REVIEW OF FINITE ELEMENT ANALYSIS APPROACHES FOR CREEP MODELING OF THERMOPLASTIC COMPOSITE PIPING SYSTEMS

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ABSTRACT
Thermoplastic fiber reinforced polymer composite (TP-FRPC) pipes are gained attention in industry owing to their excellent corrosion resistance, high strength to weight ratio, high ultimate strain and favorable damping behavior. The high ultimate strain and damping behavior of the thermoplastic matrix protect piping from cracking and leakage when subjected to large deformations and dynamic loading. Despite the excellent mechanical properties, the inherent tendency of TP-FRPC to exhibit creep deformation as a result of continuous sliding of polymer chains in the thermoplastic matrix can negatively affect the life time and reliability of these structures. Gradual dimensional changes of a pipe caused by creep deformation is more pronounced at elevated temperatures where the thermoplastic matrix is softer. Thus, the analysis of such pipe structures to evaluate their short- and long-term creep behavior is essential. The present article reviews recent developments and approaches for finite element (FE) modeling of TP-FRPC structures. Typically, FE modeling is the technique of choice due to the potent formulation of this numerical technique that enable simultaneous simulation of complex geometries and advanced material formulations for anisotropic viscoelastic FRPCs. Firstly, linear and non-linear viscoelastic material models applicable to FE modeling are reviewed. Then, methods available to apply viscoelastic formulations to anisotropic FRPC structures are explored. Since only few works on creep modeling of viscoelastic anisotropic FRPCs have been reported in the technical literature, the objective of this review article is to discuss current techniques as well as potentially available approaches for FE modeling creep of TP-FRPC structures.

1 INTRODUCTION
An increasing demand for hydrocarbon resources requires the development of advanced reliable extraction and transportation techniques for oil and natural gas fossil resources [1]. Most of fossil resources, including crude oil, heavy oil, and natural gas are corrosive due to the existence of chemical compounds of carbon dioxide (CO_2), hydrogen sulfide (H_2S), organic acids, dissolved gases, salt water and ions such as Cl^- [1]. Thus, transportation pipelines, which are an indispensable part of the production process, are subjected to corrosion. In particular, if a pipeline is made of conventional steel, excessive material loss may occur [2]. Damage caused by corrosion may eventually lead to unpredicted leaks and ruptures with significant hazards to humans, substantial economic loss and environmental pollution [1]. To that end, the substitution of steel pipes with corrosion-resistant polymers is of interest. Polymer-based and especially fiber reinforced polymer composite (FRPC) piping systems are receiving increasing attention due to the excellent corrosion resistance of these materials and also their high strength to weight ratio that enables the design and fabrication of lighter structures [2].

The polymer matrix in a FRPC structure can be made from corrosion resistant thermoset or thermoplastic polymers [3]. In thermoset FRPC pipes, the matrix is made of a thermoset resin such as epoxy or bismaleimide for low and high temperature applications, respectively [4]. Thermoset FRPC pipes, which are typically fabricated by filament winding, possess the highest physical properties among commercially available composite pipe systems [3]. However, some inherent properties of the thermoset matrix may limit the application of these structures. Since the chemical reaction during the curing of thermosets is irreversible, thermoset FRPC pipes cannot be reheated for melting and fusion when needed, such as in design of pipe fusion joints and coupler connections. Moreover, thermosets are typically brittle, which is a principal factor that negatively affects the applications of these materials for piping systems. Pipes made with a thermoset matrix are typically rigid with little flexibility and are prone to cracking of the brittle matrix, especially when subjected to large deformations, dynamic or impact loading. For example, it was shown that in pressurized structures the formation of interconnected matrix cracks is responsible for leakage failure [5].

