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USING DAMAGE MODELS TO PREDICT FATIGUE IN STEEL AND GLASS FIBER REINFORCED PLASTIC

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Abstract

Three cumulative damage models are examined for the case of cyclic loading of AISI 6150 steel and S2 glass fiber/epoxy composite. The Palmgren-Miner, Broutman-Sahu, and Hashin-Rotem models are compared to determine, which of the three gives a more accurate estimation of the fatigue of the materials tested. In addition, comparison of the fatigue life of the materials shows the superiority of the composite over the steel at lower mean stresses, and that of steel to the composite at higher mean stresses.

1. Introduction

Technological advances require light and durable structures, as is the case in the automotive industry. For this reason, composites have replaced metals in many applications. In the case of heavy-duty vehicle suspensions, the market has expanded to composite leaf springs as a replacement of the conventional steel ones. Composites weigh less than metals and have high strength and stiffness [5]. When selecting a material for cyclic loading applications, knowledge of its fatigue life is

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crucial. It is impossible to predict the fatigue failure of individual specimens, and therefore a statistical approach in determining the fatigue life of materials is necessary. The Weibull distribution helps to predict the fatigue life and failure of materials by using failure data from specimens subjected to certain loading conditions, and is essential when the materials involved are brittle as in the case of composites [5, 10].

Contrary to the case of homogeneous isotropic materials such as metals, where fatigue failure is characterized by the initiation and propagation of a crack, fatigue failure in composites is the result of accumulated damage [5, 11]. The damage generated in a material under loading can be predicted by using damage models even when minimum information on the fatigue of the material is known.

2. Damage Models and Materials

This study will use the following three damage models to predict and compare the damage caused in AISI 6150 steel and unidirectional glass fiber reinforced plastic (GFRP), S2 glass fiber/epoxy, under cyclic loading conditions:

Palmgren-Miner [6, 12, 13]:

$$\left(\sum_{i=1}^{n} \frac{n_i}{N_i}\right) K = 1, \tag{1}$$

Broutman-Sahu [4, 6]:

$$\left(\sum_{i=1}^{n} \frac{(\sigma_{Ultimate} - \sigma_i)}{(\sigma_{Ultimate} - \sigma_{i+1})} \frac{n_i}{N_i}\right) K = 1, \tag{2}$$

and Hashin-Rotem [6, 9]:

$$\left(\sum_{k=1}^{i-1} \left(\frac{n(k-1)}{N(k-1)}\right)^{\frac{(1-Sk)}{(1-S(k-1))}} + \frac{n_i}{N_i}\right) K = 1, \tag{3}$$

$$Sk = \frac{\sigma_k}{\sigma_{Ultimate}}, \tag{3a}$$

$$S(k-1) = \frac{\sigma_{k-1}}{\sigma_{Ultimate}}, \tag{3b}$$

where n_i is the number of cycles under the applied stress, N_i is the number of cycles to failure under this same stress, σ_i and σ_k are the stresses applied, and K is the number of repetition of the loading cycle. When each of these equations equals to 1, the damage accumulated leads to failure. However, damage is still being caused even, if the right hand side of the above equations is less than 1 [1].

A classification of the damage models can be made based on their linearity or non-linearity, and according to the parameters required for their calculation [5]. Consequently, Palmgren-Miner is a linear stress independent model, Broutman-Sahu is a linear stress dependent model, and Hashin-Rotem is a non-linear stress dependent model.

The materials investigated in this study are AISI 6150 steel with an ultimate tensile strength of 1.24GPa [7], and a unidirectional laminate composite with +/–5° fiber orientation and ultimate flexural strength of 1.28GPa [3].

AISI 6150 is a chromium-vanadium steel commonly used in the manufacturing of leaf-springs for heavy-duty vehicles. For the production of leaf-springs, the steel is quenched in oil at 850°C and then tempered at 500°C. A surface treatment of shot peening is then followed, in order to induce compressive residual stresses to the surface of the leaf spring and therefore, enhance its fatigue life [2, 7, 8, 13]. The shot peening intensity used is approximately 0.3 in the Almen C scale. In this study, the steel data used is based on experiments carried out on chromium-vanadium steel springs that have undergone, quenching, tempering, and shot peening.

