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COMPOSITES IN BRIDGES

University-Based Research, Education, and Technology Transfer Program

AGREEMENT NO. 359704, WORK ORDER 89

FINAL REPORT

March 2002

By M. Elgaaly

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16. Abstract

Glass has been the predominant fiber in use because of an economical balance of cost and strength. Glass fibers are elastic until failure and exhibit negligible creep under controlled, dry conditions. E-glass comprises approximately 80 to 90 percent of the glass fiber commercial production. Polyester and Vinyl ester are the resins most commonly used in Civil Structural applications; Epoxy resins are used in aircraft, aerospace, and defense applications. Fiber reinforced plastic (FRP) products are available in bars, meshes, two and three dimensional grids, and structural shapes similar to steel. Most of the products are produced by pultrusion.

Civil Structural Engineering applications of FRP have increased over the past few years. This is due to a high strength-to-weight ratio, high resistance to chemical attacks, low electric conductivity, vibration damping, high resistance to fatigue, low coefficient of thermal expansion, and most importantly tailor ability. Lack of communication between the composites and the construction industries resulted in a delay in the development of composites as building construction material. Unfortunately, companies in the composite industry have independently developed competitive products rather than working together to develop a large market. Moreover, they have not become involved in developing standards and specifications.

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Prepared for

Commonwealth of Pennsylvania
Department of Transportation

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PTI 2002-28

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

COMPOSITES IN BRIDGES
FINAL REPORT

FIBER REINFORCED COMPOSITE MATERIALS

Glass has been the predominant fiber in use because of an economical balance of cost and strength. Glass fibers are elastic until failure and exhibit negligible creep under controlled, dry conditions. E-glass comprises approximately 80 to 90 percent of the glass fiber commercial production. Polyester and Vinyl ester are the resins most commonly used in Civil Structural applications; Epoxy resins are used in aircraft, aerospace, and defense applications. Fiber reinforced plastic (FRP) products are available in bars, meshes, two and three dimensional grids, and structural shapes similar to steel. Most of the products are produced by pultrusion.

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MECHANICAL PROPERTIES AND STRUCTURAL BEHAVIOR OF PULTRUDED SHAPES

For Pultruded Fiber Reinforced Plastics, the strength-to-stiffness ratio is much larger than that of steel or concrete. Therefore, deflections usually control the design with composite structural shapes. The effect of shear deformation in calculating the deflection of FRP beams cannot be ignored; see figures 1 and 2. The ratio between the flexure and shear moduli (E/G) is much higher for FRP beams than compared to steel beams. The results from experimental and analytical studies indicate that the E/G is about 30 for FRP I beams and 20 for FRP WF beams. It also has to be noted that vinyl ester beams have higher E and G values than polyester beams; furthermore, the E and G values differ with the size of the beam. Because of the variability of the mechanical properties of FRP shapes, the safety factors used in the design are high. The recommended safety factors are: 2.5 for flexure, 3.0 for compression and shear, and 4 when designing a connection.

Values of E and G can be experimentally determined with a variability of test results between upper and lower bounds. Polyester and Vinyl ester FRP pultruded beams manufactured by three different manufacturers were tested to determine the E and G. The variability of E and G for FRP pultruded Polyester and Vinyl ester beams is shown in figures 3 to 6. The upper bounds of E and G for both the Polyester and Vinyl ester are 6,000 and 650 ksi, respectively; while the lower bounds are 3,300 and 450, respectively. It is of interest to note that the values of E and G recommended by the manufacturers are 2,500 and 450, respectively.

The strength of FRP pultruded beams recommended by three manufactures is tabulated in table 1, for Polyester (P) and Vinyl ester (V). In the same table, values of the flexure "E" and shear "G" moduli and Poisson's ratio "v" are given.

STRENGTH OF GFRP PULTRUDED BEAMS UNDER MONOTONIC PATCH LOAD

Local crushing of the web matrix under a load applied on the top flange or over the support is a common mode of failure in GFRP Pultruded Beams. The strength of these beams under applied patch loads on the top flange was examined. Some of the beams were tested while continuously supported at the bottom flange and some were supported only at the ends to study the effect of the presence of global bending. The tests were performed using polyester and vinyl ester I-beams manufactured by three different manufacturers. Finite Element analyses of the tested beams were performed and the analytical results did agree very well with the experimental ones. Equations were given to determine the strength of GFRP Pultruded Beams under Patch loads and to calculate the effect of the presence of global bending.

Based on the experimental and analytical studies; the failure load "P_u" can be calculated from,

$P_u = (W + 4t_f)\, f_c\, t_w$, where

W = Width of the patch load along the length of the beam,

t_f = Flange thickness

t_w = Web thickness

f_c = Crushing strength

= 16.5 and 20 ksi, for Polyester and Vinyl ester, respectively

Table 2 gives P_u obtained experimentally and calculated from the above equation, for comparison.

The presence of bending will reduce Pu , as shown in figures 7 and 8 from tests and Finite Element Analysis, respectively. The following equation is recommended, namely

$(P/P_u) + 0.2836\,(M/M_u) = 1$, where

P and M are the actual patch load and moment, and

P_u and M_u are the ultimate capacities in absence of the other.

