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SYNERGISTIC EFFECTS OF ENVIRONMENTAL DETERIORATION ON FATIGUE AND FLEXURE PROPERTIES OF GLASS FIBER REINFORCED POLYMERIC (GFRP) COMPOSITES: A MULTISCALE AND MULTIPHYSICS MODEL

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Abstract. This study aims to simulate synergistic UV & moisture deterioration and demonstrate its role in changing the residual fatigue and flexure strength in architectural GFRP composite material. This study develops an experimentally validated 3D Multiphysics model at a structural level and gets this homogenization-based model to identify the degradation mechanisms observed in the experimental data. Sensitivity analyses are conducted to investigate the effect of mesh density on the accuracy of functions homogenized from micromechanical models. In addition, this macroscale model also quantifies how these degradation mechanisms weaken the strength and durability of environmentally aged composite materials. The aging-fatigue-bend macroscale model assumes that the degradation-induced damage field is concentrated within a depth to the plate surface. According to the computational results, the degradation process caused by the combined effect of UV and moisture exposure involves the removal of polymeric matter from the exposed surface. In other words, the degradation mechanism of UV exposure involves both the chemical alteration and mechanical damage of polymeric matter, primarily located at the exposed surface.

This model can be incorporated into many commercial finite element codes for a sustainability study of composite structures/systems. In future work, the models developed in this study will be combined with life cycle assessment (LCA) tools to support better sustainability-focused new material design, thus reducing costs and environmental impacts in the built environment.

1 INTRODUCTION

Buildings consume 50% of the energy produced globally and are built with highly energy-intensive materials. A critical sustainability challenge in the design and construction of the built environment is building high-quality, safe structures while accelerating a transition of the built environment into a low-carbon intensity industry. Thus, our research aims to develop innovative construction materials for a globally sustainable and circular construction economy. [13] Specifically, we are using glass fiber reinforced composite (GFRP) as an architectural material to adopt fossil-based hydrocarbon polymer in a longer life cycle, noncombustible application in the area of construction. [14] Our research efforts look to solve the dual challenge of (1) reducing the impact of construction material production and (2) enabling high-value, non-combustible applications for fossil hydrocarbons.

More broadly, this paper expands the physics-based modeling thrust of the Sustainable Integrated Materials, Structures and Systems (SIMSS) framework proposed by Lepech et al. [6] and shown in Fig. 1. As seen, the SIMSS design approach spans engineering and design scales from micrometer-scale (i.e., material microstructure [9]) to decimeter-scale (i.e., building or infrastructure performance [16, 8]) to understand the interdependencies between material constituents and microstructures, material properties and structural capacity, and structural behavior and built system performance. Life cycle assessment (LCA) methods, often supported by high-fidelity multi-physics models of building systems, can be used to quantify environmental, economic, and potentially social impact as a function of time over the lifetime of a system. [15] These indicators are then used in a feedback loop to improve system design through targeted design interventions at the appropriate and most efficient scale of design (i.e., material design changes, structural design changes, or system design changes). [6, 13]

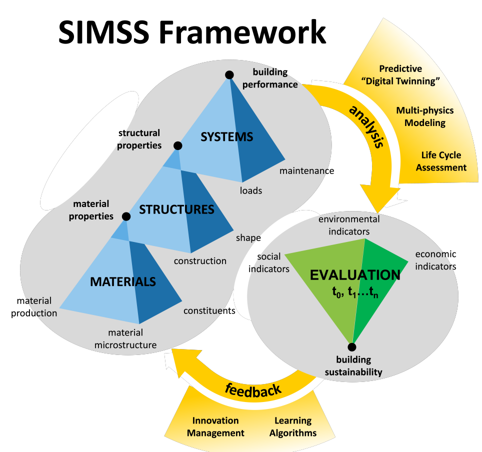

Figure 1: Sustainable Integrated Materials, Structures, & Systems Framework adapted from [6]

This paper presents a multiphysics and multiscale model described in Section 2. The model has been validated using the deterioration-fatigue-bending data published in [5, 18, 19]. To further validate the current model, fatigue damage testing (Section 3) is carried out on the Glass Fiber Reinforced Polymer (GFRP) material that is used in the GFRP façade system of the San Francisco Museum of Modern Art (SFMOMA). Finally, in Section 4, we summarize the current conclusion and outline our future work plan.

