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BEHAVIOR OF FRP COMPOSITE-STRENGTHENED BEAMS UNDER STATIC AND CYCLIC LOADING

Summary Report

SPR 387.011

RESEARCH

Oregon Department of Transportation

BEHAVIOR OF FRP COMPOSITE-STRENGTHENED BEAMS UNDER STATIC AND CYCLIC LOADING

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by

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16. Abstract

Small, concrete beams with no steel reinforcement were externally strengthened with eight different configurations of fiber reinforced polymer composites. The reinforcement configurations consisted of high and low modulus epoxy, high and low modulus fiber, and 1 and 2 composite layers. Load capacity tests were conducted for all eight configurations, and fatigue tests were conducted for two of the configurations. Beams with the higher modulus epoxy had more load capacity than beams with the lower modulus epoxy. However, this enhancement decreased as the failure mode changed from flexural failure to less desirable failure modes. The modulus of the resin had no effect on beam stiffness. The fatigue strength of the beams was strongly dependent on the load capacity of the beams; consequently, higher modulus epoxy could improve the fatigue performance of concrete beams.

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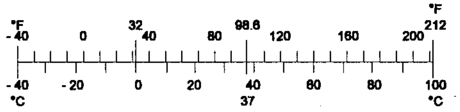
SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	millimeters squared	mm^2
ft^2	square feet	0.093	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometers squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celsius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8C + 32	Fahrenheit	°F



* SI is the symbol for the International System of Measurement

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BEHAVIOR OF FRP COMPOSITE-STRENGTHENED BEAMS UNDER STATIC AND CYCLIC LOADING

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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1.0 INTRODUCTION

Externally applied fiber reinforced polymer (FRP) composites applied as a wet lay-up are increasingly being used to strengthen, repair, and rehabilitate civil structures. Performance of a structure with composites depends on the structural design and the orientation, properties, and proportion of the constituents (fibers and polymer resin). In the case of a wet lay-up, the matrix resin is also the resin that bonds the composite laminate to the structure. The resin is critical for effectively transferring strain to the composite over the life of the structure. Design engineers can choose from many composite systems with a wide range of resin properties. It is unclear, however, whether there are resin and fiber combinations that perform better than others.

A study conducted by Oregon State University and funded by Oregon Department of Transportation investigated the effects of different epoxy resin and fiber combinations on the static and cyclic behavior of small, concrete beams strengthened with FRP composites. The results of that study are reported in a masters project report from the Department of Civil, Construction, and Environmental Engineering at Oregon State University (*Seamanontaprinya 2001*). This report is a summary of that thesis.

2.0 METHOD

2.1 STATIC LOAD TESTING

Thirty-eight unreinforced concrete beams were cast with dimensions 150 mm x 150 mm x 530 mm, using concrete with a nominal 28-day strength of 32 MPa. Twenty-four beams were reinforced with eight composite strengthening configurations using high and low modulus epoxy, high and low modulus fiber, and 1 and 2 composite layers, as shown in Table 2.1.

Table 2.1: Composite configurations for static load tests

Identification	Composite Configuration	Number of FRP Layers	Number of Specimens
CONT	Unreinforced concrete beam	0	3
1LG	Low-modulus resin with glass fiber	1	3
2LG	Low-modulus resin with glass fiber	2	3
1LC	Low-modulus resin with carbon fiber	1	3
2LC	Low-modulus resin with carbon fiber	2	3
1HG	High-modulus resin with glass fiber	1	3
2HG	High-modulus resin with glass fiber	2	3
1HC	High-modulus resin with carbon fiber	1	3
2HC	High-modulus resin with carbon fiber	2	3
			Total: 27

Mitsubishi Epotherm® L700S resin was used for the low modulus epoxy, and Tyfo® S resin was used for the high modulus epoxy. Glass fiber from the Fyfe Corporation – Tyfo® SHE-51 – was used as the low modulus fiber; and carbon fiber from the Fyfe Corporation – Tyfo®SCH-41 – was used as the high modulus fiber.

These beams, along with three unstrengthened control beams, were loaded to failure in third-point loading in accordance with ASTM C78, as shown in Figure 2.1 (*ASTM 2001*).

