METHODS FOR THE SERVICE LIFETIME PREDICTION OF COMPOSITE MATERIALS UNDER STATIC LOAD

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Abstract

Unidirectional fiber reinforced composite materials are becoming more interest in different fields of application, since the last decades also for reinforcement elements in concrete constructions in the civil industry. For a safe and durable usage of such composite materials, the material long term behavior and the service lifetime must be predicted. The present paper gives an overview of selected accelerated testing methods to evaluate the service lifetime of continuous fiber reinforced composite materials under static load. Based on short term creep or creep rupture tests in combination with the principle of time-temperature superposition it is possible to predict materials long term creep behavior within short testing times. In this work, the possibilities and restrictions of classic creep and creep rupture tests as well as the Arrhenius theory and the principle of time-temperature superposition especially for continuous fiber reinforced composites is given.

1. Introduction

Composite materials, consisting of a thermoset polymer matrix system and continuous reinforcement fibers, are becoming more interest in different fields of application. Due to their high specific strength and purposeful resistance against different environmental influences and chemicals, these composite materials are suitable for commercial usage in highly loaded reinforcement elements in concrete constructions for the last fifteen years [1,2]. For a safe and durable usage over the whole lifetime of reinforced concrete parts, the mechanical properties of the reinforcing elements, as well as the time dependent decrease of these parameters must be known. Considering the service lifetime up to one hundred years, accelerated test procedures and concepts for lifetime prediction must be known and used [3].

Composite materials with the special focus on usage in the construction industry are subjected to a broad range of various loads. Environmental influences like wet or alkaline conditions, different mechanical loads and also thermal stresses form a complex loading profile [4]. These loading conditions might not lead to immediate material or component failure, but over the whole lifetime the accumulation of various load induced damage effects will result in a certain decrease of the material properties which finally might lead to an ultimate failure of the component itself [5]. For fiber reinforced structural components the usage time normally exceeds the testing time of mechanical test

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procedures by far, so accelerated test methods and extrapolation concepts for the estimation of the long term material behavior up to the ultimate service lifetime are necessary [6]. The acceleration of experimental tests are achieved by elevating the test temperatures, increasing load levels and moreover, test procedures also can be performed under consideration of application relevant environmental conditions, for example by test arrangements immersed in acid or alkaline media [7,8]. However, physical and chemical aging reactions are not and must not be directly influenceable by increased test parameters. So accelerated test procedures require test parameters close to the real service conditions, but nevertheless all accelerations have certain limitations in the accuracy of the prediction [9,10].

2. Prediction methods

This section shows an overview of various available test and evaluation methods to describe the long term behavior of polymeric materials which also can be applied to estimate the service lifetime of unidirectional reinforced composite materials. All of these techniques require specific arrangements regarding the corresponding test equipment and testing times and also have to be selected by the experimental effort and the requested results. For experimental tests up to ultimate failure under tensile stress, fiber reinforced plastics in the civil industry require test forces up to several thousand Newton, on the other hand tests have to be examined for extended periods of time, due the limitation of the extrapolation ranges.

2.1. Arrhenius equation

The lifetime prediction by Arrhenius is based on the Arrhenius equation, which states that chemical reactions and physical processes like aging and mechanical reduction processes take place more rapidly in polymer materials at higher temperatures [10]. This effect can be useful if it is ensured that the same aging mechanisms act on the material at higher temperatures. For the experimental lifetime prediction by this method, a two-stage procedure has to be performed. In the first step, materials have to be stored in application relevant environmental conditions at elevated temperatures for different periods of time. It has to be ensured, that no physical transition range is between the maximum storage temperature and the service temperature [8,11]. After storage at elevated temperature, a characteristic mechanical material property such as elastic modulus or tensile strength has to be determined in short term tests and displayed as a function of storage time (Fig. 1) [5,12,13]. Interpolations between these single measured data points represent the time dependent material behavior at the corresponding storage temperature. A defined material property value like fifty percent residual strength is the basis for the Arrhenius plot, illustrated in Fig. 2. The slope of the Arrhenius curve indicates the activation energy, which can be seen as a parameter related to the temperature, degradation of materials and material response to environmental agents [14]. Extrapolation of the graphed Arrhenius curve to application relevant temperature provides information on the maximum usage time for the previous defined material property value. The Arrhenius method was used by Davalos et al. [14] to describe the long term behavior of glass fiber reinforced plastics in concrete environment by investigation of the reduction of tensile strength of bar shaped specimens. They also showed various activation energy levels for different types of fiber and matrix combinations under different exposure conditions, which promise a usability of composite materials as concrete reinforcement, however with a significant reduction in tensile strength over the service time. GangaRao et al. [15] showed further, that the time to reach different tensile strength levels at composite specimens immersed in cement representative pH solution does not influence the value of the activation energy, which means, that in this case there is no changing in the aging mechanisms over the storage time [5].