S2 glass fiber/epoxy is, together with E glass fiber/epoxy, a very common composite alternative to steel in the manufacturing of leaf springs for heavy-duty vehicles [3]. The unidirectional nature of the composite assures a transverse isotropic environment [1, 11]. The direction of the fibers plays a crucial role in determining the fatigue life of the material, especially in loading conditions that involve bending [1, 11].

3. Results and Discussions

Damage was calculated for a range of maximum stress amplitudes between 243MPa and 359MPa for a loading ratio of approximately 0.2. These stress amplitudes correspond to both low cycle fatigue (LCF) and high cycle fatigue (HCF) loading in both materials. A two-parameter Weibull analysis was performed for each of the three damage models mentioned above [10, 14], in order to decide upon the model that gives more realistic results for damage and fatigue life, when compared to experimental data [3, 7].

A scale parameter α and a shape parameter β for each damage model were calculated through the analysis of the accumulated damage and fatigue life (Table 1). When the shape parameter β is larger than 1, failure increases with time [14]. In the case of the two linear models for steel, we can see that the failure of the material is dependent on time. However, for the majority of our models, and especially all the models for the composite, accumulate damage independently of time. In these cases, damage is purely dependent on the loading, and the shape parameter β is less than 1. The scale parameter α gives the mean value of damage caused to the material after one loading cycle. From Table 1, we can conclude that for the case of the two linear models, damage per cycle is larger for the composite by at least one degree of magnitude. However, in the case of the nonl-inear model, Hashin-Rotem, damage caused per cycle is higher in steel, however, with no significant difference form that caused in the composite.

Table 1. Shape and scale parameters for all damage models

Damage model	β **6150 steel**	β **S2 glass fiber/epoxy**	α **6150 steel**	α **S2 glass fiber/epoxy**
Palmgren-Miner	1.18	0.28	6.21×10^{-6}	5.06×10^{-5}
Broutman-Sahu	1.89	0.37	3.51×10^{-6}	2.08×10^{-5}
Hashin-Rotem	0.40	0.42	1.17×10^{-2}	8.49×10^{-3}

The cumulative distributions for damage are shown in Figure 1(a) for steel and Figure 1(b) for the composite. As it can be seen from Figure 1(a), the two linear models coincide at lower stresses. Broutman-Sahu and Palmgren-Miner models give almost identical results up to the mean stress of 360MPa. Compared to the two linear models, Hashin-Rotem gives a higher probability of failure at stresses between 256MPa to 350MPa, and lower probability between 360MPa to 460MPa and 462MPa to 560MPa. However, it agrees with Broutman-Sahu at 485MPa. The Hashin-Rotem model estimates an approximately 95% probability of failure at 560MPa, which is just 1% higher than that estimated at the same mean stress level by the two linear models.

For the composite (Figure 1(b)), the two linear models give similar results at almost all mean stresses. For the interval between 256MPa to 350MPa, Hashin-Rotem gives a lower probability of failure than Broutman-Sahu and Palmgren-Miner. For stresses from 350MPa to 485MPa, Hashin-Rotem gives higher probability of failure, but at 485MPa gives a failure probability very close to that of the other two models. For the case of the composite, Hashin-Rotem gives failure probability at 560MPa, same as that estimated by the model for the case of the steel, which is approximately 95%, 2% lower than the estimate of the two linear models at the same mean stress.

For both materials, and especially for steel, it can be observed from the graphs that the curve based on the Hashin-Rotem model is a smooth curve resembling a best-fit line for the other two curves of the two linear damage models. It is also worth mentioning that the deviation of Hashin-Rotem from the other two models is larger in the case of the composite. The maximum deviation in steel at 360MPa is 26% less than the other two models. In the composite, Hashin-Rotem deviates the most from the two linear models between 462MPa to 485MPa. At these mean stress levels, the non-linear model gives approximately 31% more damage probability that Palmgren-Miner and Broutman-Sahu models.

