ultimate load tests indicated a safety factor of 8 based on AASHTO design loads for pedestrian bridges. Criteria for the design of triangular trussed girder structures should be based on limiting deflections, mechanical protection of stressed elements from degrading environmental factors, automated fabrication procedures, and the use of combinations of materials to effect cost benefits.

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INTRODUCTION

The investigations conducted in this project dealt with modifications to the basic structural member and extensions of tests described in a final report by McCormick and Alper.(1) The report described the development and testing of a girder composed entirely of glass fiber reinforced plastic materials. A typical laboratory test specimen is shown in Figure 1. The earlier studies suggested possible improvements in the performance of a multisectional structural unit by modification of the stiffener assembly and the addition of transverse ties between the lower chords of adjacent girder sections. Experimental testing was conducted to assess the changes in load performance of the members due to physical and geometric modifications. The current project extended from October 1, 1975, to June 15, 1976. As in previous studies, test specimens fabricated in the form of a triangular trussed girder (TTG) were used to obtain experimental data. Modular units with a triangular cross section were fabricated and tested either singly or assembled into a structure with three sections. Each successive test specimen was identified numerically.

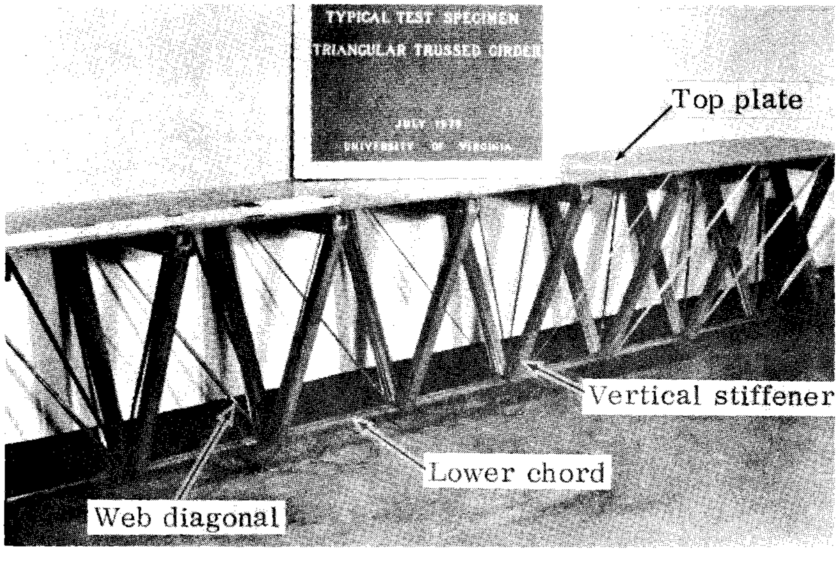

Figure 1. Typical test specimen of a single unit, triangular trussed girder.

OBJECTIVES

The objectives for the project were–

1. to improve the load-deflection performance of a tri-sectional structure by modifying an existing test specimen;
2. to improve the overall performance of the girder by modifying the present stiffener arrangement and by utilizing combinations of materials;
3. to verify an optimal design procedure by experimental testing; and
4. to establish design criteria for control of creep, fatigue, and live load deflections.

Experimental programs related to objectives 1 and 2 were completed. Objective 3 was not pursued as intended due to fabrication limitations and the application of effort toward the other objectives. Objective 4 was not completely achieved with regard to the optimization goal cited in objective 3. Finally, an investigation of lower chord connectors was conducted, although it was not specified in the working plan.

MODIFICATION OF TTG-8

Addition of Transverse Ties

Load-deflection test results were reported for test specimen TTG-8 as initially fabricated in Reference 1. TTG-8 was a test member composed of three identical girder sections as shown in Figure 1. These were bonded to a common cover plate to provide a structure with a deck surface of four ft. by eight ft. The load tests indicated the need for transverse ties between the lower chord elements of adjacent sections to reduce the lateral displacements of the chords due to rotation of the girder sections under nonuniform loading. Accordingly, transverse tensile ties were provided at each panel point by bending a single length of soft form wire (0.08 in. diameter) around the lower chord elements. Strands of fiberglass were not used for the ties because no provision had been made in the original fabrication of TTG-8 to accommodate a continuous length of tie. (A modification of the stiffener connecting element at the lower chord to provide for fiberglass ties is discussed in a later section of this report.) No particular effort was made to develop uniform tension in the wire ties, and it was apparent from visual inspection that some ties were tighter than others during the load tests.

Test Results

Measurements of horizontal deflections of the lower centerline panel point were made with a load uniformly distributed over all sections and also distributed over the centerline section only. Figure 2 shows the load-deflection relationships for these load arrangements. Previous test data from TTG-8 without the lateral ties are included in the figure for comparison of the horizontal displacements. At the 2,000 lb. level, a reduction of 33% in the horizontal displacements is noted for the full-load arrangement and a reduction of 92% is noted for the center load arrangement. It is also observed from Figure 2 that there was a reversal in the direction of displacements as the total load was concentrated near the center of the structure with the edge sections relatively free to rotate about their longitudinal axes. Since the edge sections moved toward the center section under full load, it was not expected that the (tensile) ties would have much effect upon the horizontal displacements of the edge sections. It is believed that the observed improvement resulted from a more uniform vertical deflection of all three sections when connected by fixed-length ties than had been observed previously. Measurements of the vertical deflections indicated less difference between the displacements of the center and edge sections than had been observed in load tests prior to the installation of the ties.

The lateral stiffness of the top plate assembly also had a pronounced effect upon the horizontal displacements of the edge sections. This effect was readily observed when a concrete slab 1 1/4 in. thick was bonded to the top plate. In this case, there was no detectable horizontal movement of the edge section up to a load of 2,400 lb.

The lateral restraint of the edge section provided by the wire ties was pronounced when the center section only was loaded. Tensile forces were not measured in the ties, but it was observed that small bends which were seen in the wire before loading

