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Mechanics Based Durability Modeling of FRP Bridge Deck

by
H.C. Wu
A. Yan
G. Fu
Department of Civil and Environmental Engineering,
Wayne State University
Detroit, MI 48202, USA

R.F. Gibson
Department of Mechanical Engineering,
Wayne State University
Detroit, MI 48202, USA

Abstract

Fiber Reinforced Polymer (FRP) composites, especially lightweight sandwich structures, are rapidly finding their ways into civil infrastructure application. FRP composite panels are particularly attractive as bridge deck system due to their high strength, low density, and durability, which are of importance to the bridge industry. For civil engineering application, it is essential to determine the durability performance of FRP materials under weathering conditions, especially freeze-thaw and low temperature exposure.

Since load capacity and structural stiffness of FRP decks will likely deteriorate over time, it is necessary to develop robust mechanics models that accurately describe the combined effect of load and environmental exposure at the material level, taking account degradation mechanisms and their interactions. Such durability constitutive law can be established from accelerated laboratory testing. Laboratory testing should also be correlated to field performance. Therefore such material constitutive relationships can be input to general-purpose finite element analysis for design of bridge deck for long-term durability. All of the above issues will be discussed in this paper.

Introduction

The durability of FRP materials and composites remains a major concern in their use as primary load bearing members and structures. Moreover, how load capacity and structural stiffness will change over time present a central conundrum for designers when specifying allowable loads and reductions factors. Time-dependent effects manifested by creep rupture under sustained load, fatigue under cyclic loads, and deterioration due to temperature, UV radiation, moisture and humidity, and other environmental factors may also be important in time-dependent reliability of FRP composites during their service lives. Composite structures for civil infrastructure purposes have only been in service for a relatively short time. There are few long-term data available to define environmental effects especially weathering on FRP structural components and systems.

The prediction of long-term strength of FRP laminate subject to environmental exposure is much more difficult than that of the modulus (Gibson 1994). Chu used accelerated testing data to predict long-term prperties of pultruded E-glass/vinyl ester composites exposed to weathering condition, and the predictions correlated well with his experimental results (Chu 2004). Karbhari et al. (2002, 2002a) adopted a semi-empirical approach to predict the long-term modulus and strength of unidirectional carbon/vinyl ester composites subject to freeze-thaw cycling. His study indicated that the analytical predictions are somewhat conservative for strength and freeze/thaw cycling does not have appreciable effect on modulus. FRP composites used in bridge applications are normally under sustained load, however, sustained loading was not considered in Karbhari's durability study.

To allow for sufficiently generalized descriptions of service life, credible simulations that accurately describe the combination of synergism of load and environment must be used to ensure practical and efficient design guidelines for durability. These simulations must be robust and be developed from reliable descriptions of material degradation mechanisms and their interactions, which may include characterizations from accelerated testing to extend the validity of the predictions. Such simulations must be validated over a wide range of conditions, at both the component and structural levels.

The goal of this paper is to investigate the effect of environmental exposure on long-term structural properties of FRP deck. One of the main objectives of this study is to understand the effects of time-dependent phenomena on the residual response of FRP deck. That is, to predict the long-term static behavior of structural members after they have experienced sustained load and environmental exposure for a time period t_0 or N numbers of freeze/thaw cycles.

Mechanics Procedure for Durability Prediction

A performance driven design approach has been followed to provide the framework within which the durability study of fiber reinforced plastic composite bridge deck is organized. Environmental conditions directly influence the composite's deck performance.

Quantifying the changes in the matrix and composite properties as a result of environmental exposure is a key aspect to this study. Using the environmentally dependent material parameters as input to durability finite element model, predictions of environmental effects on FRP bridge deck stiffness and load capacity can be made. In order to establish correlation between laboratory testing environment and actual field exposure, test results of all field-exposed FRP deck shall be correlated with test results of laboratory exposures. In order to have a comprehensive and verifiable record of field conditions each bridge site shall be instrumented for recording temperature, precipitation and humidity. Other than coupon level material tests the correlation shall also be conducted at the subcomponent and structure level through input of material parameters into a global FE model to identify changes at the structural level.

