Composite Structures 167 (2017) 96–102

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Stochastic fatigue analysis of glass fiber reinforced polymer pipes

Roham Rafiee

Composites Research Laboratory, Faculty of New Sciences and Technologies, University of Tehran, End of The North Karegar St., Tehran 1439957131, Iran

ARTICLE INFO

Article history:
Received 26 November 2016
Revised 25 December 2016
Accepted 28 January 2017
Available online 1 February 2017

Keywords:
Composite pipes
Fatigue analysis
Stochastic modeling
Progressive damage modeling

ABSTRACT

The fatigue lifetime of composite pipe subjected to cyclic internal hydrostatic pressure with variable amplitudes is considered. Progressive damage modeling technique is utilized on the basis of stiffness degradation for monitoring damage progress in composite structure. The modeling which consists of three different phases as stress analysis, damage estimation and mechanical properties degradation is implemented in parallel with the random generation of fatigue loading pattern. All involved parameters defining the fatigue loading scheme, including maximum stress amplitude, mean stress amplitude and number of cycles are treated as random variables resembling real conditions of pipes in the operational field. Therefore, instead of deterministic fatigue analysis as a normal practice regulated by normative standards for the experimental analysis, full stochastic fatigue modeling is conducted. Obtained results are statistically analyzed and the probability of each estimated fatigue lifetime is reported.

1. Introduction

Outstanding and multifunctional properties of composite materials such as light weight, high strength and stiffness and more importantly their corrosion resistance have stimulated industrial centers to exploit the technology of composite materials in the infrastructure of countries, especially in the form of Glass Fiber Reinforced Polymer (GFRP) pipes for water and waste water transmission lines. Although they are considered as a promising alternative to traditional competitors like concrete, asbestos, polyethylene and steel pipes, their long-term performance is required to be characterized properly. GFRP pipes are expected to sustain their mission during a period of 50 years [1], thus evaluating their long-term performance is of great importance in the early stages of their design process assuring the conformity of products with the requirements of the international standards [1,2]. The certification procedure of GFRP pipes also necessitates conducting a series of long-term qualification tests [2–4]. In one category of these long-term tests, a series of long-term hydrostatic tests is conducted to evaluate the long-term mechanical performance of GFRP pipes either from creep or fatigue viewpoints [2]. In the former, pipe samples are subjected to constant internal pressures while in the later cyclic pressures are applied to the pipe samples. Measured up to 10,000 h, the obtained time-to-failure data points are extrapolated till 50 years using a regression analysis to estimate the working pressure of GFRP pipes at the end of design lifetime [2]. Analyzing long-term pressure of a commercial GFRP pipe is one of the most challenging issues for industrial centers due to the cumbersome qualification examinations required in certification procedure.

Conducting a literature survey on performed studies in the field of GFRP pipes [5], it can be seen that in spite of performed theoretical and/or experimental investigations on the long-term behavior of GFRP pipes from creep viewpoint [6–16], very limited attempts have been done in the field of fatigue analysis of GFRP pipes [17–21]. Following the reflected procedure A in ASTM D 2992 [2], almost all conducted investigations on the fatigue analysis of GFRP pipes have been performed experimentally [17–20]. The fatigue behaviors of GFRP pipes in the form of S-N curves have been presented and different observed failure modes in the form of whitening, leakage initiation and burst failure were reported at various applied internal pressure levels [17–20]. Recently, Rafiee and Eslami [21] have theoretically simulated fatigue phenomenon in a GFRP pipe using progressive damage modeling. Resembling reflected test procedure in ASTMD D 2292 [1], they have also estimated the fatigue lifetime of an industrial pipe subjected to alternating hydrostatic pressure with various stress levels [21].

Dictated by international rules and regulations [2], deterministic procedure is employed for experimental fatigue analysis of GFRP pipes wherein maximum and minimum amplitudes of loading are constant. Subsequently, obtained test reports are interpreted as qualification examination and realistic fatigue lifetime of the GFRP pipes cannot be estimated. This article deals with the fatigue analysis of GFRP pipes subjected to cyclic internal pressure with variable amplitudes in accordance with the realistic

E-mail address: Roham.Rafiee@ut.ac.ir

http://dx.doi.org/10.1016/j.compstruct.2017.01.068
0263-8223/

nature of GFRP operational conditions. In contrast to the constant amplitude loading pattern reflected in ASTM D2992-06 [2], the main sources of randomness in fatigue loading of GFPR pipes are identified and thus variable amplitude loading schemes are randomly generated. Consequently, stochastic fatigue modeling is implemented originated from experienced random loading spectrum during the service lifetime of GFRP pipes. Appropriate progressive damage modeling is stochastically implemented to predict fatigue lifetime of GFRP pipes under practical operational conditions. Therefore, the capability of GFRP pipes to sustain their mission is evaluated from the fatigue point of view. The remaining of the article is organized as it follows: The accumulated fatigue damage modeling procedure which is employed as the core component of stochastic simulation is briefly explained in Section 2. Then stochastic implementation of the fatigue modeling procedure is outlined in Section 3 taking into account identified random variables. Finally, results followed by discussion are presented in Section 4.

