

FATIGUE AND FAILURE EVALUATION OF MODULAR FRP COMPOSITE BRIDGE DECK

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ABSTRACT

Load cycling fatigue and strength evaluations for modular fiber reinforced polymer (FRP) composite decks are presented. The FRP composite deck is made of pultruded components that are bonded and interlocked. The emphasis of this work is to present an innovative fatigue experimental qualification program for FRP composite bridge decks. Fatigue live loads are computed based on AASHTO highway bridge specifications. Variations of strain and deflection measurements with number of cycles and mode of failure after load cycling are used to characterize the fatigue and strength performance of the FRP deck. Limitations in applying the existing AASHTO highway bridge specifications to fatigue design of FRP composite decks are discussed.

INTRODUCTION

Construction of highway bridges with modular FRP composite decks requires the understanding of the deck performance under traffic loads. Traffic loads, mainly due to heavy trucks, induce repetitive stress cycles on bridge decks during the service life of the structure. The first modular FRP composite bridge decks were installed in low-volume rural roads in West Virginia: Laurel Lick Bridge and Wickwire Run Bridge. In order to extend the application of FRP bridge decks to high-volume roads, the long-term fatigue performance needs to be experimentally established. Cyclic loads can lead to delamination of the FRP composite material, adhesive failure of the bonded joints or fracture initiation at the deck bolted connections. This work introduces an experimental program that was developed to qualify FRP composite decks for highway bridge applications.

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FRP COMPOSITE DECK

The FRP composite bridge deck (U.S. patent pending) is made of pultruded components that are placed transversely to the traffic direction and are supported by longitudinal beams [1]. The FRP deck consists of double trapezoid (DT) components connected with full-depth hexagons (HX) that provide mechanical interlock and an extensive bonding surface. The fiber architecture consists of E-glass fibers in the form of multi-axial stitched fabrics, continuous rovings, chopped strand mats and continuous fiber mats. The matrix is a weather-resistant vinyl ester resin. Creative Pultrusions, Inc. fabricated the FRP deck components with the trade name Superdeck™.

DESIGN APPROACH

The design of FRP composite decks is based on the AASHTO LRFD Specifications [2] and the AASHTO Standard Specifications [3]. The LRFD specifications defines reliability-based limit states to be considered in bridge deck design and provides load combinations and load factors. However, neither a reliability calibration nor the material resistance factors for FRP composite decks are available in current bridge specifications. A discussion on the extension of LRFD specifications to composite materials bridges is presented by Mertz and Kulicki [3]. In order to proceed with the design of FRP composite bridges, and until the LRFD specifications are extended to these new bridge materials, simplifying and generally conservative assumptions needs to be made.

For the design of the FRP Deck, three limit states are considered: (1) Service, (2) Strength, and (3) Fatigue. The service limit state prevents excessive local deck deflection that can cause premature deterioration of the wearing surface and affect the performance of joints. A standard AASHTO HS20-44 design truck load without impact is applied to compute live-load deflections. The relative deck deflection in-between adjacent supporting beams is limited to the spacing over 500. Second, the strength limit state is verified for a AASHTO HS25-44 design truck with a impact factor of 33%. Finally, the fatigue limit state is verified for cyclic loads resulting from a HS20-44 design truck with a joint impact factor of 75%. Applicable load factors for all limit states are obtained from Table 3.4.1-1 of the LRFD Specifications [2]. Compared to concrete decks, FRP composite decks have high strength capacity but are more flexible. Hence, the design of the FRP deck is stiffness driven and mainly controlled by the local deck deflection limit state. However, it is necessary to verify the strength and fatigue limit states to provide adequate safety. The computation of the design fatigue load is presented in Table I.

