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Theoretical modeling of fatigue phenomenon in composite pipes

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ABSTRACT

In this research, lifetime prediction of composite pipes subjected to internal cyclic hydrostatic pressure is considered. Progressive damage modeling technique is employed based on stiffness degradation for evaluating fatigue failure. The modeling procedure consists of three phases as stress analysis, damage evaluation and mechanical properties degradation. The applicability of the modeling in predicting fatigue lifetime of composite pipes is validated using available experimental data in literature. Due to the limited existing data on required mechanical properties of employed composite materials for investigated composite pipe, initial mechanical properties are computed and generic estimation of stiffness degradation is obtained. Then, Taguchi method is utilized to modify obtained stiffness degradation patterns in accordance with reported experimental observations. A very good agreement between theoretically predicted fatigue life time and experimental data imply on acceptable level of accuracy of fatigue modeling procedure. Finally, fatigue lifetimes of an industrial composite pipe subjected to different varying internal pressure are predicted and its long-term behavior over the span of 50 years of continuous operation is estimated as the dictated requirement by international rules and regulations.

1. Introduction

The application of polymeric composite materials is booming in different industrial sectors due to the growing demand for employing structures with high performance and light weight. Moreover, the simplicity of manufacturing procedures for fabricating complicated structures from geometrical point of view have also rendered composites as a competitive candidate for the extensive spectrum of applications spanning from the high-tech industries to the low-tech segments. Subjected to cyclic loadings, composite materials have considerably greater lifetime during their missions in comparison with other conventional materials [1–4]. This key feature of composites necessitates the understanding of their behavior against fatigue phenomenon so that this prospect can be exploited as much as possible. In contrast to metals wherein a propagation of a single dominant crack accounts for fatigue failure, several micro-cracks appears in matrix during the early stage of the fatigue loading and then different damage mechanisms can be experienced by composite materials [5,6]. Therefore, a clear understanding of the damage initiation and evolution is required for predicting fatigue lifetime in composite structures.

A full-scale fatigue test is required for the certification procedure of almost all load bearing structures like airplane wings, wind turbine blades or pipes approving the design procedure. Due to this fact that required experimental setup for full-scale fatigue experiments is a costly process, theoretical modeling of fatigue failure in the design stages play an important role in development of new products.

Dictated by the guideline mentioned under Procedure "A" of ASTM D2992-06 [7], the certification practice of GFRP pipes is in need of a series of fatigue tests on at least 18 samples categorized under qualification tests. The pipe samples are exposed to cyclic internal pressure at several different levels whilst cycles to failure are measured [8]. Cycling rate is adjusted to at least 25 ± 2 cycles per minute [8] and pressure values are chosen in a manner to ascertain a distribution of failure points ranging from 1000 to 15,000,000 cycles [7]. The costly experimental setup and the lengthy duration of tests have turned the certification procedure of GFRP pipes into a very challenging issue practically. Therefore, simulating fatigue phenomenon on GFRP pipes is an essential task prior to a mass-production establishment in order to evaluate the performance of GFRP pipes in the design stage. Performing a review on literature, it can be seen that fatigue analysis of Glass-Fiber Reinforced-Polymer (GFRP) pipes are just limited to experimental observations [9–20].

The present research focuses on simulating fatigue phenomenon on a GFRP pipe using theoretical modeling. A brief review is conducted on the developed fatigue modeling techniques in the preceding section and a proper approach is chosen as the

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core part of simulation process. The suitability of selected method for the purpose of fatigue analysis of GFRP pipes is evaluated comparing the estimated lifetimes with available experimental data on a specific GFRP pipe, afterwards. Due to the limited available experimental data, Taguchi method [21] is employed as a virtual laboratory to extract required data for theoretical fatigue modeling in conjunction with reported lifetimes for GFRP pipes in literature . Finally, Simulating experimental practice regulated by normative standards [7,8], the fatigue lifetimes of an industrial GFRP pipe subjected to different levels of cyclic internal pressure are theoretically predicted as a case study.

2. A brief review of fatigue modeling in composites

Developed fatigues models for the composite materials can be classified into four main groups based on their core competency: (i) fatigue life models, (ii) phenomenological models for residual mechanical properties, (iii) physic-based methods, (iv) continuum damage mechanics approaches, and (v) progressive damage modeling.

The fatigue life models have been constructed on the basis of S-N curves or Goodman-type diagrams [2]. These models are not able to capture different failure mechanisms associated with composites [22–24]. They are also in need of cumbersome and extensive experimental data which should be repeated for any new lay-up configurations.