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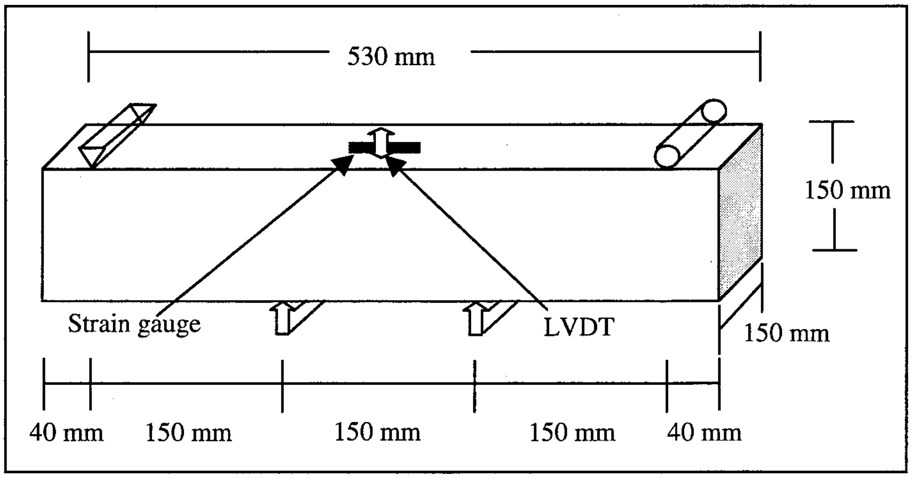

Figure 2.1: Test configuration

2.2 FATIGUE TESTING

The remaining 10 beams were reinforced with two composite strengthening configurations, as shown in Table 2.2.

Table 2.2: Composite configurations for fatigue tests

Identification	Composite Configuration	Number of FRP Layers	Number of Specimens
CONT	Unreinforced concrete beam	0	1
1LG	Low-modulus resin with glass fiber	1	5
2HC	High-modulus resin with carbon fiber	2	5
			Total: 11

These beams, along with one unstrengthened control beam, were fatigue tested at 0.5 Hz under the third-point loading shown in Figure 2.1. The minimum load for each test was maintained at 0.67 kN (150 lb). The 1LG configuration was the low stiffness and strength condition, while the 2HC configuration was the high stiffness and strength condition of the eight composite combinations.

3.0 RESULTS AND DISCUSSION

3.1 LOAD TESTS

The results of the load tests are summarized in Table 3.1, and the failure modes of the tests are described in Table 3.2.

Table 3.1: Results of load tests

Configuration	Load (kN)	Deflection (mm)	Strain (microstrain)	Post-Crack Stiffness (kN/mm)	Failure Mode
CONT	27	0.04	230		Flexure
	29	0.05	200		
	30	NA	190		
	Mean = 29	Mean = 0.03	Mean = 210	0	
1LG	97	3.23	12500	20	Flexure with FRP rupture
	98	3.27	11900	19	
	127	4.43	15500	20	
	Mean = 107	Mean = 3.64	Mean = 13300	Mean = 20	
2LG	142	2.99	10200	36	Shear and flexure
	189	3.79	13300	41	
	195	3.78	14900	42	
	Mean = 175	Mean = 3.52	Mean = 12800	Mean = 39	
1LC	141	2.28	7800	47	Shear and flexure
	149	3.17	8600	35	
	158	3.09	9000	38	
	Mean = 149	Mean = 2.85	Mean = 8500	Mean = 40	
2LC	179	1.97	5400	74	Shear
	199	1.86	5400	88	
	210	2.48	6100	67	
	Mean = 196	Mean = 2.10	Mean = 5600	Mean = 77	
1HG	134	4.23	16400	23	Flexure with internal shear failure of laminate
	136	4.70	16300	20	
	143	5.29	17100	18	
	Mean = 138	Mean = 4.74	Mean = 16600	Mean = 20	
2HG	196	3.96	12600	42	Shear and flexure. 2 failed with concrete crushing
	203	4.69	14600	35	
	220	4.13	14600	42	
	Mean = 206	Mean = 4.26	Mean = 13900	Mean = 40	
1HC	159	3.38	9600	38	Shear and flexure. 2 had internal shear failure of laminate
	171	3.46	11600	38	
	174	3.13	9300	42	
	Mean = 168	Mean = 3.32	Mean = 10200	Mean = 39	
2HC	196	1.87	5200	83	Shear
	201	2.07	5400	76	
	223	2.17	6300	82	
	Mean = 206	Mean = 2.04	Mean = 5600	Mean = 80	

