A novel approach to evaluate lifetime of complex plastic applications
Part I: Short fiber reinforced plastics (SFRP)

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Abstract

Lifetime evaluation methodologies are gaining more focus and importance in the area of fiber reinforced engineering thermoplastics. Plastic applications are potentially subjected to harsh environments, where the lifetime of components can be significantly reduced. Failure due to fatigue and its consequent lifetime evaluation is particularly based on empirical studies, due to the interaction of multiple factors. The methodology proposed here based on 3D-optical techniques together with digital image correlations (DIC), establishes a generalized energy based fatigue model. The methodology is illustrated on a short fiber reinforced plastic (SFRP) specimen, typically used as a representative part in pressurized fluid applications. This fatigue model will include different influential parameters like R-ratio, pressure, temperature, and the presence of a weldline, which are seen as critical parameters for failure. The fatigue model is developed using algorithms with surface strain energy density (SSED) that acts as a damage parameter of the component lifetime.

Introduction

In many areas relevant to everyday life, such as automotive, engineering or transportation, components are exposed to strong cyclical or continuous load, and it is essential to ensure a high level of reliability. For modern industries, a lightweight construction is highly required, which often affects strength. Manufacturers want to design the service intervals to be as long as possible, therefore the use of quick test methods/solutions on components/parts is still a challenge that industries face.

Conventional failure of polymer objects on prolonged exposure to static and dynamic load (e.g. supporting structures, high-pressure pipes) limits their ultimate useful lifetime. Even though conceptually the present method can be widely used for static loads, this paper focuses on application, which leads to failure by means of dominant dynamic loads. Short fiber reinforced polymers (SFRP) are used widely in a variety of industrial sectors due to their favorable strength to weight ratio. Even though fatigue behavior of SFRP has been investigated in past decades based on Stress- life (SN), Strain-life (EN), or energy models (WN), research is focused on fatigue behavior under constant load conditions or simple geometries [1, 2, 3, 4]. This includes load parameters such as load ratio, temperature, multi-axiality, etc. Even though studying these effects under fixed conditions is an option, this is not a cost-effective approach, because of the large number of experiments required at each test condition. Currently available state-of-the-art approaches are often not application oriented and are, therefore, difficult to translate into widely applicable approaches (a few examples of application complexity are shown in Figure 1).

As an example of traditional fatigue models [5, 6, 7], concepts of local SN-curves were developed for polymers. Currently, overly conservative strain or stress based design criteria prevent the utilization of a faster characterization method [8]. SN-stress approaches are based on concepts, reflecting the effect of influencing parameters on fatigue life. In other words, for SFRP plastics, multiple parameters such as fiber orientation [9, 10, 11, 12], notches [13, 14], mean stress [15] and their superimposed interactions have to be considered. The challenge in these techniques is to find applicable material models that can describe material behavior under the different, abovementioned conditions, while minimizing the time, cost, and effort these tests demand. Nonlinear behavior of polymeric materials over long term is another limitation of the metal-based SN approach. Metals have linear-elastic behavior and material stiffness will not degrade/reduced until failure. In contrast, polymers have stiffness degradation as a function of time, which is investigated in detail in this work.

This paper proposes a potential solution to address these problems by introducing a generalized fatigue model based on a surface strain energy density (SSED) failure criterion. The surface strain energy density values are calculated based on optical 3D-full strain field measurements that can be correlated to the surface energy dissipation of the component [16]. However to arrive at surface energy or physical energy dissipations, normally radiographs, thermography, acoustic emission etc. are used [17, 18]. The motivation behind this paper is to consolidate the 3D-stereographic image with digital image correlation DIC techniques to analyze the surface damage accumulation on each cycle.

The goal of this paper is to establish a novel fatigue material model using SSED and to validate the material model on a more complex part.
Theory

SSED ($\Delta W_s$) is an abbreviation for surface strain energy density - which is a modified form of strain energy density - SED ($\Delta W$), a very well established fatigue parameter in literature [8]. Since the strain energy density values are obtained from an in-situ complete field of surface from the DIC systems, the abbreviation SSED ($\Delta W_s$) is used.

If we examine the stress-strain hysteresis curve we can calculate the total energy absorbed by the samples because of deformation, by finding the area under the curve, $\Delta W$. Generally, we define $\Delta W$, the strain energy density as:

$$\Delta W = \int \sigma \, d\varepsilon$$

Where $\sigma$ is the applied stress (MPa), $\varepsilon$ measured strain (%), which are the principal components. As the material is unloaded, the stress returns to zero but there is permanent deformation in the material. As seen in the schematics in Figure 2, only the strain energy density (marked as blue area, elastic surface strain energy density $\Delta W_{SE}$) is recovered and the rest (marked as orange area, dissipate energy loss $\Delta W_{SL}$). Therefore, if we assume the stress-strain cyclic response to be linear and elastic, the stress-strain curve will be a straight line. For most polymers, a non-linear visco-plastic deformation is observed. Strain energy density, $\Delta W$ can be studied based on either dissipated energy loss $\Delta W_{SL}$ (observed at low cycle fatigue - LCF) or $\Delta W_{SE}$ (observed at high cycle fatigue - HCF). In this work, SSED $\Delta W_s$ will be interpreted as damage parameter describing how much mechanical energy the SFRP can absorb under a visco-elastic and visco-plastic deformation.

