An enhanced fatigue residual life prediction model based on fatigue driving stress by considering loading interaction effects

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Abstract

It has been demonstrated that the loading history takes into account the loading sequence and loading interaction effects. Nonlinear damage models based on fatigue driving stress theory consider the loading sequence but exclude the loading interaction effects. In this study, a novel evolution curve for fatigue driving stress was created by including the loading interaction factor in the equation of driving stress evolution. Through using fatigue driving stress equivalence, the remaining fatigue life under varying amplitude loading was then predicted by an enhanced fatigue driving stress model. Compared with Miner's rule, the K-R model, Zhu's model, and Li's model, this new model gave more accurate and reliable predictions.

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Abstract

It has been demonstrated that the loading history takes into account the loading sequence and loading interaction effects. Nonlinear damage models based on fatigue driving stress theory consider the loading sequence but exclude the loading interaction effects. In this study, a novel evolution curve for fatigue driving stress was created by including the loading interaction factor in the equation of driving stress evolution. Through using fatigue driving stress equivalence, the remaining fatigue life under varying amplitude loading was then predicted by an enhanced fatigue driving stress model. Compared with Miner's rule, the K-R model, Zhu's model, and Li's model, this new model gave more accurate and reliable predictions.

Keywords

Fatigue, life prediction, fatigue driving stress, loading interactions, loading sequence

Nomenclature

fatigue strength constant	cumulative damage
fatigue strength index	fatigue damage state of 1^{st} stage loading
fatigue life	fatigue damage state of 2^{rd} stage loading
the number of cycle	new equivalence equation
equivalence equation	applied stress
fatigue driving stress function	applied stress of 1^{st} stage loading
fatigue life of 1^{st} stage loading	applied stress of 2^{nd} stage loading
the number of cycle of 1^{st} stage loading	equivalent driving stress of 1^{st} stage loading
fatigue driving stress function of 1^{st} stage loading	critical fatigue driving stress
fatigue life of 2^{nd} stage loading	equivalent driving stress of 2^{nd} stage loading
the equivalent number of cycle of 2^{nd} stage loading	applied stress of 3^{rd} stage loading
the number of cycle of 2^{nd} stage loading	equivalent driving stress of 3^{rd} stage loading
fatigue life of 3^{rd} stage loading	applied stress of i^{th} stage loading
the equivalent number of cycle of 3^{rd} stage loading	equivalent driving stress of i^{th} stage loading
the number of cycle of 3^{rd} stage loading	temperature-dependent fatigue strength coefficient
fatigue life of i^{th} stage loading	the new equivalent number of cycle of 2^{nd} stage loading
the number of cycle of i^{th} stage loading	ratio of 1^{st} and 2^{nd} stage loading stresses
damage of i^{th} stage loading	ratio of i-1^{th} and i^{th} stage loading stresses

Introduction

Mechanical components generally operate under cyclic stresses of varying amplitude during their lifetime. Fatigue phenomena are generated by these stresses and it is the main cause of failure of mechanical components during operation. Assessing fatigue damage is a critical issue, and it is one of the most common structural engineering problems. In general, fatigue damage accumulation theories can be divided into two categories: (1) linear damage accumulation theories and (2) nonlinear damage accumulation theories.

To predict the remaining life of these components, it is important to establish a method for assessing the accumulation of fatigue damage. For many years, design engineers have used Miner's rule and its modifications to predict the fatigue life of components under variable loading[11]. In the linear approach, the work absorbed for each fatigue cycle is assumed to be constant and independent of one another. Nor does it take into account stress damage below the fatigue limit and the interaction between applied loads. This can lead to an order of magnitude difference between the predicted life and the test life, and such calculations may be unconservative[2-4]. Several researchers have tried to modify Miner's rule, but predictions of life expectancy based on it are often unsatisfactory because of its inherent flaws[5]. Marco and Starkey[6]first proposed a nonlinear load-related damage rule, denoting the damage accumulation as , whereis a factor depending on theth loading.

More recently, Kwofie and Rahbar[8-9] developed a novel approach to nonlinear damage accumulation based on S-N curves, referred to as the K-R model. Kwofie and Rahbar introduced the concept of fatigue driving forces that lead to fatigue damage in this model. The fatigue driving stress is a function of the cyclic stress, the number of loading cycles, and the fatigue life. This value increases with increasing loading cycles until a critical maximum driving stress is reached at the time of fracture. Residual fatigue life can be predicted by equating the fatigue driving stresses to produce cycles equivalent to the previous loading. It does not require much characterization of the material and the parameters of the model are only related to the S-N curve of the material. Later, Zuo[10] et al. made a further study based on the K-R model and proposed a new nonlinear damage accumulation rule to improve the inherent flaws in the linear damage accumulation rule and to keep it simple in its application. The main advantages of the model are its ease of use, it only requires S-N curves, and it does not require any additional material properties to account for the effects of the loading history of the material.

It has been found that in addition to the loading sequence effects to be taken into account, the load interaction effects can also impact fatigue damage at multiple stages. Abrupt changes in load amplitude under different loading sequences can cause changes in the damage evolution of subsequent load cycles, which in turn affects the remaining life of the structure. Schijve, Yarema[11] and Batsoulas[12] noted that the number of damage nuclei will lead to a load interaction effect that is greater at higher loading stresses. In addition, the number of damage nuclei produced by different loading stress levels will lead to variations in damage accumulation and this effect will increase with larger differences between stress levels.

Considering the loading interaction effects, with reference to the literature[13,14], Zhu[15] introduced a load ratio between each loading stage to describe the loading interaction effects, making an improvement to the K-R model. In order to study the loading interaction effects on damage accumulation, Peng[16] analyzed that after undergoing high-loading cycling, the damage evolution curve under low-loading cycling will be shifted based on its damage evolution curve of constant amplitude loading and this shift has a promoting effect on damage accumulation, while the opposite is true for low-high loading, providing an intuitive theoretical explanation for loading interaction effects.

The objective of this study is to present a new modified fatigue driving stress model that accounts for the loading interaction effects and is used to predict the remaining life under variable amplitude fatigue loading. The validity of this model is also verified by comparing it with Miner's rule and other models based on fatigue driving stress theory through fatigue tests of variable amplitude on several materials.

