RESEARCH IN PROGRESS: FATIGUE OF CFRP COMPOSITES

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SUMMARY: For bridge structures, fatigue is an important load condition. The fatigue life diagram for unidirectional CFRP composites is shown. This diagram represents the 95% lower confidence level and is useful in conservatively estimating the fatigue life of the CFRP composites when used as a sole structural material. For hybrid systems, understanding the fatigue behavior of the individual materials is relevant to understanding system behavior. The first test in a series on flexural fatigue testing of steel beams reinforced with CFRP composites adhesively bonded to the tension flange is discussed. The work in progress is presented including laboratory test results obtained to-date. This project demonstrates the positive strengthening effect of CFRP composites to steel bridge girders.

KEYWORDS: CFRP composite, steel, fatigue, hybrid system

INTRODUCTION

In the interest of pursuing the rehabilitation/strengthening alternative for bridge structures in lieu of a larger bridge replacement program, FRP composites are viable alternative construction materials. For bridge structures subject to cyclic loading, fatigue is an important limit state in design. Traditionally, fatigue strength of a material is represented by stress category of design detail and a corresponding S-N curve (fatigue life diagram). For steel, fatigue strength is well documented in various codes such as AISC-LRFD Manual of Steel Construction or AASHTO Bridge Design Manual. For unidirectional CFRP composites in bridge application, no usable document summarizing the fatigue strength was available. The primary author therefore undertook an evaluation of existing fatigue data which had been generated in the context of aerospace, marine, and mechanical applications, for a wide range of composite material systems under various loading conditions. A review of that existing data revealed select data as suitable to bridge infrastructure application [1, 2]. A summary of that select data is a preliminary step in defining the fatigue life diagram of unidirectional CFRP composites for stress Category A detail in T-T axial fatigue with test frequency 20 Hz or less, without environmental concerns. Understanding the individual fatigue behavior of materials is relevant to understanding the fatigue behavior of a system comprising those individual materials. A research program at the University of Arizona is currently ongoing to understand the fatigue behavior of a steel beam reinforced with CFRP composite. The test results of a hybrid beam is presented herein. The objective of the test was to observe the fatigue category of detail at the CFRP composite ends.

Axial Fatigue of Unidirectional CFRP Composite

Frequency of fatigue load effects internal heating of the composite, and therefore, fatigue life. The review of laboratory data suggested limiting the test frequency of fatigue load to 20 Hz with observed specimen surface heating 10^{o}C, or less. This controlled selecting from the aerospace, marine, and automobile industry suitable data to represent bridge application [1, 2]. The data represented a stress Category A detail in tension-tension axial fatigue. Graphing the data in Figure 1 shows a distinct data band to which a lower bound confidence level is established [1]. This lower bound represents a fatigue life diagram from which unidirectional CFRP composite fatigue strength is estimated. The S-N curve and the stress Category A detail define the tension-tension axial fatigue strength of unidirectional CFRP composite. The data is inconclusive of a fatigue limit.

