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Fatigue life of carbon-epoxy laminated composites: combining thermo-mechanical analysis and residual strength model

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Résumé :

L'un des critères majeurs intervenant dans le dimensionnement de structures composites est la tenue à long terme sous sollicitation mécanique répétée. Deux difficultés importantes émergent dans le développement d'un critère de fatigue : (i) la prise en compte de la dispersion naturelle des résultats d'essais dans la détermination de la courbe de Wöhler (courbe S-N), (ii) la durée des essais de fatigue et le nombre important d'éprouvettes qui engendrent des coûts importants.

Concernant la première difficulté, Sendeckyj a proposé une approche basée sur l'évolution de la résistance du composite au cours du chargement cyclique pour déterminer une courbe de Wöhler et lui associer une probabilité de rupture [1]. L'identification de cette méthode requiert à la fois des données quasi-statiques (pour décrire la dispersion à l'aide d'un modèle de Weibull à deux paramètres) et des données de fatigue (pour l'identification du modèle de résistance résiduelle). Cependant, la campagne de fatigue nécessaire pour son identification s'avère longue et coûteuse.

Afin de réduire la durée et le nombre d'essais nécessaires à cette identification, une solution consiste à utiliser la méthode d'auto-échauffement [2]. Le protocole d'auto-échauffement consiste à estimer la courbe de Wöhler moyenne à partir de l'énergie dissipée déduite de mesures thermiques sur une unique éprouvette. Cette méthode permet donc de réduire drastiquement la durée de la campagne d'essais de fatigue. Cependant, ni la dispersion naturelle des essais, ni la partie correspondant aux faibles nombres de cycles, ne sont aujourd'hui estimées pour ces matériaux.

Le but de cette étude est de combiner ces deux approches (résistance résiduelle et mesures thermiques) afin d'identifier de façon rapide une courbe de Wöhler complète avec la dispersion associée. La durée de vie à grand nombre de cycles est estimée par le protocole d'auto-échauffement. La distribution de rupture est quant à elle estimée à partir des essais quasi-statiques.

Cet article détaillera cette approche couplée et présentera les résultats obtenus sur un stratifié composite en fibres de carbone et matrice époxy.

Abstract:

Long-term durability under repeated mechanical loading is a major criterion for design of composite structures. The development of a fatigue criterion faces two major difficulties: (i) the proposal of a load/life curve (S-N curve) describing the natural dispersion of the fatigue tests and (ii) the duration of these tests.

In order to deal with the first point, Sendeckyj proposed an approach based on a so-called residual strength that fits S-N curve and associates a failure probability [1]. The procedure to identify this model requires quasi-static and fatigue tests. This fatigue campaign could be large and time consuming.

A solution to decrease the duration of the tests consists in using a self-heating-based method [2]. The principle is to estimate a mean S-N curve from the thermal dissipation, inferred from temperature measurements on a single sample. This method reduces drastically the duration of the fatigue tests campaign. However, neither the associated dispersion nor the low cycle fatigue part is estimated for now for this class of materials.

The goal of the study is to combine the two approaches (residual strength and thermal measurements) in order to identify the S-N curve and the related dispersion. The fatigue lifetime for high cycles loading is estimated by the heat-build up protocol. Quasi-static tests and a few fatigue tests are used to estimate the failure distribution based on a two-parameters Weibull model.

The article will detail this approach and will present the results obtained on laminated composites carbon-epoxy manufactured from unidirectional plies and 2D-woven plies.

Mots clefs: Composite, Fatigue, Self-Heating, Residual Strength

1 Introduction

Fatigue campaigns are widely used to characterize long-term durability of materials and develop a fatigue criterion as it is a major concern in the design of structures. Such a campaign faces two difficulties: the natural scattering of fatigue tests that need to be considered in the estimation of the load/life curve (S-N curve) in order to get a sufficient degree of confidence in the estimation; and the duration and cost of these tests due to the determination of this natural scattering and the high cycles lifetime part. First, this study will present the Sendeckyj's approach as a solution to associate a failure probability to the S-N curve using a so-called residual strength. Then, the self-heating-based method will be presented as a solution to obtain a fast estimation of the mean S-N curve by using a single specimen. Finally, the combination of both methods to obtain a fast estimation of the S-N curve associated to a failure probability will be considered.

2 Material

The material used in this study is a carbon-epoxy laminated composite. This laminate is composed of unidirectional plies and 2D-woven plies. Composite plates, made of pre-impregnated plies, have been assembled by the author and cured under autoclave cycle.