A final observation regarding the probability of failure shows that the composite starts with higher probability of failure at lower stresses (28% failure probability estimated by the linear models for the composite, as compared to 15% for steels), but slowly shows lower cumulative damage than steel between 350MPa to 485MPa[1]. This can be explained by the inhomogeneous nature of composites that fail due to damage accumulation, and the fact that in steel failure is based on crack initiation and propagation. From the above comparison, we can conclude that the composite accumulates damage from the beginning of loading when a crack in steel is most probably not even initiated yet. However, at the point, where we see the failure probability for steel to be higher than that of the composite, we can conclude that a crack in the steel material has formed and is being propagated. At the highest mean stress, where calculations were made, at 560MPa, the composite's failure probability estimate given by the two linear models is 3% higher than the estimate in steel. The composite material's components, matrix and fibers, do not carry equal amounts of loading and as a result fatigue differently. Damage accumulation may occur through a range of microstructural mechanisms such as fiber fracture and fiber/matrix deboning [11]. For this reason, the composite ends up with a higher chance of failure at 560MPa. This can also be understood by looking at the fatigue life curves of the two materials (Figure 2). The mean stresses 256MPa to 360MPa correspond to HCF above 10^6 cycles for the composite, but only 10^5 for the steel. The damage accumulation leading to failure of the composite is also obvious from the graphs as the LCF, 460MPa to 560MPa of mean stress, is less than that of the steel.

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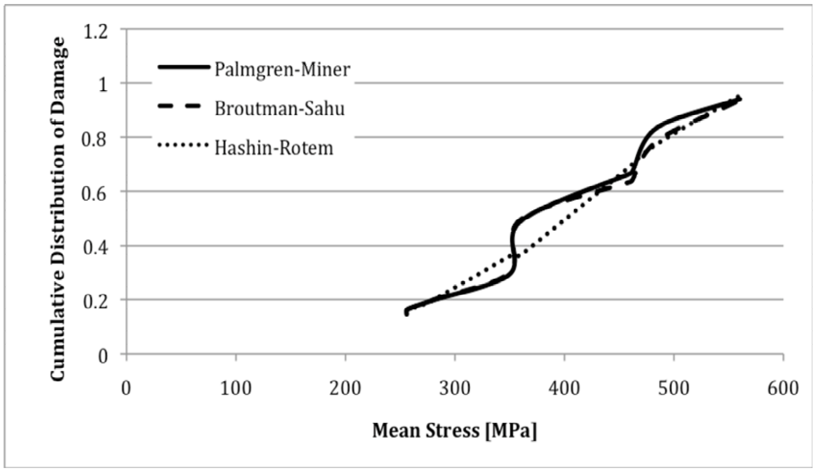
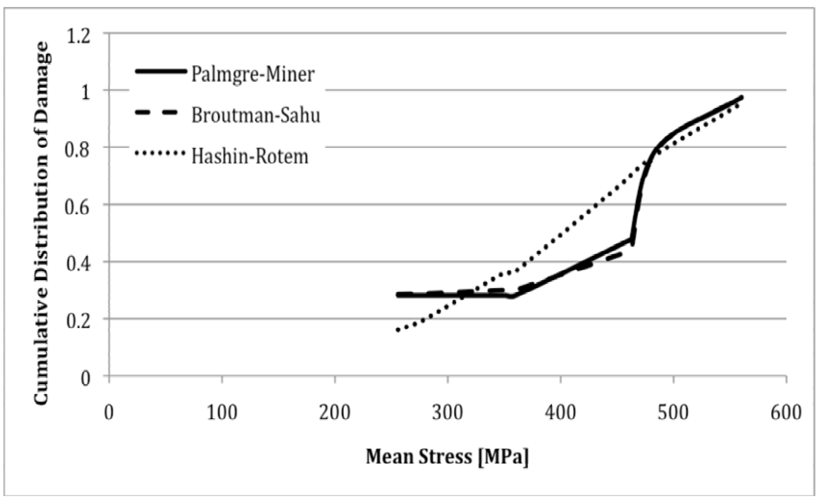
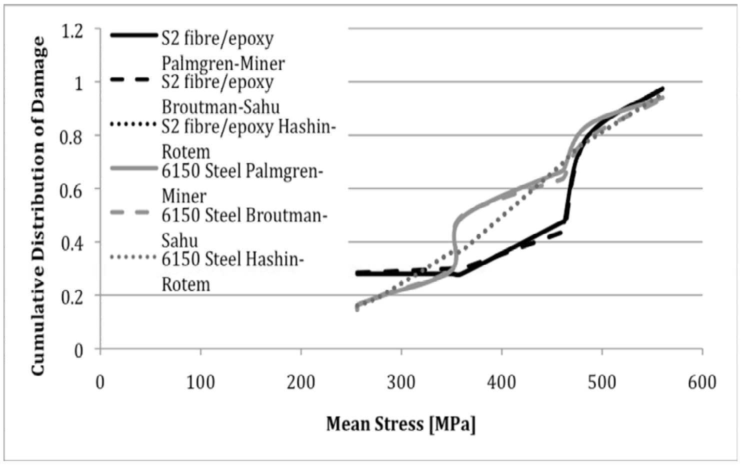
[1] The Hashin-Rotem model gives similar results in both materials. The ultimate tensile strength (UTS) of both the steel and the composite differ by 40MPa in magnitude, with the composite having the higher UTS. The non-linear nature of the Hashin-Rotem model fails to account significantly for this small difference in the magnitude of the ultimate strength. As a result, this model gives almost identical results for the probability of failure, under the same mean stress, for the two materials.