Although thermoplastic fiber reinforced polymer composite (TP-FRPC) pipes have lower strength compared to thermoset equivalents, cost advantages and some beneficial properties, owing to the use of a thermoplastic matrix, have made such piping structures an attractive choice for a variety of applications. In general, TP-FRPCs provide the potential for lower manufacturing costs, given the material's quasi-infinite shelf-life, basic storage requirements, and the re-meltability of the thermoplastic matrix. TP-FRPC pipes can expediently be manufactured by local heating of pre-fabricated reinforced tapes during a tape winding process, which, as opposed to wet filament winding of thermoset FRPCs, eliminates the need for curing and other post-treatment processes. Moreover, due to the viscoelastic behavior of thermoplastics, TP-FRPC pipes are considerably more resistant to dynamic loadings with better fatigue performance. In fact, the viscoelastic properties of thermoplastics can provide damping to minimize vibrations in piping systems in the oil and gas industry. Despite these attractive properties, the inherent tendency of TP-FRPC to exhibit creep deformation as a result of continuous sliding of polymer chains in the thermoplastic matrix can negatively affect service life [6]. Dimensional changes and realignment of fiber reinforcements caused by gradual creep in TP-FRPC piping systems can be significant. Creep effects are even more pronounced when the material is heated to elevated temperatures, for example, in the case of hot fluid flows or exposure to environmental heating sources such as sunlight [3].

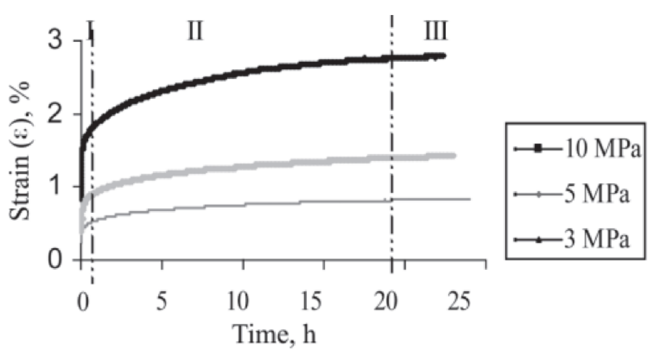
The time-dependent, viscoelastic behavior of polymers is responsible for creep and progressive deformation under a constant load, which can eventually lead to premature failure and leakage of the pipe body and/or coupler connections. The gradual expansion of pipe may lead to stress concentration at the edge of a coupler joint due to different creep rates of the components. Conversely, if a coupler creeps radially at a higher rate compare to the pipe, leakage and failure may occur. These examples emphasize the importance of assessing the creep behavior of TP-FRPC pipe and coupler components. To that end, analytical and numerical analyses that enable the prediction of short- and long-term creep behavior of TP-FRPC structures must be carried out when designing TP-FRPC piping systems. The determination of the extent and rate of deformation of TP-FRPC structures due to creep is not a trivial task, and the development of advanced models is required, given the anisotropic and non-homogeneous, and, in some cases, non-linear viscoelastic nature of these materials. Finite element (FE) modeling has been established as a reliable method for assessing the creep behavior of structures, owing to potent formulation of this numerical technique that enable modeling of complicated material formulations and geometries. However, the number of studies focusing on the development of FE models to predict long-term creep behavior of TP-FRPC pipe and coupler systems and FRPC structures in general is limited. The objectives of the present article are twofold: (1) The review conventional formulations available for FE modeling of creep of viscoelastic polymers, and (2) the study of techniques that enable viscoelastic formulations to be applied for modeling of anisotropic FRPC structures.