FATIGUE BEHAVIOR OF PULTRUDED BEAMS

The fatigue behavior of FRP beams is controlled by the matrix rather than the fibers, and they exhibit better performance under repeated loads than other construction materials. Polyester and Vinyl ester beams made by three manufactures were tested under cyclic patch loads to determine their fatigue life. The fatigue tests were conducted to failure or to 10 million cycles, whichever occurred first. The objectives of these tests were; to establish S_r-N curves, investigate if there is any stiffness degradation under repeated loads, and to study the effect of the beam size on the fatigue strength (beams with depth of 4 to 12 inches were used).

The mode of failure in all the tests was crushing of the web matrix in the transverse direction under the applied patch load. During the tests, no stiffness degradation was observed until immediately prior to failure. Curves relating the transverse compressive stress range "Sr" to the number of cycles to failure are given in figures 9 and 10 for the Polyester and Vinyl ester beams, respectively. Curves relating the bending stress range to the number of cycles from the same tests are plotted in figures 11 and 12. Equations were developed from the test results to determine the number of cycles to failure "N" as a function of the transverse compressive stress range "S_r". These equations are:

For Polyester Beams: $\mathrm{Log}(N) = 12.17 - 11.07\,\mathrm{Log}(S_r)$, and

For Vinyl ester Breams: $\mathrm{Log}(N) = 10.67 - 7.56\,\mathrm{Log}(S_r)$.

The above equations and the test results are plotted in Figure 13, and as can be noted the vinyl ester beams exhibit higher fatigue life for the same stress range than the polyester beams. The effect of the beam size is demonstrated in Figure 14, and as can be noted the smaller size beams have higher fatigue life.

Manufacturer		Strongwell	Bedford	Creative Pult.
Longitudinal tensile strength (Ksi) [ASTM D-638]	P	30	30	33
	V	30	30	37.5
Transverse tensile strength (Ksi) [ASTM D-638]	P	7	7	7.5
	V	7	7	8
Longitudinal compressive strength (Ksi) [ASTM D-695]	P	30	30	33
	V	30	30	37.5
Transverse Compressive strength (Ksi) [ASTM D-695]	P	15	15	16.5
	V	16	15	20
Shear strength [ASTM D-732]	P	4.5	4.5	5.5
	V	4.5	4.5	6

Manufacturer		Strongwell	Bedford	Creative Pult.
Longitudinal flexural strength (Ksi) [ASTM D-790]	P	30	30	33
	V	30	30	37.5
Transverse flexural strength (Ksi) [ASTM D-790]	P	10	10	11
	V	10	10	12.5
Modulus of elasticity "E" (Ksi) Full section	P	2500	2500	2500
	V	2500	2500	2800
Shear modulus "G" (longitudinal direction)	P	425	450	420
	V	425	450	420
Poisson's ratio [ASTM D-3039]	P	0.33	—	0.36
	V	0.33	—	0.36

TABLE (1) Recommended Strength and Mechanical Properties

Case No.	Section (material)	Span (in)	W (in)	L / d	Ult. Load (Kips)		Eqn. / Exp.
					Exp.	Eqn.	
1	P 4x4x1/4"	20	3	5	15.9	15.9	1.000
2	P 4x4x1/4"	30	3	7.5	14.3	14.5	1.014
3	P 4x4x1/4"	40	3	10	13.6	13.4	0.985
4	P 4x2x1/4"	20	2.5	5	15.2	15.9	1.046
5	P 4x2x1/4"	36	2.5	9	10.1	12.3	1.218
6	P 3x1.5x1/4"	30	1.0	10	5.4	6.8	1.259
7	P 3x1.5x1/4"	24	1.0	8	5.8	7.2	1.241
8	V 4x2x1/4"	20	2.5	5	17.1	18.3	1.070
9	V 4x2x1/4"	36	2.5	9	12.3	15.4	1.252
10	V 3x1.5x1/4"	30	1.0	10	6.3	8.1	1.286
11	V 3x1.5x1/4"	24	1.0	8	7.4	8.7	1.176
Average ratio							1.141

Table (2) Comparison Between P_u (local web crushing capacity) Obtained Experimentally and Calculated from Equation

