Assessment of Long-Time Behavior for Bridge Girders Retrofitted with Fiber Reinforced Polymer

Adel Elfayoumy and Nasim Uddin

Department of Civil, Construction and Environmental Engineering, University of Alabama at Birmingham, Birmingham 35294, USA

Abstract: Maintaining both the safety and serviceability of deteriorating highway bridge networks necessitates suitable BMS (bridge maintenance system) tools that can maximize cost effectiveness. Numerous experiments have been conducted to detect the long-term mechanical properties of the epoxy resin materials used in FRP (fiber reinforced polymers) strengthening and maintenance technique. Experiments were used to develop a short-term test and construct a model that can reliably predict the long-term behavior of epoxy resin. Furthermore, FEA (finite element analysis) models were developed, using the ANSYS software, to simulate three unstrengthened and FRP strengthened prestressed concrete girder bridges of different configurations. Models simulate the original and aged properties of construction and retrofitting materials under the application of AASHTO (American Association of State Highway and Transportation Officials) fatigue truck and a site-specific fatigue truck in different scenarios. These models were used to develop the bridge performance chart for the capacity of the bridge, with and without strengthening interventions, as a BMS tool. The results show an immediate significant improvement in the concrete tensile stress with the intervention of FRP strengthening.

Key words: Increasing heavy vehicle load, bridge management, FRP strengthening.

1. Introduction

The economical allocation of limited funding for maintaining both the safety and serviceability of deteriorating highway bridge networks necessitates suitable BMS (bridge maintenance system) tools that can maximize cost effectiveness. Some of the available practical BMS software package systems determine the timing and types of maintenance interventions based on discrete conditions that result from visual inspections [1]. Numerical procedures have recently appeared in the literature that searches for optimal maintenance planning. Therefore, predicting the lifespan of a strengthened bridge using FRP (fiber reinforced polymers) laminate can be one of the bridge management's important tools.

The FRP and the adhesive material's (resin) long-term performance has a direct influence on the long-term performance of the strengthened structural members. One major obstacle is the current lack of

sufficient information on the long-term performance of FRP used in the repair of concrete structures. That fact has a direct effect on the acceptance of these materials in the civil engineering community. A set of short-term (time-accelerated) tests on FRP and resin materials have been developed [2] to construct a model that reliably predicts the long-term behavior of a strengthened structure.

Furthermore, fidelity FEA (finite element analysis) models for the original and strengthened bridge girder using ANSYS software has been developed. These models simulate three PSC (prestressed concrete) girder bridges of different spans subjected to a site-specific fatigue truck [3] and AASHTO (American Association of State Highway and Transportation Officials) fatigue truck, as shown in Fig. 1. Both original and aged properties of the girder material and epoxy resin material [2] were modeled to provide time-deformation curves at the most critical sections of the girder. This model is aimed at developing a bridge performance tool that may help the bridge's owners decide when to perform maintenance on the bridge.

Corresponding author: Adel Elfayoumy, Ph.D., research assistant, research fields: SHM (structural health monitoring) and bridge management. E-mail: afayoumy@uab.edu.

Fig. 1 Configurations of the considered fatigue trucks: (a) AASHTO fatigue truck; (b) site-specific fatigue truck.

Fig. 2 Schematic diagram of bridge configurations: (a) 60 ft; (b) 140 ft.

2. Literature Review

The corrosion of the prestressing tendons is a major problem of the prestressed concrete structures. They may corrode without developing any signs, such as outward stains. These corroded strands may debond or break without warning. Once one wire (or strand) breaks, its load is redistributed to others that may not have the residual capacity to sustain the extra load, so the risk to the element increases very quickly. The maintenance of the serviceability of the prestressed structures includes the management of the strands' corrosion [4].

The fatigue strength of concrete is approximately 55% of the static strength for compression, tension and flexure. Moreover, concrete will exhibit a finite fatigue

life regardless of the magnitude of stress range [5]. These two reasons were sufficient to make most of the previous researches on the prestressed concrete fatigue focus only on the fatigue behavior of the prestressing strands. Accordingly, most concrete is designed in such a way that its fatigue strength is not controlled.

3. Finite Element Analysis

Fidelity finite element models were developed using ANSYS program for three prestressed concrete girder bridges of different spans (60-ft, 90-ft and 118-ft long) designed as per AASHTO LRFD (load and resistance factor design) specifications (Fig. 2). All model bridges were modeled to simulate the unstrengthened and FRP-strengthened situations. In the case of FRP-strengthened, an adhesive material (Epoxy

Sikadur-300) of 0.04 inch (1 mm) thickness and FRP laminate of 0.40 inch (10 mm) thickness were used to simulate the most widely used strengthening techniques.

