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Modeling creep in polymeric composites: Developing a general integrated procedure

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ABSTRACT

General integrated procedure for evaluating creep in polymeric composites is developed which is applicable to any arbitrary composite structures. Non-linear long-term creep phenomenon of composites is simulated on the basis of viscoelastic behavior of polymer. Limited short-term experimental measurements on pure resin are required to simulate creep evolution in composite laminates. The modeling procedure starts at lamina level and results are extended to the laminate level relying on incremental procedure. In each sub-step, the stress/strain distributions are updated in accordance with modified mechanical properties. Adaptive time step selection is developed to reduce required runtime for modeling procedure. The results of the theoretical creep evaluation are in a good agreement with available long-term experimental data for composite plates. A case study on cylindrical structure is also performed and obtained results are compared with published data. It is revealed that for the case of cylindrical structure taking into account variations of fiber orientations and cylinder radius arisen from creep evolution is of great importance.

1. Introduction

In recent decades polymer matrix composites have been received significant attention due to their outstanding properties including low weight, corrosion resistance, easy fabrication process and low maintenance. The utilization of composite materials in civil engineering structures has necessitated the prediction of their long-term mechanical performance. Polymeric materials and thus polymeric composites show a time dependent behavior arisen from viscoelastic/viscoplastic nature of polymers. Subsequently, investigating creep in polymeric composite plays an important role in development of their application in infrastructure sector such as pipes, tanks and vessels subjected to constant loading in a long period of time.

Experimental study of creep in composite structures requires a time consuming and costly experimental setup. Moreover, the whole experimental study should be repeated for any variation in materials and/or lay-up configurations. This has hindered industrial centers from developing new products due to the huge time and cost required for certification procedures regulated by international rules and regulations. As a consequence, modeling creep phenomenon in composite structures becomes an important issue for predicting service lifetime of composite structures subjected to long-term applications.

Some studies concentrated on time dependent behavior of composites and presented several modeling approaches [1–6]. In this group, failure evaluation is not considered and mechanical behavior of lamina/laminate of composite is investigated. Some investigations have focused on creep induced failure and strength degradation using experimental studies [7,8]. They have reported long term creep failure on the basis of available short term data using extrapolation.

The majority of studies in the field of evaluating creep in polymer matrix composites (PMCs), focused on characterizing short term linear creep behavior of composites and their polymers. In these studies researchers tried to present different empirical and/or rheological models for predicting short term behavior of single lamina. Applicability of these models is limited to the small range of composites and only for short term linear creep. Experimental observations for different polymers and their composites were the key factor in these studies [3,9–12]. Some investigations focused on nonlinear viscoelastic behavior of polymers and their composites while single layer has been analyzed [13,14].

TTSP is an accelerated life prediction methodology which is first applied to composites by Brinson et al. in 1978 [15] and later with his colleagues (Morris et al. 1980 [16]; Brinson et al. 1982 [17]; Hiel et al. 1983 [18]).

Simulating long term creep using short term experimental data, some researchers used superposition principles such as

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Time–Temperature Superposition Principle (TTSP) or Time–Temperature–Stress Superposition Principle (TTSSP) [9,12,19–21]. The majority of these studies focused on short fiber composites or a single lamina of long fiber composites.

Generally, for fiber reinforced polymer composites, creep is much more evident in polymeric matrix experiencing viscoelastic behavior in comparison with fiber. Thus, for long fiber composites, mechanical behavior along fiber direction is assumed to be elastic as matrix plays insignificant role in longitudinal direction. But, viscoelastic behavior is taken into account for both transverse and shear directions due to the major role of matrix in these directions. For the case of short fiber composites, creep can be observed in all directions. These composites can be assumed as an isotropic material. Thus, a single master curve accounting for long term creep behavior of composite is proposed for short fiber composites; while for shear creep, different sets of experiments should be performed.

Limited studies presented theoretical methods to predict long term creep in multi-directional laminated PMC composites due to the complicated modeling procedure of creep phenomenon in transversely isotropic materials.

Dilard et al. [22] presented a method to simulate and evaluate creep and creep rupture in Graphite/Epoxy laminate. In their model, creep of single plies is evaluated using a nonlinear viscoelastic model for single lamina. They used lamination theory to extend the results to multilayered composites. Tuttle and Brinson [1] presented a model to assess creep in multi-directional laminated composites. In their study, creep of lamina is estimated in single ply using the Schapery nonlinear model [5] and then using Classical Lamination Theory (CLT), creep at laminate level is evaluated.