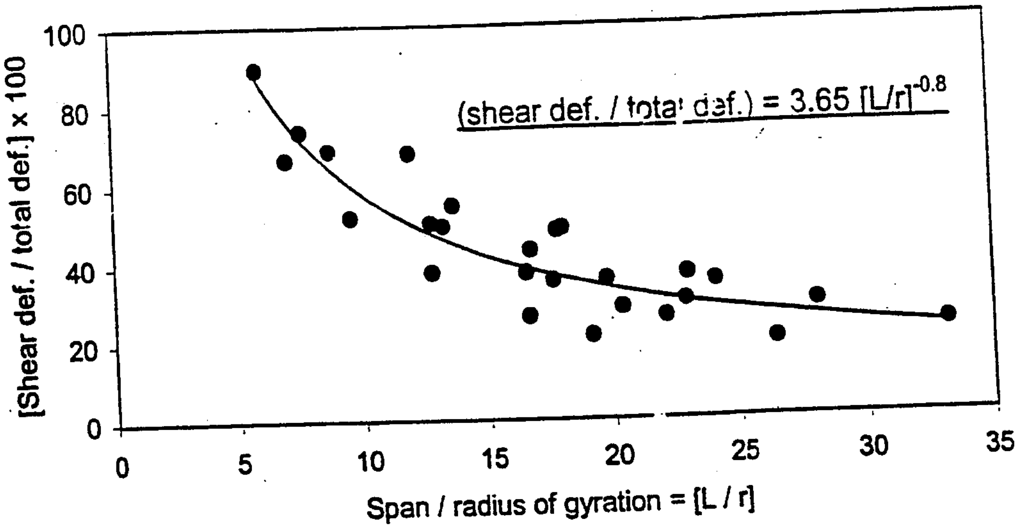

Figure (1) Deflection Due To Shear Effect
Polyester Pultruded Beam

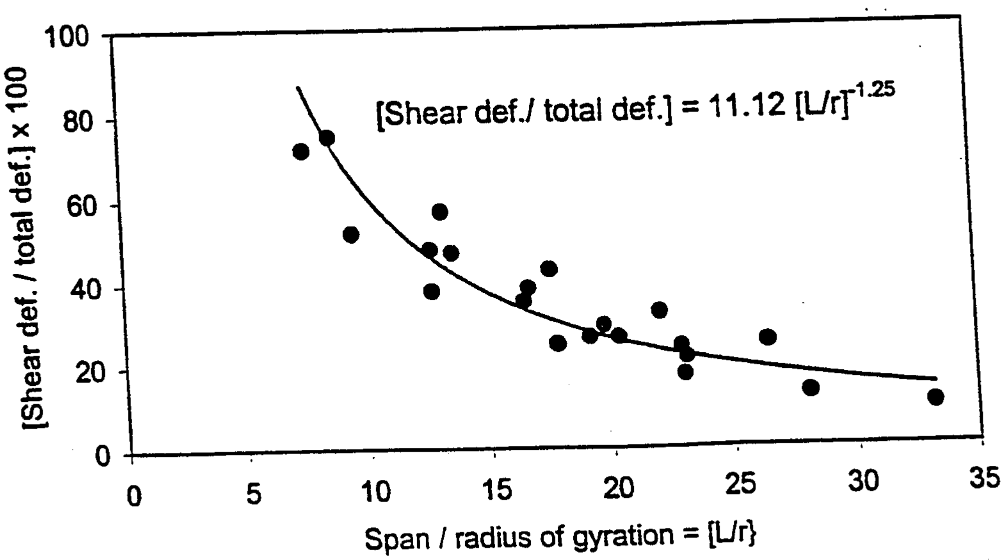

Figure (2) Deflection Due To Shear Effect
Vinyl ester Pultruded Beam