Specimens of 250 mm x 25 mm x 3.6mm have been drawn in a bigger plate. These dimensions have been chosen according to the standard ASTM - D 3039-D 3039M [3]. As the specimen obtained were too thin, tabs of 50 mm have been bonded to the specimens on each side and at each end in order to have a higher thickness so the testing machine could grab the specimen. Thus, the gage length of the specimen is 150 mm.

3 Sendeckyj's approach

In order to estimate a S-N curve describing the natural scattering of the fatigue tests, Sendeckyj proposed an approach based on a so-called residual strength that fits S-N curve and associates a failure probability [1].

3.1 Method

The Sendeckyj's approach is based on the evolution of the composite's strength during a cyclic loading. This strength is called the residual strength. By assuming that the mechanisms responsible of the dispersion are the same for quasi-static and fatigue tests, a S-N curve can be estimated and associated to a failure probability [1]. The procedure to identify this model requires quasi-static and fatigue tests. The S-N curve obtained is valid for a particular loading frequency and a particular loading ratio. Beyond the failure probability, another benefit of the Sendeckyj's approach is the estimation of the fatigue lifetime for a wide lifetime range: from quasi-static loading to high cycles loading.

3.2 Results

As a first step, this method has been identified using a classical protocol based on a sufficient number of quasi-static tests in order to obtain enough scattering and on some tests at low cycle fatigue (around 10^3 number of cycles at failure) and others at high cycle fatigue (around 10^6 number of cycles at failure). The result of the application of this approach on the laminated composites is shown in Figure 1. A first estimation of the S-N curve is obtained by using only 6 quasi-static results and 4 fatigue results.

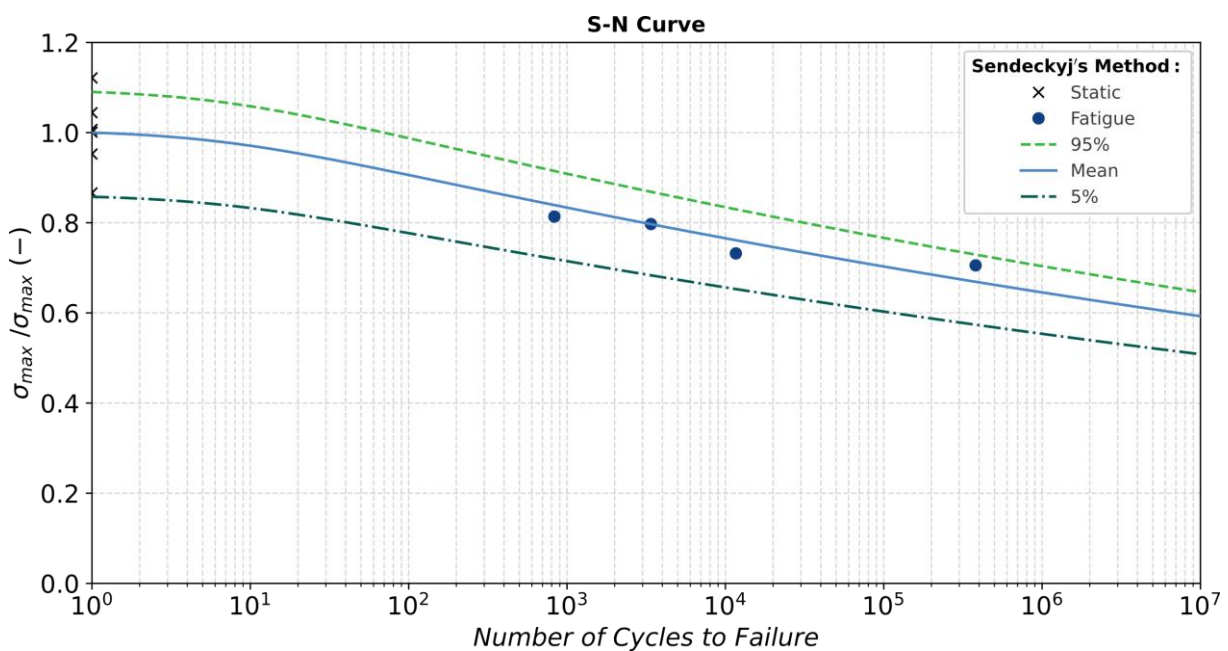


Figure 1: S-N curve of the laminated composites obtained with the approach of Sendeckyj

From this evaluation, it seems that this fatigue campaign could be large and time consuming to be trustworthy enough, particularly if fatigue lifetime for high cycles loading is seek in the study.