The AASHTO Standard Specifications [3] assumed two million cycles to evaluate fatigue and fracture in steel structures. This relatively low number of cycles is compensated with the adoption of high fatigue loads. For example, for 50 years life span of a bridge deck and an average daily truck traffic of 500, the number of axle load will exceed 15.5 million. However, the actual axle loads will be smaller than the HS20-44 design truck used for fatigue evaluation, which is based on a strength limit state.

TABLE I. COMPUTATION OF DESIGN FATIGUE LOAD RANGE

Fatigue limit state	Art. 3.4.1	$\eta \gamma (LL + IM) < \phi R_n$		
Factor: nonductile		$\eta_D = 1.00$		
Factor: nonredundant (failure critical)		$\eta_R = 1.00$		
Factor: operational importance		$\eta_i = 1.00$		
		$\eta = \eta_D \eta_R \eta_i = 1.00$		
Impact factor for deck joints, all limit states		$IM = 0.75$		
Fatigue load factor	Table 3.4.1-1	$\gamma = 0.75$		
Fatigue load range		$\Delta P = \eta \gamma (1 + IM) LL$		
Combined factor		$\eta \gamma (1 + IM) = 1.31$		
Vehicular live load (LL): one design truck, 145 kN per axle, 2 axles spaced 9 m			Art. 3.6.1.4	
LL	Axle Load	Wheel Load	Fatigue Load Range	
Design truck	kN	kN	kN	kip
HS20-44	145	72.5	95.16	21.39

The fatigue resistance of FRP composite decks is not well established. Available fatigue data, typically from aerospace applications, is not comprehensive of the type of fiber and resin materials and fabrication processes used for FRP decks. In order to develop a practical qualification test and, in agreement with AASHTO Standard Specifications, two million cycles were adopted to evaluate the fatigue response of the FRP deck. Furthermore, the experimental fatigue load was increased by 50% to account for extended service life, as shown in Table II.

TABLE II. COMPUTATION OF EXPERIMENTAL FATIGUE LOAD RANGE

Number of fatigue cycles		2,000,000	
Deck specimen composed of three DT components with two HX			
Aspect ratio		3	
		m	in
Simply supported span		2.74	108
Deck width		0.91	36
		kN	kip
Fatigue load range		$\Delta P = 95.16$	21.39
Conservative factor for extended service life		$cf = 1.50$	
		kN	kip
Design Experimental Fatigue Load Range		$cf \cdot \Delta P = 143$	32
Adopted Experimental Fatigue Load Range		$(cf \cdot \Delta P)_{\text{experim.}} = 147$	33
Maximum Experimental Fatigue Load		156	35
Minimum Experimental Fatigue Load		9	2

FATIGUE TESTS

Two FRP deck specimens made of three DT components connected with two HX components were used for testing, as shown in Figure 1. The deck specimens were simply supported with a span length of 2.74 m (108 in) and a width of 0.914 m (36 in). A rectangular patch load of 250 x 500 mm (10 x 20 in.), with the larger dimension parallel to the cells was applied at the center to simulate the action of a wheel load. Fourteen longitudinal and transverse strain gages were placed on the top and bottom faces of the deck (SG1 to SG13).

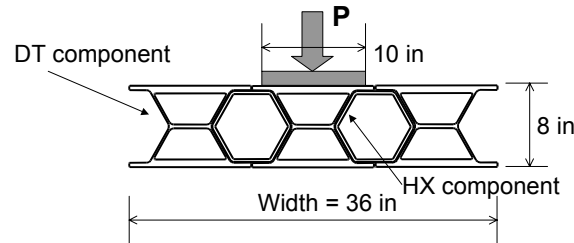


FIGURE 1. CROSS-SECTION OF FRP DECK TEST SPECIMEN

Fifteen LVDTs (Linear Voltage Differential Transducer) were mounted on the top face of the deck to measure vertical deflections (LT1 to LT15). In addition, three displacement gauges were mounted on the bottom face of the deck (LB1 to LB3).