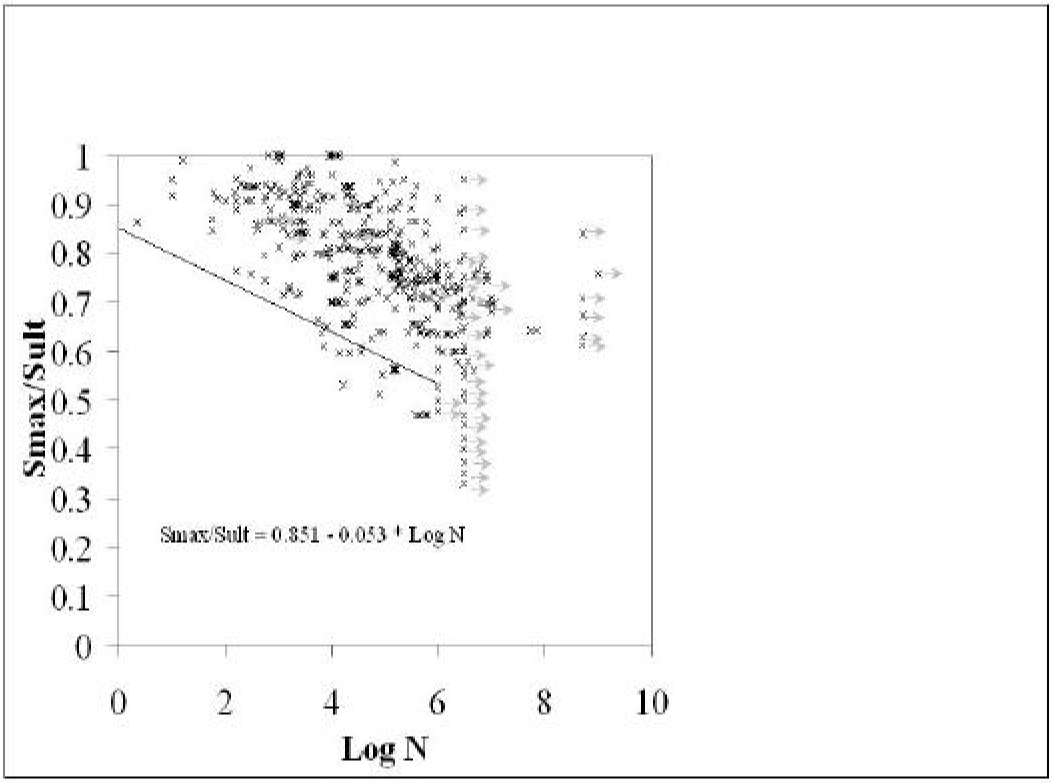

Figure 1. Unidirectional CFRP Composite Fatigue Life Diagram

HYBRID SYSTEM OF STEEL BEAM REINFORCED WITH CFRP COMPOSITE

Hybrid System

The material properties for each of the components comprising the system are given in Table 1 [3]. Monotonic testing of one layer of CFRP/epoxy composite (15 coupons each sized 254 x 25.4 x 1.5 mm) provided an ultimate tensile strength of 533.5 Mpa and an elastic modulus of 56.7 Gpa. As for the S5 x 10 A36 steel beam, two sections 914.4 mm long were groove weld connected to form one 1.83 m long beam. The groove welds were ground flush on the outer surface of both flanges (but not the inner flange surfaces or web). One layer of CFRP composite was applied (wet lay-up) to the outer surface of one flange of the S5 x 10 A36 steel beam. The CFRP composite spanned 304.8 mm centered on the steel beam groove weld and within the 508 mm distance between central load points as shown in Figure 2 [3]. The groove weld is considered beam centerline and the strain gages are referenced with respect to the centerline. The CFRP composite strengthened flange was the tension flange under fatigue loading.

Table 1. Material Properties

Steel Beam	Carbon Fiber	Epoxy (Resin and Hardener)
S5x10 A36 steel	Unidirectional T-250 12K	Jeffco 9600AT-1
E = 29,000 ksi (200 Gpa)	E = 33,000 ksi (227.5 Gpa)	Tensile Modulus = 181 ksi (1.25 Gpa)
Shear Modulus = 11,000 ksi (75.8 Gpa)	Tensile Strength = 530 ksi (3.65 Gpa)	Tensile Strength = 6 - 7.5 ksi (41.4 - 52.7 Mpa)
Elongation = 25 %	Elongation = 1.4 %	Elongation = 7.65 %
Density = 490 lb/ft^3 (7.85 g/cm^3)	Density = 111 lb/ft^3 (1.76 g/cm^3)	Bond Strength = > 3.05 ksi (21.13 Mpa)
Coefficient of thermal expansion 6.5 x 10^{-6} in/in/^{o}F (11.7 x 10^{-6} m/m/°C)	Axial Coefficient of thermal expansion 0.11 x 10^{-6} in/in/^{o}F (0.2 x 10^{-6} m/m/°C)	Min. Application Temp. 55^o F (12.8° C)

Flexural Fatigue

Four point loading defined the one-way flexural fatigue test under load control. With four point loading, the central portion of the hybrid beam was under pure bending. Other factors defining the test included a 1.5 Hz test frequency, an R ratio of 0.1, and a maximum stress of 227.5 Mpa. Stain gages were used including 350-ohm resistance for the CFRP composite and

120-ohm resistance for the steel. The strain gages were placed at various distances within the central load points on both the CFRP composite and steel beam as shown in Figures 3a-3d [3].

