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Additional insights into fatigue life prediction

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Fatigue process is well recognized to be a significant damage mechanism in metallic and non-metallic structural components. As such, very high percentages of service failures are attributed to the phenomenon of fatigue. The extreme volume of activity in this field indicates its complexity. This beside implications on design philosophy and material history under various circumstances. Fatigue degradation and damage tolerance calls for reliability based design methodologies. In this context analysis are complemented by specimens up to full scale testing. Once again, this pattern alone indicates inherent limitations in solely deterministic solutions. The current study is centered on a attempt to stretch damage mechanics concepts to wire-rope application particularly in terms of life prediction. Mainly the desire remains in searching for an appropriate guideline for replacement by cause, combined with periodic inspection procedures. This has been already established in practical situations.

1. INTRODUCTION

1.1 General

The competitive behavior of fatigue crack initiation introduces a fundamental difficulty in establishing a unified or a kind of universal approach for cyclic cumulative damage evolution. Simply put, fatigue is in fact a localized phenomena by nature that leads to various uncertainties in terms of fatigue strength and life prediction. Needless to mention that fatigue life prediction is a critical design issue, thus, extensive efforts have been invested in order to assist here. Generally, fatigue life prediction is founded either by following global approaches or mechanistically considerations. The background for the latter considers the notion of the role of two damage stages namely, crack initiation and propagation. Distinction is also applied between initiations or propagation controlled processes. Nowadays, the application scale e.g. small volume application introduces a different meaning to initiation controlled processes. The current paper describes a case study as related to wire-rope performance for various applications. This specific case serves only as a vehicle that enabled the development of some insights into the complexity of fatigue life prediction. In more of a deterministic fashion, life prediction can be based on load/stress-life or strain controlled-life information. These two approaches are completely different with some attraction to load-life data due to engineering purposes. Regardless the adopted approach the distinction between initiation and propagation stages still prevail and should be explored and elaborated. A completely different avenue is based on damage mechanics concepts, for example the linear Palmgren-Miner formulation [1.2]. This global approach and related modifications have limitations being documented already in the literature. High scattering in such predictions might result from variations of the remote state of stress, load interaction effects and others. More extrinsic variables provide additional concerns including environmental interaction. For the sake of simplicity such variables are not included in the present papers scope. Obviously better vision of the real service circumstances results in significant improvements of fatigue analysis and life assessment.

1.2 Additional Background Remarks

For the specific application of wire-rope performance, an extensive methodology has been developed by Feyrer [3] following damage mechanics concepts [4]. This global approach that follows phenomenological description along principals of irreversible thermodynamics provides the foundation for damage mechanics. By realizing origins for damage accumulation Feyrer with the assistances of specific modifications included wire-rope segments under the conventional concepts of elastic-plastic fatigue. As known, both rules Palmgren-Miner or Mansom Coffin can be deducted from damage mechanics. Thus, by modifying the engineering information based on the S-N curves namely, the known relationship given by,

$$N_T=K(S)^{-m} \tag{1}$$

Where N_T is the total fatigue life, K and m are adjusted coefficients and S the remote stress. This provided a first step of a working function to be proposed for the wire-rope application. In order to appreciate such activities that includes empirically a modified working function according to equation [1] its enough to realize the relevant multi variables involved. This effort has been initiated and elaborated in reference [3]. For life prediction the methodology is following the linear damage accumulation similar to the known formulation for a solid segment.

2. EXPERIMENTAL PROCEDURES

Wire-ropes with controlled material, processing elements and construction have been tested at ambient temperature. All ropes were produced from cold drawn wires of carbon steel with composition near eutectoid. Variations in the wire-ropes construction, strength and dimensions were included. All the wires have been tested according to the relevant standards and fatigue test have been performed to the final wire-rope product. Fatigue tests were carried out at the university of Stuttgart utilizing in this stage just a simple bending setup and close inspection regarding damage evolution. At the same time simulations have been proposed according to the methodology elements as described in section 1.2.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The simulation as compared to the experimental results indicated in general more of conservative predictions. As mentioned the fatigue experiments of the wire-rope in the range of 10-16mm in diameter were performed in simple bending. Tensile force, bending length and the contact area have been specified. Wire breakage was tracked by inspection and not by non-destructive-testing technique. The total rope life was established after the breakage of one strand. According to standards visual inspection for the rope discarding rely on the number of wire breaks associated with a specific rope length that scaled with the rope dimensions. One issue that became apparent for engineering assessment is the ratio between life that is based on the number of wire breakage and the total rope life. Note, that practical procedure actually follows periodic inspection with attention only to the number of wire breakage. In fact, this provides an engineering criterion for the rope discarding. Nevertheless, the main point in the study is far beyond the present case study. The requirement to include statistical considerations on different levels becomes inevitable. Global approach that is applied to a localized problem, can promise only some progress in terms of a guideline. However activities along quantitative understanding of endurance, can serve a very important role in processing improvement and quality control. Moreover such integrative approach, can contribute to the whole application design. Finally, two additional remarks are in order. First, it becomes apparent, that fatigue life prediction, even, for a sound and solid segment, is only a first order approximation. Stretching similar methodologies to flexible wire ropes introduces higher order of assumptions beside many limitations. For example, in a wire rope that is not a rigid segment the problem of the stress distribution; fretting fatigue aspects and wear provide additional origins for scattering. Nevertheless Feyrer methodology intends to propose a framework of good correlation and consistent trends on top of emphasizing critical variables. Notice that this methodology is experimentally based. Even in alternative approaches that are based on crack initiation and propagation kinetics, life prediction still remains a long term goal. Clearly, the understanding of crack extension kinetics enables the formulation of fatigue life values as often proposed by integration of crack propagation rates relationship, according to the significant achievements of fracture mechanics. Second, fatigue damage concerns are not limited only to macro structures. In principle structure integrity awareness is even accentuated in small volume structures. This is expressed by reliability tests of electronic components, thin film or multy layers technology. Referring to the nano scale, life is defined by crack initiation that is the most controversial stage in fatigue damage. Attention to this stage has been addressed elsewhere [5] with interesting conclusions. The total damage concept, even in such fine scale applications, provides practical benefits. Fatigue crack initiations life in copper under strained control fatigue resulted in a kind of Manson-Coffin description. However, for this fine scale structure, the fatigue ductility exponent deviated from a macro structure behavior, indicating a scale dependency that is not surprising. The length factor in general, is a major issue in small volume problems, and intensive efforts are invested on theoretical and experimental interfaces. This scale awareness clearly applies also to the fatigue life prediction. That remains an important practical problem considering product guarantee. As known, such guarantee can be based only on the state of the art as related to damage evolution. Audigier et al [6] have addressed the problem of reliability considering the thermo mechanical behavior and damage accumulation in electronics assemblies. In that study, fatigue life prediction adopted a modified Manson-Coffin rule. As mentioned, this rule is in fact a damage mechanics approach. This interesting attempt is only one example as related to the broad aspects of fatigue life prediction regardless the structural scale.

4. CONCLUSIONS

Accordingly the following is concluded.

1. Fatigue life prediction is scale dependent.
2. Damage mechanics as a guideline promises an appropriate framework for the formulation of fatigue life.
3. Regardless a specific methodology, modifications are frequently required, beside additional procedures.
4. The localized nature of fatigue damage imposes limitation if global methodology for life prediction is adopted.

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