Cumulative Distribution of Damage
Mean Stress [MPa]
Palmgren-Miner
Broutman-Sahu
Hashin-Rotem
0
0.2
0.4
0.6
0.8
1
1.2
0
100
200
300
400
500
600

(a)


Cumulative Distribution of Damage
Mean Stress [MPa]
Palmgre-Miner
Broutman-Sahu
Hashin-Rotem
0
0.2
0.4
0.6
0.8
1
1.2
0
100
200
300
400
500
600

(b)



(c)

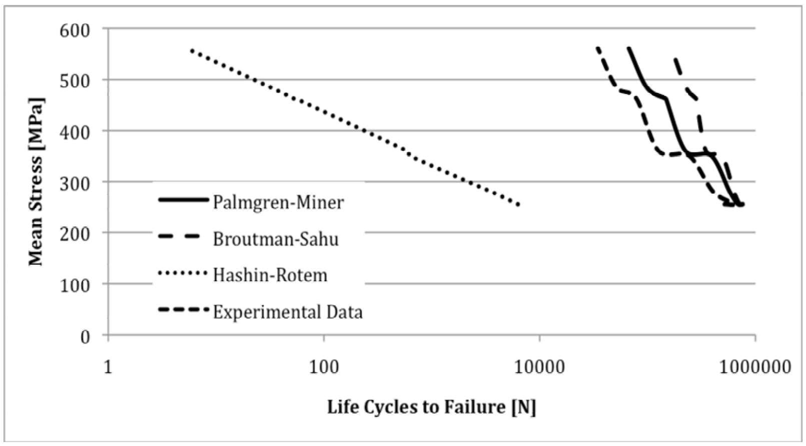
Figure 1. Cumulative distribution of damage versus mean stress: (a) AISI 6150 steel, (b) S2 glass fiber/epoxy composite, and (c) both materials.

Figure 1 shows cumulative damage distribution for one cycle ($K = 1$). The fatigue life of the materials can be calculated by calculating the value K, when each of the three models equals to 1, i.e., at failure. Figures 2(a) and 2(b) give the mean stress versus cycles to failure for the steel and composite, respectively. The short dash line in each graph is experimental data from literature [3, 7].