To assess the degradation of FRP bridge deck, the first step begins by defining the geometry, layup (orientation of plies within the laminate), environmental condition, and pre-straining level. Using this information the deteriorated modulus and strength of the laminate and matrix, as a function of time t or numbers of freeze/thaw cycles N, can be determined by employing micro-mechanics and laminate theory.

Then, an in-house finite element model will be used to determine stress distribution and displacement of the FRP deck after time t or numbers of cycles N. Determination of load capacity of FRP bridge deck will depend upon four criteria, which are:

(1) First ply failure;
(2) Interface shear stress failure;
(3) Local buckling of web or skin;
(4) Limitation of displacement in service condition.

When simulation results meet any criterion above, the ultimate load capacity of the deck is reached.

Failure Analysis of FRP Deck

For composite sandwich material, failure modes include face yielding, face buckling, core shearing, and local indentation. There are three main categories of fracture of FRP composite sandwich deck considered in this study: first ply failure, core shear failure and local buckling. FRP composites will have some degree of delamination, broken fibers and cracked matrix, but any of those is only significant if the damage grows to occupy large and/or critical areas of the material so that the component starts to lose its integrity. Thus, we also consider the interface shear stress between core and skin to determine possible delamination.

Several possible failure modes are discussed in the following sections:

First ply failure

It is assumed that initial failure of any layer of a laminate implies laminate failure, which is referred to as first-ply failure criterion. Such first-ply failure criterion provides a conservative estimate of the laminate failure load since first failure in the form of matrix cracks may not lead to laminate failure. There are various failure criteria for composite laminates. The most frequently used ones are the Tsai-Hill, Hoffman and Tsai-Wu criteria.

$$E_{sf} = \left(\frac{\tau_{xz}}{S_{xz}}\right)^2 \; or \; \left(\frac{\tau_{yz}}{S_{yz}}\right)^2 \qquad (4)$$

These interactive criteria are formulated in such a way that they take account of stress interactions. The objective of this approach is to recognize the fact that when a multi-axial stress state exists in the material the failure load may well differ from those when only an uni-axial stress is acting. The Tsai-Hill criterion is selected as failure index in this study. The Tsai-Hill criterion, which has proven to be successful in a wide variety of circumstances, defines the failure as:

$$\left(\frac{\sigma_1}{S_L^2}\right)^2 - \frac{\sigma_1\sigma_2}{S_L^2} + \left(\frac{\sigma_2}{S_T^2}\right)^2 + \left(\frac{\tau_{12}}{S_{LT}^2}\right)^2 \geq 1 \qquad (1)$$

Where ‘1’ is fiber’s longitudinal axis, ‘2’ is normal to the fiber’s axis. The values of the strength used in this equation are chosen depending on the direction of σ_1 and σ_2. For example if σ_1 is tensile S_L^+ is used, and if σ_2 is compressive S_T^- would be used. Subscript “L” represents longitudinal direction and “T” transverse direction. Superscript “+” represents tension and “-“ denotes compression. S_{LT} is in plane shear strength. The failure index can be expressed as:

$$E_{fpf} = \left(\frac{\sigma_1}{S_L^2}\right)^2 - \frac{\sigma_1\sigma_2}{S_L^2} + \left(\frac{\sigma_2}{S_T^2}\right)^2 + \left(\frac{\tau_{12}}{S_{LT}^2}\right)^2 \qquad (2)$$

Where E_{fpf} is failure index for first ply failure.

Shear stress failure

A FRP bridge deck is a sandwich structure where the web core is wrapped by outer skin shells. The core web system and outer surfaces are bonded together to form an integral unit. Therefore, the shear stresses at the interfaces between the web and the outer surfaces may result in shear failure if the bonding agent does not provide enough shear strength.