SOLID65 element was used to simulate girder and deck, and resin material and FRP laminates were simulated using SOLSH190 elements. Prestressing strands were resembled as element LINK190. They were simulated by only two numbers of tendons with the same total area and the same point of action of the resultant prestressing loads of the total number of tendons. All elements were meshed that the mesh size is identical at the interfaces between the girder and epoxy and between epoxy and FRP. The "INISTATE" order in ANSYS was utilized to assign the prestressing stress in strands.

3.1 60-ft Long Bridge

A simply supported bay, 60-ft long designed as per AASHTO LRFD specifications, with total width of 32 ft, was modeled. The model consists of four AASHTO-PCI (Precast/Prestressed Concrete Institute) I-Girders (III) with 20 of 0.5 inch diameter Grade-270 strands layered, as 10-6-4 with six of harped strands. In strengthening intervention case, 28-ft long and 24-inch height FRP wrapping was applied at the mid-span of the deteriorated girder.

3.2 118-ft Long Bridge

An existing bridge, I-565 located on Route/Bin 52 in Madison County (Huntsville, Alabama), with a simply supported bay 118-ft long, total width of 38.50 ft, and diaphragm 30 ft apart was modeled. The model consists of five typical PCI-Bulb-Tee girders type (BT-72) of 7.67 ft apart with 38 numbers of 0.5 inch diameter Grade-270 strands, layered as 12-12-12-2 with eight of harped strands. In case of strengthening intervention, 54-ft long and 40-inch height FRP wrapping was applied at the mid-span of the deteriorated girder.

3.3 140-ft Long Bridge

A simply supported bay 140-ft long, total width of

32 ft, and diaphragm 35 ft apart was modeled. The model consists of six of AASHTO-PCI I-Girder (VI) with 56 of 0.5 inch diameter Grade-270 strands, layered, as 12-12-12-12-8 with 10 of harped strands. In case of strengthening intervention, 70-ft long and 40-inch height FRP wrapping was applied at the mid-span of the deteriorated girder.

4. Modeling Assumptions

Table 1 shows the initial mechanical properties of the bridge's main elements at time of construction and the initial mechanical properties of the strengthening material at the time of intervention, such as modulus of elasticity in all directions (E_X , E_Y , E_Z).

The fatigue trucks load was applied to the bridge deck at 10-ft width traffic lane as a static load in such a way to produce the maximum load effect at the mid span of the bridge. In fatigue study, the dynamic load was increased by 15% to comply with the AASHTO fatigue and fracture limit state [6], as shown in Fig. 3.

In addition to the material self-weights, all models were initially subjected to the prestressing stress of 75% of the strands tensile strength (f_{pu}) due to the slip of the tendons in the anchorages. Table 2 shows the prestressing strand stress values associated with different ages due to long-term losses [7].

As the changes are minors in the age-adjusted effective modulus of elasticity (E') of slab and girder [7], and prestressing stress in strands after the age of 10 years, it was reasonable to focus the study on the unstrengthened 10-year old bridges. In other words, the prestressed concrete could be reasonably assumed to be in a steady state with no more losses in the strands' prestressing stresses and the modulus of elasticity, due to long-term effects. With the intervention of FRP strengthening, the changes in the stress range in the

Table 1 Initial mechanical properties.

Element	Strength (ksi)	E_X (ksi)	E_Y (ksi)
Deck	4.50	3,860	3,860
Girder	8.00	5,147	5,147
Strands	270	28.50	-

(a)

(b)

Fig. 3 Current traffic load: (a) site-specific fatigue truck; (b) AASHTO fatigue truck (Fatigue I).

Table 2 Prestressing stress in strands due to losses.

Age (year)	60-ft long	118-ft long	140-ft long
0	202.50	202.50	202.50
5	173.92	176.30	170.73
10	173.75	176.15	170.55

prestressing strands could be neglected [8]. The long-term mechanical properties of construction and

strengthening materials are shown in Table 3.

5. Results and Discussion of Unstrengthened Bridge

Meeting the expected increase in the freight demand could be accommodated by increasing the traffic load and/or traffic volume. The increase in traffic volume

accelerated the fatigue problem (if initiated).

However, it has no effect on the load-effect over the bridge and the fatigue threshold (limits) for both concrete and strands. So, the finite element model was utilized only to study the bridges under the current traffic load and the doubled traffic load.

5.1 Current Traffic Loads

Figs. 4 and 5 show respectively the maximum stresses in prestressing strands and concrete flexural stress distribution due to the application of the both fatigue trucks on all bridges.