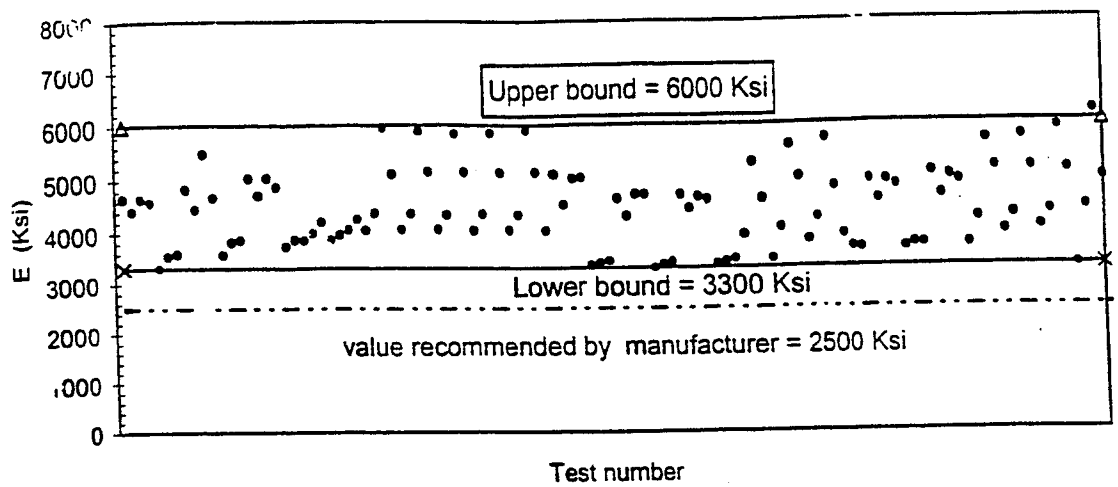

Figure (3) Variability of E – Polyester

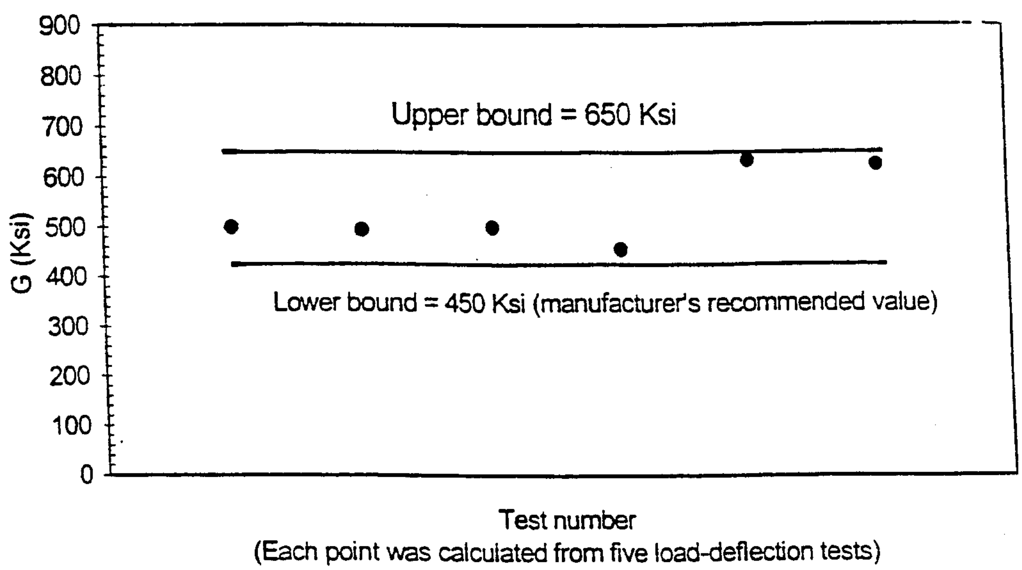

Figure (4) Variability of G – Polyester

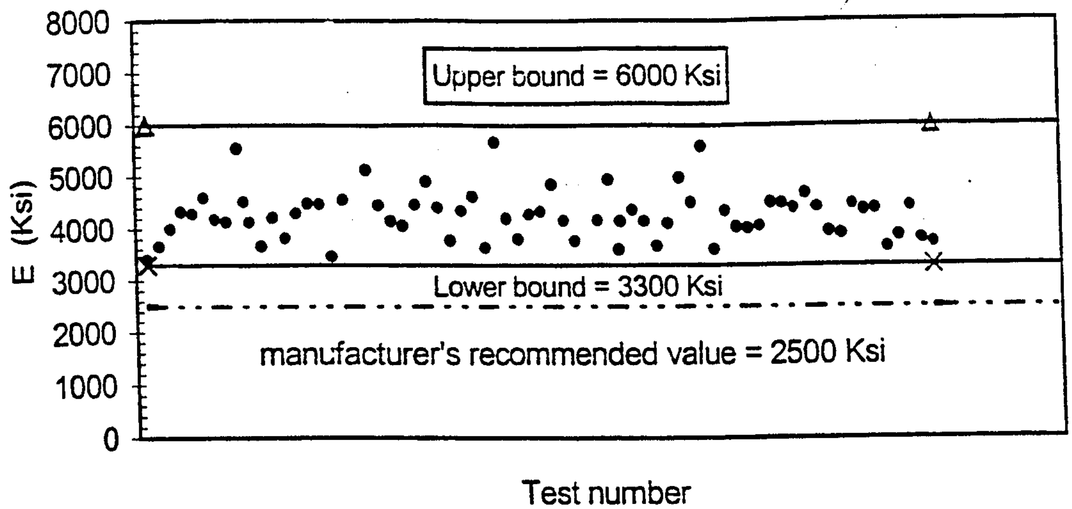

Figure (5) Variability of E – Vinyl ester