2 FE CREEP MODELING OF POLYMERS

Thermoplastic polymers may exhibit hyperelastic behavior, Mullins stress softening, plastic deformation, and viscoelastic characteristics owing to their specific chemical structure. The time-dependent response of polymeric materials can be divided into two groups, i.e., linear and non-linear viscoelasticity. In linear viscoelastic materials, the stress is proportional to strain at any given time [7]. In other words, the creep compliance is independent of the stress level. The creep compliance is defined as [8]

$$D(t) = \frac{\varepsilon(t)}{\sigma_0} \tag{1}$$

where $\varepsilon(t)$ and σ_0 are strain and the applied stress, respectively. The graphs in Figure 1a depict the strain-time curves of high density polyethylene (HDPE) for three different loading conditions. As shown in Figure 1b, after normalizing these curves with respect to the applied stress σ_0, the creep compliance of all curves collapse on a single curve, suggesting linear viscoelastic behavior within the studied loading regime. The significance of linear viscoelasticity in modeling of polymer creep is that the superposition principle applies [7], that is, each applied loading contributes independently to the final deformation, which considerably eases the determination of a final material response. Also, a linearity assumption may enable the application of a time-temperature-stress superposition principle for predicting the long-term creep behavior of polymers by data obtained from short-term creep experiments. Consequently, in FE modeling of polymers, an experimental evaluation of the linear or non-linear viscoelastic behavior is an important first step to be taken in order to select the correct FE material model formulation. In the following sections, recent material models developed for linear and non-linear viscoelastic materials for FE formulations are reviewed.



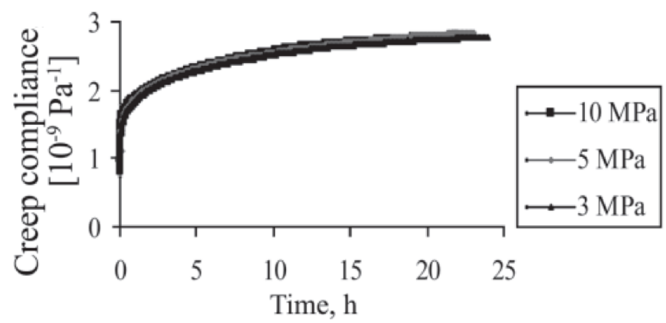


Figure 1. Compressive creep of HDPE for applied stress values of 3, 5 and 10 MPa;
(a) compressive strain and (b) compressive creep compliance versus time [8]

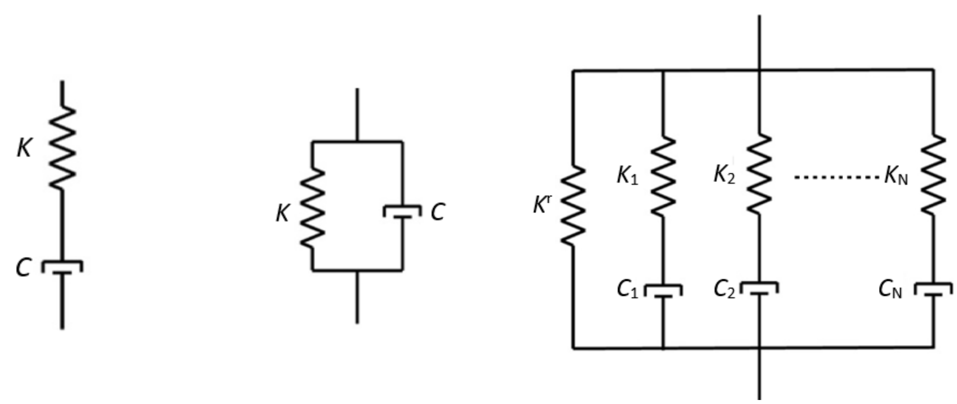
2.1 Linear Viscoelastic Models

Most of linear viscoelastic models are based on a set of linear spring and dashpot elements to represent the elastic and viscous behavior of the material, respectively [7, 9]. The springs and dashpots can be arranged in different configurations to model specific material behavior. The simplest arrangement of such models are the Kelvin and Maxwell models, see Figure 2. In most cases, the basic Kelvin and Maxwell models are inadequate for accurately capturing the mechanical response, and hence, advanced series and/or parallel configurations of dashpots and springs are required. One of the most widely used configurations for linear viscoelasticity in FE simulations is in the format of a spring in parallel with Maxwell elements, known as the generalized Maxwell model, as shown in Figure 2c. The number of Maxwell elements in this model is determined based on the mechanical response of the studied material. By the use of the superposition principle, the characteristic equation for the relaxation modulus can be described by the Prony series as [9]:

$$E(t) = E^r + \left(E^u - E^r\right)\sum_{i=1}^{N} w_i e^{\left(-\frac{t}{\tau_i}\right)} \tag{2}$$

where E, w_i, τ_i and N are the relaxation modulus, weight factors, relaxation time, and the number of Maxwell elements, respectively. The Prony series parameters can be determined by relaxation, creep and dynamic mechanical testing at controlled temperatures. Since the linear assumption is valid for this formulation, the parameters determined by either of the above-mentioned testing techniques lead to similar values for the Prony series parameters.

The creep deformation of polymeric materials when subjected to loading is due to the deformation and re-arrangement of molecular chains, minimizing localized stresses over time. Thus, the creep deformation of some polymers under loading may take a long time which requires long-term experiments for evaluation. This may pose problems for creep testing of TP-FRPC piping systems since manufactured pipe can only be tested for a limited timeframe that is in most cases much shorter than the actual service life. The solution to that problem is to employ the time-temperature-stress superposition that enables the use of short-term experiments for predicting the long-term performance. In this technique, the notion is to conduct creep or relaxation tests at raised temperatures or stresses to establish the relationship between time, stress and temperature. When knowing this correlation, the long-term behavior of a thermoplastic polymer under loading can expediently be predicted by conducting only a short-term test at higher temperature or stress level [7]. Accordingly, the second step in FE modeling the long-term creep behavior of a thermoplastic polymer material, such as a thermoplastic matrix FRPC piping system, is to evaluate the applicability of the time-temperature-stress superposition principle. When employing a time-temperature-stress superposition method, a master curve is generated by conducting a number of short-term isothermal tests to extract the required parameters. The fact that the time-temperature-stress superposition is only valid for a linear viscoelastic region region emphasizes the importance of carefully considering the linear viscoelasticity assumption for modeling the long-term creep behavior of polymer materials [10].



(a) (b) (c)

Figure 2. Spring and dashpot element model configurations: (a) Maxwell, (b) Kelvin and (c) generalized Maxwell [7, 9]

2.2 Non-linear Viscoelasticity

In non-linear viscoelastic materials, the creep compliance is a function of the applied stress. In such cases, the material models explained in Section 2.1 and the superposition principle do not apply. Although a number of material models have been developed to account for non-linear viscoelasticity of polymers in previous studies [7], only newly emerging advanced material modeling approaches applicable to FE modeling are discussed in this article.

2.2.1 Bergstrom-Bischoff Three Network Model

The three network model (TNM) was developed by Bergstrom and Bischoff and is an extension of the Bergstrom-Boyce material model [11, 12]. This advanced model is capable of incorporating the non-linear viscoelastic and plastic response of polymers when subjected to small and large strains. This model consists of three sets of springs and dashpots arranged in a parallel configuration network as shown in Figure 3. In this configuration, networks A and B capture the viscoplastic response and initial modulus of a thermoplastic. The formulation of these networks is based on the energy activation mechanisms of the amorphous and semi-crystalline domains. The network C is responsible for the large strain response of the material that is formulated based on the entropic resistance for molecular structure alignment. Details about the formulation of this model can be found elsewhere [12, 13]. The three network model can capture hyperelastic behavior, Mullins stress softening, plastic deformation, and non-linear viscoelastic response of thermoplastic materials as has been validated in some previous studies [12]. Accordingly, this model can be considered as a potent formulation for FE simulation of the non-linear viscoelasticity of the matrix in TP-FRPC structures. The challenging part for employing this model is calibrating the model parameters which may require advanced data fitting methods.