$$\Delta W = f(\Delta \varepsilon \times \Delta \sigma)$$

This function depends on material properties [19]. Either single or double power law based on Morrow energy model [20] is examined for the fatigue model for various fatigue mechanisms where the relationship between fatigue life ($N_f$) and strain energy density ($\Delta W$) can be written as follows:

$$N_f^m \times \Delta W = C$$

Where $m$ is the fatigue exponent, and $C$ is material ductility coefficient. Similarly, a double power law model can be also formulated with two different coefficients of $m_1$ and $m_2$. The $m_1$ and $m_2$ exponents are used to represent the slope in LCF and HCF regimes respectively.

Experimental

Within this framework, various protocols were used during the fatigue experiments on pressurized components to generate a 3D stress state. These components are discussed based on experimental setup along with DIC. Nevertheless, the setup can also be used for any other loading apparatus and conditions that demand a long-term testing.

Material

The material selected is a SABIC NORYL™ FE1630PW resin, which is a PPO™/PS blend polymer, reinforced with 30% short glass fibers. This particular material class is chosen as it exhibits excellent corrosion properties, hydrolytic stability, high temperature resistance, low water absorption, and good mechanical performance for the application used in this study [21].

Test setup

To validate the methodology on application level, different fatigue tests have been performed on the pressure vessel (PV), subjected to internal water pressure with varying conditions like: pressure, $R$-ratio \([R = \sigma_{min} / \sigma_{max}]\), temperature (room temperature and elevated temperature), with/without weldline and at a constant frequency of 1 Hz. The PV samples are gated from side and top to bring in the effect of weldline and non-weldline effectively.
PV is an element level sample that represents a pressurized water/other fluid application. The detail of the validation test setup is shown in Figure 3. Strain measurement on full field, which is an important requirement for SSED calculation, is performed with a digital image correlation (DIC) system (see setup of DIC cameras in Figure 3, a).

**Fatigue evaluation region (DIC)**

The fatigue evaluation is performed by measuring the surface major strain (first principal strain) over the surface during the cyclic loading. The region to evaluate for fatigue depends on understanding the regions with largest surface strain or regions critical to failures.

For pressure vessels, the stress distribution in the form of hoop stress (hollow cylinder) is homogeneous and surface strain can be evaluated on any region (constant diameter regions). In case of complex parts, the region to evaluate can be identified using anisotropic modelling simulations [7]. This approach encourages a through-process-modelling (TPM) establishing a processing-morphology-property relation for SFRP materials. TPM process incorporates the influence of fibre orientation into the numerical calculations. If the TPM is not an option, investigations can be done with prior testing to identify the critical regions. These evaluation regions will change with each application and finding the right surface for analysing can become difficult as these often have complex shapes with more than one curvature.

![Fatigue evaluation region (DIC)](image)

**Figure 4: Surface strain on (a) PV gated from top without weldline (b) PV gated from side with weldline (c) closer view of the strain contour on the weldline**

Evaluation region for calculating the surface strain is an important criterion, demonstrated with an example of a weldline and non-weldline samples. For non-weldline samples, based on the homogenous principal strain vector and observed distribution, restricted region is selected as seen in Figure 4 (a). For weldline samples, the evaluation region is based on the location of the weldline (crack initiators) as seen in Figure 4 (b). The strain evolutions of these selected regions of the specimen are monitored along the lifetime until failure. When the weldline is encountered, a close view of Figure 4 (c), shows a high scatter, hence a larger area is selected over the weldline.

For the SFRP material investigated in this study, a constant strain amplitude $\Delta \varepsilon$ is observed over the lifetime, although the absolute strain value changes. Nevertheless, this indicates that no cyclic softening/hardening effects were observed during the strain evolution. Once the fatigue evaluation regions are analysed and the strain measurements are performed on the surface, a specific algorithm is used to evaluate the SSED.

**Differentiation of LCF and HCF**

With lower peak stress superimposed with variable factors like temperature, $R$-ratio, fiber orientation etc., the dissipated energy loss of material becomes minimal as seen in Figure 5. In other words, at HCF, surface energy loss $\Delta W_{SE}$ observed is minimal ~towards 300,000 cycles, thereby calculating the $\Delta W_{SE}$ will not be possible. Therefore the analysis has to be differentiated between LCF and HCF. At low cycle fatigue (LCF), higher surface mechanical energy loss $\Delta W_{SL}$ is dissipated (see Figure 5). Similarly, for elevated temperature, the lost loop energy gets higher, for the same stress amplitude.

