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T. Park[a], M. Kim[a], B. Jang[a], J. Lee[b] & J. Park[a]

[a] Department of Aerospace and Mechanical Engineering, Korea Aerospace University, Goyang 412-791, South Korea

[b] Department of Smart UAV Development, Korea Aerospace Research Institute, Daejeon 305-806, South Korea

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A nonlinear constant life model for the fatigue life prediction of composite structures

T. Park[a], M. Kim[a], B. Jang[a], J. Lee[b] and J. Park[a]*

[a]*Department of Aerospace and Mechanical Engineering, Korea Aerospace University, Goyang 412-791, South Korea;* [b]*Department of Smart UAV Development, Korea Aerospace Research Institute, Daejeon 305-806, South Korea*

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The constant life diagram (CLD) can predict stress-life curves for various stress ratios under variable amplitude loading by using limited fatigue experimental data. The predictive accuracy of the constant life formulation is very important because fatigue analysis results are significantly affected by the accuracy of the estimated S–N curve. In this study, a nonlinear constant life formulation is developed to estimate more accurate S–N curves for previously developed CLDs. Four CLDs are presented and their predictive accuracies are compared with the proposed model on composite materials fatigue data. The accuracy is compared between actual fatigue data and the predicted S–N curve for the arbitrary load condition, for which no experimental data exists. Finally, the results reveal that the proposed model can predict the most accurate S–N curves with simple calculation processes compared to the results of previous constant life models.

Keywords: constant life diagram; fatigue life prediction; composites; S–N curves

1. Introduction

Composite materials are widely used for aircraft and spacecraft due to their lightweight and excellent mechanical properties compared to metals. This is due to the directional characteristics of composite materials. Until now, many studies have been done on the fatigue failure of composite materials because fatigue is one of the main causes of failure. The critical points for estimating fatigue life are the selection of equation type for the S–N curves, the statistical processing of fatigue data, selection of the proper CLD model, fatigue failure criterion, and damage summation rule.[1–3] Among these critical points, this paper is focused on the effect of the CLD formulation on the fatigue life prediction of composite materials.

The classic linear Goodman diagram is the most widely used CLD.[4,5] However, it is not suitable for composite materials because of its damage mechanism under tension, and its compression loading is different. Thus, the straight lines connecting the ultimate tensile strength (UTS) and ultimate compressive strength (UCS) with constant life data points of the $R = -1$ line are improper for the purpose of describing the fatigue life behavior of composite materials.

Therefore, several CLD models have been presented in previous literature for the fatigue behavior of composite materials.[6] Starting from the basic idea of the linear

*Corresponding author. Email: jungsun@kau.ac.kr

Goodman diagram and nonlinear Gerber equation, different modifications have been proposed.

In the modified Goodman diagram concept, analytical expressions of any desired S–N curve, the so-called piecewise linear CLD, have been developed.[2] This model is based on the linear interpolation between S–N curves with different *R*-ratios. Early studies show that the piecewise linear CLD model is relatively accurate compared with the linear, Kawai, Harris model when more than three S–N curves are available.[6] Also, a more accurate estimation of fatigue life is possible with more S–N curves using a piecewise linear CLD. On the other hand, the piecewise linear CLD is not suitable to describe the fatigue behavior when fewer S–N curves are available due to its linear characteristics. Kawai et al. have proposed a nonlinear CLD that can be derived by using only one critical S–N curve.[7,8] The critical *R*-ratio is defined as the ratio of the UCS to the UTS of a material. The main drawback of this model is the need for experimental data for this critical S–N curve. Harris et al. have proposed a semi-empirical CLD model.[9–11] The Harris model is based on fitting the entire set of S–N data with a nonlinear equation. The Harris CLD constitutes a set of continuous lines from the tensile strength to the compressive strength of the material. The shortcomings of this model are that it requires a relatively difficult multivariate fitting process and the adjustment of the parameters based on the experience and fatigue data.

In this study, a nonlinear constant life diagram (CLD) formulation is proposed to improve the shortcomings of previous theories, such as low accuracy and calculation complexity. With simple calculations and a small number of available S–N curves of at least three *R*-ratios, the presented CLD model is suggested to describe fatigue behavior more precisely with varying *R*-ratios. In order to apply the newly proposed CLD to fatigue analysis, the predictive accuracy of the CLD should be tested first. Accordingly, the predictive accuracy for the proposed CLD model is verified and the results are compared with previous CLD theories. In the verification process, S–N curves for specific *R*-ratios are plotted for two types of composite materials by applying the presented and previous CLD theories. Furthermore, predictive accuracy is calculated by comparing the predicted results with experimental data. Finally, the results are compared and evaluated to confirm the usefulness of the proposed CLD model.