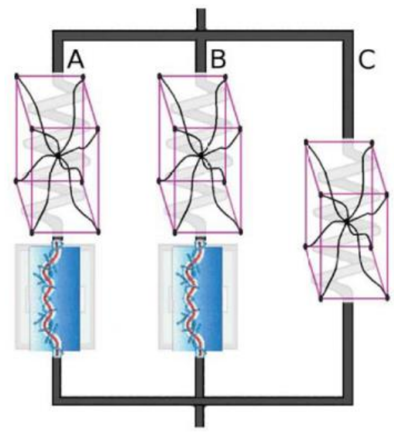


Figure 3. The configuration of elements in Bergstrom-Bischoff three network model [12]

2.2.2 Parallel Rheological Framework

The parallel rheological framework (PRF) model was developed by Hurtado *et al.* [14, 15] to predict the non-linear viscoelasticity of elastomers. The model is also capable of accounting for hyperelastic behavior, Mullins effect and permanent set caused by plastic deformation in elastomers. The PRF model has been implemented in the commercial finite element software Abaqus [14] (Dassault Systèmes, Vélizy-Villacoublay, France), and is based on the superposition of finite strain viscoelastic and elastoplastic networks that are arranged in parallel [15]. The arrangement of springs and dashpots in the PRF model is similar to the generalized Maxwell model shown in Figure 2c. The number of elements in the network are arbitrary and should be selected in a manner ensuring that the model incorporates the non-linear viscous behavior under large deformations. The elastic response in each network is defined by the hyperelastic strain energy potential to account for the non-linear large deformation of the elastomeric material. The load share of the material stiffness is defined by a material parameter known as stiffness ratio such that [16]

$$\sum_{i=0}^{N} S_i = 1 \quad (3)$$

where S_i is the stiffness ratio of i_{th} network. The network *r* (see Figure 2c) is the equilibrium with a purely elastic or elastoplastic formulation. If the modeling of the permanent set caused by plastic deformation is of interest, isotropic work hardening based on a scalar variable such as equivalent plastic strain can be defined for this network [15,16].

The viscoelastic response of the elastomer is obtained by defining the creep potential function as [16]

$$G = G(\sigma) \quad (4)$$

where σ is the Cauchy stress. The flow rule is defined as

$$D = \frac{3}{2\tilde{q}}\dot{\bar{\varepsilon}}\bar{\tau} \quad (5)$$

where $\bar{\tau}$ is the deviatoric Kirchhoff stress, $\dot{\bar{\varepsilon}}$ is the equivalent creep stain rate and $\tilde{q}$ is equivalent deviatoric Kirchhoff stress. $\dot{\bar{\varepsilon}}$ can be derived from one of the following creep law models [15, 16]:

a) Power law strain hardening model

$$\dot{\bar{\varepsilon}} = \left(A\tilde{q}^n\left[(m+1)\bar{\varepsilon}\right]^m\right)^{\frac{1}{m+1}}, \quad (6)$$

b) Power law model

$$\dot{\bar{\varepsilon}} = \dot{\varepsilon}_0\left(\left(\frac{\tilde{q}}{q_0 + a < p >}\right)^n\left[(m+1)\bar{\varepsilon}\right]^m\right)^{\frac{1}{m+1}}, \quad (7)$$

c) Hyperbolic-sine law model

$$\dot{\bar{\varepsilon}} = A(\sinh B\tilde{q})^n, \text{ and} \quad (8)$$

d) Bergstrom-Boyce model

$$\dot{\bar{\varepsilon}} = A(\lambda - 1 + E)^c(\tilde{q})^m. \quad (9)$$

In equations 6 to 9, $\bar{\varepsilon}$ is the equivalent creep strain, *p* is the Kirchhoff pressure and *A*, *m*, *n*, q_0, $\dot{\varepsilon}_0$, *C* and *E* are material model parameters. The selection of the creep law model depends on the material that is to be modeled and the type of available experimental data. Overall, the PRF model enables accurate modeling of the mechanical response of non-linear and linear viscoelastic elastomers that are subjected to large deformations. This model has been employed in a few recent studies for creep modeling of polymers, and the comparison of the numerical results with experiments has shown excellent agreement, which is attributed to the potent formulation of the PRF model [17, 18].