The captured minimum and maximum strands' stresses and concrete tensile stresses are shown in Table 4. This illustrates that although the prestressing strands' stress range did not exceed AASHTO limits (10 ksi), the concrete tensile stress, in some cases, exceeded the Limit State III. This declares the presence of enough cracks that let the deteriorating materials to ingress into the strands to initiate corrosion. Those bridges with tensile stress greater than the limit state needed to be strengthened to encase the concrete in such a way to cover the cracks and protect the prestressing strands against corrosion.

5.2 Double Truck Weight

All bridges were exposed to 1.5 times of the doubled unfactored fatigue truck weight (Fatigue I) with IM (impact factor) of 15% [6]. Similarly, Table 5 shows the concrete tensile stresses and prestressing strands' stress range due to these applied loads.

Generally, the stress range, in all cases, did not

exceed the AASHTO limit. This means that the bridges do not have strands fatigue problems. However, the concrete tensile stresses in all bridges were way above the limitations that declares cracks initiation.

Consequently, the internal prestressing strands have a high probability of being corroded that affects their capacity and the precompression level as well.

6. Results and Discussions

Generally, Tables 4 and 5 show that all the strands' stress range of all bridges was below the AASHTO limits and safe against fatigue problem in terms of stress range. Under the CTL (current traffic load) of the site-specific fatigue truck, only 118-ft and 140-ft long bridges concrete tensile stresses exceeded the Service Limits III. Also, under the DTW (double traffic weight load) case of both trucks, all bridges' concrete tensile stresses were greater than the Limit State III. Those bridges whose sum of tensile stress exceeds the Service Limit State III are in need to be strengthened. The FRP strengthening technique with resin material was used in all bridges those need to be retrofitted.

6.1 Current Traffic Loads

Under the site-specific fatigue truck loading, only 118-ft and 140-ft long bridges were strengthened by FRP and resin material. Applying AASHTO Fatigue II loading factor (0.75) to the strengthened model, Fig. 6 shows stress distribution of concrete and FRP laminates of the strengthened bridges.

The FRP strengthening intervention was used not only to encase the concrete to protect the prestressing

Table 3 Mechanical properties materials degradation.

Time (years)	Deck			Girder		
	E_X (ksi)	E_Y (ksi)	E_Z (ksi)	E_X (ksi)	E_Y (ksi)	E_Z (ksi)
0	3,860	3,860	3,860	5,148	5,148	5,148
>30	1,575	1,575	1,575	2,100	2,100	2,100
Time (years)	Epoxy			FRP		
	E_X (ksi)	E_Y (ksi)	E_Z (ksi)	E_X (ksi)	E_Y (ksi)	E_Z (ksi)
10	362.6	362.6	362.6	7,803	1,054	7,803
30	362.6	362.6	362.6	7,803	1,054	7,803
100	360.8	360.8	360.8	7,803	1,054	7,803

Fig. 4 Maximum pressurizing strands stress distribution (site-specific fatigue truck and AASHTO fatigue truck): (a) 60-ft long bridge; (b) 118-ft long bridge; (c) 140-ft long bridge.

Fig. 5 Concrete flexural stress distribution—current traffic: (a) site-specific fatigue truck; (b) AASHTO fatigue truck.

Table 4 The summary of current traffic FE (finite element) model's results (Fatigue I).

Truck type	Bridge span (ft)	Strands' stress (ksi)		Stress range (ksi) Δf	AASHTO limits (ksi)	Concrete tensile stress (Fatigue I) (ksi)	AASHTO limit $(0.19\sqrt{f'_c})$ (ksi)	Remarks
		f_{max}	f_{min}					
Site-specific fatigue truck	60	178.87	175.28	3.59	10	0.416	0.537	No strengthening
AASHTO fatigue truck		178.24	175.28	2.96	10	0.372	0.537	No strengthening
Site-specific fatigue truck	118	184.08	180.29	3.79	10	0.636	0.537	Need strengthening
AASHTO fatigue truck		183.24	180.29	2.95	10	0.521	0.537	No strengthening
Site-specific fatigue truck	140	181.26	178.55	2.71	10	0.624	0.537	Need strengthening
AASHTO fatigue truck		180.68	178.55	2.12	10	0.532	0.537	No strengthening

Table 5 Double truck weight FE model's results summary (Fatigue I).

Truck type	Bridge span (ft)	Strands' stress (ksi)		Stress range (ksi) Δf	AASHTO limits (ksi)	Concrete tensile stress (Fatigue I) (ksi)	AASHTO limit $(0.19\sqrt{f'_c})$ (ksi)	Remarks
		f_{max}	f_{min}					
Site-specific fatigue truck	60	182.40	175.28	7.12	10	0.711	0.537	Need strengthening
AASHTO fatigue truck		181.36	175.28	6.08	10	0.623	0.537	Need strengthening
Site-specific fatigue truck	118	188.25	180.29	7.96	10	0.971	0.537	Need strengthening
AASHTO fatigue truck		186.40	180.29	6.11	10	0.822	0.537	Need strengthening
Site-specific fatigue truck	140	183.89	178.55	5.34	10	0.843	0.537	Need strengthening
AASHTO fatigue truck		182.47	178.55	3.92	10	0.728	0.537	Need strengthening

tendons against harmful environmental materials, but also to help the concrete and prestressing tendons as well in load resisting. Table 4 shows the reduction in the captured concrete tensile stress in FRP strengthened girders is about 42% of the unstrengthened bridges. The immediate improve in the concrete tensile stress is depicted in Fig. 7.