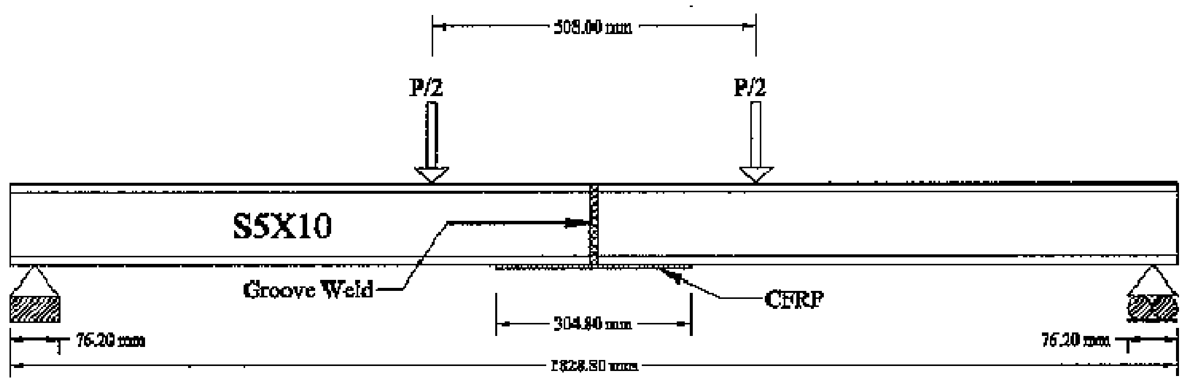

Figure 2. Test Set-Up for the Hybrid Beam

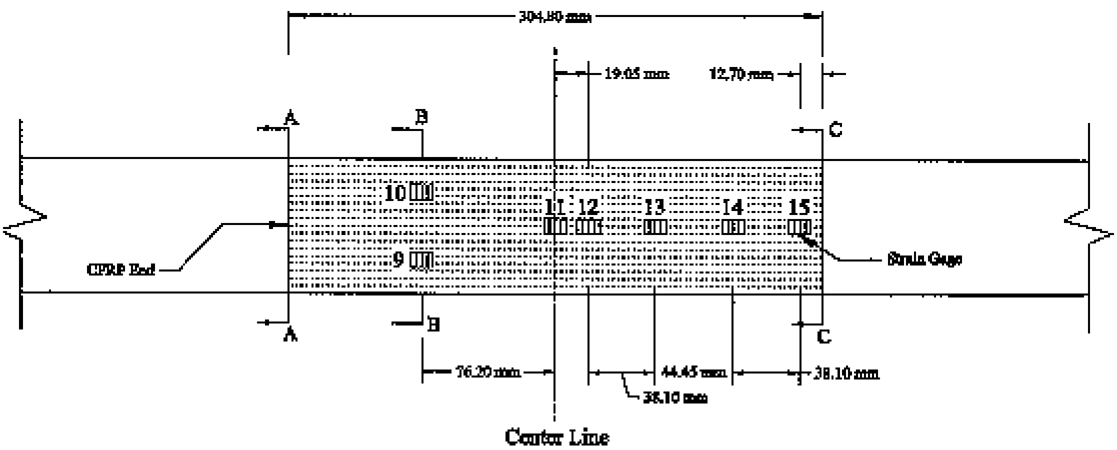

Figure 3a. Exterior Surface of Steel Tension Flange Showing CFRP Composite and Strain Gage Locations