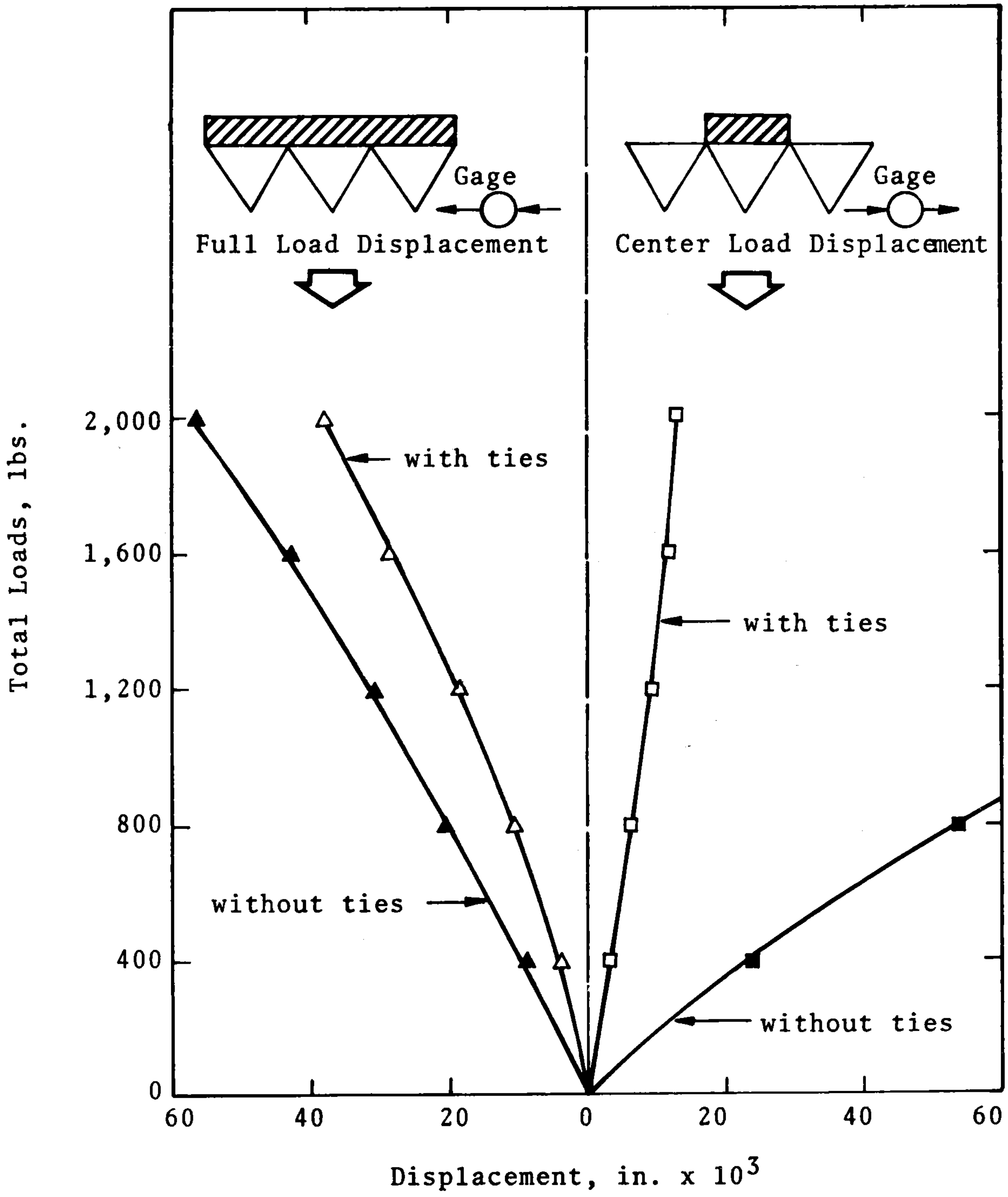

Figure 2. Horizontal displacements of TTG-8 edge section for two different load arrangements.

remained unchanged during the loading sequence. If the forces had been over several pounds in magnitude, the bends in the wire would have straightened out. A more precise measurement of the forces in the ties was not considered relevant to the investigation, since it appeared that minimal constraint by the tie was sufficient to prevent outward displacement of the edge section.

Addition of Concrete Slab

A normal weight (150 pcf) concrete slab 1 1/4 in. thick was bonded to the top plate of the structure with an epoxy adhesive (Sikadur Hi-Mod). The compressive strength of companion concrete test cylinders exceeded 3,500 psi when load testing of the TTG-8 specimen was resumed. The compressive modulus of the concrete was determined as 2.5×10^6 psi from the test cylinders. However, a value of 2.3×10^6 psi was used in the numerical analysis of the structure for convenience in matching the compressive modulus of the pultruded* plate assembly.

Load Test Results: Short-Term

Deflection and strain measurements were made for varying static load magnitudes and arrangements. A detailed description of the instrumentation and procedures used for load testing are included in Appendix A. Data for vertical deflections at the midspan of the center section are shown in Figure 3. Of particular interest was the behavior of the structure for loads applied both before and after the concrete slab was cast on the cover plate. A significant reduction in deflection (38%) was observed due to the slab when the load was applied to the center section only, whereas the deflection was reduced by 11% when the load was applied to all sections simultaneously. These results emphasize the need for a top plate with greater stiffness than that developed by the two 1/4-in. thick glass reinforced plastic (GRP) plates in order to properly transfer loads laterally between sections within the structure.

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*Pultrusion is a mass production process used to form structural plates and shapes by pulling resin impregnated fiber glass roving and cloth through a die which is heated to cure the resin rapidly.

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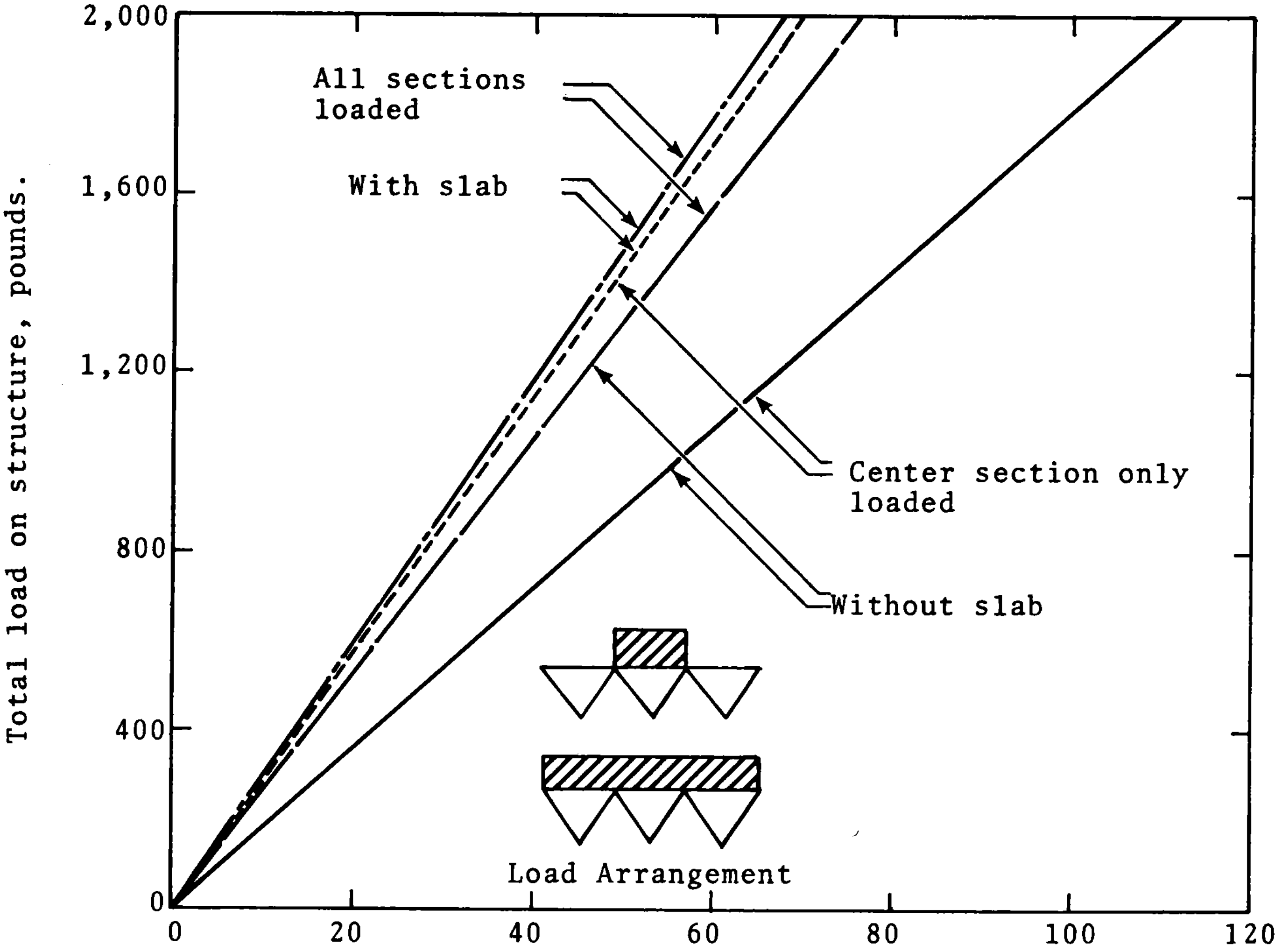

Figure 3. Deflection of TTG-8 at midspan of center section. Load uniformly distributed on top plate or slab.

The measured strains and the corresponding stresses computed in the lower chord and web tensile elements were comparable to those observed in previous tests with the same structure. The maximum computed stresses (strain time modulus of elasticity of 7 x 10^6 psi) at a design load of 85 psf on the structure was approximately 8,500 psi.

In general, the stress values due to the design load were considered to be low when compared with an ultimate strength of 100,000 psi for the tension strands. It was also noted that neither the addition of the transverse ties to the lower chords of the sections nor the addition of the concrete slab decreased the difference in stress magnitudes among the tension elements. The web diagonals as a group were more highly stressed than the lower chord elements as a group. Adjustments in the cross sectional areas of the strands will be required to achieve a more uniform stress distribution among the elements.