4 Self-heating-based method

4.1 Experimental Method

A solution to decrease the duration of the tests consists in using a self-heating-based method. The heat-build up protocol consists in submitting the sample to a sequence of cyclic loading steps defined by a fixed stress ratio and an increasing peak stress value. Its objective is to determine the relation between the cyclic dissipated energy and the applied stress thanks to thermal measurements [2-4]. The dissipated energy during a cycle is related to the evolution of the temperature thanks to the heat equation. Under some assumptions (not recalled here for sake of consistency) including adiabaticity, it is possible to show that the energy dissipated per cycle is proportional to the rate of temperature rise determined during a few numbers of cycles.

4.2 Results

The self-heating curve (Figure 2) represents the evolution of the dissipated energy with the maximum stress applied in a specific block.

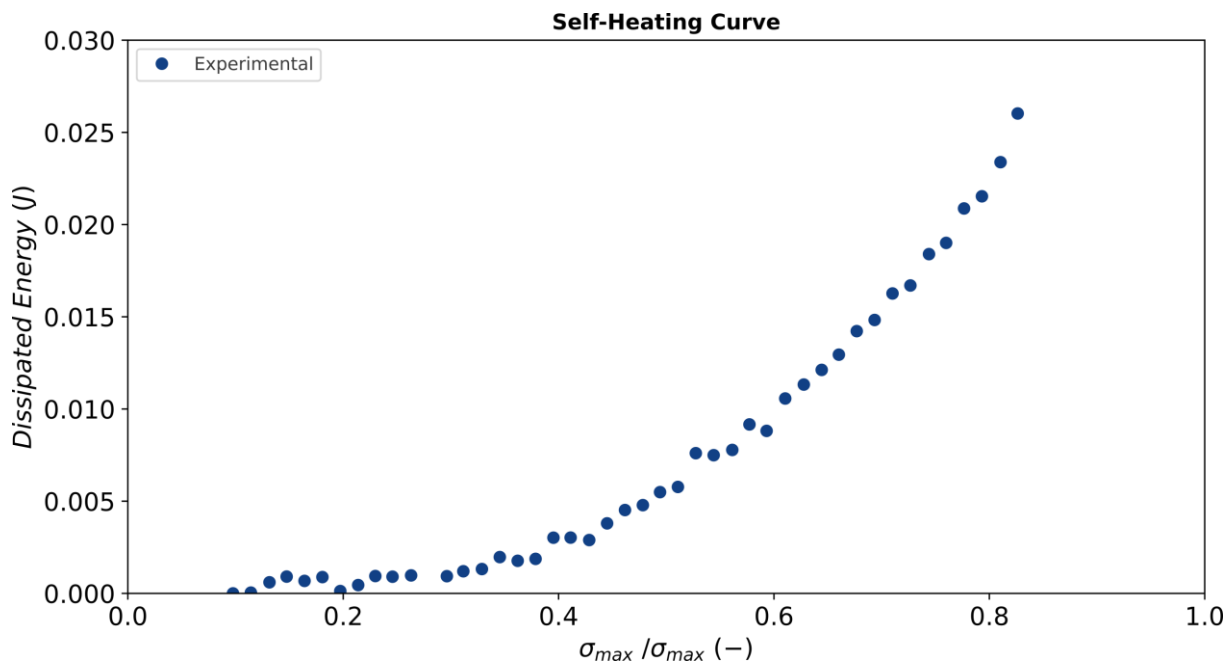


Figure 2: Self-Heating curve of one specimen

It has been shown that this self-heating curve can be divided into 3 distinct zones for composites materials [4] (Figure 3). The first zone corresponds to a very low dissipation. In the second zone other mechanisms are involved and a high increase of dissipation can be observed. The stress corresponding to the transition between these two zones is usually arbitrarily related to a fatigue

lifetime of 10^6 cycles to failure. This value of 10^6 cycles to failure has been verified on a large range of polymer-based matrix materials [2-4].