2. Theories on constant life models

CLDs have been created to consider the effect of the mean stress and material anisotropy on the fatigue life of composite materials. A CLD acts as a master diagram and represents constant fatigue life behavior for the entire range of loading types, which are compression–compression (C–C), tension–compression (T–C), and tension–tension (T–T) loading. A CLD makes it possible to estimate an S–N curve for a specific stress ratio for which no experimental S–N data exists. A CLD is composed of three main parameters, which are the mean stress, σ_m, alternating stress, σ_a, and *R*-ratio, $R = \sigma_{\min}/\sigma_{\max}$, which is defined as the minimum stress over the maximum cyclic stress.

2.1. Linear Goodman CLD

The linear Goodman CLD model is based on a single S–N curve from the fatigue test which is carried out under fully reversed loading.[4,5] As can be seen in Figure 1, where a linear Goodman CLD is presented, constant life lines are generated by connecting constant life data points and static strengths. Unknown S–N curves can be

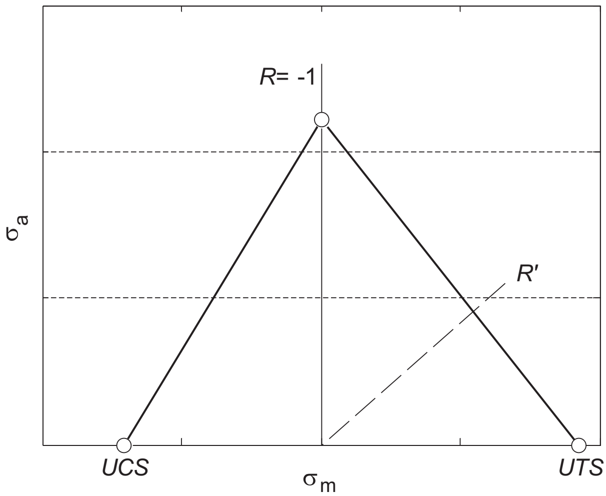

Figure 1. Schematic of the linear CLD.

simply plotted by linear interpolation. The theory for the linear CLD is modified from the Goodman diagram. The general formulae of the linear Goodman constant life model are:

$$\sigma_a = \begin{cases} \sigma_{a0}(1-(\sigma_m/\mathrm{UTS})), \text{ For } & \sigma_m > 0 \\ \sigma_{a0}(1-(\sigma_m/\mathrm{UCS})), \text{ For } & \sigma_m < 0 \end{cases} \tag{1}$$

where σ_{a0} is the cyclic stress amplitude for a given constant value of life N under cyclic fatigue loading. In this paper, the linear Goodman CLD is called the linear CLD for convenience.

2.2. Piecewise linear CLD

The piecewise linear CLD can be derived by linear interpolation between constant life data from known S–N curves.[2] The piecewise linear CLD requires a limited number of S–N curves for different R-ratios and the static strengths of the material (UTS and UCS). To represent the entire range by piecewise linear model, typical S–N curves at $R = 10$for C–C loading, $R = -1$ for T–C loading, and $R = 0.1$ for T–T loading patterns are used. The piecewise CLD is shown schematically in Figure 2. The constant life lines are constructed by connecting the same fatigue life cycle data points on each of the available S–N curves. Unknown S–N curves can be estimated by linear interpolation between constant life data points and the static strength data. Analytical expressions of the piecewise linear CLD have been developed for the following descriptions of the entire region:

(1) If R' is in the T–T sector of the CLD, and between UTS and the first known R-ratio in the tension region, R_{1TT},

$$\sigma'_a = \frac{\mathrm{UTS}}{\frac{\mathrm{UTS}}{\sigma_{a,1TT}} + r' - r_{1TT}} \tag{2}$$

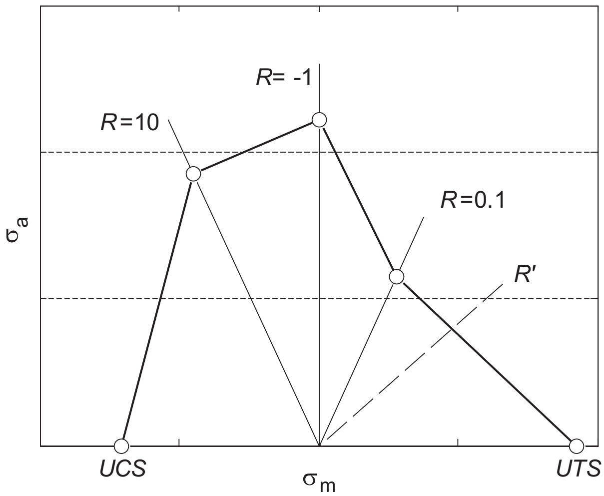

Figure 2. Schematic of the piecewise linear CLD.

where σ'_a and $\sigma'_{a,1TT}$ are the stress amplitudes corresponding to R' and R_{1TT}, respectively, and $r_i = (1 + R_i)/(1 - R_i)$, and $r' = (1 + R')/(1 - R')$.