2 MULTISCALE MODELLING OF GLASS FIBER REINFORCED POLYMER (GFRP) COMPOSITES

2.1 Mesoscale Modeling of GFRP Representative Volume Element (RVE)

The authors developed a mesoscale model that captures synergistic degradation mechanisms of fiber-reinforced polymer composite materials subjected to long-term environmental exposures. [13, 9, 16] Specially, this study develops a new multi-physics model with extrinsic deterioration, deformation, and material intrinsic microscale morphology using the finite element method. Validated against experimental studies published in the literature ([5, 18, 19]), results of a case study analysis indicate that the synergistic effect of combined UV and moisture exposure on composite material degradation is more severe than the simple linear superposition of each exposure's damage.

Fig. 2 (a) shows an RVE model for a three-layer, plain weave, woven polymer composite used in the construction of an actual building; the façade of the San Francisco Museum of Modern Art (SFMOMA), in San Francisco, California. The microstructure of the RVE is built using details of the micromorphology of the fiber-reinforced polymer composite panels supplied by Kreysler & Associates for the SFMOMA façade. For the interface of this RVE, it is assumed that the glass fiber yarn and matrix are perfectly bonded. [13]

In this computational example, the RVE is exposed to 250 hours of continuous UV radiation with an irradiance level of 0.68 w/m^2 at a wavelength λ, equal to 340 nm and a temperature, T, equal to 60 °C. The inward radiative heat flux, q^{rad}, enters the RVE through the top surface. There is no inward flux through the bottom surface or side surfaces. The four lateral surfaces are constrained using a symmetric boundary condition. The mesh consists of 205,930 elements with a minimum quality of 0.04075 and an average quality of 0.6503. The construction of the geometry follows the method proposed in [17]. [13]

The change in mass as a function of time in Fig. 2 (b) shows a sudden decrease in degradation rate after 15 hours of UV exposure. After this time, the degradation remains stagnant in the top layer adjacent to the surface that is exposed to ultraviolet radiation. Fig. 2 (a) shows residual stresses concentrated around the fiber-matrix interface. [13]

2.2 Macroscale Modeling of GFRP

The multi-physics macroscopic model that uses parameters homogenized from the mesoscale model in Section 2.1 has been developed by the authors in [7, 14, 8]. This model enables the simulation of synergistic UV-moisture deterioration effects on mechanical performance composite materials at the structural component scale. The model can fit with experimental data and capture different deterioration mechanisms precisely.

Specifically, the macroscale model uses the Continuum damage model (CDM) to couple with other models, such as the water transportation, heat transfer, and UV degradation models. The constitutive model is implemented for finite element analysis using the external material library

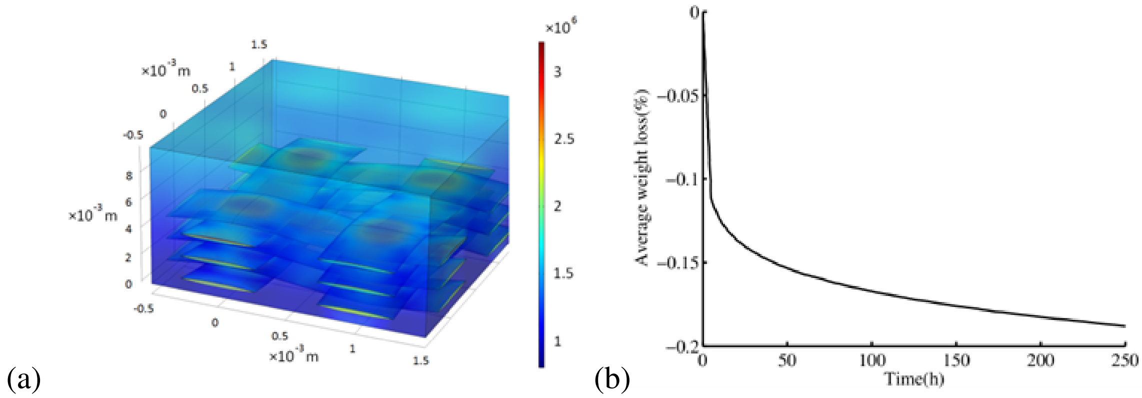

Figure 2: (a) Von Mises stress contour for the SFMOMA façade RVE after 250 hours UV exposure simulation (Unit: MPa), and (b) change in RVE mass, as a function of time, for the 3-layer plain weave composite. [13, 9]

in the COMSOL. In the Continuum damage model (CDM) of orthotropic material, Young's modulus and shear moduli are functions of the damage variable D ($D \in [0,1]$).

