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Fatigue assessment of metallic structures under variable amplitude loading

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Abstract

Many types of mechanical structures (cars, air-planes, trains) and civil engineering structures (bridges, wind turbines, offshore structures) are subjected to random in-service loading. Normally the load effects in these structures are composed of different stress ranges and mean stresses which are within the elastic limit of the material.
One main problem with fatigue assessment under variable amplitude loading is the performes of fatigue life regarding load sequence effects. In this study a model deals with the problem of fatigue life assessment under variable amplitude loading composed of differing stress ranges and mean stresses which are within the elastic limit of the material take into-account the load sequence effects is developed.
Computing of the stress range and the mean stress, in specific time based on the preceding load histories, consider load sequence effects. Using Palmgren-Miner damage rule and the new computed stress range and mean stress lead to predict the fatigue life. An evaluation of the model using data of five diffrent metals availbe in the literature has been investigated. The results showed that the proposed model describes the effect of the load sequence in elastic loading well.

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Keywords: Fatigue; variable amplitude; block loading;Load sequence

1. Introduction

Fatigue life prediction under variable amplitude loading is of great importance to engineers and designers. Designing structures submitted to random loading needs models that take into account the loading history in an accurate way. In engineering, the design is carried out using a simplified model ignoring load sequence and interaction effects (such as the rainflow (Rychlik I. (1987)) method). A large number of studies have been investigating the combination of both load sequence and interaction effects in variable amplitude loading. None of these considers loading conditions where only load sequence effects are relevant. (S. S. Manson and G. R. Halford (1981)) proposed double cumulative damage

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rule which was verified by (H. Gao et al. (2014)) based on experimental work. The conducted conclusion showed that there is a huge difference in the predicted fatigue life compared to the experimental life for the material Mn16. (H. Gao et al. (2014)) suggest that this may be caused by considering the influence of the number of cycles without considering the stress level of each cycle. They proposed an adjustment to the Manson Halford model where they consider the stress level effects in the cumulative damage. A verification of this model with reference to experimental data of different type of steel have been studied and the results confirm the accuracy of the modified model. However, all these tests are limited to loading with two stress levels and two materials. (A. Aeran et al. (2017)) developed a model to study both load sequence and interaction effects based on interaction factor depend on the applied load. However, with this method interaction effects are considered with the same value for brittle and ductile metal.
However, all previously mentioned studies have been concentrated on both load sequence and interaction effects.
Typical variable amplitude loading of metallic structures is composed of repeated blocks defined with varying stresses which are within the elastic limit of the material. see Fig. 1. To answer this need, a fatigue damage model taking into account only load sequence effects is required.
In this paper an investigation of the load sequence effects for the fatigue life prediction under repeated variable amplitude loading blocks are studied.

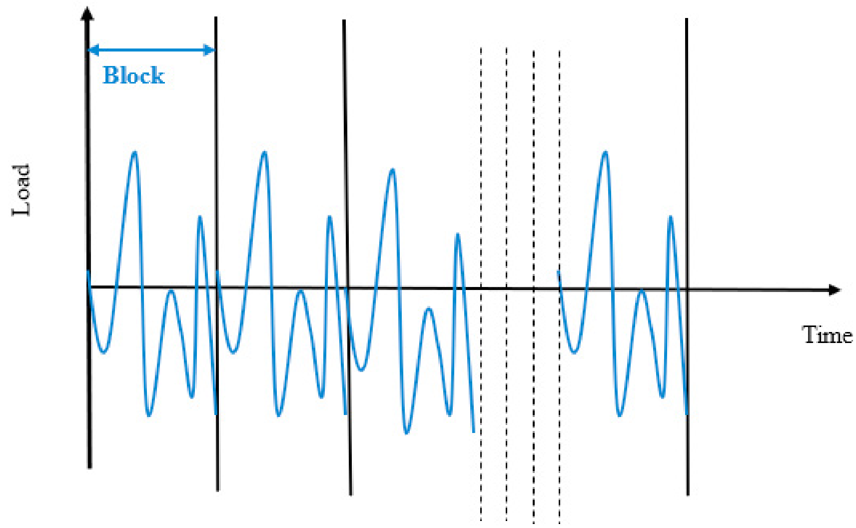

Fig. 1. Variable amplitude loading presented by repeated block loading

2. Proposed model

In this study, a model considers the load sequence effects in the prediction of fatigue life under a variable amplitude is developed.

The model computes at any specific peak (see Fig. 2) the stress range and mean stress that account for all previous load history, which are then used in fatigue life prediction using the S-N curve.