Table 3.2: Failure modes

Failure Mode	Description
Flexure	Flexure crack develops from tensile side in the center of specimen between loading points and propagates to compression side.
Shear	Shear crack develops on the tensile side of specimen near support and propagates about 45° angle to the loading point.
Shear and flexure	Shear crack propagates to the center of specimen, shifts to flexure, and continues to propagate to the compression side.
Internal shear failure of laminate	Shear stress in the resin exceeds its capacity
Concrete crushing	Flexural cracking with concrete crushing on compression side.

As expected, beams with 2 layers of a particular fiber type had higher load capacity and stiffness than beams with 1 layer. Also, carbon fiber produced higher capacity and stiffness in the beams than the glass fiber. The resin had no effect on the stiffness; however, the high-modulus resin increased the load capacity up to 29%. A smaller increase in load capacity – as low as 5% – was observed when the failure mode switched from a desirable flexure failure to shear failure modes in beams strengthened with the higher stiffness composite configurations. This result indicated that for properly designed beams, the resin could appreciably affect the load capacity of the beam.

3.2 FATIGUE TESTS

The fatigue test results are shown in Table 3.3. Load ratios were calculated using the following equation:

$$R_1 = \frac{L}{L_{ult}} \qquad \textbf{(3-1)}$$

where

R_l = load ratio,

L = applied load, and

L_{ult} = static ultimate loading capacity

Table 3.3: Fatigue test results

Configuration	Load Amplitude (kN)	Load Ratio	Number of Cycles	Failure Mode
CONT	29.0	1.000	1	Flexure
	22.2	0.766	136000	
1LG	107.0	1.000	-	Flexure
	72.8	0.680	80	
	64.3	0.601	180	
	55.5	0.519	1200	
	44.6	0.417	36000	
	40.0	0.374	648000	
2HC	206.0	1.000	-	Shear and Flexure
	105.0	0.510	11700	
	104.9	0.509	13700	
	89.1	0.433	32400	
	86.4	0.419	99800	
	81.0	0.393	916400	

Figure 3.1 shows that the higher strength and stiffness composite configuration, 2HC, provided better fatigue response. Figure 3.2 indicates that the fatigue strength of the composite-strengthened beams is strongly dependent on the capacity of the beams. Equations were established to predict fatigue life for the beams used in this study.