The first specimen was subjected to two million load cycles with a frequency of 3 Hz. for a load range from 9 kN (2 kip) to 156 kN (35 kip), as shown in Table II. Every half a million cycles a static load test was conducted and strains and deflections were measured. The variations in deflection with number of cycles at three locations on the top face of the deck are depicted in Figure 2.

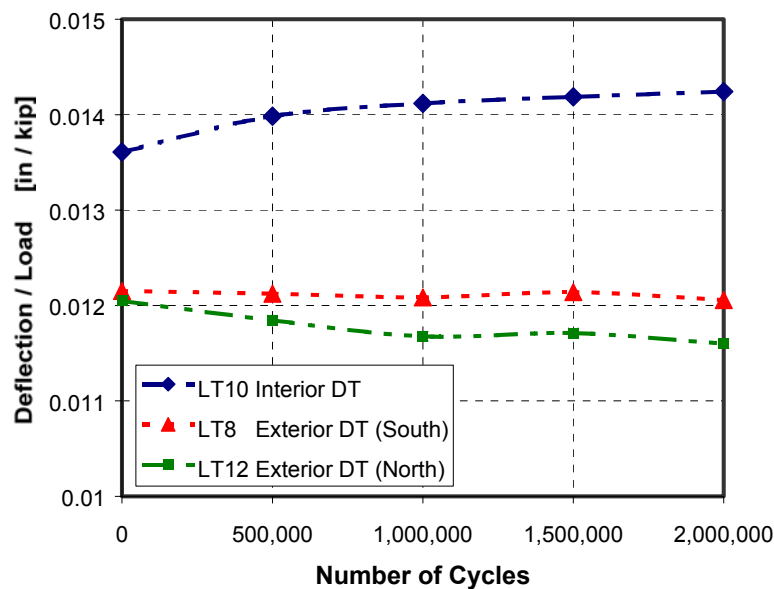


FIGURE 2. VARIATION OF DEFLECTIONS WITH FATIGUE CYCLES

In Figure 2, we observe that the deflection of the interior deck component increases with number of cycles, while the deflections of the exterior components are reduced. These variations indicate that the shear load transfer between the interior and the exterior component decreases slightly with load cycling. After two million cycles the change in deflections with respect to the initial values was about 4%. The small reduction in load transfer corresponds to small joint slip that was captured by the strain variations on the bottom face of the deck, as shown in Figure 3. No other damage or crack propagation was observed after two million cycles. The fatigue tests were conducted at the U.S. Army Construction Engineering Research Laboratory (USACERL) in Champaign, Illinois.