Load Test Results: Long-Term

Upon completion of the short-term static load tests, the structure was loaded with concrete blocks to a total load of 3,200 lb.(100 psf). Figure 4 is a photograph of the test arrangement. Vertical deflections and strain measurements were recorded as the structure underwent deformation over a period of 140 days. Figure 5 indicates the deflection creep behavior of the structure as measured by gages located at panel points in an edge section. The data shown were corrected for settlement of the end supports. From these data, it is observed that apparent primary creep extended through a period of approximately 60 days before a noticeable change occurred in the deflection rate. The secondary creep rate was not clearly defined due to the scatter of deflection measurements and the relatively short period of time available for the observations. However, estimated values for the slopes of the two 60-day curves shown are between 0.01 and 0.04 in. per year with a best fit value of 0.03 in. per year. These values compare favorably with the value of 0.03 in. per year obtained from a previous creep test of TTG-6 with a live load of 150 psf (see Reference 1, p. 20).

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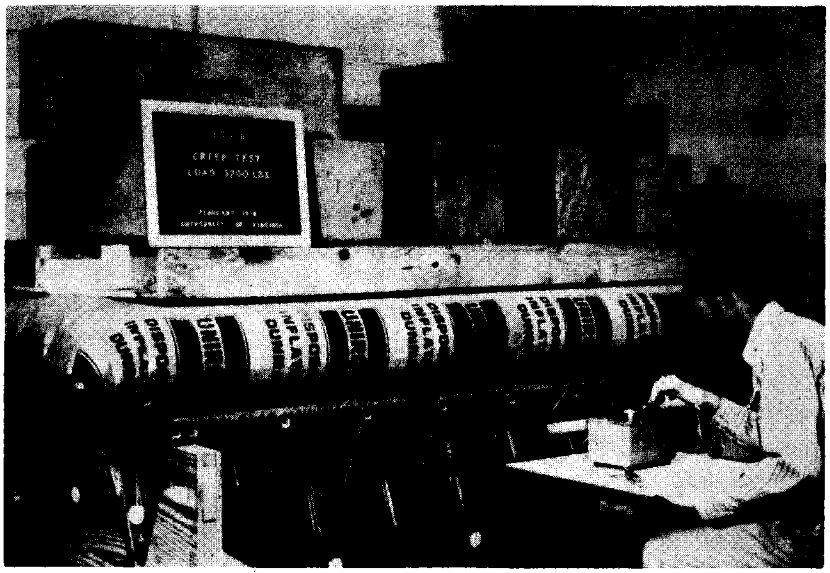

Figure 4. Creep test of TTG-8 with total load of 3,200 lb.

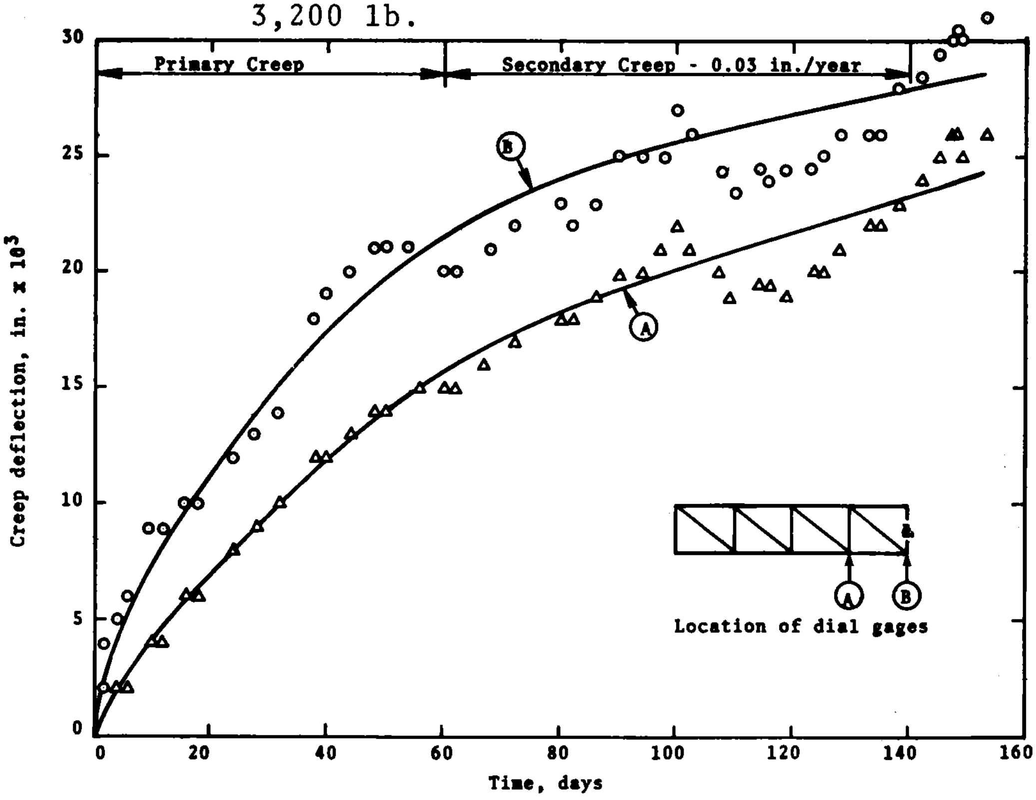

Figure 5. Creep-deflection of TTG-8 with live load of 100 psf.

Modification of Stiffener Assembly

All test specimens through TTG-9 had been fabricated with vertical and transverse (top plate) stiffeners composed of pultruded rods or tubes. In the more recent specimens, two vertical stiffeners at each panel were connected at their top ends to the ends of the transverse stiffener with steel pins. They were connected to the lower chord by means of a GRP insert cast for the purpose. While this arrangement appeared to perform well, several questions had been raised about the behavior of the pin-connected joints during load testing. Therefore, a single-piece, rigid-joint stiffener assembly was designed to replace the three-piece assembly. The triangular shape was retained for the geometry of the stiffener assembly and a channel shape was selected for the cross section of each leg. A mandrel was constructed to fabricate the stiffener by a filament winding process. Figure 6 is a photograph of the completed stiffener and disassembled mandrel. Figure 7 shows one of the stiffeners being wound. As shown in Figure 6, a 1-in. square pultruded tube with wall thickness of 1/8 in. was wound into the channel recess of the top portion of the stiffener to provide a smooth bond surface for the top plate and sufficient anchorage for the web diagonals. Short lengths of pultruded angles were also wound into the lower apex of the stiffener to receive and support the lower chord strands. Fabrication of the stiffeners presented no serious difficulties once a procedure was established. However, after curing, some of the glass strands did not appear to be properly wet-out and other regions of the stiffener appeared to be resin-rich. It was determined that improper resin distribution in the glass roving was due to drainage of the resin before it gelled. This condition could be alleviated by using a resin formulation with a shorter gel time. Approximately four hours were required to assemble the mandrel, wind one stiffener, and clean the equipment. The stiffeners were cured at 120°F for approximately two hours to assure full polymerization of the polyester resin.

Thirteen stiffeners were wound for use in the fabrication of TTG-10 and for individual load testing. Figure 8 shows a stiffener loaded in a testing machine with a pointer indicating the nature of failure of a flange at the ultimate load of the specimen. A load was applied to simulate the action of the truss forces when the stiffener was positioned in a loaded girder. This load test also provided an EA (modulus times area) value that was required for the theoretical analysis of the girder. An ultimate strength of 2,500 lb. was determined for the stiffener, which compares to the design load of approximately 700 lb. for each stiffener. The EA value decreased nonlinearly over the load range, but provided a value of 0.4×10^6 psi-in^2 at the design load. Performance of the modified stiffener assembly will be discussed in the following sections.

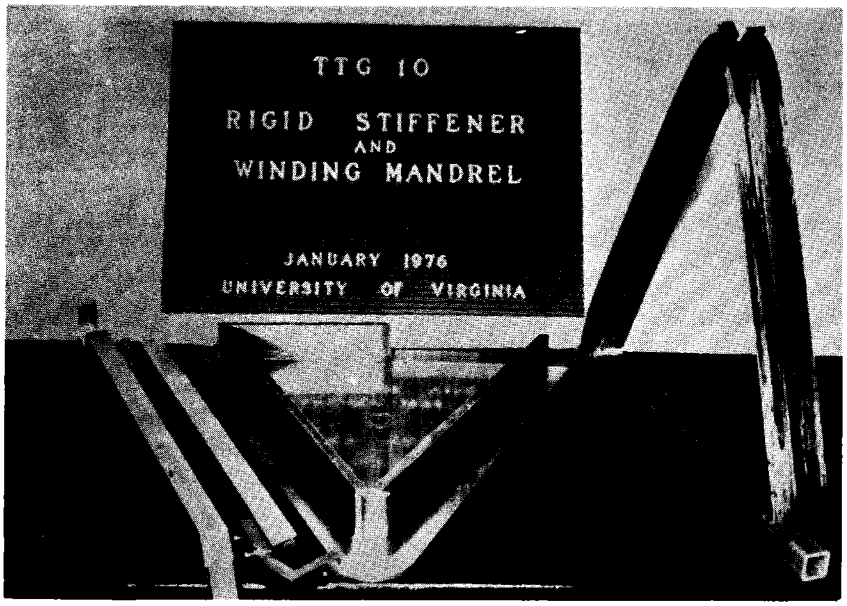

Figure 6. View of finished rigid stiffener and disassembled mandrel used for filament winding the stiffener.