Models based onfatigue driving stress theory

2.1. Fatigue driving stress theory

It is well known that the S-N curve of a material can be expressed using a power function as follows:

whereis the fatigue strength constant, is the fatigue strength index, is the applied cyclic stress, andis the fatigue life.

In the new approach to nonlinear damage accumulation developed by Kwofie and Rahbar[8,9], it is argued that although the applied loading is constant, the transient driving loading, which varies continuously with fatigue loading, is the primary causative factor for damage accumulation and is defined as the fatigue driving stress.

For a given stress loading, the fatigue driving stress function can be expressed as:

Where is the life-fraction of load and is an increasing function with respect to , as the number of loading cycles increase from zero to , increases from to Thus, at we have

Thus it is expected that while the applied cyclic load may be constant, the fatigue driving stress will increase with cycling until the fatigue strength constant is reached, at which point fracture of the specimen is expected to occur[9].

2.2. Existing models based on fatigue driving stress theory

2.2.1.K-R model

By equivalence of fatigue driving stress, models based on fatigue driving stress theory have been developed. Taking a two-stage cyclic loading as an example, the fatigue lives corresponding to different stresses loading and are and respectively, and the growth law of fatigue driving stress is presented in Figure 1.

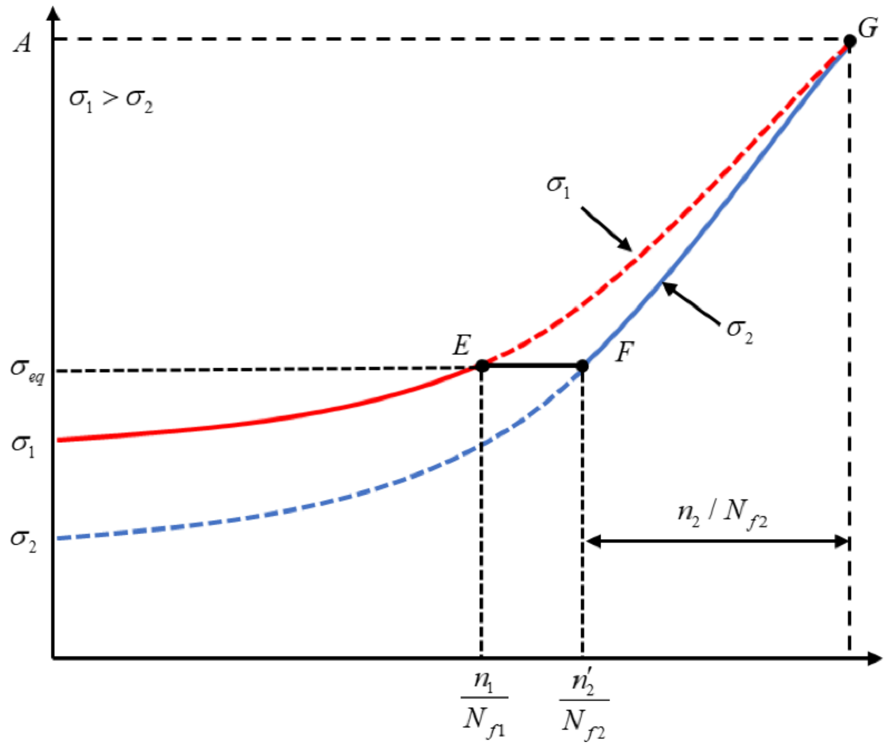

FIGURE 1 Growth law of fatigue driving stress under two-stage cyclic loading

According to Figure 1, under a high-low loading sequence, the member is first loaded under stress for cycles, and the fatigue driving stress reaches point E. Then we have

Assuming that the member is loaded under stress for cycles to point F such that points E and F have the same fatigue driving stress and is the equivalent number of cycles under stress loading, the fatigue driving stress at point F can be expressed as

Because the E and F points have the same fatigue driving stress, equations (4) and (5) are required to be equivalent. Then equating the fatigue driving stress reached by cycles of loading at stress to the fatigue driving stress reached by cycles of loading at stress, according to equation (2), the equivalence equation can be expressed as

The equivalent driving stress at points E and F can be expressed as:

Equation (7) shows that the fatigue driving stress achieved by loading stressat life-fraction of is equal to the fatigue driving stress achieved by loading stress at life-fraction of .

Subsequently, if the loading is continued for cycles under stress to achieve the equivalent driving stress, we have

If fatigue failure occurs under the second stage of loading, then the fatigue driving force will follow the path FG from until the critical fatigue driving stress is reached. From equations (7) and (8) we can get

Taking equation into the equation, the remaining life fraction of the second stage of loading is obtained as

Similarly, if there is a third stage of loading, then the fatigue driving stress reached by cycles of loading stress is equal to the fatigue driving stress reached by ()cycles of loading stress , then the equivalent equation can be expressed as

The equivalent driving stress is expressed as

Then if the loading is continued for cycles under stress to reach the equivalent driving stress, we have

Combining equation(7), equation (8), and equation (12), equation (13) can be transformed as

Thus, for a multi-stage cyclic loading with stresses of , loading cycles of , and fatigue failure lives of , the equivalent fatigue driving stress takes the form of

At fracture, the critical fatigue driving stress will be equal to the fatigue strength constant

Taking the equation into the equation, a new damage model is defined in the form of equation (17)

Therefore, each item on the left-hand side of the equation defines the damagedue to applied loading stressas

where is the cycle life fraction under loading stress, is the fatigue failure life of loading , and is the life of the initially applied loading . Thus, the cumulative damage can be expressed as

When fatigue failure occurs at =1, the remaining life fraction of the ith load is

2.2.2. Modified K-R model

Zhu model

In order to consider the load interaction effects, Zhu[15] et al. proposed a modified K-R model by imposing a load ratio between two stages to obtain a multi-stage residual life prediction model as

Li model

Since the K-R model only considers fatigue damage at a constant temperature, Li[17] et al proposed a modified K-R model at variable temperatures. Fatigue driving stress was initially normalized to

where is the temperature-dependent fatigue strength coefficient.