(2) If R is located between two known R-ratios, R_i and R_{i+1},

$$\sigma'_a = \frac{\sigma_{a,i}(r' - r_{i+1})}{(r_i - r')\frac{\sigma_{a,i}}{\sigma_{a,i+1}} + (r' - r_{i+1})} \tag{3}$$

(3) If R' is in the C–C sector of the CLD, and between UCS and first-known R-ratio in the compression region, R_{1CC},

$$\sigma'_a = \frac{\text{UCS}}{\frac{\text{UCS}}{\sigma_{a,1CC}} + r' - r_{1CC}} \tag{4}$$

where σ'_a and $\sigma'_{a,1CC}$ are the stress amplitudes corresponding to R' and R_{1CC}.

2.3. Kawai CLD

Kawai et al. have developed an asymmetric CLD and designated the anisomorphic constant fatigue life diagram.[7,8] The main feature of this formulation is that it can be constructed simply by using only one critical S–N curve, having a specific R-ratio which is defined as the ratio of the UCS to the UTS of the material. The CLD formulation is based on three main assumptions:

(1) The stress amplitude for a given constant value of fatigue life is greatest at the critical R-ratio.
(2) The shape of the constant life lines change progressively from a straight line to a parabola form with the changes in fatigue life.

(3) The CLD is bounded by the static failure envelope which consists of two straight lines connecting the maximum stress amplitude on the critical S–N curve with the tensile strength and compressive strength.

A schematic representation of the Kawai CLD is shown in Figure 3. The Kawai CLD theory depends on the position of the mean stress, σ_m, and the formulation of the model is as follows:

$$\frac{\sigma_a^\chi - \sigma_a}{\sigma_a^\chi} = \begin{cases} \left(\frac{\sigma_m - \sigma_m^\chi}{\mathrm{UTS} - \sigma_m^\chi}\right)^{(2-\psi_\chi)}, \text{ For } & \sigma_m^\chi \leq \sigma_m \leq \mathrm{UTS} \\ \left(\frac{\sigma_m - \sigma_m^\chi}{\mathrm{UCS} - \sigma_m^\chi}\right)^{(2-\psi_\chi)}, \text{ For } & \mathrm{UCS} \leq \sigma_m \leq \sigma_m^\chi \end{cases} \tag{5}$$

where σ_m^χ and σ_a^χ are the mean stress and alternating stress component for a given constant value of life, N under critical R-ratio, which is $\chi = \mathrm{UCS}/\mathrm{UTS}$. The variable, ψ_χ, denotes the fatigue strength ratio and is defined as:

$$\psi_\chi = \frac{\sigma_{\max}^\chi}{\sigma_B} \tag{6}$$

where $\sigma_B\ (>0)$is the reference strength to define the peak of the static failure envelope in the $(\sigma_m - \sigma_a)$ plane.

2.4. Harris CLD

Harris et al. have developed a semi-empirical equation based on fatigue experimental data obtained from carbon fiber-reinforced plastic (CFRP) and glass fiber-reinforced plastic (GFRP) materials.[9–11] The CLD arising from the Harris model is shown in Figure 4. The general form of the Harris CLD model is as follows:

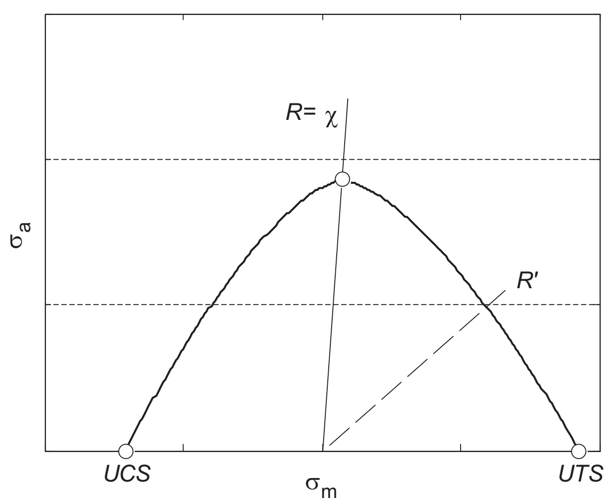

Figure 3. Schematic of the Kawai CLD.

$$a = f(1-m)^u (c+m)^v \tag{7}$$

where a and $m$are the normalized stress amplitude, respectively, σ_a/UTS, and the normalized mean stress component, σ_m/UTS, and c is the normalized compression strength, UCS/UTS, In Equation (7), f, u, and v are three adjustable parameters that are functions of fatigue life. The parameter f mainly controls the height of the curve, and it is a function of the ratio of the UCS to the UTS The exponents u and v determine the shape of the constant life line in the tension and compression region. Parameters, f, u, and v in the general form are considered as functions of fatigue life. From related studies, these parameters are found to be changing linearly with the logarithm of fatigue life, log N, for a wide range of carbon fiber and glass fiber composite materials [10]:

$$\begin{aligned} f &= A_1 \log N + B_1 \\ u &= A_2 \log N + B_2 \\ v &= A_3 \log N + B_3 \end{aligned} \tag{8}$$

where the parameters A_i and B_i are determined by fitting Equation (8) to the available experimental data for different loading cycles. Beheshty and Harris [10] have shown that the selection of the form of Equation (8) for the parameters u and v can be applied for a wide range of composite materials, especially CFRP laminates. However, parameter f is very sensitive to the examined material and its values vary between GFRP and CFRP laminates.