Figure 7. Fabrication of rigid stiffener by filament winding with glass roving impregnated with polyester resin.

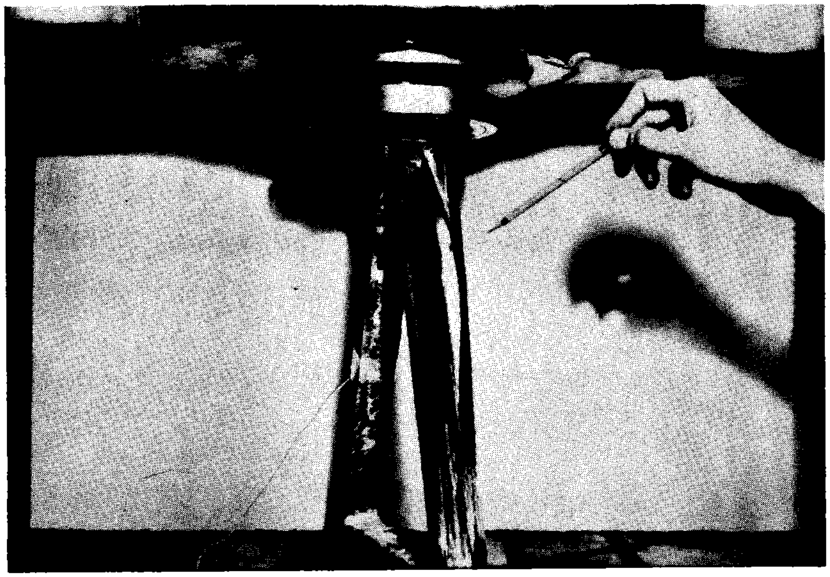

Figure 8. Load test of rigid stiffener showing the separation and buckling of a flange portion of the stiffener. Failure occurred at 2,500 lbs.

Fabrication and Testing of TTG-10

Specimen TTG-10 was fabricated with the filament wound stiffeners described previously and with the same dimensions and tension strand area as were used in TTG-7. The purpose of this experiment was to generate comparative data in order to evaluate the performance of the rigid stiffener assembly relative to the pin-connected stiffener used in previous test girders. Figure 9 shows the stiffeners attached to the top plate of TTG-10 prior to winding of the tension strands. Polyester resin and two 1/4-in. steel bolts were used to connect each stiffener to the plate. Figure 10 shows TTG-10 after winding of the tension strands and prior to removing it from the mandrel. A pultruded cover plate, 1/4-in. thick, was bonded to the top plate with polyester adhesive prior to load testing, which provided a total thickness of 1/2 in. for the top flange of the girder. The total weight of the girder was 67.9 lb.

Figure 11 shows a load test in progress using an air bag to distribute the load uniformly over the surface of the cover plate. A total load of 5,500 lb. (515 psf) was applied to the girder before failure occurred in the joint between an end-panel stiffener and the top plate. The ultimate live load– dead load ratio was therefore 81. Figure 12 shows the stiffener displaced approximately 3 in. from its initial position after failure. Just discernible in the photograph are the two bolts which sheared at the plate-stiffener interface. Also visible in Figure 12 is a web diagonal which buckled when the attached stiffener displaced.

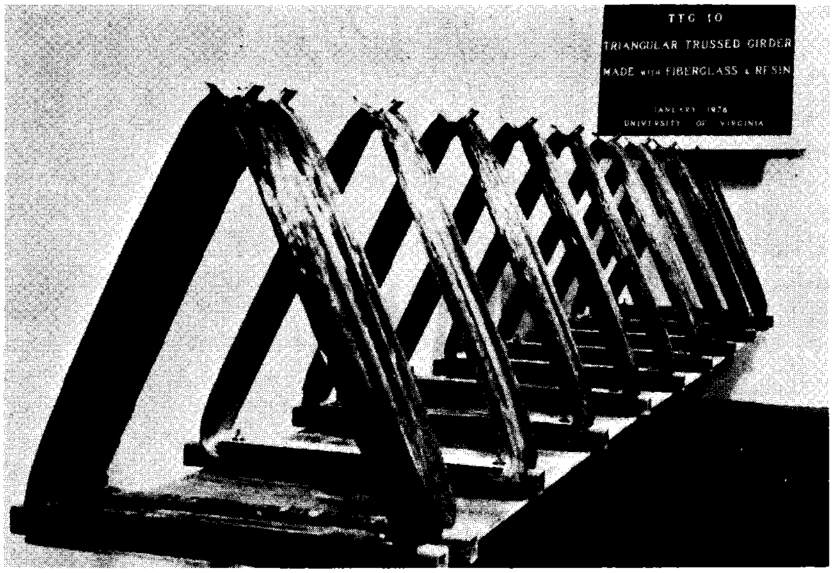

Figure 9. Assembly of stiffeners to the top plate prior to winding the tension elements of TTG-10.

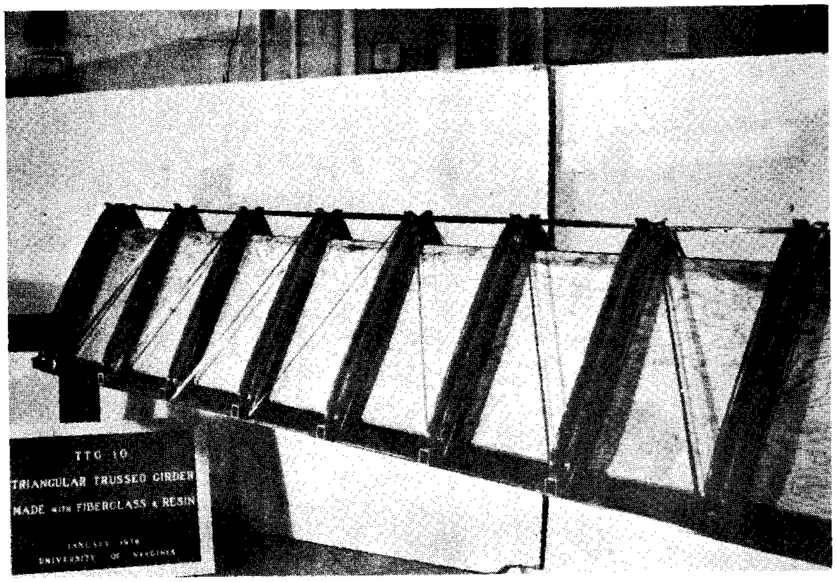

Figure 10. Specimen TTG-10 after winding tension elements and prior to removal from the mandrel.

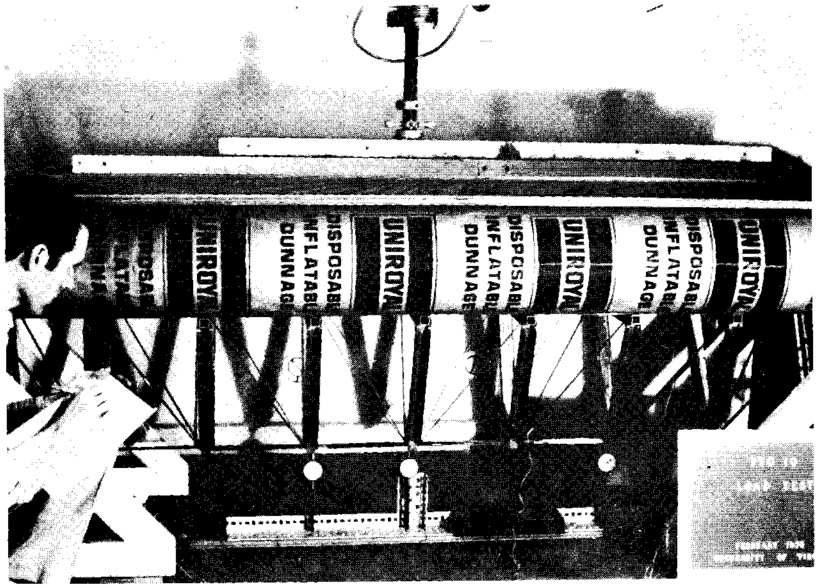

Figure 11. Testing TTG-10 with a uniformly distributed load. A load of 5,500 lb. (515 psf) was required to cause failure.