Using a backward implicit method, Gramoll et al. [23] presented a stable solution technique for obtaining nonlinear viscoelastic state of composite laminates under plane loading. In their study Prony series is taken as viscoelastic model.

Guedes [6] proposed a CLT based method for predicting creep in composite multilayered plates. Schapery integral was used to account for nonlinear viscoelasticity and different loadings and boundary conditions were studied. Originated from classical plate theory, CLT is suitable for the specific geometry of plate without curvature due to its basic assumptions. Thus, the applicability of this research is limited to specific geometries. Furthermore, Dillard et al. [24] found that the effect of the free edge is more significant for long term compliance of laminates. It is very well known that CLT is not able to take into account the edge effect which becomes pronounced for narrow specimens.

More recently, Guedes et al. [2] used an analytical approach to predict creep in Carbon/Epoxy cylindrical structure and presented their method in a computer code named RESFLU. The Schapery model was used to predict nonlinear creep in single plies and 3D elasticity was used to predict creep in multidirectional laminated composite. Evaluating creep phenomenon using the theory of 3D elasticity, elastic constitutive relations are replaced with viscoelastic constitutive equations. Therefore, complex differential equations are required to be solved and exact solutions are only available for specific geometries.

Performing a review on the literature, it can be seen that among theoretical studies on evaluating creep in polymeric composites, no comprehensive model has been presented which can be used for different laminate configurations and geometries. The main goal of this article is to develop a general process for modeling creep phenomenon in polymeric composites in an integrated procedure. The novelty of the developed modeling is twofold: one it is not limited to any specific geometry as Finite Element Analysis (FEA) is employed for stress/strain distribution; and the other, it only needs limited short term experimental measurements for long-term creep evaluation.

2. Theoretical modeling

The overall framework of modeling consists of three main parts. First of all, creep modeling is conducted on a single ply. At lamina level, short term experimental results for compliance components of matrix are extended to long-term creep evaluation. Then, the outputs of long-term creep modeling of matrix are converted to the non-linear viscoelastic behavior of matrix. Afterward, the nonlinear viscoelastic behavior of matrix is fed into micromechanics to evaluate the creep in lamina. The outputs of creep evaluation at lamina level are extended in order to capture creep behavior of laminated composites. Different stages of developed modeling procedure are explained in proceeding sections.

2.1. Lamina creep modeling

As a general strategy at the lamina level, variable stress distributions and non-liner viscoelastic behavior are taken into consideration for creep evaluation. At lamina level, extracting short-term linear compliance members, obtaining long-term linear compliance components and deriving non-linear long-term compliance members are considered. The developed global viscoelastic model at lamina level can be applied to all layers as the main advantage. Therefore the accuracy of final creep evaluation for laminate highly depends on the accuracy of this model.

2.1.1. Short-term compliances of matrix

At the first stage, short-term creep experiments are conducted on pure resin. The simple creep-tension tests are carried out on dumbly shaped specimens of pure resin. Then, variations of compliances with respect to time are obtained. At this stage the durations of experiments are usually limited between one hour and 10 h [1,18,25]. Developed modeling procedure in this research is just in need of the short term experimental data.

2.1.2. Long-term compliances of matrix

Viscoelastic models obtained from short term experiments are usually bounded to evaluate creep for the duration of conducted tests or only a little further (by extrapolation techniques).

Over past two decades numerous studies have been done on various superposition techniques and their validity for different polymers in different situations. TTSP is the most widely accepted technique for extending short term results to the long term data for the linear viscoelastic behavior. This principle converts temperature effects into time dimension such that creep behavior of polymer in high temperatures is assumed to be equivalent to the creep behavior of polymer over longer periods of time at lower temperature. In other words, the long term creep response at low temperatures behaves almost the same as short term creep data at higher temperatures. Since long term creep is aimed to be predicted in this study, the linear viscoelastic model of lamina should be equipped with the capability of long term creep evaluation as well. The validity of TTSP application for the case of Epoxy resins as a thermosetting polymer and thermo-rheologically simple material was reported previously [25]. Thus, TTSP can be applied to the short term creep results of this resin. The outputs of previous section which are short term linear compliances of polymer are fed into TTSP to obtain long term linear compliance components, accordingly.

It is worth mentioning that a number of short term isothermal tests at different temperatures should be conducted on pure polymer specimens to provide a master curve in operating temperature. Afterwards, required constants for TTSP are extracted. Since TTSP is valid for linear viscoelastic region [19], isothermal tests should be performed in the linear region.