2.5. *Proposed CLD model*

In this study, a nonlinear constant life model is proposed to describe the fatigue behavior of composite materials. Plotting constant life data in the $(\sigma_m - \sigma_a)$ plane

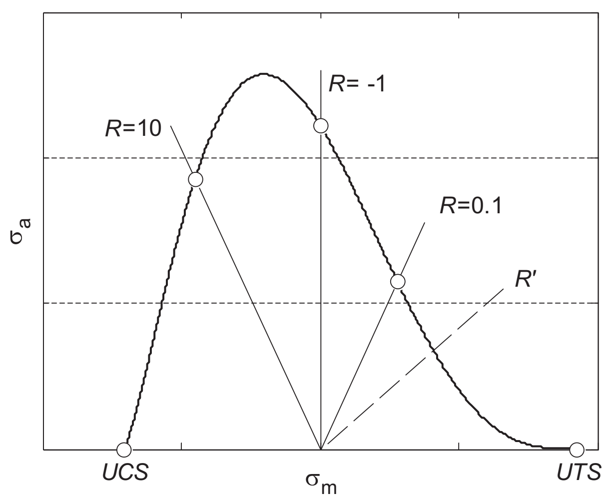

Figure 4. Schematic of the Harris CLD.

using S–N curves for different R-ratio shows that constant life data vary with fatigue life cycles as well as loading type (i.e. compression or tensile loading). Also, the constant life line changes its shape depending on fatigue life cycles, N. It usually shows either a parabolic form (concave or convex) or a linear form. Nonlinearity is reflected in the proposed CLD, yet it has simple equations and easy calculation processes. This formulation depends on the position of the mean stress and fatigue strength under fully reversed loading at a given value of fatigue life. The following simple expressions represent the proposed CLD model, and Figure 5 illustrates that:

$$\sigma_a = \begin{cases} \sigma_{a0}\left(1 - (\sigma_m/\mathrm{UTS})^{\alpha_T}\right), & \text{For} \quad \sigma_m > 0 \\ \sigma_{a0}\left(1 - (\sigma_m/\mathrm{UCS})^{\alpha_C}\right), & \text{For} \quad \sigma_m < 0 \end{cases} \tag{9}$$

where σ_{a0} is the cyclic stress amplitude for a given constant value of life, N, under fully reversed loading. The tensile and compressive exponential parameters, α_T and α_C, reflect the trend of the constant life data position. These parameters can be calculated from the following equations:

$$\alpha_T = \left\{ \sum_{i=1}^{n_T} \frac{\log(1 - \sigma_{a,i}/\sigma_{a0})}{\log(\sigma_{m,i}/\mathrm{UTS})} \right\} / n_T \tag{10}$$

$$\alpha_C = \left\{ \sum_{i=1}^{n_C} \frac{\log(1 - \sigma_{a,i}/\sigma_{a0})}{\log(\sigma_{m,i}/\mathrm{UCS})} \right\} / n_C \tag{11}$$

where n_T and n_C are the numbers of S–N data for the CLD in the tension and compression regions, except for under fully reversed loading; $\sigma_{a,i}$ and $\sigma_{m,i}$ are the stress amplitude and mean stress for a given constant value of life at the ith S–N curve. The material characteristics in the tension and compression regions can also be found because they reflect the material fatigue strength in their respective regions.

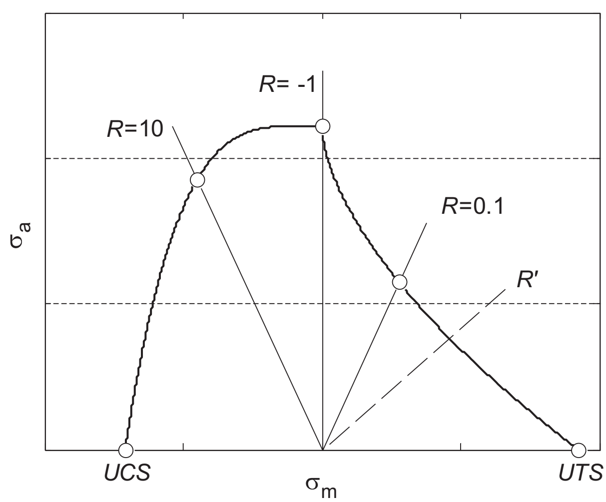

Figure 5. Schematic of the proposed CLD.