6.2 Double Truck Weight

In this case, as the concrete tensile stress of all bridges exceeded the Service Limit III, these bridges need to be strengthened. Applying the fatigue load Factor II to both truck and rerun the FEM (finite element model). The induced concrete tensile stresses were captured and recorded in Table 5. All the unstrengthened and strengthened maximum concrete tensile stress of site-specific and AASHTO fatigue trucks were depicted in Fig. 10.

7. Conclusions

The aim of this research was to develop BMS (bridge maintenance management system) tools for

unstrengthened and FRP strengthened bridges using the ANSYS FE model. These tools can maximize cost effectiveness, considering limited allocated funding, to maintain bridges functionality. Due to the lack of information about the long-term properties of the polymers used in the FRP retrofitting mechanism, a set of experimental work was executed to develop the master curve of the polymer parameters. This concludes that the changes in creep strain values and depreciation in the value of the modulus of elasticity over 100 years were not significant (less than 1%).

The long-term properties of the polymer were used to develop an ANSYS FE model to study the effect of the cyclic loads (fatigue) over prestressed concrete bridges under the current weight and double weight effect of the site-specific fatigue truck and the AASHTO fatigue truck, too. Three bridges of different spans (60-ft, 118-ft and 140-ft) were designed according to the AASHTO LRFD specifications. These bridges were subjected to the site-specific frequent truck (85 kip) and the AASHTO fatigue truck.

Fig. 6 Concrete and FRP flexural stress distribution of strengthened bridges—current traffic: (a) 118-ft long bridge; (b) 140-ft long bridge.

Fig. 7 Concrete tensile stress improvement with FRP intervention: (a) 118 ft; (b) 140 ft.

Fig. 8 Concrete tensile stress (site-specific fatigue truck)—double truck weight: (a) unstrengthened bridges (60-ft, 118-ft and 140-ft); (b) FRP strengthened bridges (60-ft, 118-ft and 140-ft).

Fig. 9 Concrete tensile stress (AASHTO fatigue truck)—double truck weight: (a) unstrengthened bridges (60-ft, 118-ft and 140-ft); (b) FRP strengthened bridges (60-ft, 118-ft and 140-ft).

(a)

(b)

(c)

Fig. 10 Concrete tensile stress improvement with FRP intervention: (a) 60-ft; (b) 118-ft; (c) 140-ft.

Table 6 FRP strengthening impact on the concrete tensile stress (current traffic load).

Truck	Bridge span (ft)	Concrete tensile stress (ksi)		Reduction (%)
		Without FRP	With FRP	
Site-specific fatigue truck	118	0.636	0.28	41.66
Site-specific fatigue truck	140	0.624	0.29	42.00

Table 7 FRP strengthening impact on the concrete tensile stress (double truck weight).

Truck	Bridge span (ft)	Concrete tensile stress (ksi)		Reduction (%)
		Without FRP	With FRP	
Site-specific fatigue truck	60	0.711	0.295	29.00
AASHTO fatigue truck		0.623	0.270	27.40
Site-specific fatigue truck	118	0.971	0.372	42.40
AASHTO fatigue truck		0.822	0.331	42.30
Site-specific fatigue truck	140	0.843	0.350	42.00
AASHTO fatigue truck		0.728	0.310	41.70

Under the current traffic conditions scenario, for all bridges, the AASHTO fatigue truck did not develop stress ranges or concrete tensile stress greater than the AASHTO limitations. But the concrete tensile stresses developed by site-specific fatigue truck exceed the service limits state limitations for the 118-ft and 140-ft long bridges. Therefore, the strengthening is needed for 118-ft and 140-ft long bridges under the site-specific fatigue truck load. The intervention of the FRP for those bridges that need strengthening (118-ft and 140-ft) reduced the recorded concrete tensile stresses by about 42%.

Under double traffic load scenario, for all bridges, both trucks develop concrete tensile stress greater than the limitations but the strands stress ranges are still lower than the stress threshold. Therefore, all the examined bridges needed strengthening using the FRP mechanism. The intervention of the FRP strengthening reduced the stress by about 28% for 60-ft-long and 42% in 118-and 140-ft-long bridges.

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