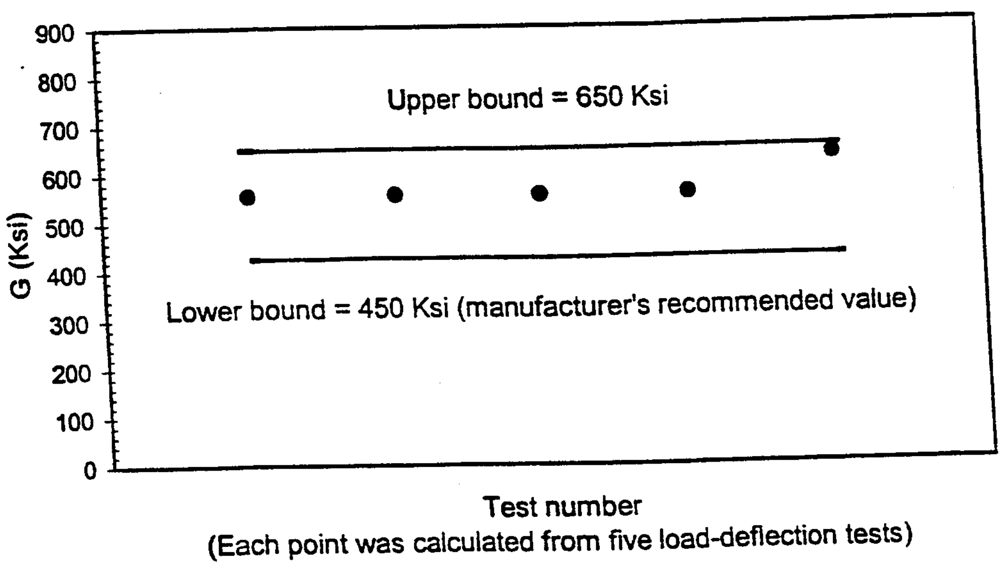

Figure (6) Variability of G – Vinyl ester

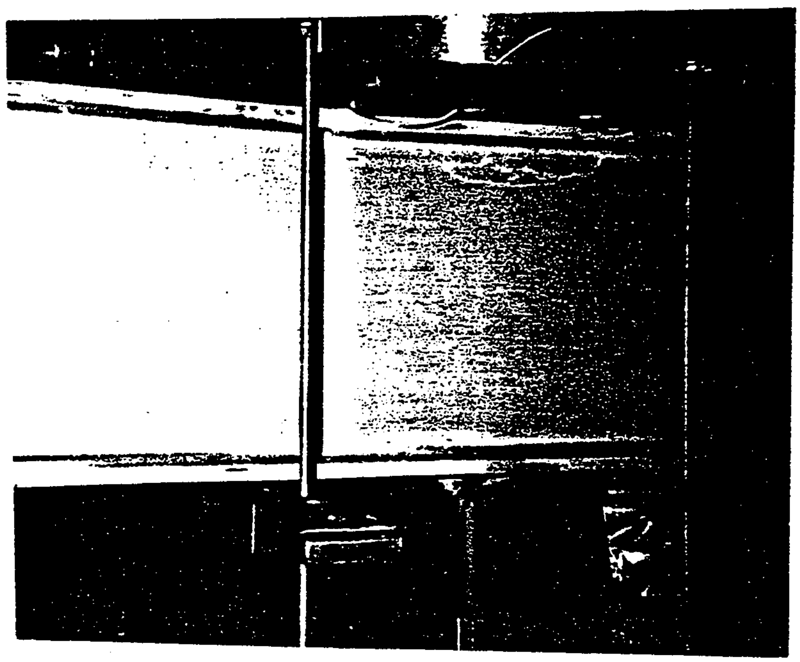

Figure (7) Local Crushing of the Web Matrix under a Load Applied on the Top Flange