As was mentioned in section 2.1., the use of a time-temperature superposition principle is important in modeling of thermoplastic FRPCs since it enables the prediction of the long-term behavior of elastomers from short-term creep testing data. In a recent study, Ropers *et al.* [17] investigated the applicability of this principle to the PRF model. Interestingly, it was shown that the changes in properties by temperature variation can be modeled by employing the Prony series and the use of the material behavior at a reference temperature and appropriate shift factors for the viscoelastic elements [17]. Although in this study it was shown that for a specific polymer the time-superposition principle may apply for the PRF model, further validation by studying different elastomeric polymers is required.

3 FE CREEP MODELING OF FRPC STRUCTURES

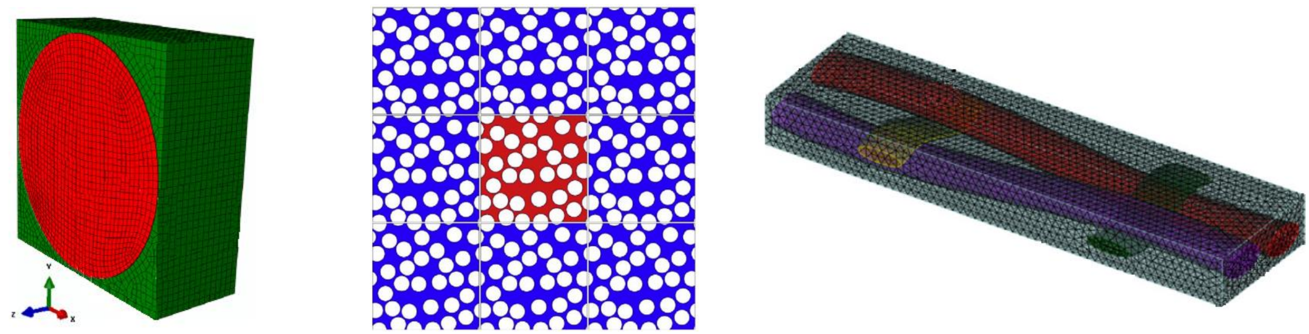
3.1 Anisotropic Viscoelastic Material Models

The models discussed in section 2 of this manuscript only apply to isotropic polymeric materials. However, the mechanical properties of TP-FRPC structures are anisotropic due to the existence of two phases of thermoplastic matrix and high-strength elastic fibers. In fact, previous studies have shown that the FRPC structures usually do not present any creep in the direction of the fibers due to the high strength and stiffness of the fibers compared to the matrix. Most of the creep in these structures occurs at the transverse and shear directions due to the major role that the matrix plays in these directions [10]. Due to the anisotropic properties in conjunction with the viscoelastic response, the development of characteristic equations that can model the viscoelastic response of FRPC is not a trivial task. To that end, while a number of previous studies have focused on developing linear and non-linear viscoelastic models for isotropic polymers, only a few works have been reported on creep behavior of anisotropic TP-FRPC [6, 10].

In some previous models, the classical laminate theory (CLT) was employed to extend the results from a creep model of a simple single lamina to multi-directional laminated composites [10]. In most of these studies, a creep model such as the Schapery integral was employed to model the creep of a single ply with a simple geometry. The CLT was then used to extend the results to multi-directional composite laminates. Due to the simplifying assumptions made, the applications of these models are limited to specific geometries and cannot be employed as a material formulation for FE modeling of any desired geometry. On the other hand, in a recent study, Zobeiry *et al.* [9] developed a viscoelastic material model for transversely isotropic FRPC structures by employing the differential formulation of the generalized Maxwell model for the linear viscoelastic formulation [9]. The characteristic equations obtained was used to develop a material subroutine for the general purpose finite element code Abaqus. Even though the model was restricted to linear viscoelastic analyses, it is possible to apply this model to desired geometries including reinforced anisotropic cylinders under internal pressure.