The remaining life fraction for the second-stage loading at a temperature different from the first stage can be obtained based on the equivalence of fatigue driving stress.

where and are the temperature-dependent fatigue strength coefficients for the first stage and the second stage respectively.

In order to consider the effect of the first-stage loading on the remaining life fraction of the second stage, Li et al obtained the following expression by proposing to use as a pre-cycling factor.

Extending the model to multi-stage loading as

Li and Zhu give a modified form of the K-R model by adding a power exponential term to the remaining life model respectively, but do not give a specific explanation of the reason for the correction.

3. A new residual life prediction model

3.1.Loading interaction theory

According to damage equivalence, variable amplitude loadings can be equated to a constant amplitude loading, as shown in Figure 2.

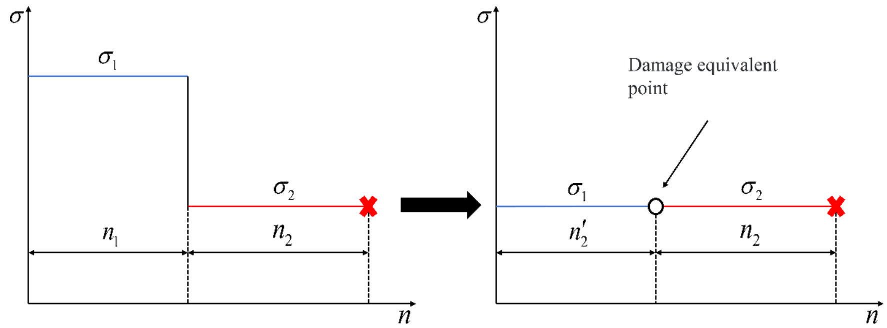

FIGURE 2 Damage equivalence

Figure 2 shows that cycles at high loading have exactly the same damage state as cycles at low loading . However, in view of the rationality of fatigue damage equivalence under different stress levels, studies[18-19] point out that the traditional damage equivalence state does not exist under different stress levels. According to this point of view, in the fatigue driving stress model, equivalence according to equation (6) is not sufficient as well. In particular, for the high-low loading sequence, it tends to speed up the damage evolution process under low loading, whereas for the low-high loading sequence it is the reverse. At the same time, the greater the difference between the stress levels applied, the greater the effect. This phenomenon (loading interactions) is usually described in terms of load ratio and has been reported by Corten and Dolan[20], Freudenthal and Heller[21], Morrow[22], and Huang[23] et al.

More recently, targeting the flaws of traditional damage equivalence methods, Peng[16] proposed a fatigue damage equivalence rule by considering the loading interaction effects. Generally, according to the principle of damage equivalence, points A and B in Figure 3 have the same damage state, which can be represented by the concept of fatigue damage state as:

The damage evolution path is then OABE, but the loading of the second stage retains its damage evolution trend under constant amplitude loading, ignoring the interaction effects between the loadings. After undergoing high-loading cycling, the damage evolution curve under low-loading cycling will be shifted based on its damage evolution curve of constant amplitude loading and this shift has a promoting effect on damage accumulation, while the opposite is true for low-high loading. The damage curve after the offset can be assumed to be AN, and the damage curve AN is shifted and extended to give an equivalent damage curve OFE with low loading applied alone, as shown in Figure 3. Unlike the OBE, this damage curve OFE takes into account the interactions between high and low loadings.

Thus, by considering the load interaction effects, the damage accumulation path is OA-AF-FE, and the corresponding equivalent state of fatigue damage can be described as

The function represented by curve OBE has the same starting point and ending point as that represented by curve OFE, and curve OFE can be transformed by curve OBE. In general, this transformation relation is power exponential. Peng[16] modified Ye's model with the proposed method by taking loading interactions into account, and in comparison to Miner's rule and Ye's model, the modified model has a more satisfactory forecasting result .

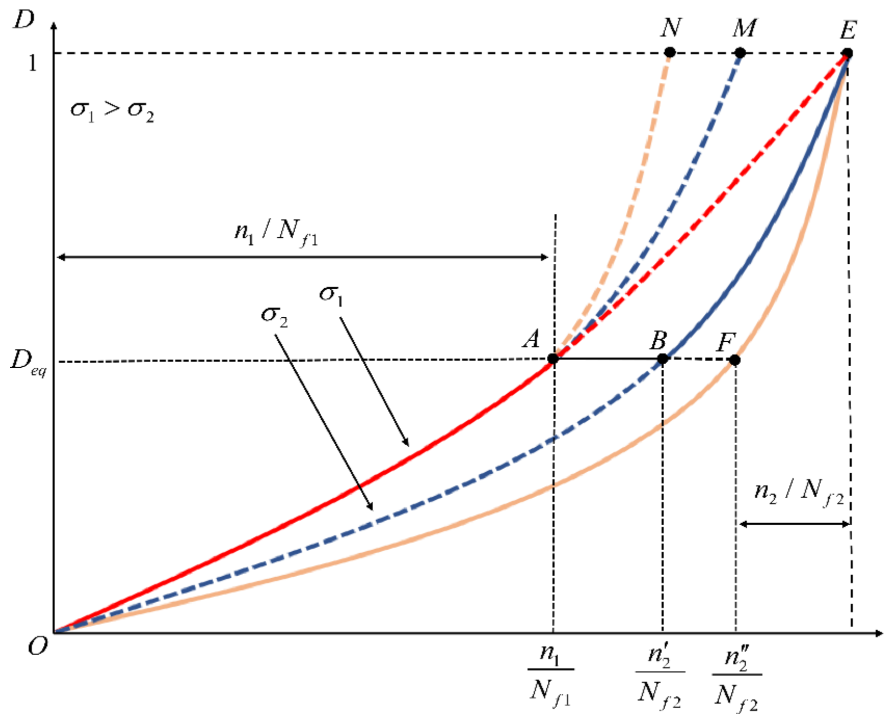

FIGURE 3 Fatigue damage evolution under two-stage high-low loading

3.2.A new residual life prediction model considering loading interaction effects

In order to consider the loading interaction effects, the fatigue driving stress model is modified. From the evolution of the fatigue driving stress in Figure 1 and the damage evolution in Figure 3, the fatigue driving stress curve after an offset can be assumed to be EI, as shown in Figure 4.