The studies constructed based on the reduction of mechanical properties are either accomplished by stiffness or strength reduction [25–38]. In this category, the residual strength/stiffness of specimens is measured during the cyclic loadings. Then a mathematical description of strength/stiffness degradation versus number of cycles is presented by curve fitting through experimental data. Therefore, these approaches are in need of extensive experimental characterization for each mechanical property.

Categorized under the physic-based techniques, a proper unit-cell of investigated composites is firstly chosen and its stress and strain fields are derived accordingly. At the level of macro, homogenized stresses are computed; however at the level of micro, stress components in the constituent materials are needed. Thus, a multi-scale analysis for predicting crack initiation and propagation and also stiffness reduction is performed using micromechanics models including stress-transfer mechanisms, shear-lag method and variational approaches [39–45]. The main drawback of these techniques can be found in their dependency to the ability of employed micromechanics models in analyzing various damages mechanisms associated with composites. Furthermore, the performance of these models is considerably limited by applied boundary conditions, loadings and various lay-up configurations.

In continuum damage mechanics approaches [46–52], a damage variable is defined and its growth is related to thermodynamics principles. Stiffness reduction is evaluated at lamina level and thus these methods can be applied to any lay-up configurations regardless of the loadings. In this category, some advance numerical techniques have been developed to predict crack initiation and crack propagation [53–56].

Progressive damage modeling techniques are usually a combination of failure criteria, fatigue life models and degradation rules for mechanical properties [2,4]. As a general routine, stress analysis is performed at each cycle of loading and the occurrence of failure is examined. If the failure takes place, the mechanical properties of the corresponding failed region is suddenly degraded, otherwise the mechanical properties of the whole material region are gradually degraded based on elapsed cycles. This process continues until the whole layer experience catastrophic modes of failure. As the main advantage, these techniques can take into account the history of loading. To the best knowledge of the authors, the most comprehensive form of progressive damage modeling technique for fatigue analysis of composite structures have been developed by Shokrieh and Lessard [57,58]. Called "Generalized Material Property Degradation Technique", the model consists of stiffness and strength degradation in all materials direction accompanied with normalized fatigue life assessment. The model can be used for any arbitrary lay-up configuration, since it is in need of characterizing the behavior of constitutive Uni-Directional (U-D) plies. Thus, full characterization of each configuration is not required. Despite the proper performance of the model in predicting fatigue lifetime of composites, the model is very time consuming. A more simple and facilitated fatigue modeling technique was constructed by Shokrieh and Zakeri [59] on the similar platform of previously developed model [2,4]. The modeling which is called "Cumulative Fatigue Damage Modeling (CFDM)" can estimate damage status in any composite laminated from the start of loading to the final failure of component. Thus, the fatigue lifetime of a composite component can be predicted. The developed modeling was successfully employed to predict the fatigue lifetime of a wind turbine blade using stochastic simulation [60]. The CFDM model is chosen in this study for the purpose of predicting fatigue lifetime of a composite pipe. This modeling is briefly elaborated in the next section.

3. Description of CFDM technique

The CFDM technique can simulate fatigue behavior in composites with any geometry and various lay-up configurations under general loading conditions using simple experimental data on U-D specimens subjected to uniaxial loading. This technique contains three major components as: stress analysis, damage estimation and stiffness degradation. These three components are executed cycle by cycle for evaluating the damage growth through an incremental procedure. Prior to fatigue simulation, initial material properties, maximum and minimum fatigue load and incremental number of cycles are defined. This phase is considered as model preparation.

The induced in-plane stress components in each layer are computed using Classical Lamination Theory (CLT) at the first stage. The in-plane stress components are obtained at each loading cycle and used in the next stage for damage evaluation.In the second stage, normalized damage estimation is utilized to assess the damage progression at each cyclic loading [59]. This model takes into account the role of stress ratio and stress level in damage accumulation and provides a rational trend of damage growth with respect to the number of cycles. The normalized damage parameter ($\tilde{D}$) is defined as below [59]:

$$\tilde{D} = f(\sigma, \sigma_{ult})D \tag{1}$$

where D is damage parameter and $f(\sigma, \sigma_{ult})$ is a function of stress state obtained through experimental data of Uni-Directional (U-D) specimens.A complete series of relationships between normalized damage parameter ($\tilde{D}$) and normalized number of cycles ($\tilde{N}$) has been established by Shokrieh and Lessard for a specific carbon/epoxy composites [57]. Normalized number of cycles is defined using below equation [57]:

$$\tilde{N} = \frac{\log(n) - \log(0.25)}{\log(N_f) - \log(0.25)} \tag{2}$$

where, n and N_f denotes number of applied cycles and cycles to failure, respectively. N_f is computed using following equation for a U-D ply subjected to uniaxial loading [61]:

$$u = \frac{\ln(a/f)}{\ln[(1-q)(C+q)]} = A + B\log N_f \tag{3}$$