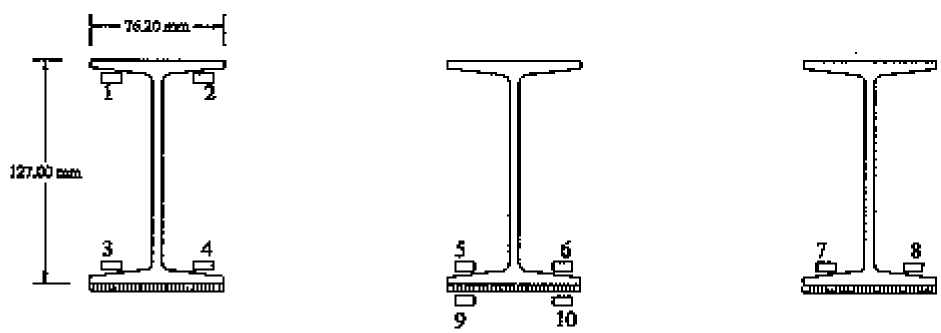

Figure 3b. Cut (A-A) *Figure 3c. Cut (B-B)* *Figure 3d. Cut (C-C)*

DISCUSSION

The hybrid beam was tested in one-way flexural fatigue with a fatigue maximum stress well below the ultimate tensile strength of the CFRP composite and the yield strength of the steel beam. Also, Figure 1 indicates that for CFRP composite to achieve one million cycle fatigue life in tension-tension axial fatigue, fatigue maximum stress is limited to 50% of ultimate tensile strength. The test fatigue maximum stress of 227.5 Mpa is below the 50% ultimate tensile strength (266.8 Mpa). This presumes that the CFRP composite on the steel tension flange acts primarily in tension (simulates tension-tension axial behavior). Therefore, failure occurs not in the main section of steel beam nor in the composite, but either in the steel flange at the CFRP composite ends or at the «toe» along the tension steel flange groove weld. In essence, the CFRP composite behaves as a cover plate that is adhesion bonded rather than welded (which is used for connecting steel cover plates to steel beam flanges). The method of using adhesion bonding rather than welding to connect the flange strengthening material eliminated the weld heat affected zone in addition to eliminating any welding discontinuities that could become a fatigue crack initiation site. Therefore, the stress concentration in the steel tension flange along the CFRP composite edge and at the composite end is lower than that due to welding. The question arises as to whether the stress concentration with adhesion bonding is significantly lower such as not to cause fatigue cracking. The first step is answering this question was to start with the above described test hybrid beam.

During fatigue testing, the strain gages (1, 2, 9, 10) indicated slight rotation (torsion) of the cross-section under loading. This may be attributed to mild misalignment of the steel section and the potential for the loading placed mildly unsymmetrical.

The strain gages (3, 7, 8) on tension steel flange located 152.4 mm from centerline showed similar strain over fatigue life. This indicates consistent load carrying capacity in the steel flange at the composite ends over the life of the test. Gages (9,12, 13, 14) located 76.2, 19, 57.1, 101.6 mm from centerline showed similar strain behavior over life of test. This indicated no redistribution of load over life of test. Gage 15 located 12.7 mm from composite end showed significantly lower strain throughout fatigue life. This behavior is expected as the load near the composite end would redistribute out of the composite into the steel flange.

From 700,000 cycles on, gage 11 located on the composite at the centerline (over the groove weld) exhibited significantly increasing strain. This localized increase in strain indicated the growth of a fatigue crack in the steel in the vicinity of the gage. This increase in strain also indicates the capacity of the composite was reached (maximum load carrying capacity of composite reached with redistribution of load due to fatigue cracking in steel).

At a fatigue life of 1.13 million cycles the test was terminated.   The hybrid beam was subsequently subjected to monotonic loading to determine the residual strength. Gage 11 and 12 at centerline and 19.1 mm from centerline exhibited the greatest strain and thus lowest composite modulus of elasticity. Gage 15 exhibited the least strain and thus greatest composite modulus. The remaining gages on the composite exhibited similar behavior of moderate strain and thus similar modulus. The final failure of the hybrid beam was due to out of plane buckling accentuated by a region of fast fracture extending from the fatigue crack. The composite spanning the fatigue crack remained intact (composite did not sever).