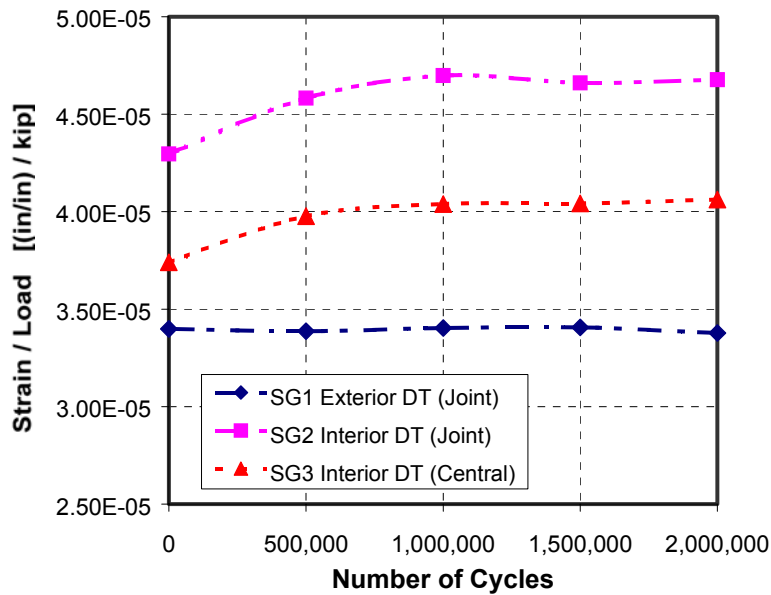


FIGURE 3. VARIATION OF LONGITUDINAL STRAINS WITH FATIGUE CYCLES

FAILURE TESTS

Two FRP deck specimens were tested to failure under a central rectangular patch load. The first deck was non-cycled and the second one was the one that was “fatigued” as described in the previous section. The failure load for the non-cycled deck was 577 kN (129.7 kip). The mode of failure observed was transverse shear failure resulting in delaminations of the inclined web elements and cracking of the HX components. Although, the failure was at the component joint there was no adhesive failure. The damage observed was interlaminar shear failure in the pultruded material. The patch load damaged the top flange of the FRP deck leading to a substantial reduction in the transverse load capacity to adjacent components. However, the deck did not collapse after the localized failure and exhibited load path redundancy resulting in a limited but safe post-failure reserve strength.

The FRP deck that was load cycled was also tested to failure. The failure load of the cycled deck was only 4 % smaller than the failure load for the non-cycled deck specimen with approximately 10 % more central deflection (See Figure 4). The deflection to failure of the non-cycled FRP deck was 7.3 times the service load deck deflection and corresponds to the simply supported span over 59.3. The extensive area under the load-deflection curve in Figure 4 indicates that the FRP deck has excellent energy absorption capability. The post-failure load capacity of the FRP deck is 37 kip and 35 kip for the non-cycled and cycled decks, respectively. It is worth noticing that the post-failure strength exceeds 1.75 times the HS25-44 wheel load. Even after failure the FRP deck will hold a design truck. The failure tests were conducted by USACERL engineers at the TAM Laboratory of the University of Illinois at Urbana-Champaign.

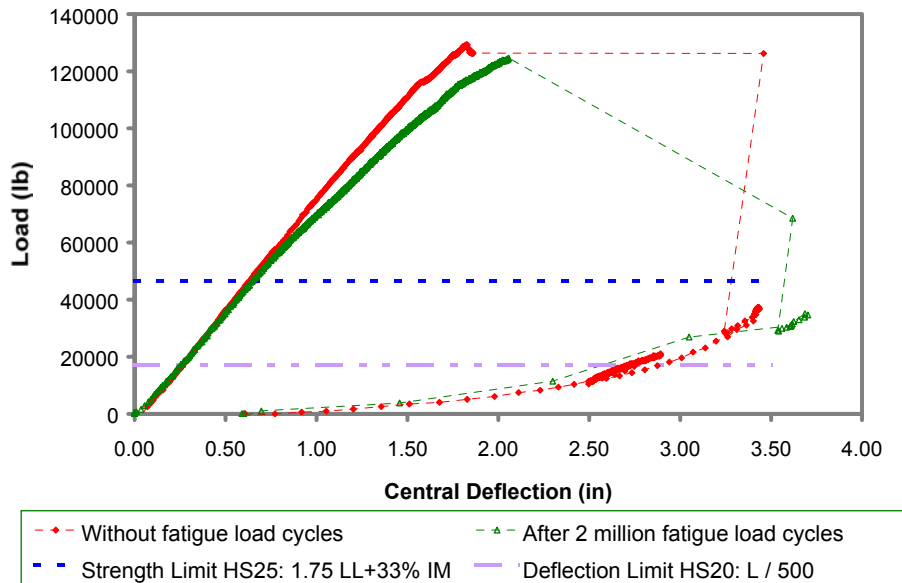


FIGURE 4. FAILURE TESTS OF FRP DECK

CONCLUSIONS

The FRP composite deck performed satisfactorily for two million cyclic loads without major fatigue damage. Fatigue cycling had a limited effect on the FRP deck stiffness and strength. The FRP composite deck exhibited a safe failure mode with considerable energy absorption and adequate post-failure reserve strength.

ACKNOWLEDGMENT

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