2.1. Determination of mean stress and stress range

A block loading *Blk* is defined by the loading applied in the time segment $[t_{start}, t_{end}]$(with t_{start} start time, t_{end}: end time). Evaluation of the load sequence effects is performed at any time $t_{current}$ such that ($t_{start} < t_{current} <= t_{end}$). based on the data history of the variable amplitude loading applied in the time segment $[t_{start}, t_{current}]$ a determination of the mean stress at the current time σ_m ($t_{current}$) can be carried-out.

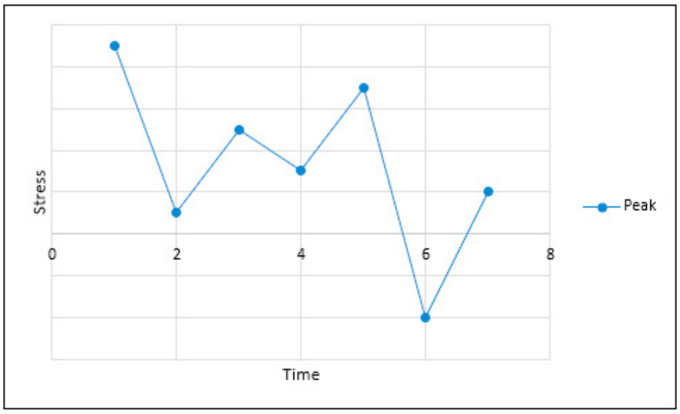

Fig. 2. stress-time curve with specification of loading peaks

The expression of mean stress at the current time as function of the peaks (numbers and values) of the corresponding time segment is presented in eqatuion (1).

$$\sigma_m(t_{current}) = \frac{1}{t_{current} - t_{strart}} \sum_{j=t_{start}}^{t_{current}} \sigma(t_j) \tag{1}$$

with

- t_i: a peak loading
- t_{start}: start time (start peak)
- $t_{current}$: current time (current peak)

Based on equation (2) the determination of the stress amplitude at the current time (which considers the effect of the load history within the corresponding time segment [t_{start},$t_{current}$]) can be computed.

$$\sigma_a(t_{current}) = \sigma(t_{current}) - \sigma_m(t_{current}) = \sigma(t_{current}) - \Big(\frac{1}{t_{current} - t_{strart}} \sum_{j=t_{start}}^{t_{current}} \sigma(t_j)\Big) \tag{2}$$

Equation (3) gives thus the stress range at the current time.

$$\Delta\sigma(t_{current}) = 2\big(\sigma(t_{current}) - \sigma_m(t_{current})\big) \tag{3}$$

A mean stress correction of the new computed stresses (mean stress and stress range) with any mean stress correction law leads to determine the stress range at the current time with zero mean stress. For example, equation (4) shows Morrow law.

$$\frac{\sigma_a(t_{current})}{\sigma_{ar}(t_{current})} + \frac{\sigma_m(t_{current})}{\sigma_{fB}} = 1 \tag{4}$$

With

- σ_a ($t_{current}$): the stress amplitude at the current time
- σ_{ar} ($t_{current}$): the stress amplitude to be determined (i.e. with zero mean stress)
- σ_m ($t_{current}$): the mean stress at the current time
- σ_{fB}: the true fracture strength of the material.

2.2. Fatigue life predciton

For a given block of varaible amplitdue loading, the mean stress and the stress range in each peak are computed based on eqautions (1) and (3). Using Basquin law and the new computed stresses after mean stress correction, the fatigue life N_{fj} of each peak can then be determined. The fatigue damage of the given block D_{blk} is computed by Miner rule using eqaution (5).

$$D_{blk} = \sum_{j=1}^{n} \frac{1}{2N_{fj}} \tag{5}$$

With n is the total number of peaks per block.
A decution of the number of blocks to failure N_{pre} is given by eqaution (6).

$$N_{pre} = \frac{1}{D_{blk}} \tag{6}$$

The digram in Fig. 3 shows a flowshart of the model for a given block loading.

3. Expriemantal investigation

In order to verify the presented model, a comparison is made between predicted and experimental fatigue life of test specimens made by 5 different materials and subjected to periodic block loading. The tests are obtained from (Colin, J. (2009)), (Colin, J. et al. (2010)) and (Lindsey J. (2011)). In all tests, maximum stresses in the specimens are below the yield strength of the material and the loading blocks are repeated until failure. The mechanical properties of the used material are given in Table 1.

Table 1. Summary of mechanical proprieties of the studied material.