After failure, the hybrid beam was examined for fatigue cracking. The CFRP composite was removed. The adhesion bond between composite and steel remained intact during the fatigue life and subsequent residual strength test. In fact, the adhesion surface showed few air bubbles (which were expected due to hand wet-lay-up construction process). The composite resin did show regions of distress (cracking perpendicular to flange stress) during residual strength test. The groove welded tension flange region was removed to expose the fatigue crack. Indeed, a semi-elliptical fatigue crack had formed at the toe of the groove weld on the inner surface of the steel beam tension flange. The semi-elliptical fatigue crack had grown into a through-thickness fatigue crack. Essentially the majority of fatigue life is represented at 1.13 million cycles. Figure 4 shows the hybrid beam test at 1.13 million cycles plotting at Category A detail. However, a fatigue life of 700,000 cycles is relevant with respect to transition from fatigue crack initiation site to fatigue crack and this life indicates at Category B detail. Without the composite, the steel beam with groove weld (not fully ground) is regarded as Category C.

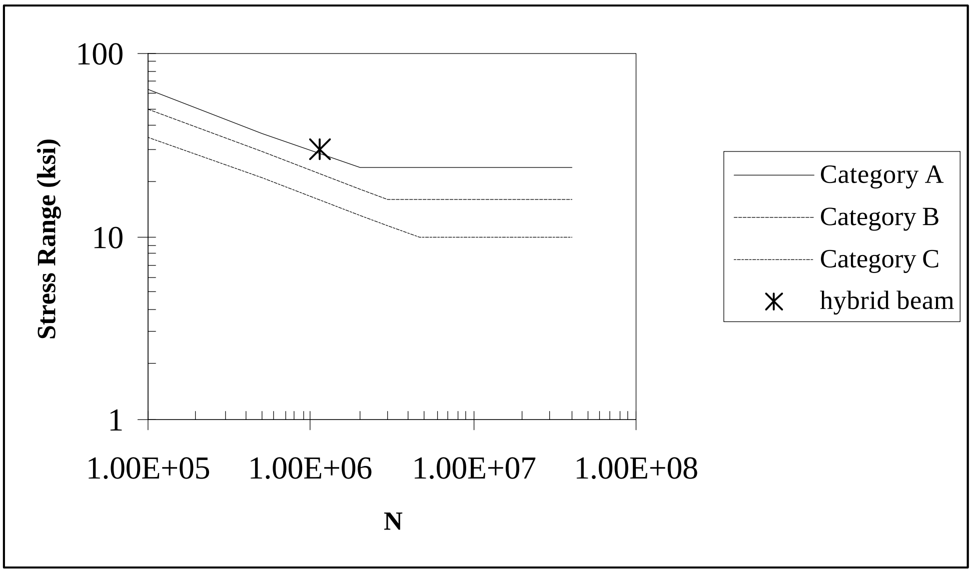

Figure 4. Hybrid Beam Fatigue Life versus Category of Fatigue Life.

CONCLUSIONS

The steel beam with tension flange strengthened with one layer CFRP composite spanning the pure moment region was tested in one-way flexural fatigue and subsequently for residual strength. The adhesion bond between composite and steel tension flange remained intact during the fatigue test (1.13 million cycles) and residual strength test. Although the fatigue test was stopped at 1.13 million cycles, failure would have occurred due to the continued growth of and fast fracture from a fatigue crack which had initiated at the toe of the groove weld on the inner surface of the steel beam tension flange. The CFRP composite remained intact spanning the fatigue crack during fatigue testing and residual strength test. However, the amount of composite was not sufficient to prevent the growth of fatigue crack once initiated from weld discontinuities. The addition of CFRP composite to the steel beam with groove weld increased the anticipated fatigue life from Category C to essentially Category B. No fatigue cracking was observed in the steel tension flange at the ends of the CFRP composite. The stress concentration due to composite end is significantly lower that that due to groove weld discontinuity. Further testing is currently underway whereby the thickness of CFRP composite varies and the groove weld condition (to force failure) is eliminated.

REFERENCES

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