$$E_i(D) = (1-D)^2 E_i^0, \quad i = 1,2,3 \tag{1a}$$

$$G_{ij}(D) = (1-D)^2 G_{ij}^0, \quad ij = 23,31,12 \tag{1b}$$

The continuum damage mechanics or CDM-based variable D provides a measure of the reduction of the stiffness tensor with increasing damage. Brittle damage has been established to be a nonlinear function of the equivalent strain rates. The details can be found in [12, 10, 11]. The damage accumulation law of CDM for fatigue used in this investigation is given in Eq. 2, which is derived in [20] within the framework of irreversible process in thermodynamics by assuming a brittle damage mechanism and elastic strain domination. [7, 14]

$$\frac{dD}{dN} = \frac{\bar{B}}{q(1-D)^{2q}}\left({\sigma^v_{max}}^{2q} + {\sigma^v_{min}}^{2q}\right), R < 0 \tag{2a}$$

$$\frac{dD}{dN} = \frac{\bar{B}}{q(1-D)^{2q}}\left({\sigma^v_{max}}^{2q} - {\sigma^v_{min}}^{2q}\right), 0 \leq R < 1 \tag{2b}$$

where N is the number of cycles. $\bar{B}$ and q are material variables that come from fatigue test. R is the ratio of maximum and minimum load. In this study, R is equal to 0.1 according to the experiment. σ^v_{min} and σ^v_{max} are the maximum and minimum effective (Mises) stress, respectively. The total number of cycles in fatigue load N is given by $N = \sum_{i=1}^{I} \Delta N_i$, where i is the simulation load cycle number, and I is the total number of simulation load cycles. [7, 14]

Fig. 3 (a) shows the degraded and fatigued three-point bending simulation results. It is the contours of the non-homogeneous field of damage variable D when the sample is subjected to maximum bending moment. When solving the fatigue-bend model, the macroscale model in [7, 14] assumes that the deterioration-induced damage field occurs on the exposed surface within a limited depth. Thus, the model defines an effective thickness reduction ratio R^t as the ratio of the undamaged zone thickness to the original thickness.

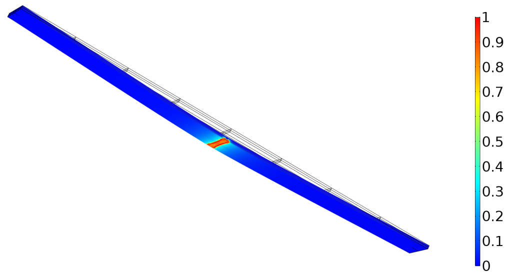

Figure 3: Oblique view of the contour of damage variable D for entire laminate subjected to 3-point bending at the moment of the maximum bending moment. The model experiences neither environmental stiffness degradation nor fatigue prior to bending. [7, 14]

Fig. 4 shows the curve of the failure bend moment in terms of R^t, with $D(\delta = 0mm) = 0$. δ is the deflection. From Fig. 4 (a), R^t for various degrees of degradation can be obtained. For the undegraded case, $R^t = 1$. A number of fatigue models with specific R^t and $D(N = 0) = 0$ have been calculated in COMSOL. Their end values $D(N = 100,000) = 0$ are collected and compared to the experimental data. Fig. 4 (b) shows the solved function of $\bar{B}$. Other functions and parameters such as R^t and q can be found in [7]. Fig. 4 (b) shows that the fatigue properties of the reduced thickness model exhibit significantly less sensitivity to various degradations. This lack of sensitivity proves the rationality of the assumption of R^t. [7, 14]