By employing the quadratic delamination failure

$$\left(\frac{\tau_{xz}}{S_{XZ}}\right)^2 + \left(\frac{\sigma_z}{S_Z^+}\right)^2 \geq 1 \qquad (3)$$

criterion proposed by Brewer and Lagace (1988) delamination initiation is predicted based on the out-of-plane stresses and strengths (Senne et al. 2000). Failure occurs when

where τ_{xz} and σ_z are the out of plane interlaminar stresses at a point in the laminate and are compared to the respective interlaminar shear strength S_{xz} and interlaminar tensile strength S_z^+. If the second term in Eq. (3) is negligible, so that the shear delamination criterion takes on the simplified form

Where E_{sf} is failure index for shear delamination failure and S_{yz}, S_{xz} are interlaminar shear strengths.

Local buckling

Buckling of laminates is an instability, which is characterized by excessive transverse deflections under in-plane compressive forces. Instability is a critical strength limit state for design specifications. It must be sure that the structure will not undergo any local or global instability prior to reaching its ultimate strength. A FRP bridge deck is a thin-walled structure. The webs and top surface under vehicular wheel load will be subjected to compressive stresses, which may lead to local buckling. Failure of sandwich panels in bending can occur under the loading point due to local indentation. Failure is due to core crushing under the indenter or wheel load.

To obtain the buckling predictions with ABAQUS a *BUCKLE step must be run. In this step normal values of load are applied. The magnitude that is used is not of significance, since eigenvalue buckling is a linear perturbation procedure: the stiffness matrix and the stress matrix are evaluated at the beginning of the step without any of this load applied. The *BUCKLE step calculates the eigenvalues that, multiplied with the applied load and added to any “base state” loading, are the predicted buckling load. The eigenvectors associated with the eigenvalues are also obtained.

Deflection limit

Under general vehicular loads, the deflection of a structural bridge deck is limited to the span length divided by 800 (span/800). To meet this serviceability limit requirement, the stiffness of FRP deck should be guaranteed to exceed a certain value during its entire service life. An in-house layered model is developed to predict the long-term displacement under truck wheel load considering deteriorating material properties over time.

Simulation of Target FRP Deck

An experimental FRP honeycomb sandwich deck panel was tested by Hardcore Composites (2001) and used in this study. It should be noted that the selection of the Hardcore sandwich deck is for illustration purpose only. The proposed scheme is applicable to other FRP deck including those made by pultrusion, although the details of the mechanics modeling of the deck itself need to be properly modified for different construction types. In the panel test, the size of the sandwich panel was 4460 mm × 1830 mm. The composite panel was made with a 6-ply face skin at the top and bottom of the sandwich structure and a lightweight core in the middle. The whole deck was simply supported by three steel I-beams, as shown in Figure 1. The load was applied over a 250 mm × 600 mm bearing plate with a 6.4 mm-thick Neoprene pad to simulate a factored wheel load of a HS25 truck. Very good agreements between predicted and measured displacements of the two monitoring points (Point E and W in Figure 1) have been observed when the panel is subjected to 110kN or 208kN load. If the same loading test is repeated after the panel is subjected to different levels of environment exposure, the displacements at these two control points will vary with the exposed time duration t. Although such environmental durability test was not conducted experimentally, the numerical durability model described above would be performed to investigate the environment exposure effects on the changes of displacement considering material property deterioration due to freeze-thaw cycling.

The FRP sandwich panel was further analyzed using the durability finite element model to determine the long-term performance of the FRP deck. We selected ABAQUS as the finite element analysis tool and HYPERMESH as the pre- and post- processor. The in-house layered model was incorporated into ABAQUS to determine normal stresses at each sub-layer and interlaminar shear stresses. The mesh of the composite panel is shown in Figure 1. For local buckling analysis, the grid mesh of the web core is formulated to include core failure under local truck wheel load.