3. Verifications

The predictive accuracy for the proposed CLD is verified by comparing the estimated S–N curves from each CLD model. For the verifications, two kinds of E-glass/polyester multidirectional specimens cut at 0° on-axis and 45° off-axis from a laminate with the stacking sequence of $[0°/(\pm 45°)_2/0°]T$ are used.[12] Fiber and matrix materials are E-glass from Ahlstrom glassfibre and polyester resin from Chempol 80 THIX by Interchem. The laminate is comprised of two UD layers, unidirectional lamina of 100% aligned fibers, and two stitched ±45° layers.[13] CLDs are constructed for two specimens using the corresponding fatigue data retrieved from the reference paper by

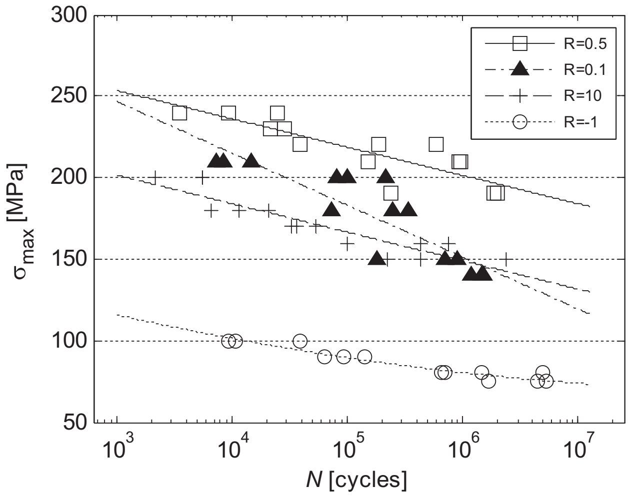

Figure 6. S–N curves for material #1.

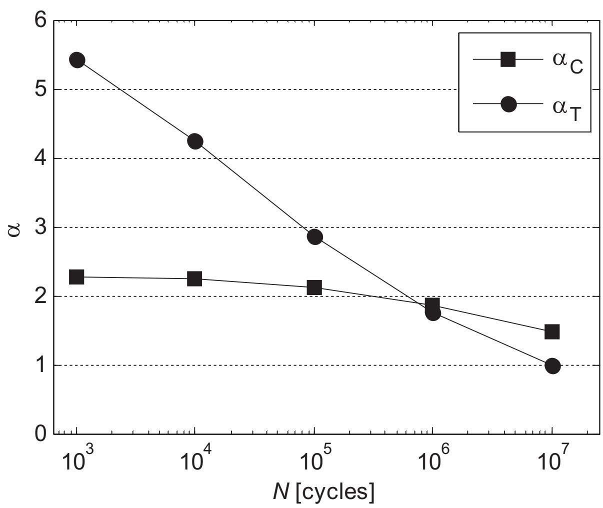

Figure 7. Exponential parameters for material #1.

