FATIGUE OF ADHESIVELY BONDED STRUCTURAL ELEMENTS - RESIDUAL STRENGTH MODELS

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***Abstract**: The use of adhesive in joining gives many advantages when compared to traditional joining methods. However, adhesive joints exhibit change in their properties under service conditions. Fatigue loading has one of the strongest influences on joint properties, especially on joint strength. In this paper the residual strength fatigue models available in literature are presented together with evaluation of their advantages and disadvantages for describing fatigue under constant and variable amplitude fatigue loading.*

***Key words**: adhesive joints, fatigue, variable amplitude fatigue, constant amplitude fatigue, residual strength*

1. Introduction

Adhesives have been used for joining metals for more than 80 years. Their wider usage became possible in 1942, with the development of phenol formaldehyde modified adhesive – Redux 775, with high strength and excellent environmental resistance [1]. It was used successfully in structural application in aircraft industry. This was followed by development of different types of adhesives, e.g. epoxy and polyurethane adhesives, and more extensive use in aircraft and automotive industry and civil engineering. The ease of practical operation and suitability for bonding adherends with complex geometries, as well as its ability to join dissimilar materials, low manufacturing cost, good strength-to-weight ratio, high stiffness and more uniform stress distribution, are some of the advantages of adhesives when compared to traditional joining methods. For design of adhesive joints extensive knowledge of material properties is needed, and due to this fact many methods for testing adhesive joints have been developed in past few decades, which are thoroughly summarized in [2]. However, material properties of adhesives can change due to environmental influences such as humidity and temperature. Together with difficulties in reliably predicting the performance of adhesively bonded joints under irregular cyclic loading, these factors limit the wider application of adhesively bonded joints and lead to non conservative or over-conservative design.

2. Fatigue loading

With respect to long term service life, fatigue is considered to be most important form of loading structural adhesive joints [3]. Fatigue loading in most cases has irregular character, i.e., loading cycles with different mean value and amplitude, which is known as

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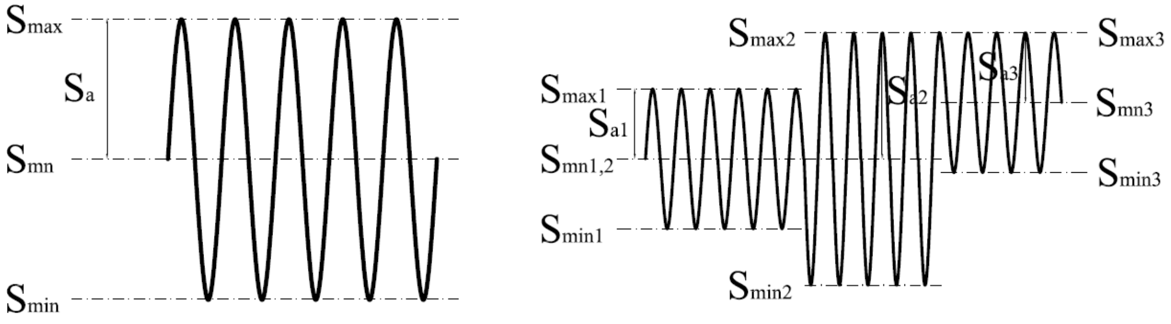
variable amplitude fatigue (VAF). However, most of the studies to date are done on constant amplitude fatigue (CAF). In recent years, there have been increased efforts to develop new and validate existing models describing behaviour of adhesive joints subjected to VAF. The forms CAF and VAF are shown in Fig.1.



a) b)

Fig. 1. Fatigue loading: a) CAF; b) VAF

In fig.1 S_{max} is maximum stress, S_{min} is minimum stress and S_{mn} is mean stress of a constant amplitude block with the stress amplitude S_a.

Many of recent attempts to predict behavior of adhesive joints under CAF and VAF loading are based on fatigue models of composite materials. In this paper the residual strength fatigue models available in literature are described and evaluated in terms of their success in describing fatigue under CAF and VAF.