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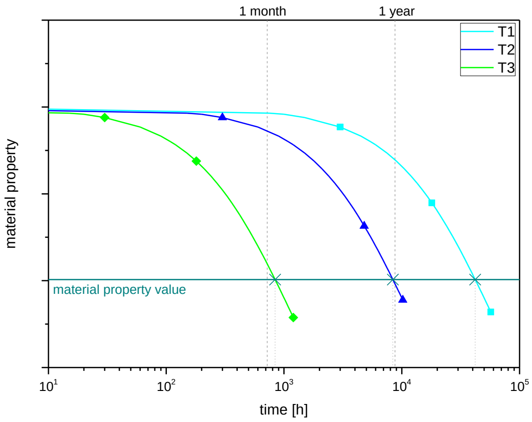

Figure 1. Schematic illustration of long term behavior of material properties, for example tensile strength (according to [5]).

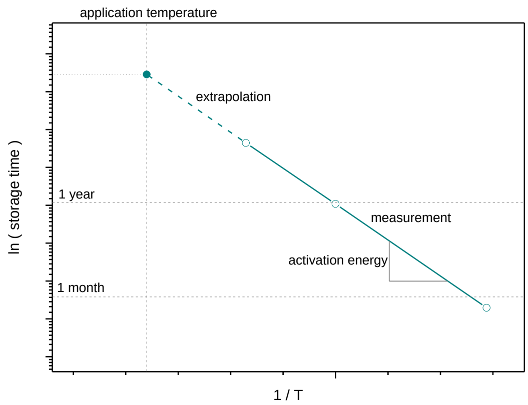

Figure 2. Schematic Arrhenius plot.

2.2. Creep extrapolation

Creep tests are a classic test procedure to characterize the long term behavior of polymer materials. Due to their low viscoelasticity composite materials with unidirectional fiber reinforcement show a slow but continuative deformation under constant stress, which is primary based on time dependent changing of the mechanical properties of the polymer composite matrix and accumulation of micro damage of the fiber matrix bond over the loading time [16,17]. Whereby common reinforcing fibers for high performance composites can be assumed with a good approximation as not creeping [16]. However on the other hand is the creep performance of the whole composite influenceable by the used fiber types as shown in the PhD thesis of Scheibe [18]. At special materials for the usage in civil industry Scheibe observed that glass fiber reinforced composites showed a creep deformation twice as high compared to pre-tension-steel over 1000 hours at a loading level of 50 percent of the short term tensile strength. On the other hand composites based on carbon fibers showed at that low stress level only marginal creep deformation within the same testing time [8,18,19]. Due to their small viscoelastic deformability continuous fiber reinforced composites show a short primary creep period, followed by a linear increase of the creep deformation over years in the secondary creep stage [20]. This effect also

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has been observed at long term creep tests performed by Meier et al. [21] at filament wound E-glass fiber reinforced epoxy box girders. They observed comparably high creep rates during the first 20000 hours, but after 25 years of testing by using a dead load arrangement the creep rates dropped to extremely low values [18].

One possibility of extrapolating experimentally determined creep curves to longer times is to describe the measured creep curves by a Findley model, provided that the deformation behavior remains the same as within the testing time [22]. For example, creep curves of epoxy or unsaturated polyester based composites with testing times over more than one year, can be extrapolated in a linear way up to two decades by using linear plotted creep curve as shown in Fig. 3 [8].

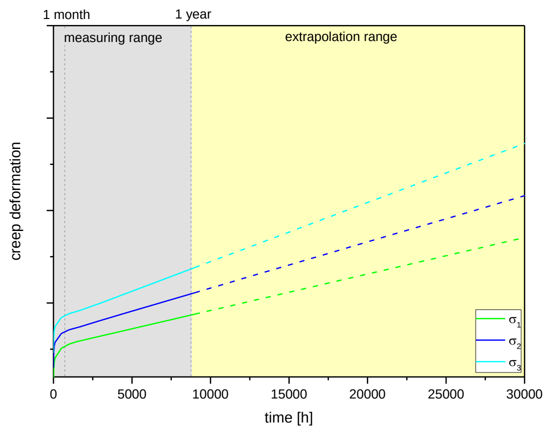

Figure 3. Schematic creep deformation (according to [20]).