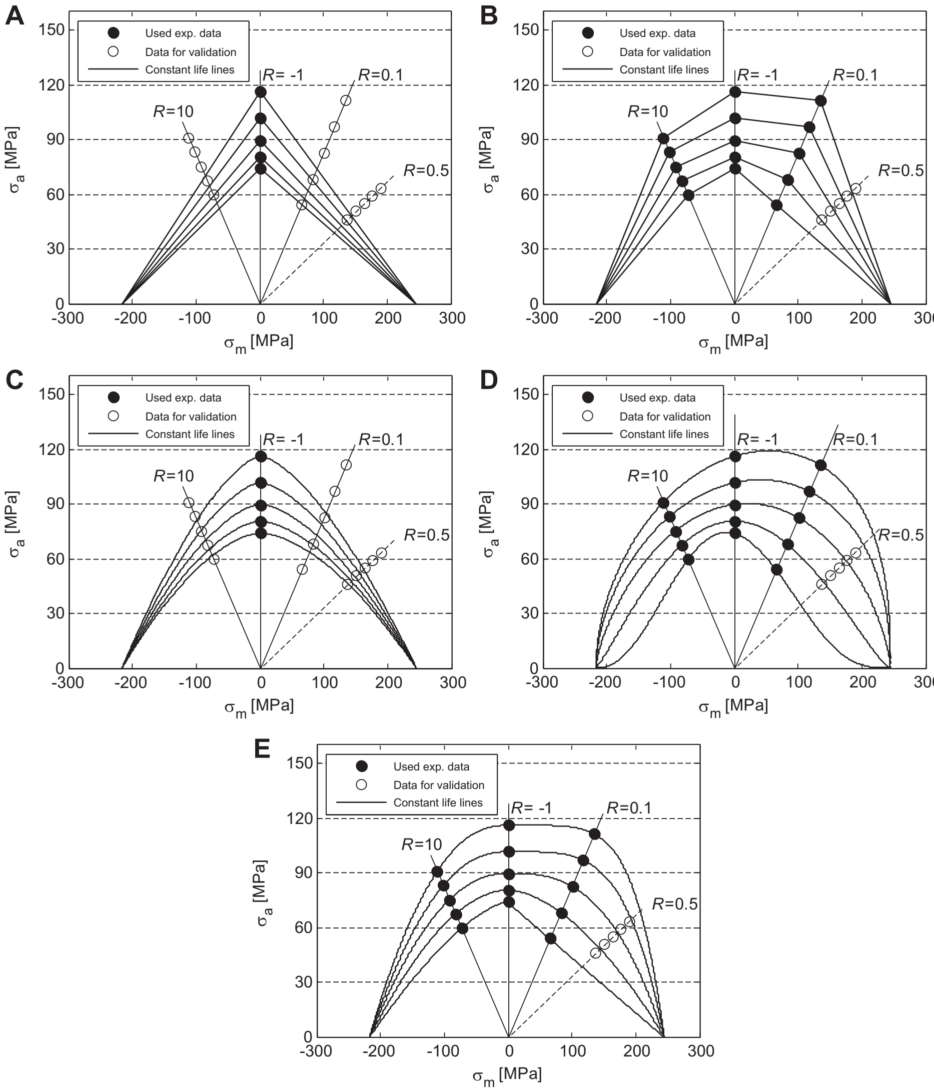

Figure 8. CLDs for material #1, (A) Linear, (B) Piecewise linear, (C) Kawai, (D) Harris, and (E) Proposed model.

Table 1. Predicting ability of the CLDs for material #1, 0° on-axis coupon.

CLD formulations	Linear	Piecewise linear	Kawai	Harris	Proposed
R^2 values	0.4922	0.6392	0.4466	0.7212	0.7627

applying CLD formulations. Finally, the predictive accuracy of the proposed CLD is evaluated by comparing the predicted S–N curves from the proposed CLD and existing theories with experimental data.

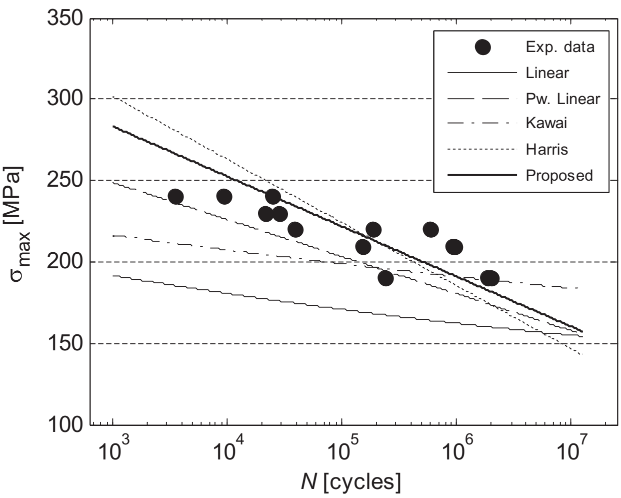

Figure 9. Predicted S–N curves for material #1.

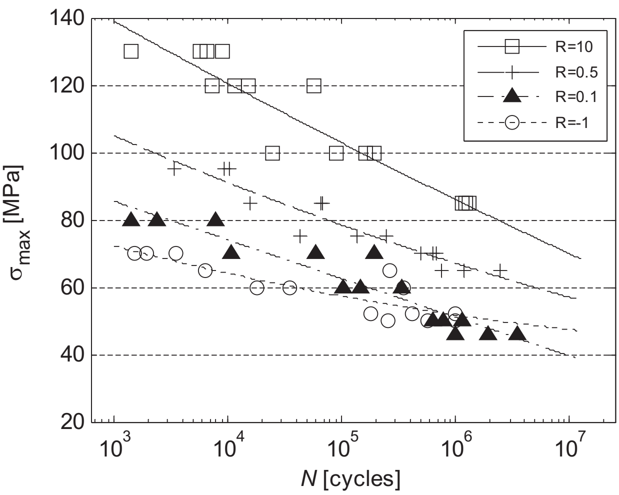

Figure 10. S–N curves for material #2.

3.1. Material #1 (0° on-axis coupon)

The first material is the E-glass/polyester 0° on-axis cut coupon. The constant amplitude fatigue test results are considered as the first example for verification of the proposed CLD. The selected test set is distributed in four S–N curves at *R*-ratios of 10, –1, 0.1, and 0.5, as shown in Figure 6. The UTS for this material is determined to be 245 MPa, while the UCS is 217 MPa.

The critical *R*-ratio for the Kawai CLD is –0.88, but no S–N curve under this *R*-ratio is available. Accordingly, the S–N curve at $R = -1$ is used for the construction of the Kawai and linear CLDs. Three S–N curves at *R*-ratios of 10, –1, and 0.1 are used for constructing the other CLDs. The exponential parameters calculated by

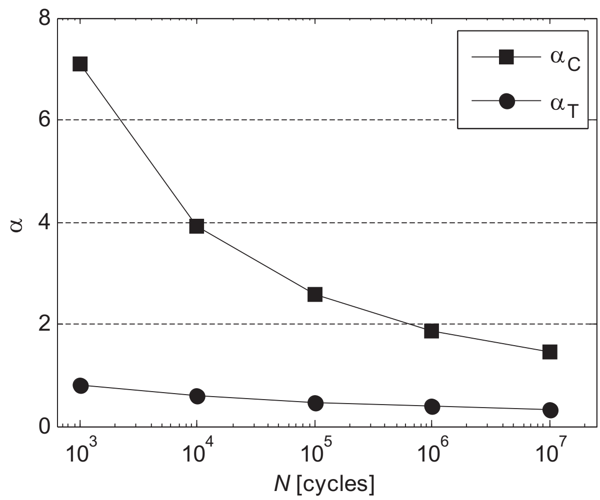

Figure 11. Exponential parameters for material #2.