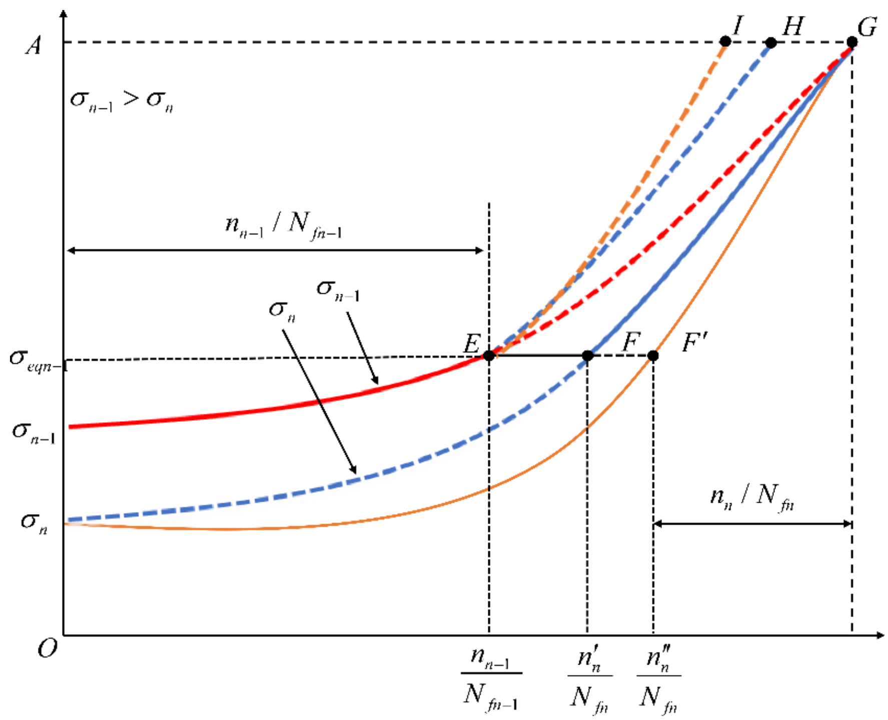

FIGURE 4 Fatigue driving stress evolution under two-stage high-low loading

After translation and extension of the fatigue driving stress curve EI, a fatigue driving stress curve F'G is finally obtained with a low loading applied alone. In contrast to EI, the curve F'G accounts for the loading interaction effects. Compared with EI, it can be expressed as:

The fatigue driving stress curve F'G is built based on curve FG, and the following conditions should be satisfied:

Under low-high loading

According to the equivalence of fatigue driving stress, the fatigue driving stress generated by cycles under stress is equal to the fatigue driving stress generated by cycles under stress according to curve F'G, as shown in Figure 3. Therefore, considering the loading interaction effects, the fatigue driving path is E F'-F'G, and the corresponding equivalent state can be described as:

According to the studies[20-23], the greater the difference between loading levels, the more significant the interaction effects are. The loading interaction effects can be described by the ratio of loading levels. Therefore, the interaction factor is defined in this paper as the ratio of loading levels of two adjacent stages,.

In order to satisfy conditions (29) - (33), referring to the Marco-Starkey model[6] or Manson model[25], we can obtain by adding the power exponent to :

Then the equivalent driving stress can be expressed as:

By taking logarithms of both sides of equation (36), the equivalent cyclic fraction under stress loading can be obtained:

If the member fails by fatigue under a secondary loading, the fatigue driving stress will follow the path from until the critical driving stress is reached.

By substituting the equation into , the remaining life fraction of the second stage of loading is obtained as

By fatigue driving stress equivalence, extending (39) to the multi-stage loading case, the remaining life fraction at the ith stage is

Where the equivalent life fraction is expressed as

Where is the loading interaction factor, expressed as the ratio of two levels of stress:

In summary, equation (40) is the general form of the residual life prediction model when considering the loading interaction effects. The unknown parameters involved in the model can be determined only by the S-N curve.

4. Comparison of predicting results of different models

Two-stage loading tests of Al2024 aluminum alloy, welded joints of aluminum alloy body, and nodular cast iron (GS61) of high-speed EMUS and four-stage loading test of aluminum alloy 6082T6 are used to verify the validity of the proposed model.

4.1. Two-stage loading

Results of alloy Al2024

The material studied by Pavlou is aluminum alloy Al2024[26]. The life of loading stress 150Mpa is 430000 cycles, and the life of loading stress 200Mpa is 150000 cycles.

Table 1 gives the experimental remaining life fraction and the predicted life fraction of Miner's rule, the K-R model, Zhu's model, Li's model, and the new model.

TABLE 1 Experimental and model prediction results of Al2024

Load level (Mpa)	Load level (Mpa)	Load sequence	Load sequence	Experimental	Experimental	Experimental	Experimental	Experimental	Ex
200-150	200-150	High-Low	High-Low	30000	30000	0.2	228700	228700	0.6
				60000	60000	0.4	101050	101050	0.2
				90000	90000	0.6	76050	76050	0.1
150-200	150-200	Low-High	Low-High	86000	86000	0.2	144500	144500	0.9
				172000	172000	0.4	133500	133500	0.8
				258000	258000	0.6	81700	81700	0.5
Miner rule	K-R model	K-R model	Zhu model	Zhu model	Li model	Li model	Li model	Proposed model	Pr mo
0.8	0.73	0.73	0.71	0.71	0.70	0.70	0.70	0.63	0.6
0.6	0.55	0.55	0.53	0.53	0.56	0.56	0.56	0.45	0.4
0.4	0.37	0.37	0.36	0.36	0.38	0.38	0.38	0.29	0.2
0.8	0.87	0.87	0.85	0.85	0.92	0.92	0.92	0.93	0.9
0.6	0.65	0.65	0.64	0.64	0.65	0.65	0.65	0.76	0.7
0.4	0.44	0.44	0.43	0.43	0.42	0.42	0.42	0.53	0.5

As can be seen in Figure 4, the sum of life fractions is 1 under Miner's rule and the other models have sums of life fractions less than 1 under high - low loading and greater than 1 under low - high loading, where the models take into account load history effects.