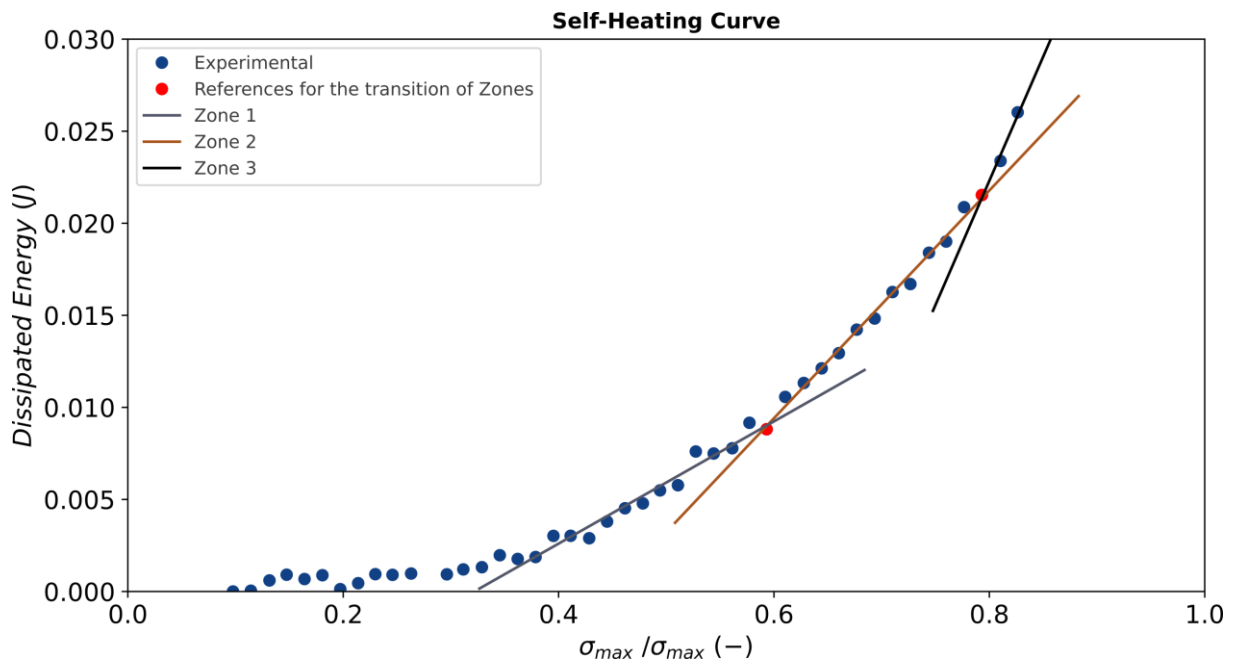


Figure 3: Self-Heating curve with the 3 zones of dissipation

The last bloc is ran to failure in order to obtain a couple of [dissipation; number of cycles to failure]. Finally, the S-N curve can be estimated thanks to an energetic criterion of the fatigue lifetime of the Basquin type (Figure 4).

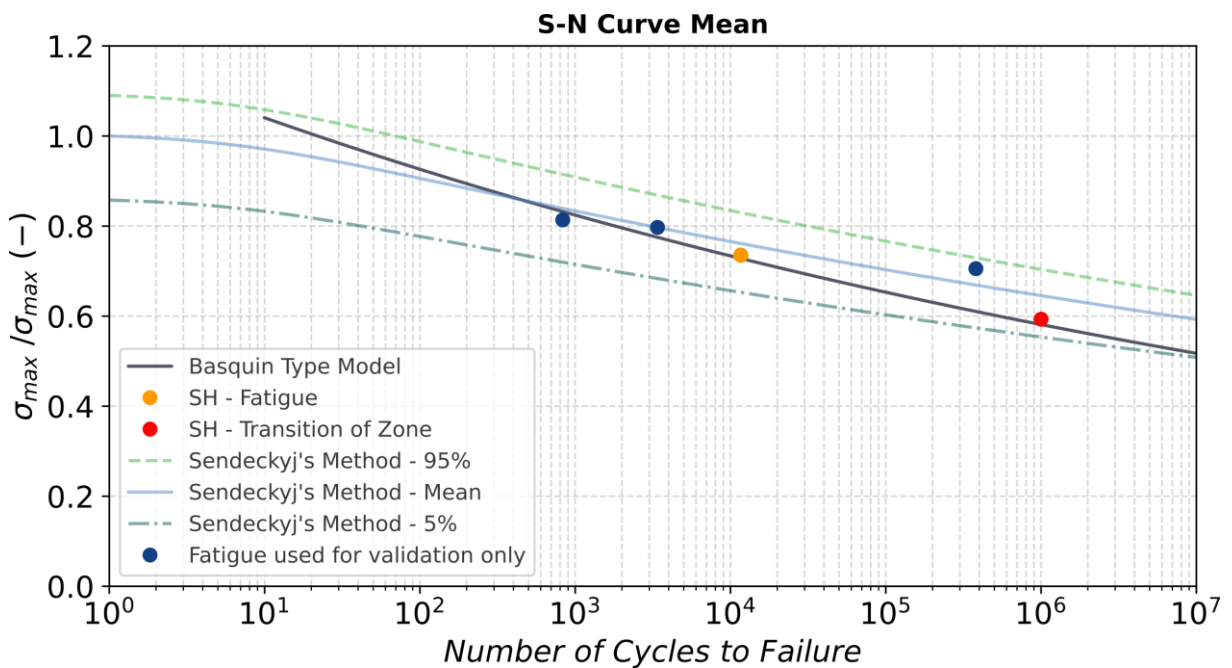


Figure 4: S-N curve (Basquin Type Model) of the laminated composites obtained by the self-heating-based method (SH).