In this work, the fatigue cycle covers both LCF and HCF, deformation energy $\Delta W_{SE}$, is used (marked in blue area in Figure 2) as a damage parameter for the fatigue model development. This parameter is denoted as elastic surface strain energy density $\Delta W_{SE}$. Another quantitative method to understand the cyclic effect differentiation between LCF and HCF is to find the cyclic damping according to Lazan [22, 23].

![Figure 5: Hysteresis loop showing the peak of stress amplitude (\(\Delta \sigma\)) and surface strain amplitude (\(\Delta \varepsilon\)) compared for different peak stresses related to cycles to failure (\(N_f\))](image)
The cyclic damping ($\lambda$) is defined as the ratio of dissipated energy (loop area) and the energy stored during an equivalent elastic loading taken as the area under loading.

$$\lambda = \frac{\Delta W_{SE}}{\Delta W_{SL}}$$  \hspace{1cm} (4)

Where $\Delta W_{SL}$ is the strain energy density loss and $\Delta W_{SE}$ is the elastic strain energy density (schematics in Figure 2).

The cyclic damping (according to Eqn. (4)), for various experiments are analyzed from initial cyclic loading phase until failure. The cyclic damping studied in this work revealed similar damping ratios during initial and final phase, even though cyclic damping ($\lambda$) is noticeably slightly higher during the final phase. When compared with the cycles to failure, the cyclic damping, presented similar behavior. Hence, the material behavior is expected to show similar linearity between cycles to failure for $\Delta W_{SE}$ and $\Delta W_{SL}$. Nevertheless, this might be an intrinsic material behaviour and will vary for different materials, an observation that has to be considered when applying this approach to other materials.

**Results and discussion**

In this section, the fatigue model of the pressure vessel (3D stress state) is discussed. As seen in Figure 6 (a) for the top-gated samples (without weldline), the experimental parameters on temperature and $R$-ratio were found to be in a normalized linear trend when compared with cycles to failure. In Figure 6 (b), the weldline results are overlaid on the results of non-weldline sample (top gate). The effect of weldline presence also followed the same trend line like the non-weldline test samples. This could be due to the SSED values evaluated from synchronized stress- surface strain values from local hotspot regions. In other words, the effect of weldline influenced for a lower fatigue life, but followed the same mechanisms as that of non-weldline samples, as the implicit material properties were expected to drive the fatigue properties. Irrespective of the temperature or $R$-ratio or weldline presence, SSED $\Delta W_{SE}$, explained the fatigue characteristics and failure behavior in a PV.

Linear regression analysis is performed on the observed data points from all the experiments, which can be modelled either by a single or by a double power law Morrow model. A single power law based on Morrow model as seen in Figure 6 (b) from regression is analyzed. This single power law model accompanied all variable parameters of the experiment with $R$-squared value of ~ 0.93. Double power law based on modified Morrow model ($\Delta W_{SE} \cdot N_f$) is investigated bringing in the possible slope shift effects for region I and II in Figure 6 (a). The double power law was more accurate with $R$-squared value reaching up to 0.98.

In the field of pressurized pipes, researchers have been made in the past to understand distinct regions (I and II) with different failure processes [24]. This quite resembles the first two modes of failure mechanism. Some of the failure mechanisms expected in a pipe are 1. Accumulation of plastic strain, 2. Slow crack growth, 3. Chemical degradation. This investigation quite resembles the first two modes of failure mechanism [24]. The first mode (accumulation of plastic strain) and second mode (slow crack growth) here are distinguished as LCF and HCF. As seen in Figure 6 the different modes of failure mechanisms in a pipe, is well captured by elastic surface strain energy $\Delta W_{SE}$ based SSED.

![Figure 6. Pressure vessels SSED results for different temperatures, R-ratio, pressure levels (a) non-weldline samples- side gated (b) overlaid results of weldline samples – side gated](image)

**Conclusions**

- The SSED model proposed in this study normalized all load cases into one single curve unlike conventional fatigue models for polymers. Using SSED as a rapid model development tool saves a tremendous amount of time, cost, and effort. For instance if a PV is considered, a similar test using a traditional approach has to be done for six different parameters instead of one with that of SSED model.
• The fatigue model based on surface energy revealed a linear relationship with respect to log cycles to failure. Consequently, generalized models were established based on it and all variable parameters like temperature, R-ratio, weldline presence, pressure levels are collapsed onto a single or double power law.

• The methodology can potentially also be translated more generally to other situations, for instance where weldlines are encountered; although further appropriate validation is encouraged. In a first approximation, the local deformation due to fiber orientation on weld-line effect can be captured successfully by the fatigue model evaluation of this approach.

• The proposed methodology thereby can evaluate or predict the failure of physical parts/applications, by correlating to the surface energy dissipation (SSED). This allows customers to use the SSED along with the experimental setup as a quality assurance analysis on manufactured parts or in a lifetime prediction software. A detailed investigation of this is planned for the future works.

References