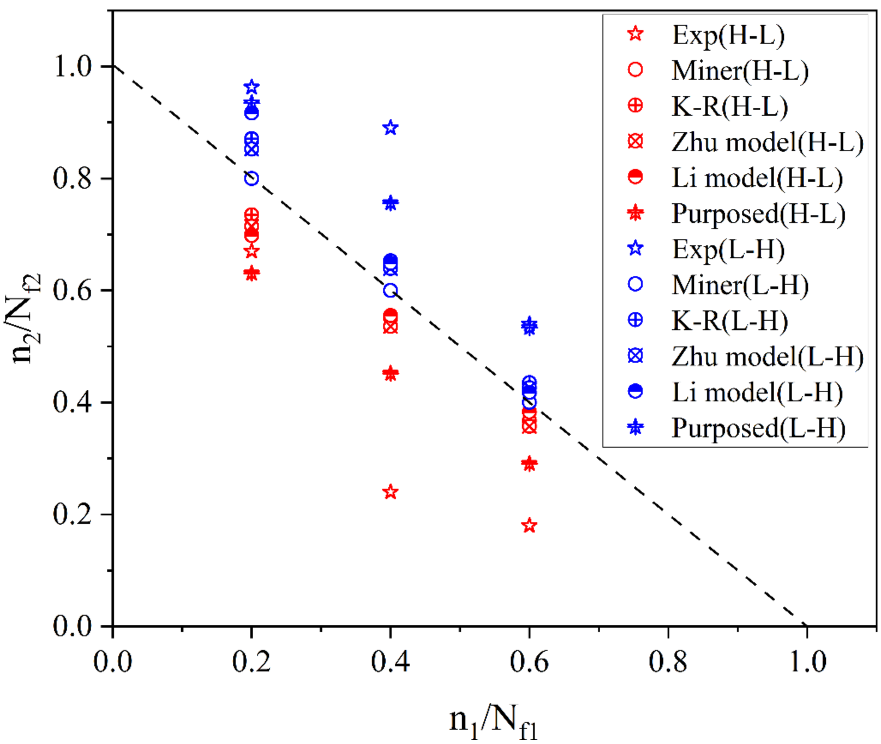

FIGURE 5 Comparison of the experimental results of Al2024 with the predicted results of the five models

Compared with Miner's Rule, the K-R model, Zhu's model, and Li's model, the model proposed in this paper have better prediction results. As can be seen from Figure 5, the predicted life of the model under high-low loading falls within the 2x error band, and the predicted life under low-high loading falls within the 1.5x error band.

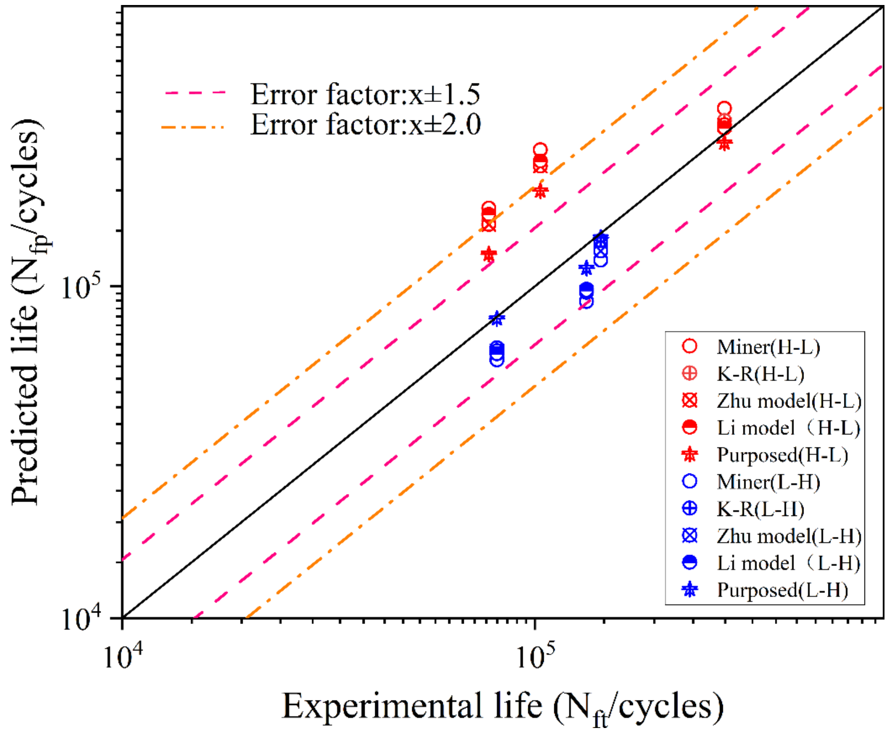

FIGURE 6 Comparison of the predictive capability of five models for the remaining life of Al2024

Results of welded joints of aluminum alloy body

The fatigue test of welded joints of the aluminum alloy body of a high-speed EMU was analyzed as an example[27]. When the loading stress of aluminum alloy butt joints is 104, 89, and 74Mpa, the fatigue life is 549300, 880500, and 1540100 cycles, respectively. The fatigue life of aluminum alloy angle joints is 619800, 952300, and 1546100 cycles when the loading stress is 93, 83, and 73Mpa, respectively.

Table 2 gives the experimental remaining life fraction and the predicted life fraction of Miner's rule, the K-R model, Zhu's model, Li's model, and the new model.

TABLE 2 Experimental and model prediction results of welded joints

Type	Load sequence	Load sequence	Load level(Mpa)	Load level(Mpa)	Load level(Mpa)	Experimental	E
Butt joints	High-Low	High-Low	High-Low	104-74	104-74	109900	1
				89-74	89-74	176100	1
	Low-High	Low-High	Low-High	74-89	74-89	770100	7
				74-104	74-104	770100	7
Angle joints	High-Low	High-Low	High-Low	93-73	93-73	309900	3
				83-73	83-73	476100	4
	Low-High	Low-High	Low-High	73-83	73-83	509200	5
				73-93	73-93	773000	7
Miner rule	Miner rule	K-R model	K-R model	K-R model	Zhu model	Zhu model	L

0.8	0.742	0.719	0.709	0.618
0.8	0.768	0.762	0.750	0.704

0.5	0.520	0.517	0.514	0.587
0.5	0.539	0.527	0.527	0.663
0.5	0.468	0.459	0.477	0.391
0.5	0.483	0.481	0.488	0.440
0.67	0.694	0.691	0.697	0.740
0.5	0.534	0.527	‘0.524	0.622

As can be seen in Figure 7, the sum of life fractions is 1 under Miner's rule and the other models have sums of life fractions less than 1 under high - low loading and greater than 1 under low - high loading, where the models take into account load history effects.