The model obtained with this method seems to give a good prediction of the fatigue lifetime compared to the Sendeckyj's method, considering it has been obtained with a single specimen. Thus, this method reduces drastically the duration of the fatigue tests campaign. However, neither the associated scattering nor the low cycle fatigue part can be estimated without further developments.

5 Conclusion and Perspectives

Finally, with self-heating-based method, the stress corresponding to the transition between the two first zones and related to 10^6 cycles seems consistent in comparison with fatigue data. Therefore, it seems reasonable to combine both approaches. Quasi-static tests are used to identify the scattering. Few fatigue tests for low cycle fatigue loading are performed and the high cycle fatigue results necessary to identify the model are replaced by the estimation of the stress at 10^6 cycles estimated by the self-heating curve. By doing so, the identification of the S-N curve and the related dispersion should be possible in a short amount of time with a limited number of specimens. Moreover, the self-heating method estimates a fatigue point for high cycle loading based on the global response of the material and not by the failure of specimen because of a defect. Thus, the natural scattering obtained for the fatigue data estimated for each specimen tested by self-heating method should be really lower than the one of a classical fatigue campaign.

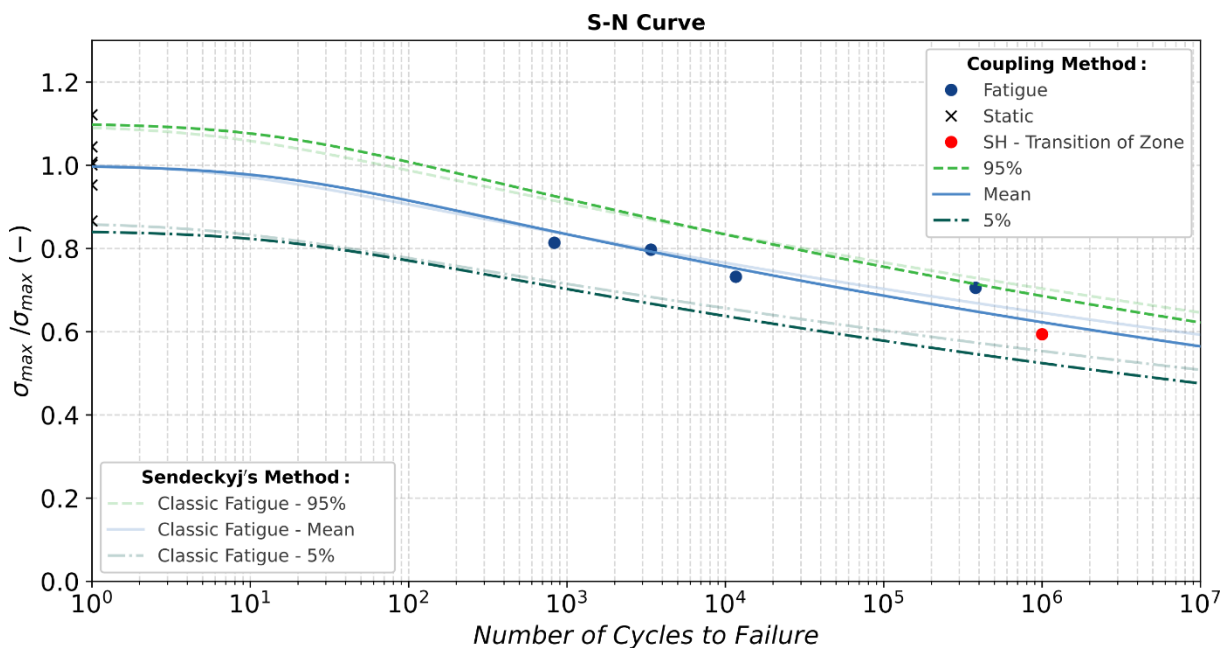


Figure 5: S-N curve of the laminated composites obtained by combining the Sendeckyj's approach and the self-heating-based method

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