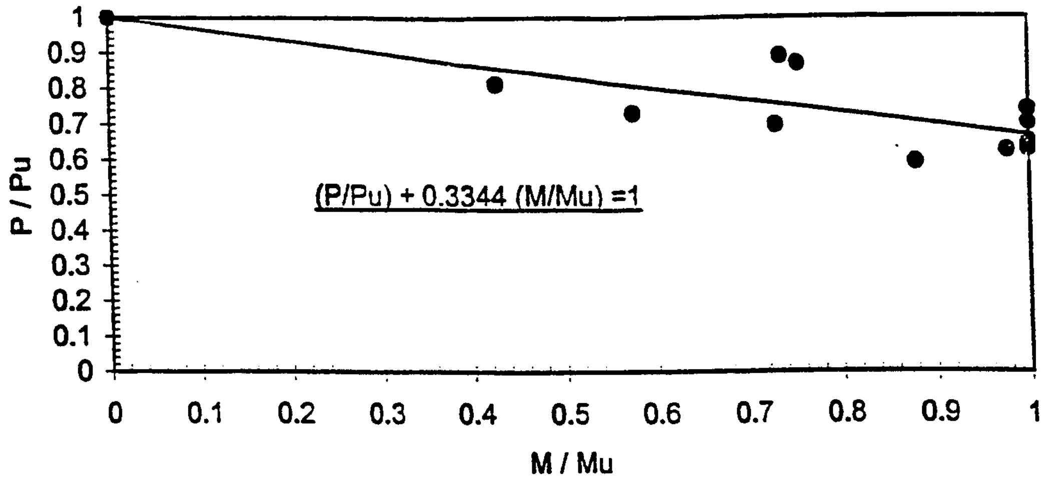

Figure (8) Effect of the Presence of Bending on P_u – From Tests

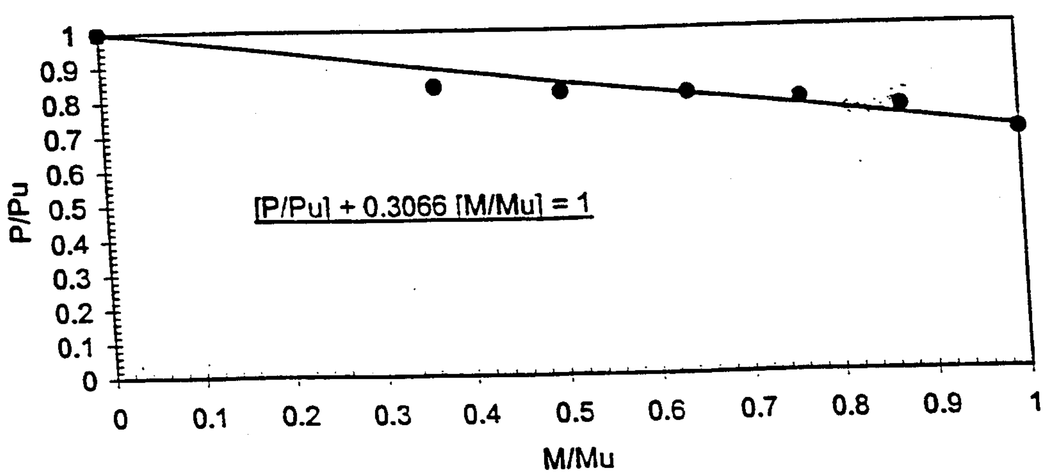

Figure (9) Effect of the Presence of Bending on P_u – From Analysis

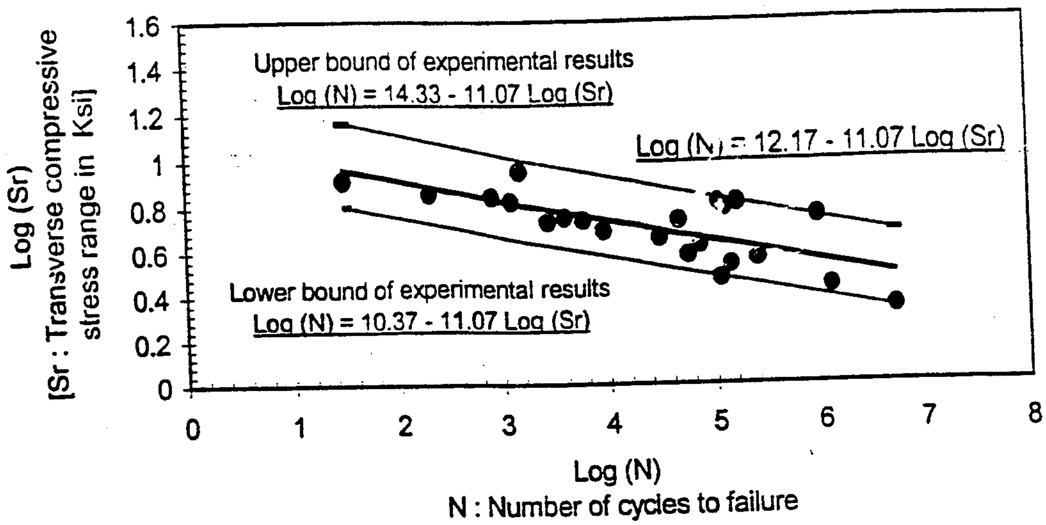

Figure (10) Sr – N Curve For Polyester Beams Based on Transverse Compressive Stress

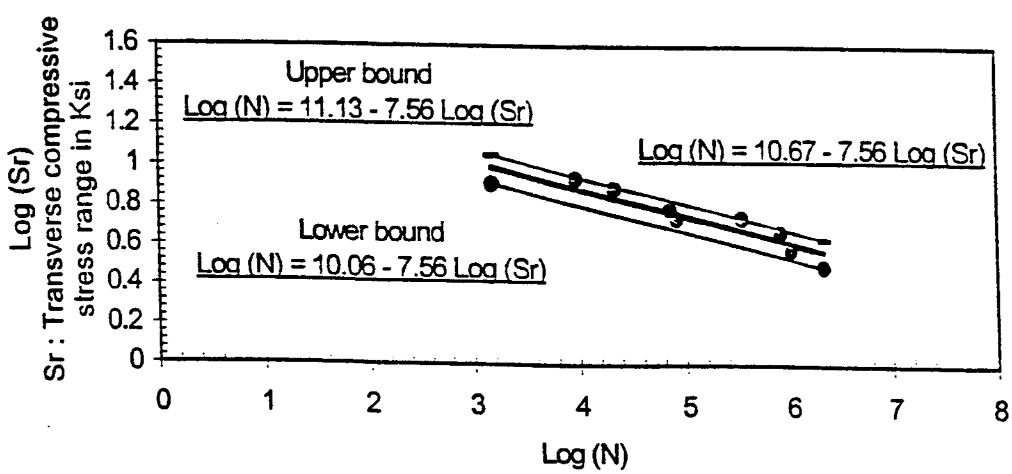

Figure (11) Sr – N Curve For Vinyl ester Beams Based on Transverse Compressive Stress