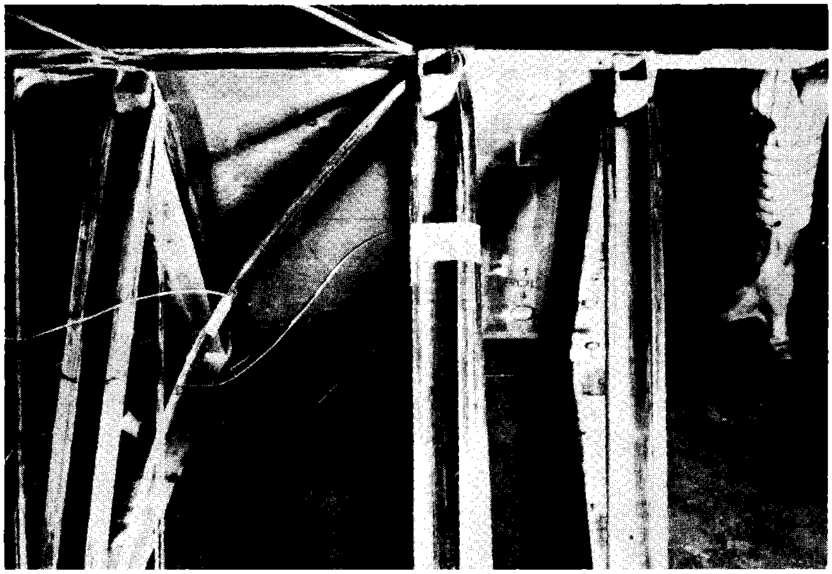

Figure 12. Failure of TTG-10 due to joint failure between lateral stiffener and plate. Buckled web diagonal was caused by movement of stiffener.

Test Results

Lower chord deflections and strains in selected chord and web elements were measured under increasing uniformly distributed loads. Figure 13 indicates the deflection values at two lower panel points for a total load up to 1,200 lb. Also plotted in Figure 13 are curves for the behavior of TTG-7 and the theoretical solution for TTG-10. The theory predicted somewhat greater values for the deflections than were measured experimentally. Disappointingly, the test data also indicated little to no improvement in the deflection characteristics of TTG-10 as compared with those of TTG-7. It had been anticipated that the use of the rigid stiffener assembly in the girder would eliminate suspected joint deformation of the pin-connected assembly. However, it appears from these data that the stiffener joint influence was not significant in the overall deflection behavior of the girder. The ultimate load failure mode of TTG-10 was different from that of TTG-7, but in both members higher strength could be achieved by using large mechanical fasteners. As in all previous test specimens, TTG-10 indicated a linear load-deflection relationship to values several times the design load.

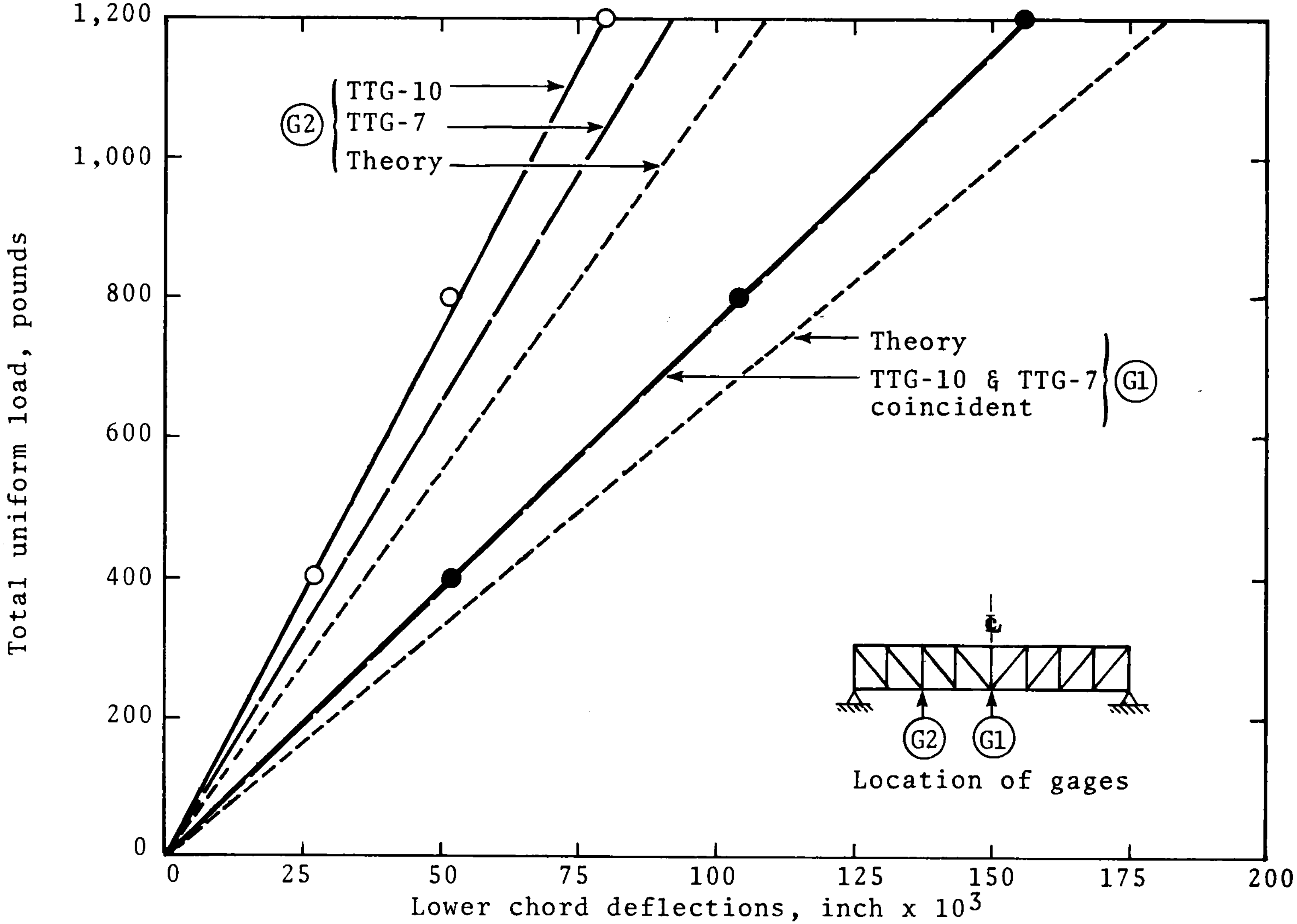

Figure 13. Deflections of TTG-10 at lower chord panel points compared with theoretial solution and similar behavior of TTG-7.

Strain measurements for one diagonal and one chord element are compared with theoretical values for TTG-10 and with experimental values for TTG-7 in Figure 14. These data represent typical variations noted for the eight different elements monitored. Some elements of TTG-10 showed less strain than companion elements in TTG-7, whereas in other elements the strain conditions were reversed. It was also observed that the most highly strained element in TTG-10 was the diagonal in the third panel from the end. The most highly strained element in TTG-7 was in the end panel as shown in Figure 14. The agreement between the theoretical and experimental strains for TTG-10 appeared reasonably good and comparable to that obtained with previous test girders. Computation of tensile stress (modulus of 7×10^6 psi times strain) in the most highly strained element of TTG-10 resulted in a value of 29,000 psi at the ultimate load of 5,500 lb. This value represents a factor of safety of approximately 20 for the strand, based on a design live load of 906 lb. on the member.