Material Properties Degradation of the Laminate

The short-term material properties of the skin laminate are used to predict the long-term material properties of the laminate as a function of time t due to environmental exposure according to micro mechanics and laminate theory. The composite material properties deteriorate with time when the composites are subject to 2hour freeze-thaw cycles and pre-straining (25% of ultimate strain capacity) in distilled water. More details of the durability testing can be found elsewhere (Wu et al. 2005). It is found that the properties of the matrix (vinylester) are more sensitive to environmental exposure than those of the composite (glass fiber/vinylester) and the fiber dominated properties E_x and E_y decrease slowly with the increase of the duration time of environmental exposure compared to matrix dominated properties G_{xy} (Figure 2).

After 50,000h environmental exposure of 2hour cycles with pre-straining in distilled water, the modulus of the matrix decreases around 25%, while longitudinal Young's modulus of the laminate, E_x, decreases only 5%. Similar results are obtained for the condition of 5h cycle and pre-straining. The changes in material properties of the same composite when stored at room temperature only can also be predicted based on moisture absorption, as shown in Figure 3. It is noted that no appreciable deterioration of any material property of both the matrix and composite after 50,000h exposure. It confirms that material properties of laminate are strongly influenced by freeze-thaw cycles under pre-straining, especially for matrix-dominated properties.

A semi-empirical approach (Yan 2005) was used to extrapolate the normalized flexural strength of the laminate as a function of exposure time t. The normalized flexural strength versus time t in various environmental conditions is plotted in Figure 4. It is shown that the 2H-PS is more severe than other conditions and the freeze-thaw cycle with pre-straining results in more rapid strength reduction. After the same environmental exposure time in distilled water, it seems that the degradation of laminate is more sensitive to number of cycles since 2h cycle conditions cause strength reduction more rapidly than 5h cycle. It is assumed that matrix dominated strength S_L^-, S_T^- and S_{LT} follows the same trend as the flexural strength in the finite element analysis of the deck in the following sections.

Long-term Serviceability Prediction

Serviceability criteria are conventionally expressed as limit on deflections, strains, or dynamic accelerations under service limit state load combinations. The time-dependent maximum displacement is used as an index of serviceability limit in this FRP deck study. The prediction of deflection versus time subject to 2H-PS condition at the points of E and W (see Figure 1), which were monitored by LVDT, is given in Figure 5. It is shown that deflection increases obviously with the increase of environmental exposure time. Under the condition of 5H-PS, the deflection increases a little more slowly than under 2H-PS. However, it is found that deflection remains almost the same under the condition of 2h freeze-thaw cycle without pre-straining as shown in Figure 6. It is shown that increasing exposure time t and/or applying pre-strain increases the overall deflection. Furthermore, it appears that the effect of pre-straining is more dominant than exposure time t.

The load displacement ratio P/δ represents the slope of the load versus deflection curve. This value is a good indicator of the deck stiffness. If the displacement of LVDT-W is used to evaluate the change of the deck's stiffness, after 10,000h and 50,000h exposures under the condition of 5h cycle with pre-straining, the stiffness decreases 5.4% and 13.3%, respectively. Under the condition of 2h cycles with pre-straining, the deck loses about 6.3% and 15.7% of its stiffness after 10,000h and 50,000h, respectively. The deck presents almost no stiffness reduction (loss of 1% and 2.7%) after 10,000h and 50,000h under the condition of 2h cycle without pre-straining. This indicates that the stiffness degradation of the deck is influenced significantly by the freeze-thaw cycle in combination with sustained load.

Long-term Ultimate Limit State Prediction

First ply failure

In this study, we adopted Tsai-Hill criterion since it is more accurate than others for E-glass fiber composites (Tsai, 1987). In this case, increments of vehicular wheel loads were added step-by-step until first ply failure occurred. The ultimate vehicular wheel loads are time-dependent corresponding to the ultimate load capacity of the bridge deck after environmental exposure time t. Ultimate vehicular wheel loads are shown as a function of exposure time t in Figure 7. It is found that after 10,000h exposure load capacity decreases much rapidly than the first 10,000h under both 2H-PS and 5H-PS conditions. The load capacity under the condition of 5H-PS loses 8.5% and 54% after 10,000h and 20,000h exposure, respectively, whereas a reduction of 15% and 62% is found under 2H-PS. Compared to stiffness deterioration, the load capacity decreases more rapidly, especially after 10,000h exposure.