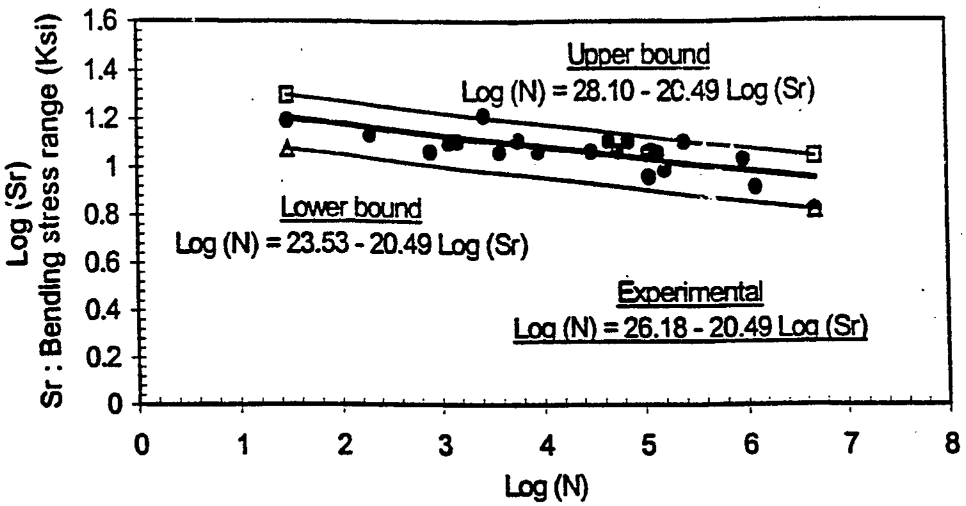

Figure (12) Sr – N Curve For Polyester Beams Based on Bending Stress

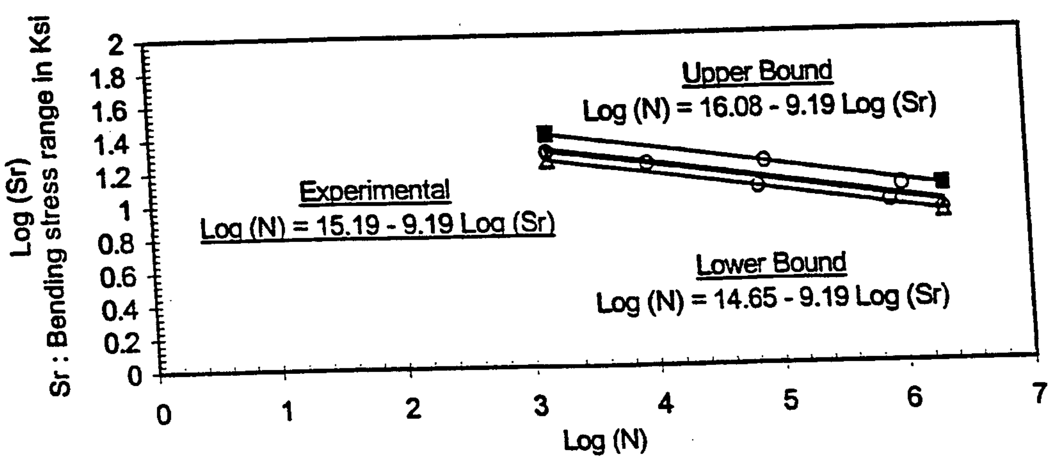

Figure (13) Sr – N Curve For Vinyl ester Beams Based on Bending Stress

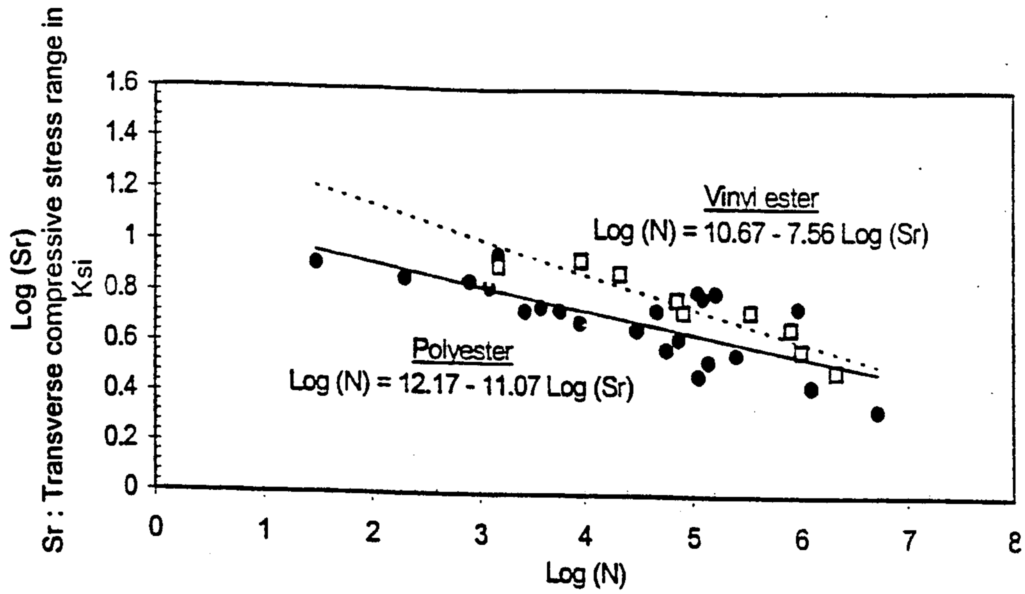

Figure (14) Sr – N Curves For Polyester abd Vinyl esterBeams Based on Transverse Compressive Stress