The **time temperature superposition** is a further approach to extrapolate creep curves to longer loading times. This approach uses the principle, that the deformation of a viscoelastic material after long loading times can be described by the deformation at higher temperatures [23]. Based on creep curves with limited testing times, which are measured at different temperatures, it is possible to create a master creep curve for one reference temperature by fixing a measured creep curve (reference temperature) and shifting the creep curves for each temperature step to longer times [6]. Fig. 4 exemplarily shows the enlargement of the time range by shifting creep modulus curves, measured at the same loading level, at different isothermal temperatures. It is also possible to use creep deformation curves to determine the ultimate service lifetime at a specified minimum creep modulus value or a maximum creep deformation value. Important for the applicability of this method is, that the material behavior is influenceable by temperature and that higher test temperatures lead to higher creep deformations and further on to reduced creep modulus values. Kontou [24] discussed these important restrictions for unidirectional glass fiber reinforced composites based on thermoset epoxy-vinyl resin at different temperatures. In the field of marine usage of glass fiber reinforced composites Miyano and Nakada [25] showed that the creep rupture time of the flexural creep strength is influenced by temperature. That means that the creep strength behavior of the material can be described by a master curve with single data points measured at different temperatures. The limitation of this method is analogous to the Arrhenius equation. It has to be ensured that the material does not age differently at higher temperatures and the temperature may not be increased over a physical transition area [10].

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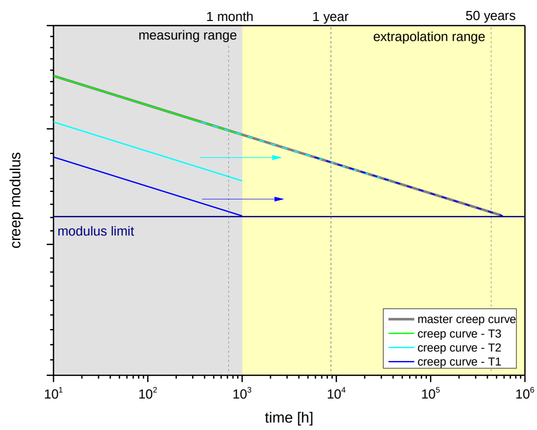

Figure 4. Schematic time temperature superposition.

2.3. Creep rupture extrapolation

Creep rupture tests are a special form of creep test, which are mainly used for polymers with low tensile strain at break. For the experimental realization no elongation measurement is required, the applied load and the measured stress-rupture time are determined for service lifetime prediction [26]. For the experimental realization, creep tests at different load levels at application-related environmental conditions have to be carried out up to ultimate specimen failure caused by static long term loading. The determined creep time and the applied stress level can be displayed in a double logarithmic diagram, as shown in Fig. 5. An extrapolation of these measured data points to higher time ranges provides the absolute load limit for the real operating times. Whereby a linear extrapolation of the experimental time range of 1.5 decades is permitted which requires testing times up to one year in the civil industry for common service life times of fifty years [1,8]. Robinson an Greenhalgh [27] used this test procedure to simulate the long term material behavior of glass fiber reinforced plastic rods in concrete representative alkaline environment, salt water and other media at room and elevated temperatures. The extrapolation of the measured test results up to a lifetime of 50 years showed a decrease of the tensile strength in the range of 50 percent and even more.

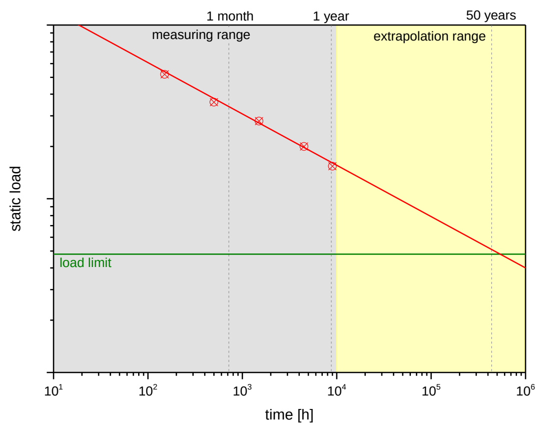

Figure 5. Creep strength values as a function of loading time and linear extrapolation up to a given load limit (schematically, according to [20]).