Shear stress failure

The shear stresses at the interfaces between the web and the outer surfaces may result in shear failure if the bond layer does not provide enough shear strength. Estimates of the transverse shear stresses are available at section integration points (listed as output variables TSHR13 or TSHR23 in ABAQUS software codes). As seen in Figure 8, the failure load decreases more rapidly than that determined by the first ply failure criterion due to environmental exposure. The bonding material between the core and skin is neat vinyl ester resin, which deteriorated more rapidly than the FRP laminate of the skin.

Local buckling failure

The buckling modes and corresponding loads can be obtained by performing finite element buckling analysis. Only the first buckling mode is useful for the purpose of bridge deck design. The local buckling failure load is much lower than the first-ply and shear failure load. It means that local buckling failure will dominate the load capacity of the bridge deck exposed to the investigated freeze/thaw cycling period because of thin wall sandwich structures.

Figure 9 gives the variation of ultimate load capacity of the bridge deck with the increase of environmental exposure time. It can be seen that ultimate load capacity decreases about 5% after 10,000h freeze-thaw cycles with pre-straining.

Conclusions

In this paper, a mechanics based durability model has been formulated to predict long term performance of FRP bridge deck under natural weathering condition. The focus is placed on the ability to predict the long term structural performance. Therefore material constituent laws accounting for both strength and stiffness deterioration over time are first developed and then incorporated into FE analysis. Such constituent relationships are established from data obtained from laboratory accelerated freeze/thaw testing and from in-field performance measurements. A degradation factor correlating laboratory time scale with actual time scale was proposed and found to be able to predict reliably the changes in stiffness and deflection of a monitored FRP bridge deck over a 5-year period. Nevertheless a much longer performance data are needed to further validate the proposed durability model especially the degradation factor.

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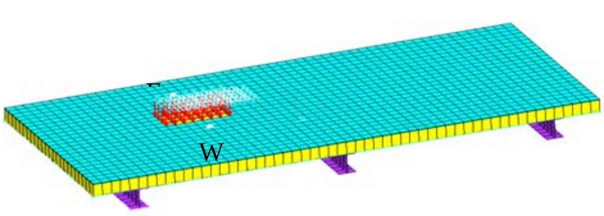