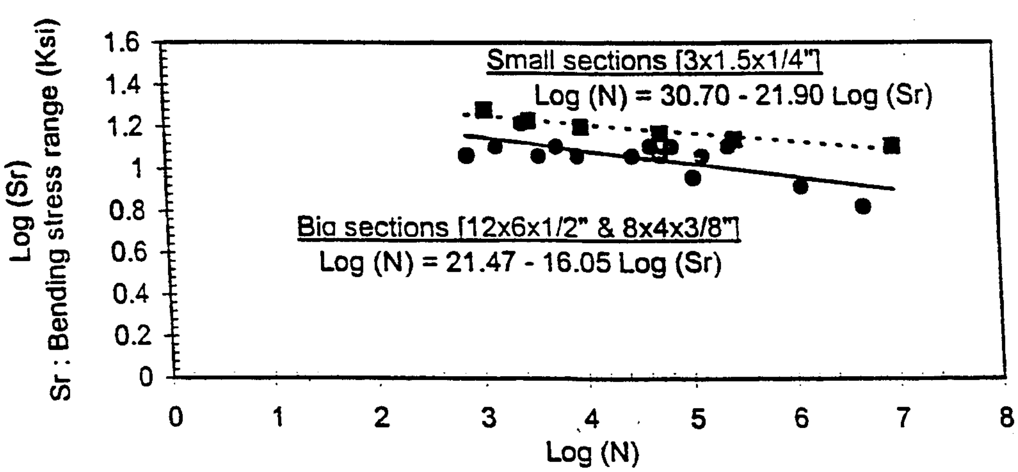

Figure (15-a) Sr – N Curve For Polyester Beams Effect of Beam Size

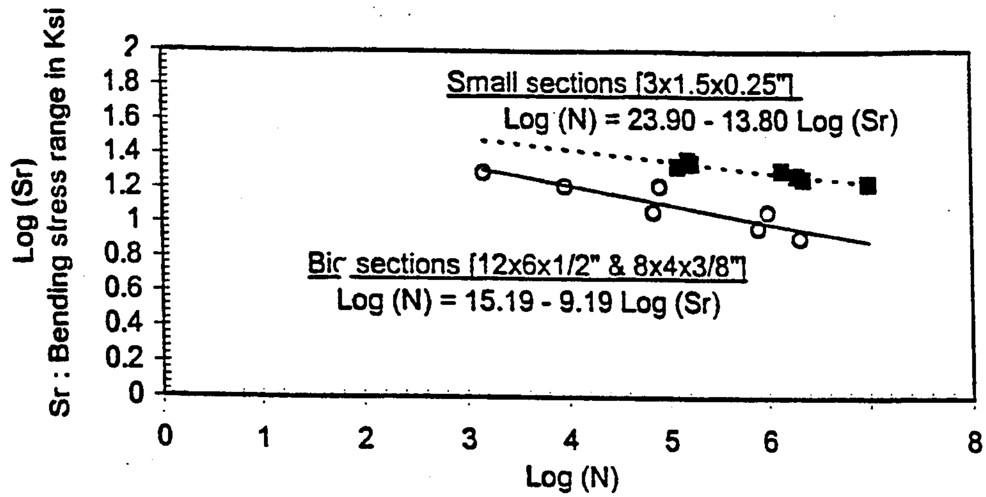

Figure (15-b) Sr – N Curve For Vinyl ester Beams Effect of Beam Size

APPENDIX

APPENDIX

Calculation of the Modulus of Elasticity "E" and the Shear Modulus "G" From Load-Deflection Lines

1. For a simply supported I-beam with span "L" loaded with a concentrated load "P" at mid span (three-point loading configuration), the value of the vertical mid-span deflection "Δ" can be calculated from the following equation;

$\Delta = PL^3/48\ EI + PL/4GA_w$ .... (1),

where "E" and "G" are the flexural and shear moduli, "A_w" is the web area, and "I" is the second moment of area about the strong axis of the cross section. One should note that the load-deflection behavior of GFRP pultruded beams is linear up to failure.

2. Equation (1) can be written in the following form,

$y_1 = (1/E)\ x_1 + (1/G)$ ....(2)

where,

$y_1 = (4\ A_w/L)(\Delta/P)$, and

$x_1 = (A_w L^2/12\ I)$.

Equation (2) represents a straight line of slope (1/E) and the intercept is (1/G).

3. Equation (1) can also be rewritten in the following form,

$y_2 = (1/G)\ x_2 + (1/E)$ ....(3)

where,

$y_2 = \{96I/(L^3+a^3-3La^2)\}\ \Delta/P$, and

$x_2 = 24\ I(L-a)/A_w(L^3+a^3-3La^2)$.

In this case the slope of the straight line is (1/G) and the intercept is (1/E).

4. The span "L", and the section properties "A_w" and "I" can be used to calculate x_1 and x_2.

5. In order to calculate y_1 and y_2, we need Δ/P, which is determined from testing (loading the beam and measuring the deflection at various load increments).

Once x_1, x_2, y_1, and y_2 are determined one can determine E and G, by plotting equations (2) and (3), and calculating the slope and the intercept. Two values for each of E and G will be determined they should be very close, and the average is to be taken.

Similar equations can be written for a simply supported I-beam with span "L" loaded with two concentrated loads separated by a distance "a" and applied at equal distances from the supports. In this case, the value of the vertical mid-span deflection "Δ" can be calculated from the following equation;

$$\Delta = (P/96\,EI)\,(2L^3 + a^3 - 3La^2) + P(L - a)\,/\,(4GA_w)$$

The same procedure outlined above, for the mid-span concentrated load, can be used to determine two values for each of E and G.These values should be very close, if not equal to, the values determined from the three-point loading. Average values of E and G calculated from several three-point and four-point loading tests were used.