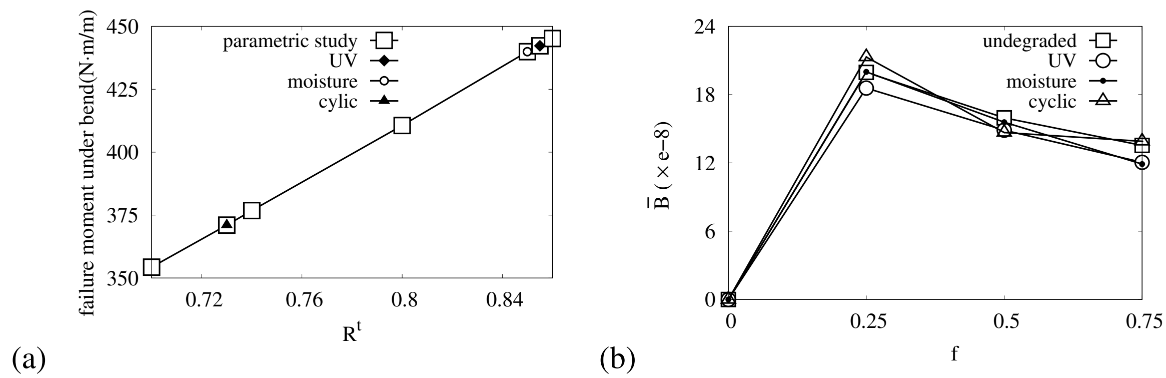

Figure 4: (a) Obtain the effectively reduced thickness ratios R^t by comparing parametric study results (failure moment .vs. R^t) to the experimental data. (b) The variable of fatigue evolution model $\bar{B}$ in Eq. 2 as a function of fatigue level. [7, 14]

3 MECHANICAL TEST

The model described in Section 2 has been validated through an experimental test performed on a cross-ply GFRP sample. In order to calibrate the mechanical parameters for a plain woven GFRP composite used in SFMOMA façade, particularly the $\bar{B}$ and q parameters in Equation 2, a fatigue damage experiment has been conducted. This experiment aims to quantify the aforementioned variables for plain woven GFRP. This section provides an update on the mechanical tests that are currently being undertaken. The results presented here are preliminary.

The experimental conditions of the fatigue tests were controlled and monitored with the MTS Test Suite Multipurpose Elite Software. The uniaxial tension-tension cyclic loading fatigue tests were performed using the MTS fatigue load frame. The test and other experimental conditions are listed in Table 1. A linear variable displacement transformer (LVDT) was used to monitor the displacement error of the frame actuator, and an extensometer was used to monitor the strain change of the samples during fatigue tests. The whole fatigue test structure is shown in Table 1.

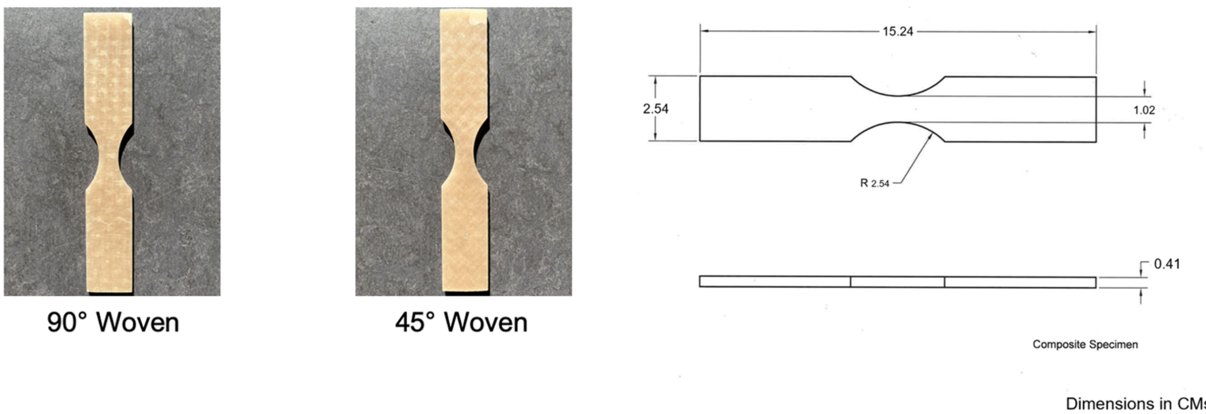

Figure 5: Photo and geometry detail of [0°,90°] sample and sample.

The test material employed large glass fiber reinforced polymer (GFRP) panels provided by Kreysler & Associates, American Canyon, CA. The panels were cut with waterjets to obtain samples described in Fig. 5. The testing panel is made from material identical to the SFMOMA façade, although it lacks a protective gel coat. In order to evaluate the orthotropic mechanical properties of the specimen under examination, tests are conducted on two categories of samples with distinct stacking sequences, namely [0°,90°] and [-45°,+45°], as illustrated in Figure 5. Prior to the fatigue-flexural test, ultimate tensile strength (UTS) for [0°,90°] and [-45°,+45°] samples are measured per ASTM D3039/D3039M [1] and ASTM D3518/D3518M [3], respectively.