Material	8620 (30HRC)	8620 (36HRC)	SAE 4340	AL-7075-T6	AL-2024-T4
Modulus of elasticity, E(GPa)	212	210	193	70.6	70
Yiled strength Sy (MPa)	693	796	1179	533	303
Ultimit tensile strength Su (MPa)	991	1145	1241	578	476
True fracture strength Sf(MPa)	1411	1586	1909	737	682

Each block loading (noted *Blk*) is composed of a number of cycles n_1 with high stress range followed by number of cycles 'n_2' having a lower stress range. The definition of a loading block *Blk* is indicated in Fig.4.
A comparison between experimental and predicted results is shown in Fig.5. In this figure the numbers of blocks to failure from experiments is given on the abscissa, the estimated number of blocks to failure is given on the ordinate and the dotted lines denote life predictions with factors of 2 from that observed in the experiments.
It is obvious from Fig. 5 that the linear damage summation using the material S-N curve gives a very poor prediction as the sequence effects are not taked into account in this model. The predicted lives are at least twice the corresponding lives from experiments. Life predictions of the tests were also performed using the SWT. (Smith RN, et al. (1970)) are presented in Fig.5.

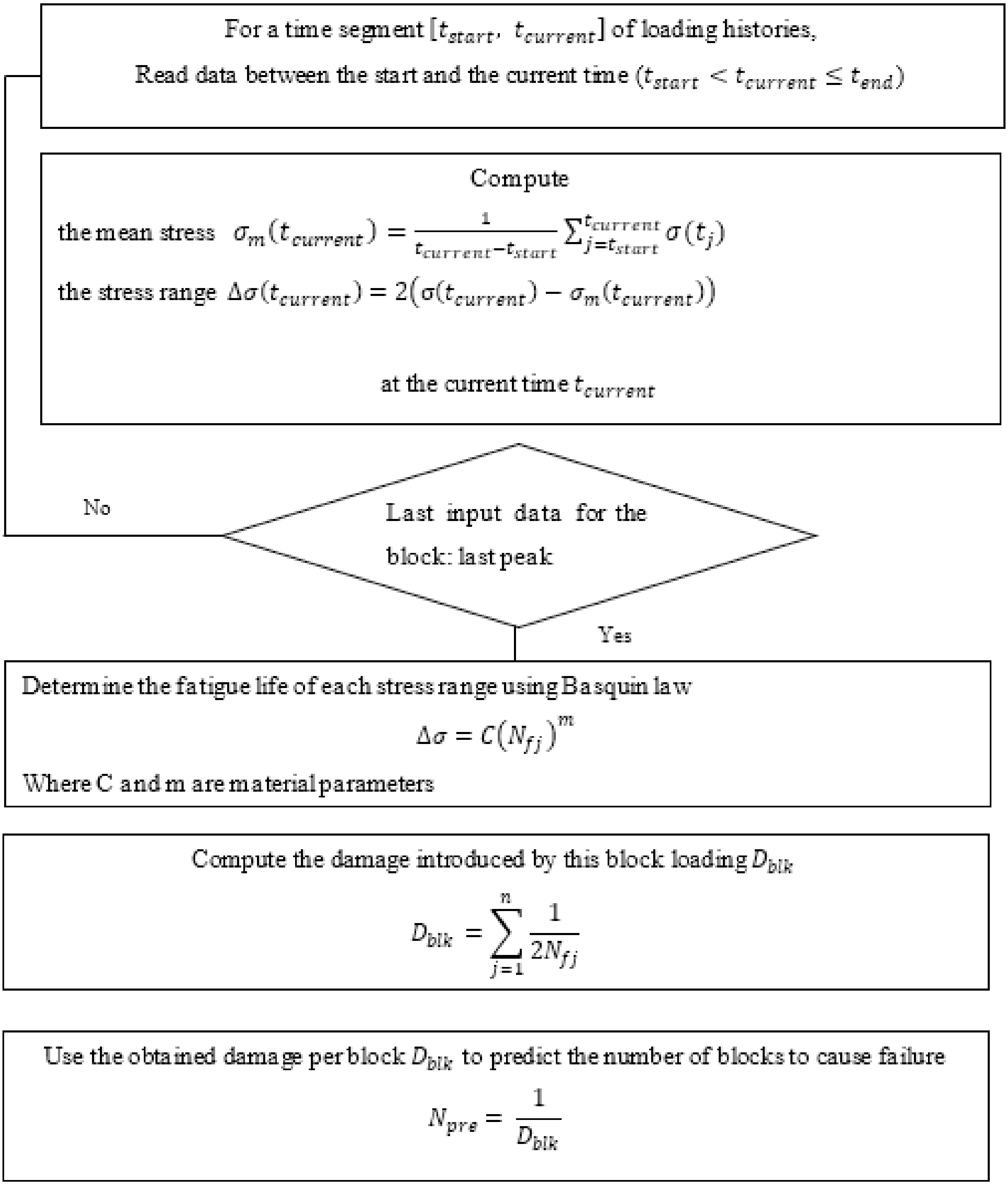

Fig. 3. Algorithm of the proposed model

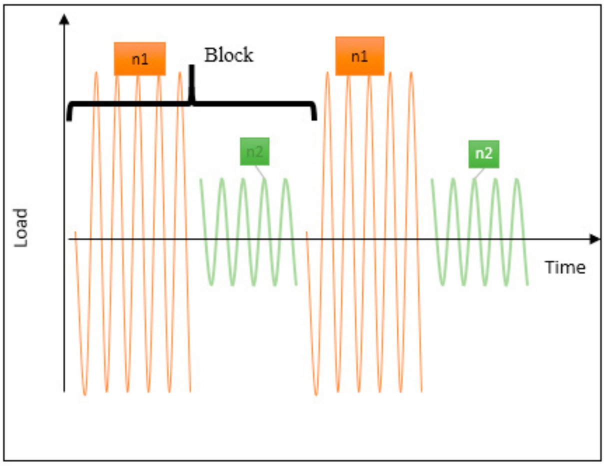

Fig. 4. Schematic representation of variable amplitude loading histories, Block loading

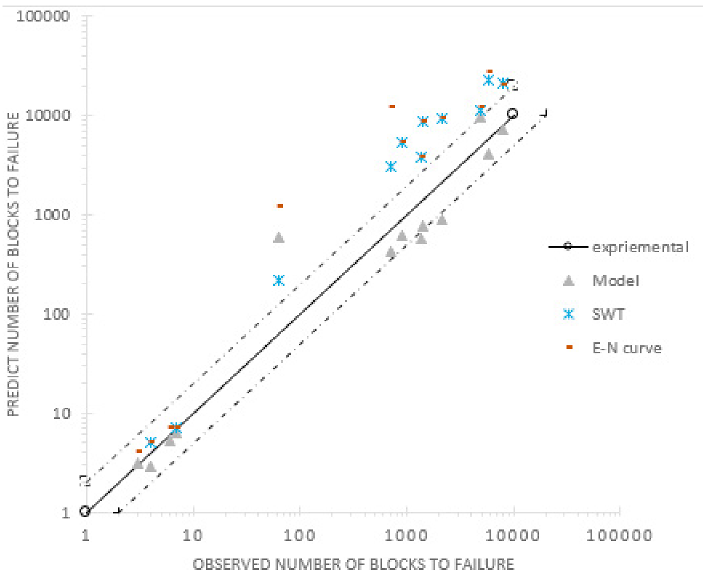

Fig. 5. A comparison between experimental and predict number of blocks to failure

4. Discussion

A model studying the load sequence effects in a repeted block of variable amplitude loading is proposed in this paper. The model treated the following points:

- Load sequence within one block *Blk*: in this point the stress range and mean stress in each peak of the *Blk* are simulated based on the previous load history. This leads to determine a corresponding block of stress ranges to *Blk*. In reality, loading is applied in continues way, therefore load sequence effects may exist within a loading block as well as between blocks.
- The model shows that, for a given block of variable amplitude loading which is repeated until failure, estimating the fatigue life by considering only the load sequence in one block may not give a reliable result in such cases. This is due to the presence of load sequence between blocks. Hence, the load sequence between blocks need to

be considered to estimate an accurate fatigue life. Therefore, a set of blocks composed of several blocks where load sequence between blocks diminishes has to be determined.

- With this model and with these new defined stresses which consider the previous history, an application of the standard prosses for designing structures against fatigue life under variable amplitude can be carried out. A limited number of experimental results are reported in theeeiterature whichre used to validate the proposed model.The proposed model should be verified by using more tests data with different materials under more complex loading, and future work is needed to examine the accuracy and efficiency of this model in dealing with real engineering components under service loading.

5. Conclusions

In this paper, a model for predicting the fatigue life of metalic strucures under variable amplitude loading is developed. An examination of this model in view of available fatigue test results on five different metals showed the succesfulness of the model to predict the fatigue life.
From the present study, the following conclusion can be made:

- The proposed model can be used to predict the fatigue life of structure subjected to repeated block of variable amplitude loading when load effects are below the yield stress of the material.
- The proposed model provides good predictions compared to other models which is confirmed by comparing to several fatigue test series and different types of metallic materials.

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