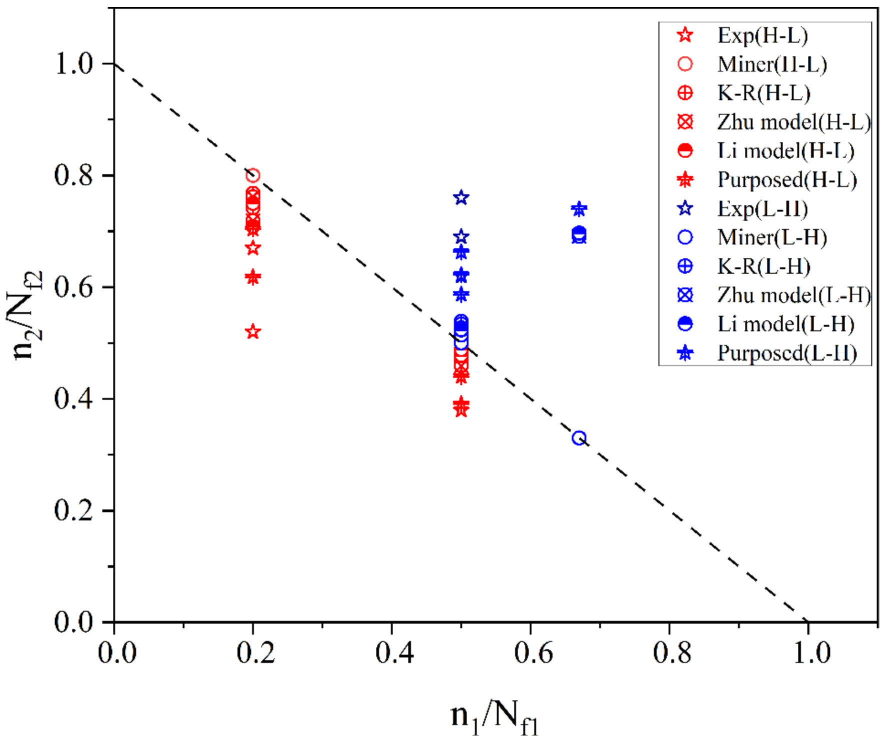

FIGURE 7 Comparison of the experimental results of welded joints with the predicted results of the five models

Compared with Miner's Rule, the K-R model, Zhu's model, and Li's model, the model proposed in this paper have better prediction results. As can be seen from Figure 8, the predicted life of the model under high-low loading falls within the 2x error band, and the predicted life under low-high loading falls within the 1.5x error band.

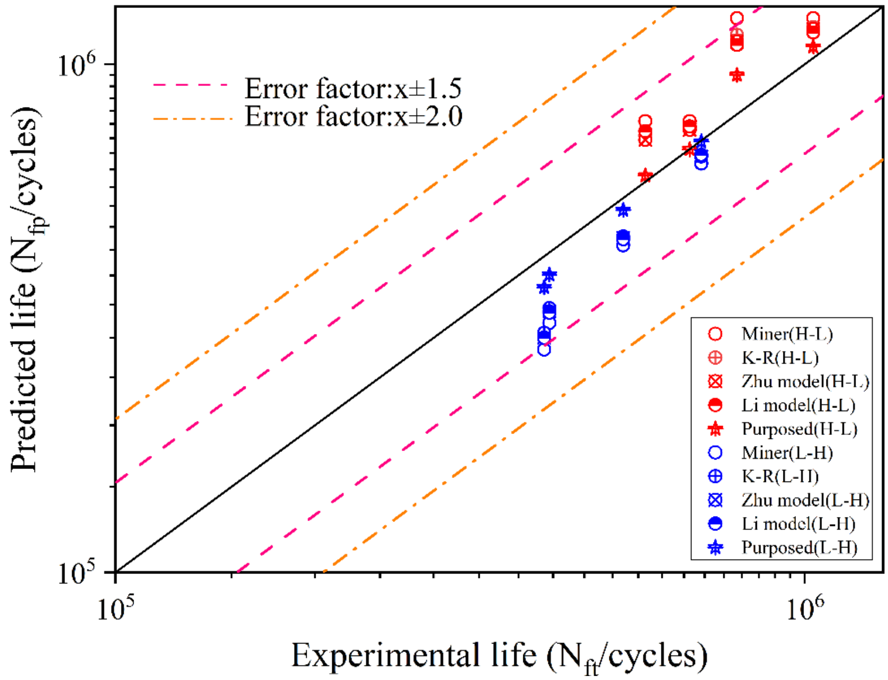

FIGURE 8 Comparison of the predictive capability of five models for the remaining life of welded joints

Results ofnodular cast iron GS61

Reference[28] gives the fatigue loading test data of nodular cast iron GS61. When the loading stress is 352, 320, and 303Mpa, the fatigue life is 112866, 322580, and 588235 cycles, respectively.

Table 3 gives the experimental remaining life fraction and the predicted life fraction of Miner's rule, the K-R model, Zhu's model, Li's model, and the new model.

TABLE 3 Experimental and model prediction results of GS61

Load sequence	Load level (Mpa)	Load level (Mpa)	Load level (Mpa)	Experimental	Experimental	Experimental	Experimental	Experimental	Ex
High-Low	352-320	352-320	352-320	50000	0.443	0.443	130510	130510	0.4
	352-303	352-303	352-303	50000	0.443	0.443	205040	205040	0.3
Low-High	320-352	320-352	320-352	110000	0.341	0.341	82830	82830	0.7
	303-352	303-352	303-352	160000	0.272	0.272	116650	116650	1.0
Miner rule	Miner rule	K-R model	Zhu model	Zhu model	Zhu model	Li model	Li model	Proposed model	Pr mo

0.557	0.511	0.506	0.519	0.478
0.557	0.488	0.477	0.500	0.438
0.659	0.718	0.713	0.723	0.752
0.728	0.831	0.816	0.865	0.874

As can be seen in Figure 9, the sum of life fractions is 1 under Miner's rule and the other models have sums of life fractions less than 1 under high - low loading and greater than 1 under low - high loading, where the models take into account load history effects.