The fatigue-flexural test comprises two distinct steps. In the first step, the sample is subjected to an arbitrary number of fatigue cycles, which are set below the maximum fatigue cycle. This paper defines the arbitrary number of fatigue cycles as the maximum number of cycles in Table 1. The second step involves subjecting the fatigued sample to three-point bending, which measures the effect of fatigue on material properties using alterations in bending failure force. The design of this fatigue-flexural test is based on the methods proposed in [5, 18, 19].

Uniaxial tension-tension cyclic loadings were performed at different fatigue levels listed in Table 2, using force-controlled mode by hydraulic MTS-312.21 machine with ASTM D3479/D3 479M [2]. Here, the fatigue level denotes the maximum applied load normalized by the ultimate strength of the original non-fatigued samples.

Table 1: Machine and test parameters for fatigue test

Machine Type	MTS 312.21
Serial Number	229
Test Frequency	5 Hz
Temperature	Room Temperature
Control Mode	Force (Load)
Ultimate tensile Strength	[0°, 90°] Plain Woven Sample: 5.8 KN [-45°, +45°] Plain Woven Sample: 2.67 KN
Maximum Number of Cycles	100,000
Rising Time	10 s
The ratio of Max/Min Load	0.1

After the fatigue test, specimens that didn't break underwent an additional three-point bending test using the MTS 858 machine per ASTM D7264/D7264M [4]. This test was conducted at a bending rate of 0.05 in/min with a support span of 12 cm to measure the residual strength. The maximum bending forces were recorded as reference points to calculate the residual strength. The preliminary results so far have been recorded in Table 2.

The three layers of woven fiber ply in the SFMOMA façade material are hand-laid during manufacturing. As a result, the material contains random voids and uncertainty in woven layer lay-up alignment. Thus, the material properties (in Table 2) are more varied and uncertain by nature compared to other GFRPs manufactured under pressure or non-hand manufacturing methods.

For future tests, more repentance tests will be conducted to examine the impact of uncertainties in the material structure on its properties. Additionally, fatigue-flexural tests at higher fatigue levels will be conducted to investigate how various fatigue strengths can harm the material and explore the underlying mechanism.

4 CONCLUSIONS AND FUTURE WORK

This paper presents a new macroscopic model that uses homogenized transportation models from the micromechanics model to simulate the effects of synergistic UV-moisture deterioration on composite materials. The study proposes a new experimentally validated model that correlates extrinsic deterioration with residual intrinsic material mechanical properties. The aging-fatigue-bend model assumes that the degradation-induced damage field is concentrated within a depth to the plate surface. According to the computational results, the degradation process caused by the combined effect of UV and moisture exposure involves the removal of polymeric matter from the exposed surface. In other words, the degradation mechanism of UV exposure involves both the chemical alteration and mechanical damage of polymeric matter, mostly located at the exposed surface. [7, 14]

Table 2: Preliminary experimental results: Residual failure loads of under three-point-bend of GFRP samples with fatigue

[0°,90°] Plain Woven Sample			[-45°,+45°] Plain Woven Sample		
Fatigue Level	Failure Bending Force	Coefficient of Variation	Fatigue Level	Failure Bending Force	Coefficient of Variation
0.2	0.6834	0.0532	0.2	0.2478	0.0692
0.25	0.6831	0.0989	0.25	0.2599	0.0663
0.4	0.6245	0.0931	0.4	0.2307	0.0861
0.5	0.4025	0.1082			
0.6	0.3087	0.0979			

The fatigue-flexure test is conducted to calibrate the material parameters of the GFRP panel used in SFMOMA façade. Preliminary results indicated that, in general, the sample's residual ability to endure bending deformation decreases as the fatigue load level increases.

The model developed in this study can be used to establish an image-based, non-destructive damage detection tool or to perform life cycle prediction. This tool will be better combined with life cycle assessment (LCA) tools (e.g. [15]) to support sustainability-focused design of low carbon emission materials, thus reducing costs and environmental impacts to the built environment. [7, 14]

For future tests, more repentance tests will be conducted to examine the impact of uncertainties in the material structure on its properties. Additionally, fatigue-flexural tests at higher fatigue levels will be conducted to investigate how various fatigue strengths can harm the material and explore the underlying mechanism. Other future work includes calibrating elastic, fatigue, and damage parameters using experimental data from complete mechanical testing.

5 CRediT authorship contribution statement

Zhiye Li: Conceptualization, Methodology, Software, Validation, Formal analysis, Visualization, Funding acquisition, Writing – original draft. Yinjian Li: Investigation, Writing – original draft. Michael D. Lepech: Supervision, Funding acquisition, Writing - Review & Editing.

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