Equations (10) and (11) are shown in Figure 7. From the exponential parameter values in the low-cycle region, it is observed that the fatigue strengths in the tensile region are higher than those in the compressive region.

CLDs based on the different formulations are presented in Figure 8. The dotted constant fatigue life points are used for making each CLD, and the S–N curves for $R = 0.5$ are predicted. By comparing the predicted S–N curves with experimental data, the predicting ability is calculated in terms of the coefficient of determination (R^2), and the results are shown in Table 1. From the results, it can be concluded that the predictions of the piecewise linear and Harris diagrams are more accurate ($R^2 = 0.64, 0.72$) than the results of the linear and Kawai CLDs. For the Kawai CLD model, the absence of critical S–N data might be one of the reasons for the inaccurate results. The proposed CLD model shows the most accurate results ($R^2 = 0.76$) for the S–N data prediction of material #1.

Figure 9 shows the predicted S–N curves from different CLD theories. The linear CLD predicted an S–N curve that is in fact significantly lower than the actual data. In this case, it is possible that fatigue damage is overestimated. The piecewise linear and Harris models have revealed relatively accurate results. However, the proposed model has produced the most accurate S–N curve, which can be seen as a regression result.

3.2. Material #2 (45° off-axis coupon)

E-glass/polyester multidirectional specimens cut at 45° off-axis from a laminate with a stacking sequence of $[0°/(\pm45°)_2/0°]T$ are used as the second material for testing.[12] A selected fatigue data-set for R-ratios of 10, –1, 0.1, and 0.5 is presented in Figure 10. Unlike the results for the 0° on-axis coupon, the compressive fatigue strength is relatively higher than the tensile fatigue strength for 45° off-axis coupons. The UTS for this material is determined to be 139 MPa, while the UCS is 106 MPa.

The critical R-ratio for the Kawai CLD is –0.76, but the S–N curve under this R-ratio is unavailable because the critical R-ratio is not a commonly used stress ratio. Accordingly, the S–N curve at $R = -1$ is used instead of the critical S–N data for the