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The experimental test of unidirectional reinforced composite materials with commonly used geometries and fiber volume contents in the civil industry requires test forces up to several thousand Newton to reach a creep rupture in reasonable testing times. Therefore, in the sense of a reasonable and economical test setup, it will be helpful to decrease the test forces and do not test until the ultimate specimen failure. By the addition of an appropriate deformation measurement system, it will be possible to test until a definite creep deformation (Fig 6) or minimum creep modulus (Fig 7) as a criterion of the component failure. In this way, the determined creep times and the applied stress levels can also be displayed in a double logarithmic diagram (Fig. 8), analogous to Fig. 5. Again, it is possible to determine the absolute load limit for the chosen maximum deformation or minimum creep modulus in the requested operating time by extrapolation of the measured data points.

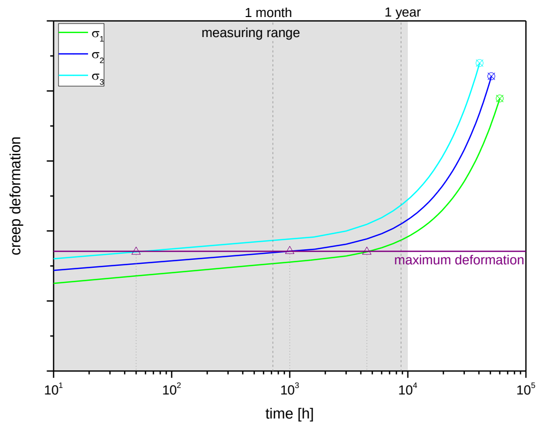

Figure 6. Schematic illustration of the maximum creep deformation.

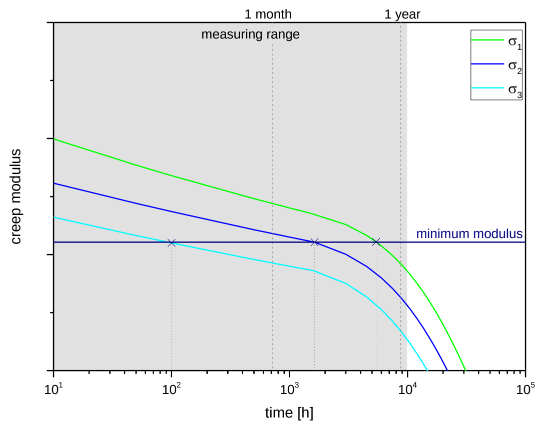

Figure 7. Schematic illustration of the minimum creep modulus.

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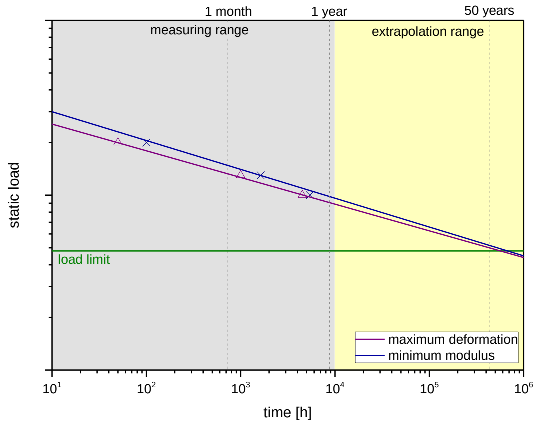

Figure 8. Creep stress values as a function of loading time and linear extrapolation up to a given load limit (schematically).

3. Conclusions and outlook

The present paper shows a short review of selected testing methods and acceleration approaches to describe the mechanical long term behavior of continuous fiber reinforced composite materials, focusing on the usage of this materials class in civil industry. In general, the cited investigation examples show the general usability of these presented methods to describe the long term material behavior of unidirectional reinforced composites. In all of these methods it always has to be considered that the description of aging and long term behavior of polymer composites is a complex topic [8]. Physical and chemical effects can act synergistic or antagonistic to the material behavior, so further investigations will be focused on improvement of time efficient prediction of mechanical long term behavior for continuous fiber reinforced composites close to service conditions. These comprehensive investigations will be based on specific high load creep tests at wet or alkaline environmental conditions and elevated temperatures.

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