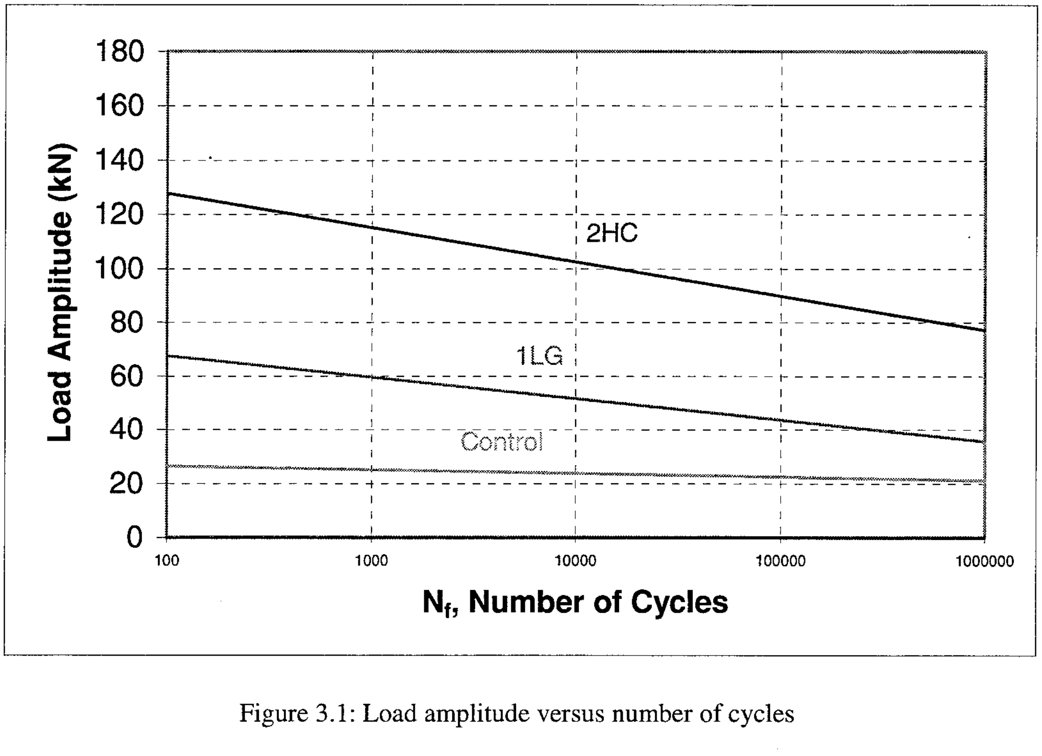

Figure 3.1: Load amplitude versus number of cycles

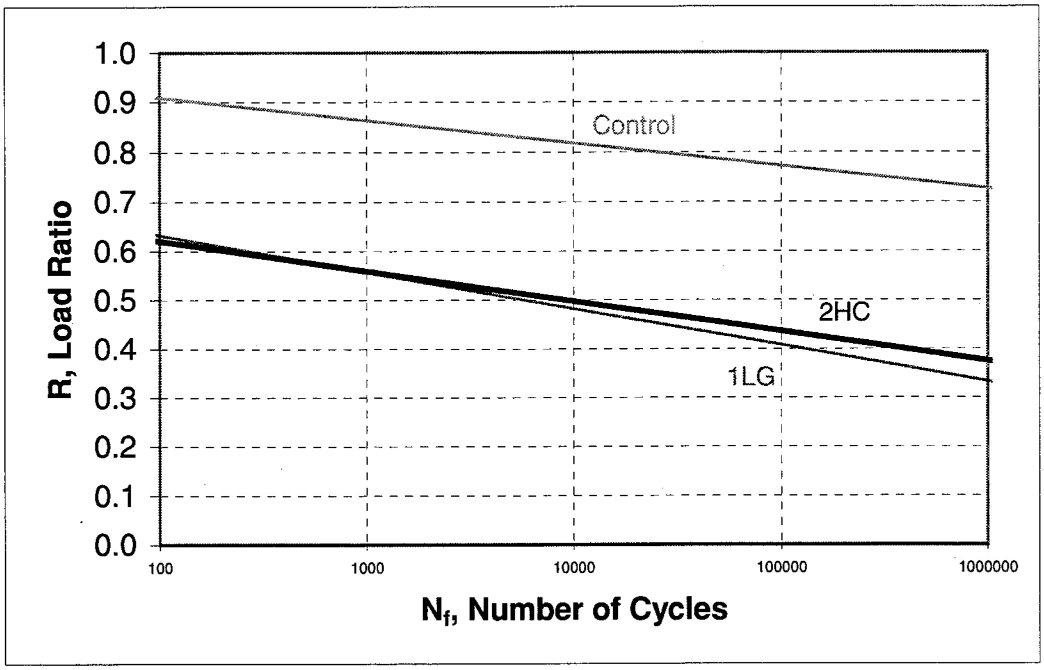

Figure 3.2: Load ratio versus number of cycles

4.0 CONCLUSIONS AND RECOMMENDATIONS

- Increasing the elastic modulus of the resin in a wet lay-up may increase the load capacity of FRP-strengthened, concrete beams. However, this enhancement decreases as the failure mode changes from flexural failure to less desirable failure modes.

- Because fatigue performance is dependent on load capacity, the resin effect may also increase the fatigue response of FRP-strengthened beams.

- The elastic modulus of the resin has no effect on the stiffness of beams.

- To verify and quantify the relationship between elastic modulus of the resin and performance, further testing would need to be conducted on full-size beams with realistic design configurations.

5.0 REFERENCES

American Society for Testing and Materials (ASTM) Subcommittee C09.61. 2001. *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading).* Designation ASTM C 78-00. West Conshohocken, PA.

Seamanontaprinya, Dharadon. 2001 (in press). *Behavior of FRP Composite-Strengthened Beams under Static and Cyclic Loading.* Masters project report, Department of Civil, Construction, and Environmental Engineering, Oregon State University.

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