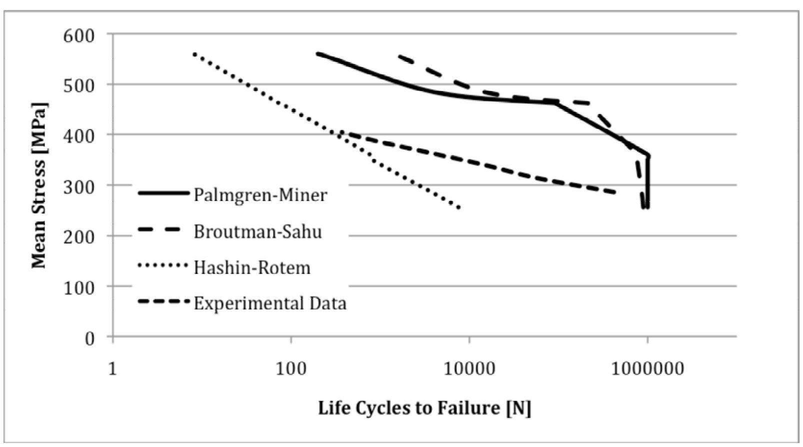
In the case of the steel, the two linear models give similar results at lower stresses up to 280MPa, while at higher stresses they differ by one order of magnitude, with the Broutman-Sahu model giving better fatigue life. The experimental results give a lower fatigue life for the same stresses, with 48% difference in life cycles at a mean stress level of 560MPa, when compared to the Palmgren-Miner result, and 79% difference when compared to results from the Broutman-Sahu model. The Hashin-Rotem model greatly underestimates the fatigue life of steel by two orders of magnitude at the mean stress of 256MPa, and more than four orders of magnitude at 560MPa.

In the case of the composite, Broutman-Sahu and Palmgren-Miner give close results up to 360MPa, and differ by 86% at 560MPa, while

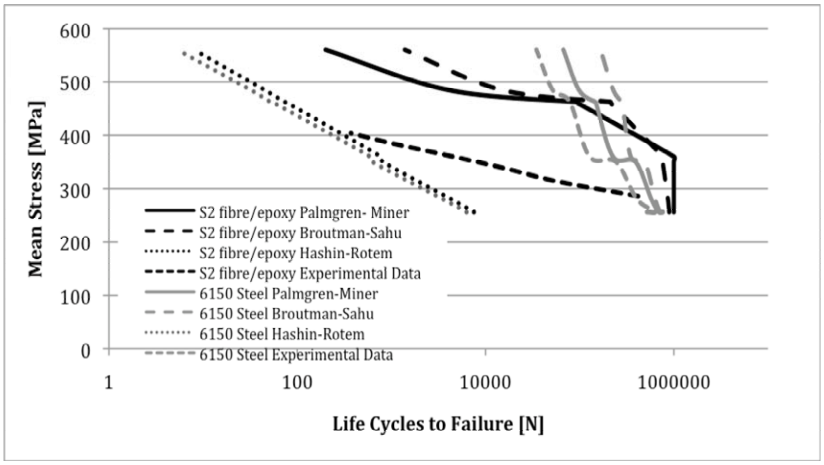
Hashin-Rotem model underestimates the composite's life, as in the case of steel, by three orders of magnitude at low mean stresses. The stress dependent model Broutman-Sahu starts with lower fatigue life at lower stresses and shows higher life predictions at higher stresses, when compared to Palmgren-Miner model. This is based on the fact that the Palmgren-Miner model is not sensitive to small changes in stress, as it is a stress independent model. Although small, these changes in stress are important in a material that fails by accumulating damage while being cyclic loaded.



(a)



(b)



(c)

Figure 2. Mean stress versus life to failure: (a) AISI 6150 steel, (b) S2 glass fiber/epoxy composite, and (c) both materials and experimental results for both materials.