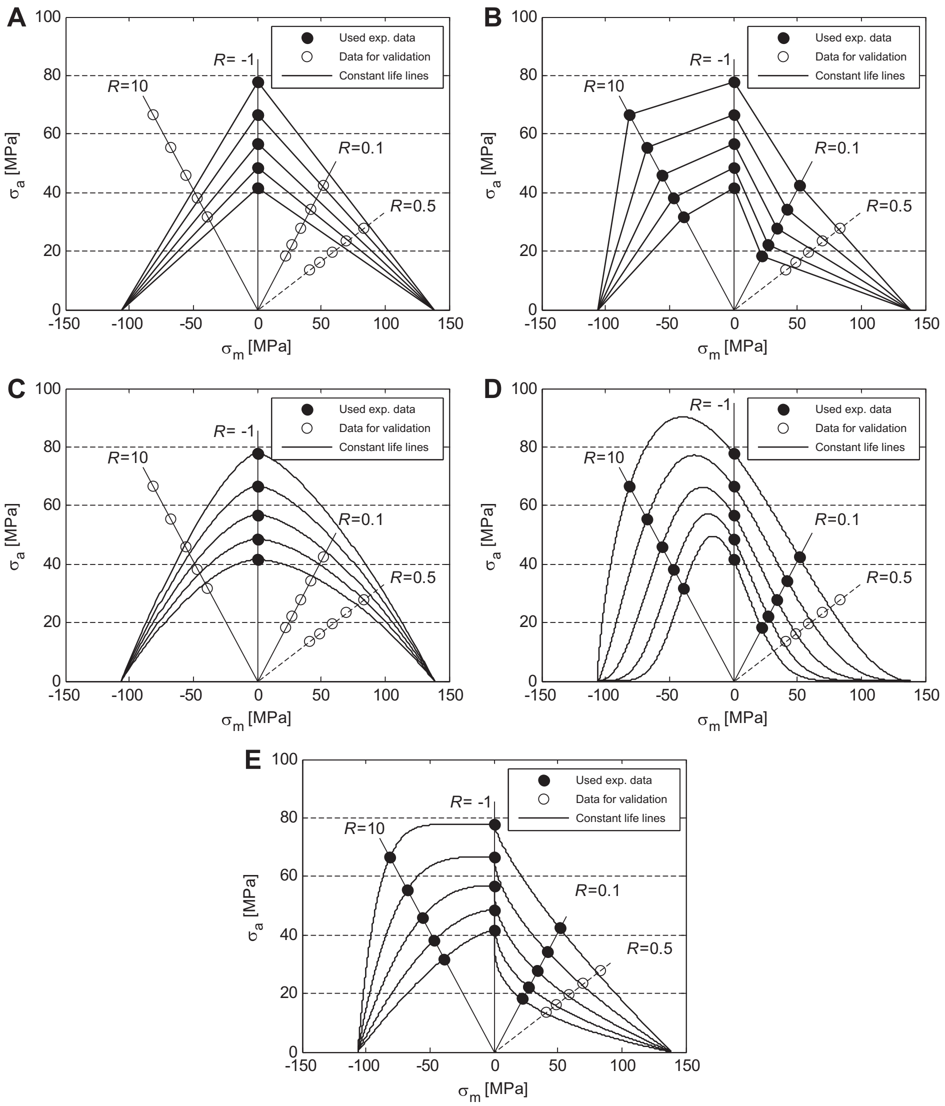

Figure 12. CLDs for material #2, (A) Linear, (B) Piecewise linear, (C) Kawai, (D) Harris, and (E) Proposed model.

Kawai CLD and linear CLDs. For other formulations, three S–N curves at *R*-ratios of 10, –1, and 0.1 are used for constructing CLDs. Also, the exponential parameters are calculated by Equations (10) and (11) and shown in Figure 11. Unlike the 0° on-axis coupon, it is observed that the compressive exponential parameter values are higher than that of the tensile exponential parameter values.

CLDs, according to the described models, are presented in Figure 12 and their predictive accuracy for $R = 0.5$ is shown in Table 2. The piecewise linear CLD has predicted the S–N curve with relatively high accuracy ($R^2 = 0.85$), but the prediction accuracy of the Harris CLD ($R^2 = 0.64$) is slightly lower than that of the piecewise linear CLD. Also, the linear and Kawai CLDs show relatively inaccurate results. From

Table 2. Predicting ability of the CLDs for material #2, ±45° on-axis coupon.

CLD formulations	Linear	Piecewise linear	Kawai	Harris	Proposed
R^2 values	0.5036	0.8524	0.4983	0.6384	0.9002

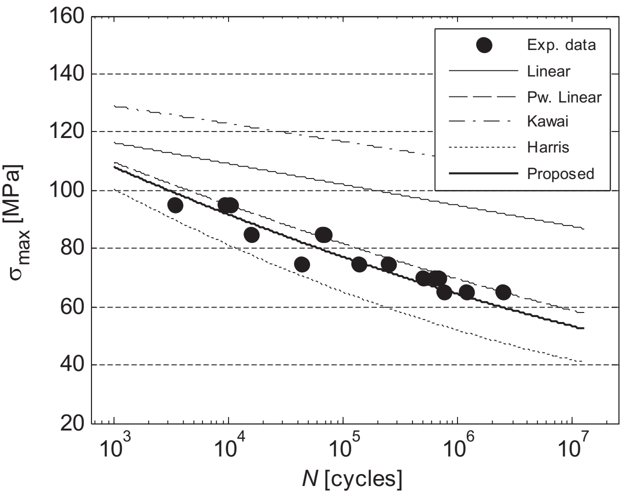

Figure 13. Predicted S–N curves for material #2.

the results of material #2, the proposed model shows the most accurate result ($R^2 = 0.90$).

Figure 13 shows the predicted S–N curves for material #2. The linear and Kawai CLDs have predicted an S–N curve that is significantly stronger than that of the actual data. In this case, the fatigue analysis result appears to be very optimistic. On the other hand, the Harris model has predicted an S–N curve that is slightly lower. The proposed model predicted the closest S–N curve, and also the piecewise linear CLD shows a relatively accurate result. As a result of this verification, it can be concluded that the proposed model produces the most accurate S–N curves among the CLD theories from the examination of both materials.

4. Conclusions

A nonlinear constant life model is proposed to enhance the accuracy of fatigue life estimation for composite structures. The proposed CLD theory offers high predictive accuracy with simple calculation processes while requiring S–N curves for a minimum of three R-ratios. In order to apply the newly proposed CLD to fatigue analysis, the predictive accuracy of the CLD should be verified. The predictive accuracy of the proposed CLD model is verified for two types of composite coupons. The results are compared and evaluated with four existing models. Finally, the following conclusions are drawn.

Simplicity is offered by the linear and Kawai models with minimum S–N data-sets. Additional experiments for the critical R-ratio are inevitable for the Kawai model because most of the databases do not have the critical S–N data. In this paper, it is possible that the absence of the critical S–N data may have been at least partly responsible for the inaccurate results of the Kawai CLD. The piecewise linear and Harris models produce relatively accurate S–N data. The piecewise linear CLD is attractive in that it uses a simple calculation process by linear interpolation through intuitive equations. The application of the Harris CLD is relatively difficult because it contains a multivariate fitting process. The proposed nonlinear CLD model is able to predict more accurate S–N curves for two types of composite coupons. Also, the proposed CLD model describes the nonlinearity of fatigue life distribution well with simple equations and calculation processes. In the future, additional research could be performed to confirm the possibility of applying the model to a wider variety of composite materials and to improve the accuracy of this model through a more realistic depiction of fatigue life behavior for composite materials.

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