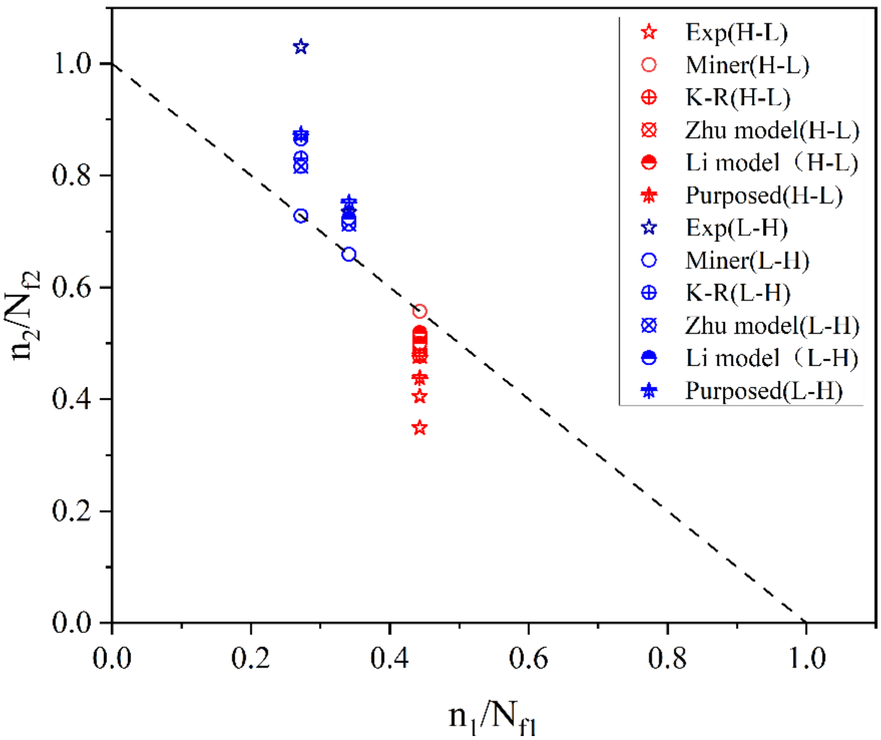

FIGURE 9 Comparison of the experimental results of GS61 with the predicted results of the five models

Compared with Miner's Rule, the K-R model, Zhu's model, and Li's model, the model proposed in this paper have better prediction results. As can be seen from Figure 10, the predicted life of the model under high-low loading falls within the 2x error band, and the predicted life under low-high loading falls within the 1.5x error band.

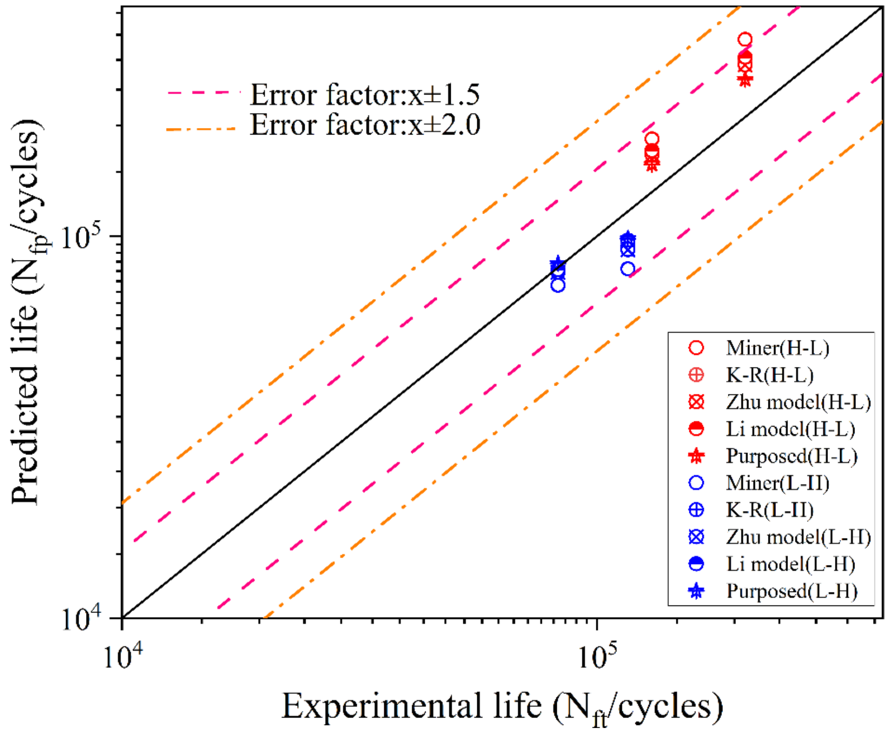

FIGURE 10 Comparison of the predictive capability of five models for the remaining life of GS61

4.2. Multi-stage loading

The four-stage loading test of aluminum alloy 6082T6 was carried out[29]. When the loading stress is 305, 280, 260, and 240Mpa, the fatigue life is 38000, 87612, 180660, and 394765 cycles, respectively.

Table 4 gives the experimental remaining life fraction and the predicted life fraction of Miner's rule, the K-R model, Zhu's model, Li's model, and the new model.