Figure 1: Test set up of the experimental FRP bridge deck

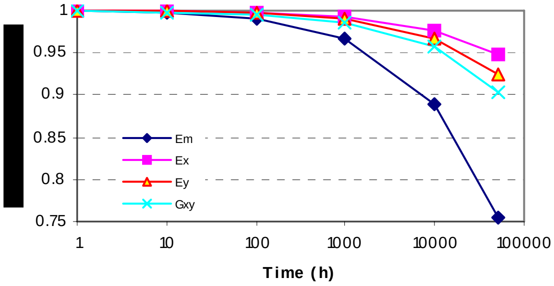

Figure 2: Material deterioration in the condition of 2H-PS

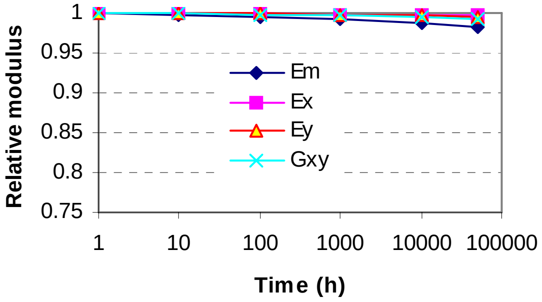

Figure 3: Material deterioration at room temperature

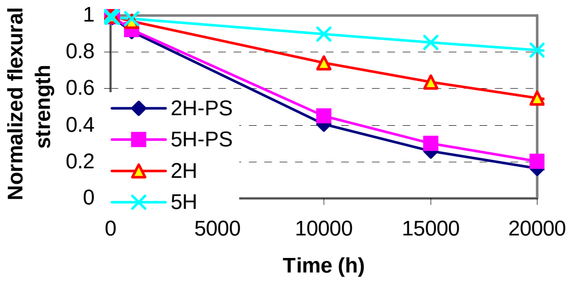

Figure 4: Strength deterioration in various environmental conditions

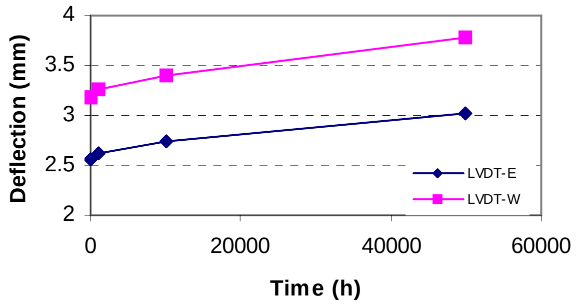

Figure 5: 2H-PS in distilled water

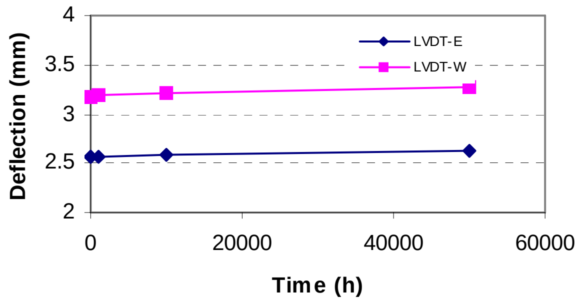

Figure 6: 2H in distilled water

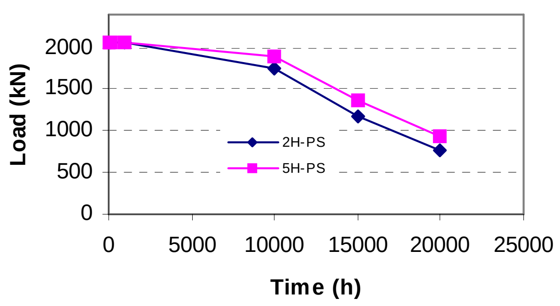

Figure 7: First ply failure load versus time

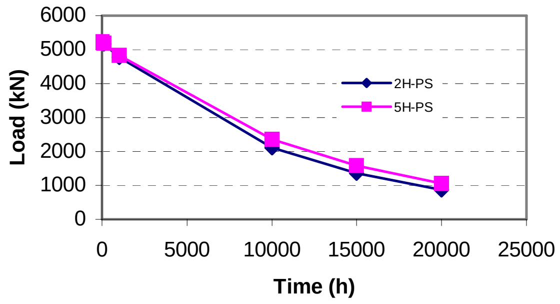

Figure 8: Shear failure load versus time

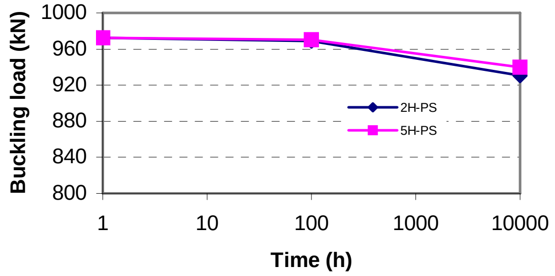

Figure 9: Buckling failure load versus time

H.C. Wu, Associate Professor
A. Yan, PhD student
G. Fu, Professor
Department of Civil & Environmental Engineering,
Wayne State University, Detroit, MI
R.F. Gibson, Professor
Department of Mechanical Engineering,
Wayne State University, Detroit, MI