3.2 Multi-Scale Approach

Even though the development of new characteristic equations for describing the anisotropic behavior of FRPC is considered as a possible solution, in cases where he material exhibits a significant non-linear response, the development of such characteristic equations is complicated. On the other hand, with advancements in computer memory and speed, the use of multi-scale models has become more prominent for modeling FRPC structures. In multi-scale methods, a representative volume element (RVE) is generated. The RVE is a representative of the properties of the microstructure that is employed for modeling the larger scale model. The determination of the size of the RVE is dependent on the microstructural properties of the material to be modeled and should be selected large enough to reduce the computation cost while at the same time small enough to capture the key micro-sized features of the structure. For example, Figure 4 shows different scales of RVEs that have been employed in previous studies [19-21].



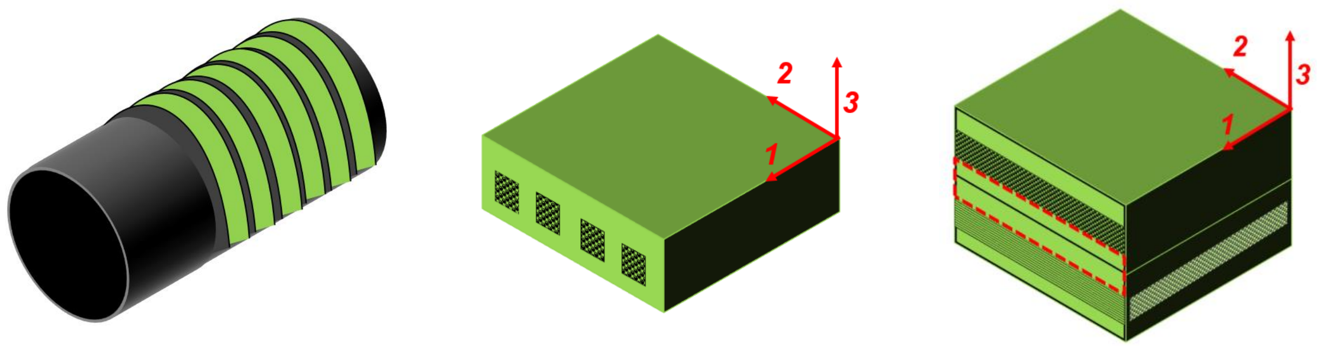
(a) (b) (c)

Figure 4. Different RVEs for multi-scale modeling; a) single fiber within the matrix [19], b) a number of fibers distributed by random sequential adsorption algorithm [20] and c) textile composite [21]

In multi-scale modeling, the stresses produced by the strain at each integration point of the RVE are averaged over the RVE and applied to the integration point of the larger scale FE model for the calculation of the stress field. The shape of the RVE in many problems is selected in such a way as to allow for periodic boundary conditions for reduced computation cost. While some recent studies have benefited from employing the multi-scale analyses for an in-depth study of fiber-matrix interactions and to evaluate the effect of fiber shape and fraction on the mechanical response of FRPC structures [20], creep modeling by a multi-scale approach is rather new. An example of such work is the recent research by Fliegener *et al.* [6] in which the creep behavior of a polypropylene-based glass fiber composite was modeled by a multi-scale technique. The results obtained showed the significant effect of the matrix nonlinearity on the effective creep behavior of the composite structure [6]. It was further shown that multi-scale modeling successfully performed the redistribution of stress within the composite material during creep loading and shifting of higher loads to elastic fibers [6]. The main advantage of multi-scale modeling the creep behavior of TP-FRPCs is that the material models applied to the matrix and fibers are defined separately and, for that reason, the development of complex anisotropic material models may not be required. In other words, the isotropic viscoelastic material behavior can be applied for the matrix while the fiber reinforcement is modeled with a simple elastic formulation. The overall accuracy and computation cost of this method is highly dependent on selected RVE as representation of the micro-scale of the material. Although multiscale techniques are considered promising, the question remains if such FE modeling techniques can be applied to complex geometries of large-scale structures such as TP-FRPC pipe-coupler systems.