Tables 4 and 5 give a comparison of the experimental results with Miner's rule, the K-R model, Zhu's model, Li's model, and the new model's prediction results

TABLE 4 Four-stage loading test results of aluminum alloy 6082T6

Load sequence	Load level (Mpa)	Experimental	Experimental	Experimental	Experimental	Experimental	Experimental	Experimental	Ex
High-Low	305-280-260-240	10950	0.288	19427	0.222	26258	0.145	52500	0.1
Low-High	240-260-280-305	103000	0.261	26258	0.145	19427	0.222	16800	0.4
Random	280-305-260-240	19427	0.222	10950	0.288	26258	0.145	43400	0.1

TABLE 5 Comparison of experimental and model prediction results of aluminum alloy 6082T6

Experimental	Experimental	Miner	Miner	Miner	K-R	K-R	K-R	Zhu	Zhu	Zhu	Li
52500	0.133	136098	0.344	98760	98760	0.250	97124	97124	0.246	92458	92458
16800	0.442	14136	0.372	18886	18886	0.497	18578	18578	0.489	20903	20903
43400	0.110	136098	0.345	124350	124350	0.315	123070	123070	0.312	110801	110801

It can be seen from Figure 10 that the proposed model has better life prediction ability under high-low loading and random loading. The predictive capability of the proposed model is similar to that of the K-R model, Zhu's model, and Li's model under low-high loading but better than that of the Miner model.

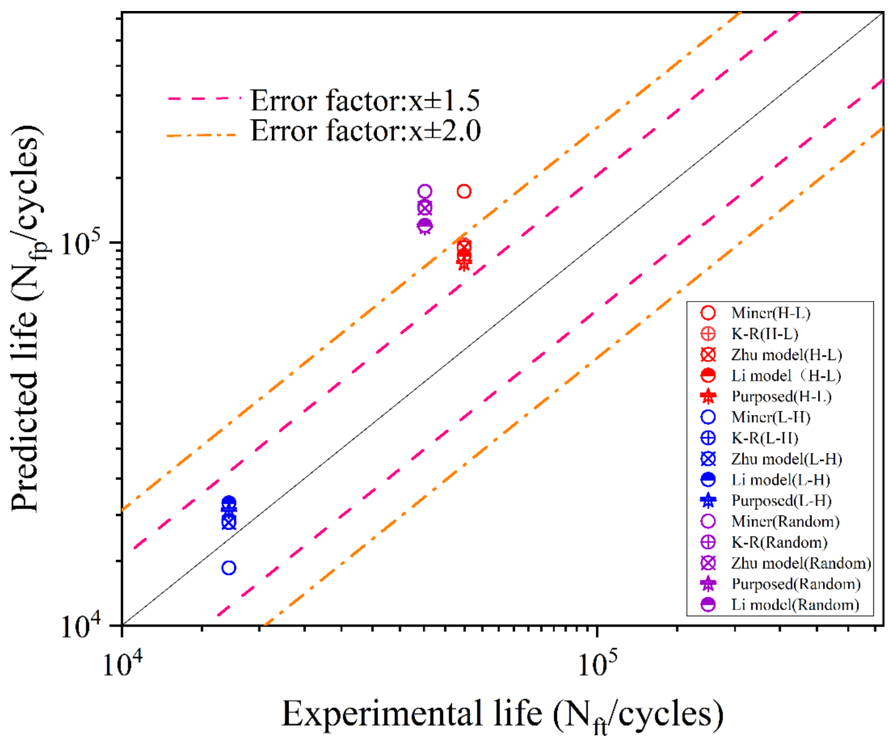

FIGURE 11 Comparison of the predictive capability of five models for the remaining life of 6082T6

5. Discussions

Based on the results of the above four tests, it is shown that the proposed model has improved the accuracy of predicting the remaining life of fatigue loading to a considerable extent compared to the fatigue driving stress model (K-R model). Miner's rule has a simple application in the form that fatigue damage at different levels can be summed linearly, but fatigue failure in many metallic materials often exhibits highly nonlinear damage behavior. The fatigue driving force model (K-R model) improves on the inherent flaws of the linear damage accumulation rule. It is a nonlinear model that requires only the S-N curve of the material. In addition, it does not require many material property parameters and takes into account the effects of the loading sequence. The K-R model has improved predictions compared to Miner's rule by having a sum of damage values greater than 1 in the low-high loading sequence and less than 1 in the high-low loading sequence. However, it was found that loading interactions are also a part of the load history and the K-R model does not consider loading interactions. Zhu's model considers loading interactions by adding the ratio of the two loading levels, while Li's model considers load interactions by adding a pre-circulation factor.

However, it was found that the improvement in the predictive capability of the two modified K-R models relative to the original model was limited, probably due to the complexity of the inherent variable amplitude loading damage evolution, and the two modified models did not provide an explanation in terms of fatigue driving stress evolution. In this paper, based on the driving stress evolution, a new driving stress evolution curve is obtained by taking into account the load interactions, so that the original evolution curve is shifted. Then, the fatigue driving stress equivalence was carried out to obtain a new fatigue residual life prediction model. In particular, compared with Miner's rule, K-R model, Zhu's model, and Li's model, the proposed model has similar prediction ability under multi-stage loading, but for two-stage loading, the proposed model has significantly higher prediction accuracy.

6. Conclusions

The main purpose of this paper was to improve the life prediction ability by studying the fatigue driving stress model, considering the loading interactions and adding the interaction factor to the fatigue driving stress model. The main work was summarized as follows:

A new fatigue residual life prediction model was proposed by analyzing the fatigue driving force evolution, based on making the original evolution curve shift. The effects of the loading interaction were considered by introducing the ratio of two stresses into the fatigue driving stress equivalence equation.

The validity of the new model was verified by using experimental data from two-stage and four-stage loadings. Compared with Miner's rule, the K-R model, Zhu's model, and Li's model, the proposed model gives more satisfactory predictions and shows the ability to combine loading sequences and loading interactions.

Highlights

1. A novel evolution curve for fatigue driving stress was created by including the loading interaction factor.
2. A new fatigue residual life prediction model was proposed.
3. Proposed model can achieve higher reliability .

Credit authorship contribution statement

Kaiwen Wang : Investigation, Methodology, Validation, Visualization,Writing - original draft ,Writing - review & editing, Supervision, Project administration. **Xu Zhao** : Writing -review & editing, Investigation, Methodology, Data curation. **Xuming Niu** : Investigation, Methodology, Writing -review & editing, Data curation. **Yingdong Song** : Validation, Project administration, Writing – review & editing, Supervision. **Zhigang Sun** : Supervision, Project administration, Writing – review & editing, Data curation.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

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