3. Fatigue models

There are several approaches to fatigue, such as fracture mechanics approach, damage mechanics approach, total life approach, stiffness degradation and strength degradation approach. Fracture mechanics approach considers material with preexisting macro crack and describes crack growth over time due to cyclic loading. It does not consider crack initiation phase of joint life, unlike the Continuum Damage Mechanics approach (CDM) where damage, on an elemental cross-sectional plane, is quantified by the surface density of cracks and cavities at that section [7]. In total life approach and strength and stiffness degradation approaches damage metric is summed cycle by cycle, but there is no differentiation between phases of fatigue, i.e. crack initiation phase, crack propagation, and slow wear-out or sudden death. Fatigue approaches are categorized by several authors in different ways [3,5,6]. The most common categorization is into mechanistic and phenomenological models. Mechanistic models are defined as those that quantitatively account for the progression of damage. They need less experimentally obtained parameters, but so far, they have mainly been used for simple loading cases, not including VAF with complicated loading spectra. Phenomenological models deal with macroscopically observable properties, such as strength or stiffness. These models are usually statistically interpreted and a large experimental effort is needed for each material, geometry and loading conditions, which is their main drawback. In this paper, phenomenological models are considered.

3.1. Owen and Howe model

Owen and Howe [8] examined the set glass chopped strand mat/polyester resin specimens, subjected to tensile or fatigue loading, and derived the nonlinear and stress independent dependence between residual strength and number of loading cycles

$$(3.1)\qquad S_R = S_0 \cdot \left(1 - \sum\left[A \cdot \left(\frac{n}{N}\right) + B \cdot \left(\frac{n}{N}\right)^2\right]\right)$$

where S_R is residual strength, S_0 is static strength, n is number of loading cycles of the stress level corresponding the fatigue life of N cycles and parameters A and B needed to be determined experimentally.

3.2. Yang and Jones model

They investigated fatigue of graphite/epoxy $[\pm 45^\circ]_{2s}$ angle ply laminates which led to development of residual strength degradation model adopted for VAF of two sequence to spectrum loading [9]. The important aspect of this model is that it accounts the load sequence effect. The residual strength for two stress level is given by the equation

$$(3.2)\qquad S_R^c(n) = S_0^c - \beta^c K S^b n\,,$$

where $S_R(n)$ and S_0 are residual strength after n loading cycles and ultimate strength respectively, β is the scale parameter of two parameter Weibull distribution of ultimate strength and b,c and K are three parameters to be determined experimentally. This was later implemented for two or multi level fatigue by taking S_0 to be equal to $S_R(n)$ after all previous loading blocs step by step.

3.3. Hashin’s model

This model [10] is based on formulation of cumulative damage model in terms of damage function that must satisfy certain conditions. It was shown that this damage function could be used with residual life and residual strength theory and that those approaches were equivalent. The residual strength for CAF was given by equation

$$(3.3)\qquad S_R^\alpha(n) = S_0^\alpha - \left(S_0^\alpha - S^\alpha\right) \cdot \frac{n}{N}\,,$$

where $S_R(n)$ is residual strength after n cycles, S_0 is ultimate strength, S is stress level and N is fatigue life corresponding to that stress level. For two level VAF residual strength is expressed in the terms of additional number of cycles Δn_2 of the second level of cyclic loading after the n_1 cycles of the first level, with the stress values of S_2 and S_1

$$(3.4)\qquad S_{R2}^\alpha(\Delta n_2) = S_{R1}^\alpha - \left(S_0^\alpha - S_2^\alpha\right) \cdot \frac{\Delta n_2}{N_2}\,.$$

Calculation of residual strength can be continued for the following blocks of VAF loading step by step.

3.4. Harris et al.

Harris, together with his co-workers, derived a power law model for calculation of residual strength [11]. This model can incorporate all types of fatigue behaviour, from slow wear-out to sudden death. Equation describing residual strength is

$$(3.5)\qquad S_R = \left(S_0 - S_{\max}\right) \cdot \left(1 - t^x\right)^{1/y} + S_{\max}\,,$$

where S_0 is ultimate strength, S_{max} is maximum stress of loading cycle, and for n being the number of cycles and N fatigue life corresponding to the stress level t is given by the equation

$$(3.6)\quad t = \frac{\log n - \log 0.5}{\log N - \log 0.5}\,.$$

3.5. Schaff and Davison model

Assuming that the residual strength is a monotonically decreasing function of the number of cycles and that the residual strength after any load history can be represented by two-parameter Weibull function they derived the residual strength equation, first for two-stress level fatigue [12], and, based on that, for multi-stress level fatigue [13]. For the two-stress level VAF residual strength can be calculated by equation

$$(3.7)\quad S_R(n_1+n_2) = S_0 - \left(S_0 - S_2\right)\cdot\left[\frac{n_{eff}+n_2}{N_2}\right]^{v_2},$$