2. Cumulated fatigue damage modeling

Cumulated Fatigue Damage Modeling (CFDM) which is originally developed by Shokrieh and Zakeri [22] is the simplified version of the "Generalized Material Property Degradation Technique" developed by Shokrieh and Lessard [23]. Classified under the progressive damage modeling techniques, CFDM is able to predict final fatigue life of a composite structure by estimating damage status at any stress level and number of cycles from the beginning of loading to the final failure. The capability of CFDM to predict fatigue lifetime of a full-scale composite structures have been previously investigated [21,24]. Recently, CFDM was successfully employed to predict fatigue lifetime of GFRP pipes subjected to the constant amplitude fatigue loading by Rafiee and Eslami [21]. It was also stochastically implemented to predict the fatigue lifetime of a composite wind turbine blade [24].

CFDM consists of three main parts: stress analysis, damage estimation and degradation of material properties.

2.1. Stress analysis and damage estimation

Stress analysis can be performed using either CLT [25] or FEA depending on the complexity of the stress distribution. For the specific purpose of this study CLT is employed since GFRP pipes are subjected to open-ended hydrostatic test and uni-axial hoop loading is governed.

Simulating cycle-by-cycle fatigue behavior of laminate under general loading condition, generalized damage estimation technique is employed [22]. In this technique, damage progression is related to the number of cycles taking into account the role of stress ratio and stress level [22]. For this purpose, a normalized damage parameter is defined as [22]:

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

where D is damage parameter and $f(\sigma, \sigma_{ult})$ is a function of stress state determined using experimental data of Uni-Directional (U-D) specimens. A complete form of $f(\sigma, \sigma_{ult})$ for carbon/epoxy composites subjected to longitudinal, transverse and shear fatigue loading is presented based on experimental data as below [22,23]:

$$f_L(\sigma, \sigma_{ult}) = S^m(1 - S)^{m-1}(1 + 3.1mC_L) \tag{2}$$

$$f_T(\sigma, \sigma_{ult}) = (1 - S)^{2m-1}(1 + 3.1mC_T) \tag{3}$$

$$f_S(\sigma, \sigma_{ult}) = 2.79S^m \tag{4}$$

in which [23]:

$$S = \sigma_{\max}/\sigma_{ult}, \quad m = S(S-1), \quad C_L = \sigma_c/\sigma_t, \quad C_T = \sigma_t/\sigma_c \tag{5}$$

where $S = \sigma_{\max}/\sigma_{ult}$ is ultimate strength. σ_t and σ_c stands for tensile and compressive strength, respectively.

The normalized damage parameter ($\tilde{D}$) is obtained based on normalized number of cycles ($\tilde{N}$) using relationships fully constructed by Shokrieh and Lessard from the beginning of loading till final failure ($\tilde{N} = 1$) [23].

Normalized number of cycles is also obtained using below equation [23]:

$$\tilde{N} = \frac{\log(n) - \log(0.25)}{\log(N_f) - \log(0.25)} \tag{6}$$

where, n and N_f stands for number of applied cycles and cycles to failure, respectively. N_f is computed using following equations [22,26]:

$$u_L = \frac{\ln(a/f)}{\ln[(1-q)(C_L+q)]} = A_L + B_L \log N_f \tag{7}$$

$$u_T = \frac{\ln(a/f)}{\ln[(1-q)(C_T+q)]} = A_T + B_T \log N_f \tag{8}$$

$$u_s = \log\left(\frac{\ln(a/f)}{\ln[(1-q)(1+q)]}\right) = A_S + B_S \log N_f \tag{9}$$

Eqs. (7) and (8) is used for fiber and matrix directions, respectively, while Eq. (9) is used for shear direction. The reflected parameters in Eqs. (7) to (9) are:

$$q = \sigma_m/\sigma_t, \quad a = \sigma_a/\sigma_t, \quad \sigma_m = \frac{(\sigma_{\max} + \sigma_{\min})}{2},$$
$$\sigma_a = \frac{(\sigma_{\max} - \sigma_{\min})}{2} \tag{10}$$

Reflected in Eqs. (7) to (9), u's and f are curve fitting parameters [23]. A's and B's are curve fitting parameters associated with normalized life curves.

It has been mentioned that Eq. (8) is not very accurate when the measured fatigue life is less than ($N < 10^3$) [26]. This problem becomes more pronounced when the dominant failure mode in pipe and vessels is leakage failure mode arisen from crack accumulation [27]. Taheri et al. [27] have mentioned that Eq. (8) is not valid for the fatigue life less than ($N < 10^3$). They have improved the current model to overcome this shortcoming [27].

2.2. Material degradation

Two sets of material degradation rules are used as gradual and sudden degradation rules. The former is taken into account while no failure is realized and the later is effective when failure happens. It should be pointed out that in the employed progressive damage modeling technique, each cracked ply is simply replaced with an intact ply with reduced mechanical properties. Although one can use advanced numerical techniques to predict crack initiation and crack propagation, in this approach the influence of induced crack due to fatigue loading is taken into account by reducing mechanical properties as an alternative approach. Categorized under the continuum damage mechanics, some advanced numerical techniques can be found in literature concentrating on predicting crack initiation and propagation [28–33].

2.2.1. Gradual degradation rules

For the sake of simplicity and reducing required runtime, stiffness degradation strategy is chosen for gradual degradation of material properties. Thus we have:

$$E = (1 - D)E_0 \tag{11}$$