Fabrication and Testing of TTG-11

Subsequent to load testing TTG-10, the GRP tensile strands were removed from the member and specimen TTG-11 was fabricated using the top plate and stiffeners used for TTG-10. Strands of resin-impregnated Kevlar 49* roving instead of glass were used to form the tensile elements for the web and low chord. The number of Kevlar 49 strands was increased by 63% to provide cross sectional areas equal to the glass roving areas used in TTG-10.

The total weight of TTG-11 was 69.0 lb., of which 1.4 lb. was Kevlar 49. The same resin and impregnating equipment was used for Kevlar 49 as was used for the glass roving without difficulty. However, there was a tendency for the individual strands of roving to segregate from the bundle of strands making up the web or chord elements. While this feature did not appear to affect the performance of the member during load testing, the irregular cross section profile of the bundle did make it difficult to obtain a smooth, solid surface for the application of bonded strain gages.

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*Kevlar 49 is a synthetic polyamide fiber manufactured by the Dupont Company. The density is lower than that of glass, the mechanical strength is equivalent to that of glass fibers, and the tensile modulus is approximately twice that of E glass.

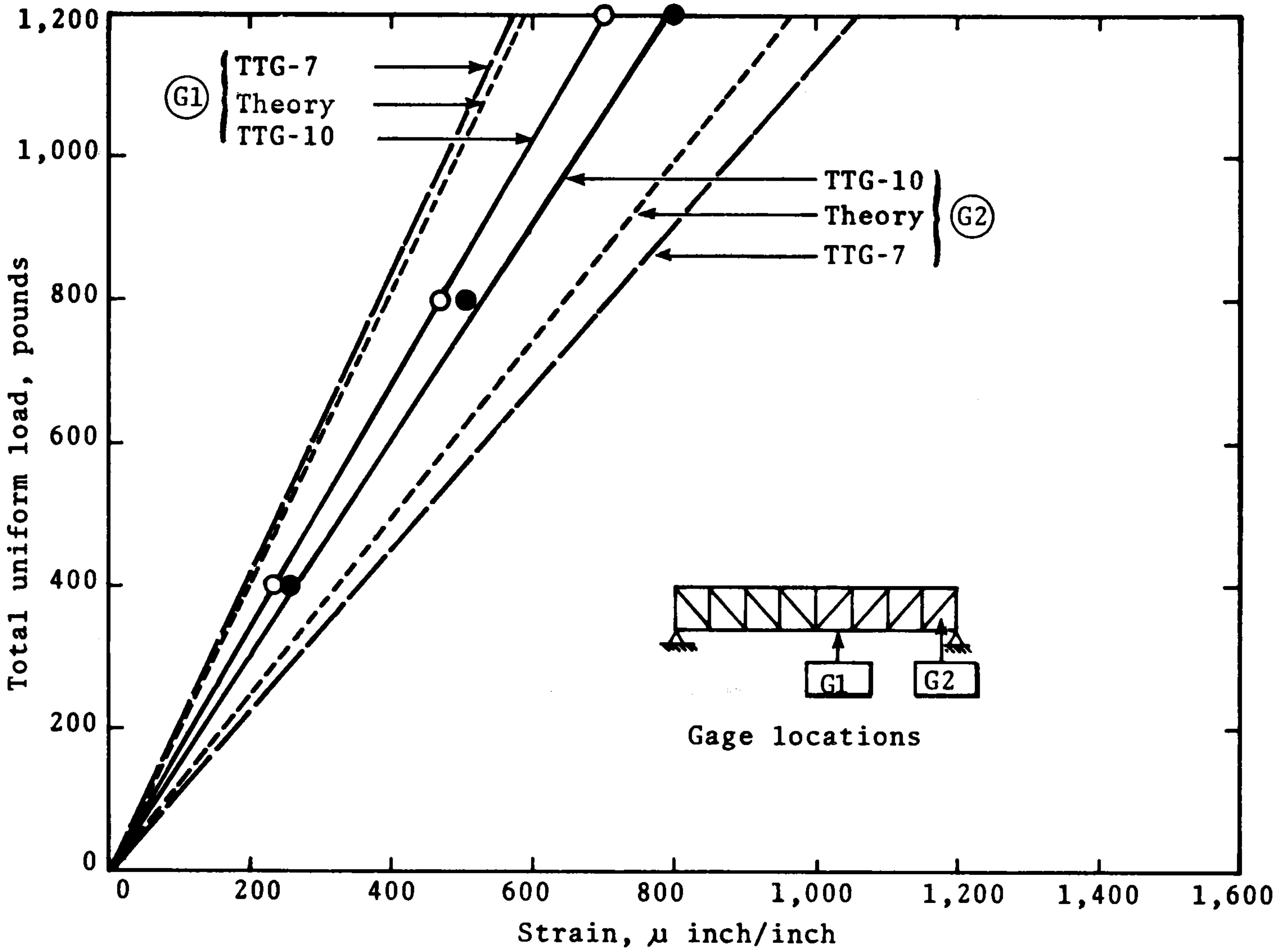

Figure 14. Strains of TTG-10 in selected elements compared with the theoretical solution and behavior of TTG-7.

Test Results

The purpose of preparing test specimens which were identical in every respect except for the material used in the tensile elements was to compare the performance and efficiency of the two materials. This comparison is shown in Figure 15, where vertical deflections at the midspan are shown for specimens TTG-10 and TTG-11 for various load values. All loads were applied to the top plate and uniformly distributed through an air bag for both tests.

Deviations of the four curves shown in Figure 15 are indicated as percentages of the larger value. From these, the improvement (41%) in the centerline deflection with the use of Kevlar 49 is quite evident throughout the load range. This was not unexpected due to the higher tensile modulus of Kevlar 49 relative to that of E glass. The experimental data of both TTG-10 and TTG-11 appear to have approximately the same deviations from the theoretical solutions for centerline deflections and were in the same range (0% to 20%) as those reported previously (see Reference 1). Again, it is noted that the theoretical solutions predict greater deflections than were measured with the test specimen.

In comparing the mechanical efficiencies and cost effective use of Kevlar 49 as tensile elements, it is noted that for a given deflection, e.g. 0.050 in. in Figure 15, the "payload" of TTG-11 would be 650 lb. versus 395 lb. for TTG-10, or an increase of 66% in load capacity. The manufacturer's unit cost per pound of Kevlar 49 is approximately fifteen times that of E glass. However, the amount of Kevlar 49 used in the tensile elements of TTG-11 was only 1.4 lb. or 2% of the total weight of the member which resulted in a net increased material cost of \$9.50 over that for TTG-10. Allowing a cost of \$20.90 (at 60% x 69.7 lb.) for the raw glass content of TTG-10, the comparable cost of TTG-11 would be \$30.40, or 1.5 times the cost of an all glass member instead of the ratio of 15 to 1 for the packaged material. Further reduction in the price differential would be achieved if the two specimens were considered on the total cost for fabrication and material. A realistic total cost cannot be assigned to the assembly of the test specimen since no record of staff time was maintained during all phases of the fabrication. However, if a price of \$4.00 per pound were used for the estimated cost, as suggested by one commercial fabricator of structural plastics, the total cost of TTG-10 would be \$278.80. The additional cost of \$9.50 for the Kevlar 49 would represent 3.4% of the total cost. It appears evident, therefore, that selective combinations of GRP materials and resin impregnated Kevlar 49 offer cost efficiencies greater than does an all glass structure.