where $S_R(n_1+n_2)$ is residual strength after certain number of cycles of both stress levels, assuming that $S_1>S_2$ and n_{eff} is the number of loading cycles of stress level S_2 that produces the same damage as the n_1 number of cycles of stress level S_1. n_{eff} is given with the equation

$$(3.8)\quad n_{eff} = \left[\frac{S_0 - S_R(n_1)}{S_0 - S_2}\right]^{1/v_2},$$

using the equations (3.9-10) for determination of fatigue parameters v_1 and v_1 according to the experimental data

$$(3.9)\quad S_R(n_1) = S_0 - \left(S_0 - S_1\right)\cdot\left(\frac{n_1}{N_1}\right)^{v_1},$$

$$(3.10)\quad S_R(n_2) = S_0 - \left(S_0 - S_2\right)\cdot\left(\frac{n_2}{N_2}\right)^{v_2}$$

This procedure can be performed for any next stress level step by step giving the residual strength after $n_1+n_2+...+n_i$ number of cycles of corresponding stress levels.

Schaff and Davison also gave equation for describing cycle mix factor (3.11). This effect is described in the next chapter.

$$(3.11)\quad CM = C_m S_0\left(\frac{\Delta S_{mn}}{S_R}\right)^{\left(\Delta S_p/\Delta S_{mn}\right)^2}$$

Where ΔS_p and ΔS_{mn} are change in peak stress magnitude and mean stress magnitude and C_m is nondimensional value which can be determined from test results.

4. Discussion

Success in predicting constant amplitude and variable amplitude fatigue behaviour depends on effects that are taken into consideration in certain model, i.e. stress related effects. In the group of stress related effects, two major effects are known: sequencing effect and cycle mix effect. It has been shown [15] that fatigue crack propagation can be different when two types of load transitions are compared. In that sense there is distinction between transition from high fatigue to low fatigue loading and transition from low fatigue to high fatigue loading. This effect is called sequencing effect. Cycle mix effect is effect of the size of the loading blocks. In two-stress-level loading, there is a difference in fatigue between two loading spectra with the same total number of loading cycles if the change between blocks of loading is more frequent in one than in the other.

There is very limited number of tests done on adhesive joints subjected to variable amplitude loading, especially on steel to steel connections. Due to this, it is hard to evaluate adequacy of each for describing adhesive joint fatigue. The presented models could be evaluated by the effect that could be taken into consideration.

Owen and Howe model can be used for multistress level fatigue but in this model accumulation of fatigue is nonlinear and stress independent. This means that the stress level effects cannot be taken into consideration with this model. This model was compared to the test results in [14], done on fiber reinforced polymer composite materials, and it shows good accuracy, but the requirement of repeated two block loading data to fit the model parameter is a significant disadvantage.

Yang and Jones model are compared to test result on graphite graphite/epoxy [±45°] [17]. It shows good correlation with tests, but it does not take into consideration load sequencing effect, such as the acceleration and retardation effects in the process of crack propagation.

Hashin's model is nonlinear, but also stress independent. It does not take into consideration stress related effects. In addition to this, this model did not show good correlation with test results given in [10].

Harris et al. model was compared to results of tests [13] done on T800/5245 CFRP system, consisting of a Toray intermediate-modulus carbon fibre in an epoxy/bismaleimide resin. The tests were conducted on several loading scenarios consisting of different stress levels. It was shown that the sequencing effect could be considered with this model.

Schaff and Davison model is one of rare models compared with the results of test done on adhesive joints [17] and gave a fairly good correlation. Its advantage is that it takes into account sequencing and cycle mix effect. It was also shown [13] that incorporation of cycle mix effect gives better results, and that the model gives excellent correlation with variety of experimental results, including highly complex loading spectrums.

5. Conclusion

Use of adhesive joints has a great potential for the future. However, adhesive joints can be highly influenced by irregular cyclic loading, which is one of the most common types of loading during exploitation phase of the structure. Fatigue effect can be fairly represented by mathematical models that determinate residual strength after certain number of cycles or blocks of loading. This type of fatigue approach is more engineering type than fracture mechanics or damage mechanics approach. In this paper several residual strength models are presented and it was pointed that they can incorporate different stress related fatigue effects. However, for application of residual strength models to describe fatigue of adhesive joints, especially to incorporate stress related effects, extensive experimental effort is needed, and there is very limited number of test results done on adhesive joints under variable amplitude loading. Most of the experiments until now have been done on composite materials. It is also necessary to be determined whether such extensive experimental effort is justified considering how big stress related effects on the fatigue of adhesive joints are.

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