It is worth mentioning that for both materials, the experimental results fall between the linear and non-linear models. In the case of the composite, the results of the damage models are more favourable at HCF levels. We can see how damage accumulation may affect composite materials, if we pay close attention to what happens when, as is the case of this study, the mean stress rises above 460MPa. At this stress level, the fatigue life of the composite drops by 72% compared to 19% in the case of steel, which fails by crack initiation and propagation mechanisms. However, it should be reminded that the experimental results for steel, are taken from fatigue tests carried out on steel leaf springs that have been surface treated by shot peening. The effect of this surface treatment cannot be accounted for when using the damage models examined in this study. As mentioned before, the fiber direction in the composite plays significant role in determining the fatigue life of the material [1, 11]. A different fiber direction than the one of the composite specimens in the experimental data used in this study could have resulted in a fatigue life higher or lower than that of steel.

4. Conclusions

Based on Figures 1 and 2, the following conclusions can be drawn:

The larger the probability of failure, the smaller the fatigue life of the material. In addition, the deviation of Hashin-Rotem from the two linear models in Figure 1 is proportional to the amount of underestimation of the fatigue life in Figure 2.

The non-linear models in both materials almost coincide, especially at lower stresses, and predict fatigue lives that show small differences between them. However, the predictions for S2 glass fiber/epoxy are slightly better than those for steel, as shown in Figure 2(c).

The linear models predict similar probability of failure for both materials at high mean stresses, above 485MPa (Figure 2(c)). The life predictions based on the linear models are better in the case of the composite at mean stresses below 460MPa. Above this stress level, the composite moves fast towards the LCF region, while steel remains above 10^5 cycles of life (Figures 2(b) and 2(c)).

One can argue therefore, that the composite is superior to steel in applications of mean stress below 460MPa. Experimental results may show otherwise, but one should keep in mind the effect of shot peening on the surface of the steel that renders the material more resistant to fatigue failure.

When comparing the cumulative distribution of damage diagrams as well as the fatigue life curves of the two materials, it is hard to decide upon a damage model that will give equally good predictions in both cases of materials. For the AISI 6150 steel, it is the linear, stress independent Palmgren-Miner model that better estimates the fatigue life of the material, when compared to experimental results. Although it gives a higher fatigue life than the one derived from experiments, it should be taken into consideration that undetected pre-existing flaws can greatly affect the life of a specimen. Such effects will demonstrate themselves by lowering fatigue life for the piece, but cannot be accounted for when using the damage models presented in this study, and as a result will not be obvious from the estimated fatigue lives.

The case of the composite seems to be a more complicated one when deciding upon an optimal damage model among the three used here. At low stresses, both linear models, and especially Broutman-Sahu, give predictions close enough to experimental results, within less than an order of magnitude. At higher mean stresses, above 400MPa, it is the non-linear model, Hashin-Rotem, which can best predict the fatigue life of the composite.

Damage models can give great insight in the behaviour of materials under different types of loading. Choosing the right model however, is an important task when overestimation or underestimation of fatigue is to be avoided. This study focuses on materials that are cyclically loaded, and experimental data from cyclic loading in bending is used to compare the predictions to [1, 3, 7]. Linear models tend to give an overestimated prediction of the fatigue life of the materials, while the non-linear models will give significantly underestimated results compared to experimentally deduced values. It is clear that for both the steel and the composite linear models give more accurate, although overestimated results. The dependence of the model on stress information is important at lower stresses in the case of composite, where Broutman-Sahu estimates were in closer agreement with experimental data. In the case of steel, experimental data and both linear models agree at low stresses. However, the stress independent model is better in predicting the fatigue life of steel [13]. This can once more be explained by the different ways in which the two materials fail. Caution should always be taken when relying on such damage models to predict probability of failure and fatigue life of an S2 glass fiber/epoxy composite and AISI 6150 steel, and if possible the estimated results should always be compared with those of experiments done on the materials, as there exist a variety of factors, such as surface treatments and defects, the effects of which cannot be accounted for in the damage models.

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