3.3 Simplifications based on Geometry and Boundary Conditions

The methods discussed in sections 3.1 and 3.2 allow for the development of models that can accurately capture the creep behavior of FRPC structures. However, development of appropriate FE models is rather complex and may also impose significant computational cost for solving. On the other hand, in some engineering problems, based on the boundary conditions it may be possible to incorporate some simplifying assumptions with minimal error. For example, in a recent study, Ropers *et al.* [17] employed the isotropic PRF model for a FE simulation of the bending of woven textile reinforced thermoplastics. In this study, the TP-FRPC was assumed to be an isotropic material since the loading applied only produced bending stresses in the direction of the fibers. Similarly, in modeling of the creep of TP-FRPC piping structures, certain assumptions and simplifications can be made to enable the use of simpler models. For instance, considering the creep evaluation of TP-FRPC pipe made by winding fiber reinforced thermoplastic tapes (see Figure 5a), the modeling approach can be simplified based on the microstructural features and type of the applied loading and boundary conditions. In multi-scale modeling of FRPC piping structures, if the fibers are accumulated in localized areas within the winding tape as shown schematically in Figure 5b, a larger scale RVE representing a group of fibers rather than a single fiber may be developed to reduce the computation efforts. This assumption is based on the fact that the displacement of fibers that are grouped together may be negligible compared to any displacement of the group cause by creep deformation of the matrix. On the other hand, if the micro-structural evaluation of the composite reveals a cross section consisting of distinct layers of densely packed fibers in matrix and polymer rich zones similar to Figure 5c, the model may be simplified by considering reinforced non-viscoelastic and viscoelastic layers of matrix. In Figure 5c the viscoelastic region is framed with dashed red lines. These assumptions are warranted based on the fact that in a dense structure of fibers, the creep between the fibers may be negligible compared to that of a thermoplastic layer that is bonded to the reinforced layers.



(a) (b) (c)

Figure 5. a) Thermoplastic FRPC pipe wound by pre-fabricated fiber reinforced tapes, b) fibers and matrix configuration in fiber reinforced tape and c) fibers and matrix configuration in bonded fiber reinforced tapes

4 CONCLUSIONS

In this study, recent FE modeling approaches to evaluate the creep behavior of polymer composite structures with focus on thermoplastic FRPCs was reviewed. It was shown in this study that due to complexities associated with modeling formulation of non-linear viscoelasticity, the first step in FE modeling of polymers is to validate the linear non-linear viscoelasticity by experiments. The generalized Maxwell model that can be formulated by Prony series was introduced as the linear viscoelastic model of choice in FE modeling. Since the determination of parameter for the evaluation of long-term creep behavior by experiments is time-consuming, the use of the time-temperature-stress superposition principle was recommended. This approach enables the use of data obtained from short-term creep testing for evaluating the long-term creep behavior. On the other hand, the three network model and the parallel rheological framework model were introduced as techniques applicable in FE modeling and capable of accounting for non-linear viscoelasticity of polymers and elastomers. The parallel rheological framework model may apply to FE modeling of a broader range of polymers due to its potent formulation and also flexibility in selecting different creep law models.

The review of the literature revealed that even though a number of studies have focused on developing linear and non-linear viscoelastic models for isotropic polymers, only a few works are available on modeling creep behavior of viscoelastic anisotropic thermoplastic FRPCs. The development of new characteristic equations by the use of differential or integral formulations is recommended for future work. Multi-scale approaches were also introduced as a potential solution for FE creep modeling of FRPCs. However, only limited work has been done in this field and the study of selecting a proper RVE for development of large-scale models such as FRPC pipe-coupler connections is recommended for future research.

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