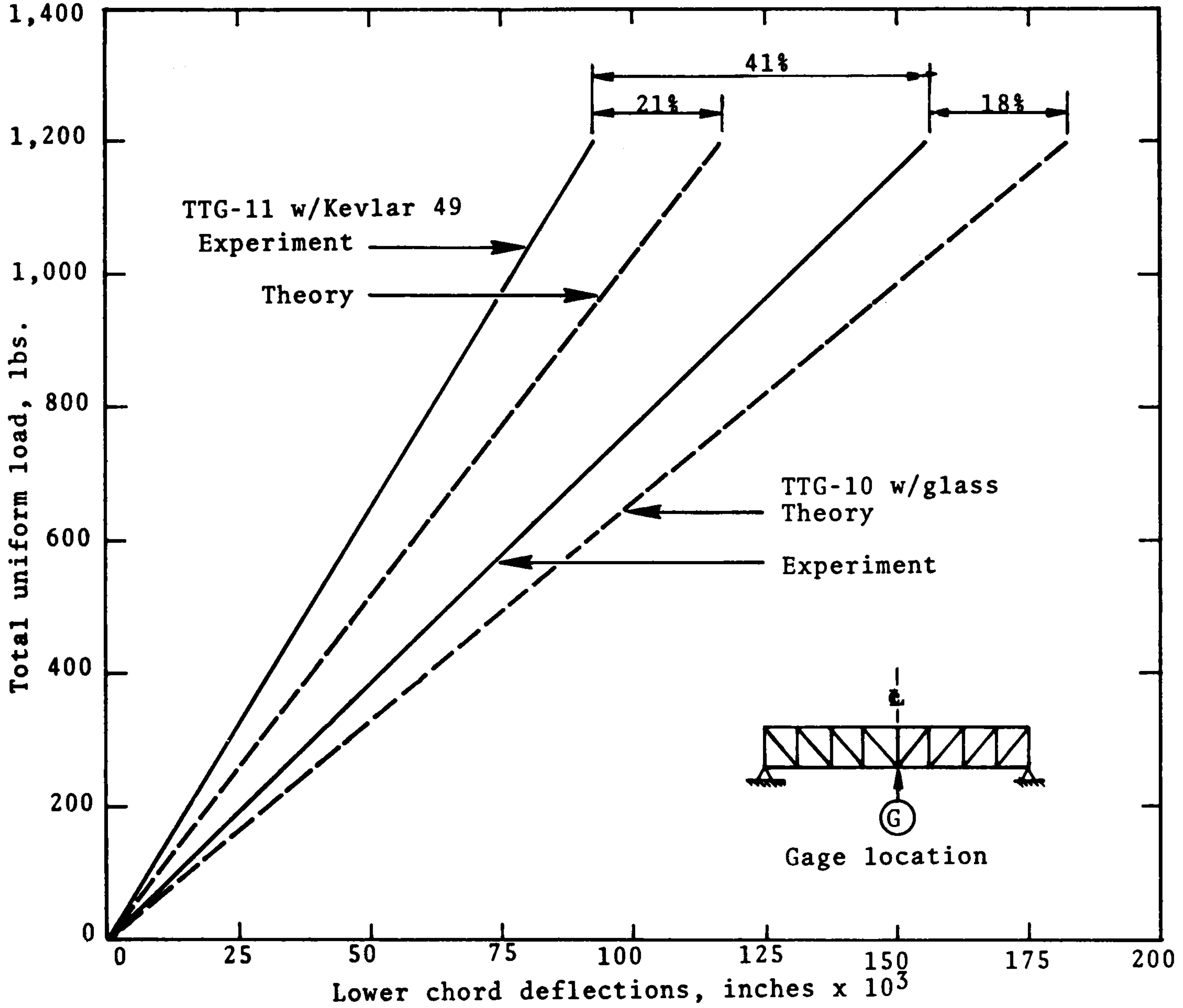

Figure 15. Comparisons of experimental deflections of TTG-10 and TTG-11 with theoretical solutions.

Fabrication and Testing of TTG-12

One final test specimen was fabricated in the current series. This specimen utilized the same plate and stiffeners which had been used previously for TTG-7 and was used to provide the following information.

1. The maximum number of strands which physically could be placed in the space formed by the top plate and a transverse stiffener.
2. Possible fabrication problems which might arise from winding cross-diagonals in selected web panels.
3. An evaluation of the behavior of a modified connector for the stiffeners at the lower chord positions.

This information was of interest, primarily for the design and anticipated requirements for a scaled-up structure to be fabricated for a proposed field study.

Test Results

1. A rectangular space 1/2 in. by 3/4 in. was provided for the roving at the top plate-stiffener location. Resin impregnated glass was then wound around the stiffener joints in the usual fashion until the recess was filled with 142 strands. However, the less compacted region of roving between panel joints filled the available space when approximately 125 strands had been placed. There was adequate space available at the lower panel points at all times. The results of this exercise provided guidance for allocating space for the number of strands required for stress or deflection criteria.
2. Desirable information was obtained from using winding patterns different from those used in the previous test specimens. Not only were cross-diagonals placed without difficulty, but the sequence of generating the web and chord elements was altered with no problems of strand segregation nor undesirable cross-over-strand buildup. The results of this procedure provided confidence in the winding pattern technique which had evolved with the various specimens. A limited test was conducted with TTG-12 to evaluate the effects of the several

modifications and to compare the performance with that of its predecessor, TTG-7. Overall, the performances of the two specimens were quite similar. The centerline deflection of TTG-12 was 22% greater than that of TTG-7. On the other hand, the strain in the most highly stressed element in TTG-7 was 14% greater than that in TTG-12. These variations are within the range of values expected for the load, support, and fabrication conditions prevalent with this type of experiment.

3. The connector for the ends of the stiffeners at the lower chord position was redesigned to provide more space than previously available for lower chord development (see Reference 1 for a description of the tee-shaped connector used for previous specimens with tubular stiffeners). The modified connector also provided anchor studs for lateral ties between girder units within a multisectional structure. The connectors were sawn from a block of cast resin reinforced with layers of woven glass cloth and glass mat. A photograph of one of the connectors and the metal mold used to cast the reinforced resin is shown in Figure 16. Figure 17 shows a connector in position in TTG-12.

The performance of the connectors in TTG-12 during the load test was satisfactory for design loads. The specimen was not loaded to an ultimate value, so it was not determined if a strength deficiency may develop in the connector at higher loads. However, none is anticipated. A slight rotation of several of the connectors was observed visually during the load test. Alteration of the mold is currently in progress to provide better seating of the stiffener tubes on the connector, which should alleviate this condition. There was no indication of instability of the stiffeners or the connectors during or after the load tests.

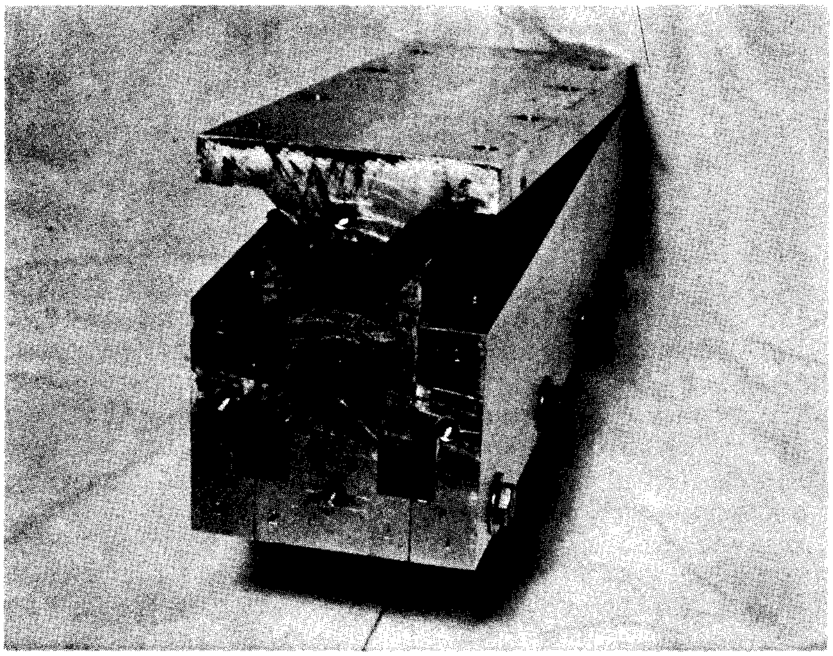

Figure 16. Connector for lower chord stiffeners cast from glass reinforced polyester shown with metal mold used for casting.

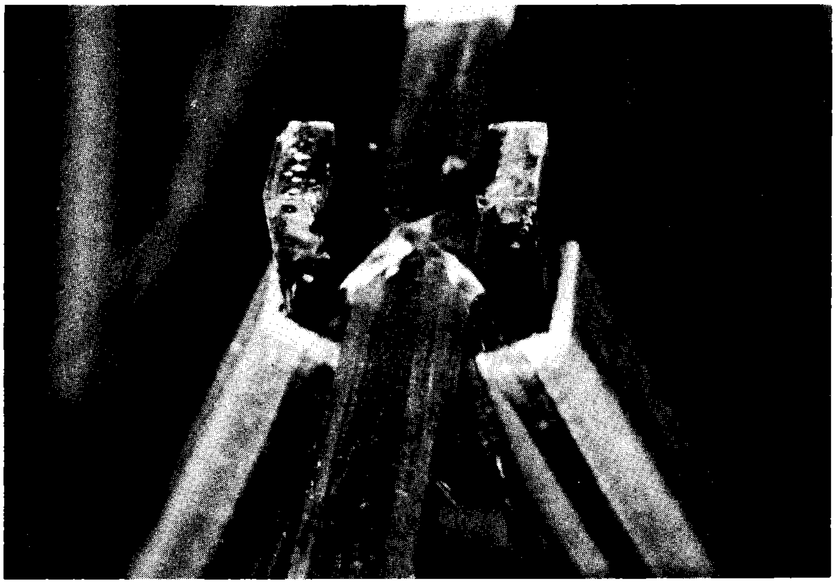

Figure 17. Lower chord view of connector and stiffeners in TTG-12.

DESIGN CRITERIA

Geometric Considerations

The only shape investigated in the studies was the basic TTG configuration with a triangular cross section, a biplanar open web, and a lower chord which was common to both webs. Experimentally, only specimens with straight lower chords and constant depths were fabricated and tested. Girders with varying depths, straight top flanges and curved lower chords were studied analytically. In addition, girders with spans up to 30 ft., depth to 4 ft. and different panel arrangements were analyzed for deflections and stresses for various load combinations.

An evaluation of the behavior of the girders in accordance with the applicable AASHTO performance specifications indicated that deflection provisions imposed the initial limitations on loads. Generally, at the limiting deflection load a safety factor of 8 against rupture was retained by the most highly stressed truss element. Even in the case of tensile elements composed of Kevlar 49, the safety factor was greater than 4 for the maximum load permitted by the deflection criterion. It therefore appears that for the given materials and configurations, the deflection limitations will always control the selection of the size and location of elements in the girders.

In nearly every experimental measurement made in the load tests, the corresponding analytically predicted value has ranged from 0 to 30% higher than the experimental measurements. While it is not recommended at this time that an empirical factor of this magnitude be applied across the board to adjust the analytical model for the girder, it appears that the analytical solution presents an upper bound for the response of the girder to static load. A girder designed in accordance with the analytical solution may therefore be expected to perform as well or better than the resulting predictions.

Manufacturing Considerations

The major portion of the weight of the experimental girders has been concentrated in the compression stiffeners and plates. All of these elements (with the exception of TTG-10 and TTG-11) have been pultruded shapes supplied from a single commercial source. Efforts to locate other sources of suitable pultruded products have been unsuccessful. A number of other manufacturers who can supply pultruded shapes either have very limited stocks or shapes are supplied only on special order. Special orders usually require large quantity purchases to reduce the unit cost of the product to a value comparable to that of regular stock items.

All assembly of compression elements and forming of the tension elements have been accomplished manually for the TTG laboratory specimens. Multi-unit production of the girders would reduce unit costs somewhat as now fabricated, but considerable man-hours of labor should be saved by forming one-piece stiffeners by molding or winding procedures. However, capital expenditures for molds or mandrels will be relatively high (in the $5,000 range) and the flexibility for dimensional change in stiffener size would be lost when compared with the three-piece arrangement of tubular, pin-connected stiffeners. The economic feasibility for forming tension elements with automatic winding equipment has not been determined, even though the procedure is technically feasible. It is anticipated that considerable development effort will be required to design and manufacture a machine suitable for this operation. Undoubtedly, a large potential market for the product must be realized to attract large development expenditures by an industrial firm.

Performance Considerations

Creep Deflection

Two laboratory test specimens have indicated secondary deflection creep rates of approximately 0.03 in. per year for designs based on AASHTO requirements for load and deflection. This rate may be reduced by overdesigning the structure to reduce tensile and compressive stresses. Even though not demonstrated in the experiment, the relatively low compressive modulus of GRP composites suggests that the compression elements may be the major source of creep deformation in the structure.

Weathering and Fire Protection

Deterioration of the stress resisting components of the TTG girder as currently proposed should not be rapid. All surfaces of structural elements will be protected from direct light by non-load bearing plates. The polyester resin coating on the glass fibers will provide protection against moisture attack. Destruction or damage of the structure by fire may be minimized by using a resin containing fire retardant additives. These materials are readily available (by special order for pultruded products) at some additional cost and with some sacrifice of mechanical properties.

Fatigue

In general, GRP composites are notch insensitive and therefore perform well in fatigue applications at relatively low stress levels. One TTG specimen has been tested under cyclic loading at high stresses and performed well. Therefore, the current girder configuration should not show distress during the course of normal service loading.

Cost Considerations

The initial cost of a structure composed of modular TTG units will depend upon the materials and labor required for assembly. Therefore, the use of pultruded products for compression elements should be minimized when a substitute component can be used. The relative mechanical inefficiency of GRP material in compression elements (compared with metals) and the relatively high unit cost (compared with concrete) require combinations of suitable materials to optimize cost benefits. For example, the materials cost of a 4 in. thick deck on girder composed entirely of pultruded plate would cost $40.40 per sq. ft., whereas the cost of a 1/2-in. thick plate and a 3 1/2-in. thick concrete slab would cost approximately $6.00 per sq. ft. On the other hand, the relatively lost cost of E glass roving and polyester materials (approximately $0.60 per pound) and the high mechanical efficiency of unidirectional glass fibers when used in tension dictate that maximum use should be made of them in the GRP design concept.

Overall cost benefits have been demonstrated in applications of GRP materials in highly corrosive environments. It is therefore anticipated that maintenance costs will be reduced from those required for structures containing steel components. However, there is insufficient long-term data available at this time to establish a precise cost-reduction factor in a design formula.

Direct labor cost reduction is associated with automated fabrication procedures and has been discussed in a previous section.

CONCLUSIONS

The following conclusions are based on data presented in this report or those presented in the earlier studies described in Reference 1.

1. The use of lateral ties between the lower chords of adjacent girders in a trisectional structure were quite effective in reducing horizontal displacements due to vertical loads.
2. The replacement on pin-connected stiffener assemblies with a single-piece rigid stiffener did not improve the load-deflection performance of the test speciman.
3. The replacement of glass strands in the tension elements with strands of Kevlar 49 improved substantially the load-deflection performance of the test specimen.
4. Long-term deflections at midspan of an 8-ft.long TTG structure which meets AASHTO specifications will increase at a rate of approximately 0.03 in. per year.
5. A TTG configuration which has been designed and fabricated to meet AASHTO load and deflection requirements for pedestrain bridges will have a safety factor of at least 8 against rupture of a joint or element.
6. The costs of materials dictate minimum use of pultruded shapes in compression and maximum use of impregnated roving strands in tension in combination with other materials to achieve maximum cost benefits.

REFERENCES

1. McCormick, F. C., and Alper, H., "Further Studies of a Trussed-Web Girder Composed of Reinforced Plastics", Virginia Highway and Transportation Research Council, Report 76-R16, November 1975.

2. McCormick, F. C., "Working Plan-- Modification Studies for a Bridge Girder of Reinforced Plastics", Virginia Highway and Transportation Research Council, Report 76-WP13, October 1975.

APPENDIX A

EXPERIMENTAL TESTING

Instrumentation

Test specimens were instrumented to obtain data for vertical deflections and strains in selected elements during loading. All deflection measurements were made with mechanical dial indicators with least readings of 0.001 inch. Strains were measured by means of electrical resistance strain gages bonded to the surface of the web and chord elements. Gages supplied by the Micro-Measurements Company, type EA-06-250 BF-350, were bonded with M-bond 200 adhesive to all specimens. 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 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 20 pounds per cylinder. Air bags, 3 x 9 x 1-foot deep, made by the Uniroyal Company, were used to spread the load uniformly over the top plate of the members. Support was provided at the ends of the test member by wooden frames built to fit the triangular shape at the cross section. A 1/4-inch thick strip of elastomeric material was attached to the support frame to ensure distributed contact along the sides of the "V" of the support frame and the vertical web elements at the ends of the member. 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 of the laboratory during the period of load testing. In general, the temperature ranged from 68°F to 75°F and the relative humidity from 45° to 65°.