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Extension of Ruiz Criterion for Evaluation of 3-D Fretting Fatigue Damage Parameter

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Abstract

Fretting fatigue is an important consideration in the design and optimization of mechanical systems and assemblies in the recent times. Empirical approaches, multi-axial fatigue considerations and fracture mechanics approaches are considered for assessing fretting fatigue damages at contact interfaces of assemblies. Ruiz criteria is an effective empirical approach for evaluation of Fretting Fatigue Damage Parameter (FFDP) and has been demonstrated in two dimensional fretting studies of a typical dovetail interface problem. The current paper considers the extension of Ruiz criterion for assessing fretting fatigue damage parameter for three dimensional problems. Two approaches viz. summation of FFDP computed independently along the two slip directions and combined maximum principal-shear stress approach have been proposed for the FFDP evaluation, considering three dimensional stress and slip components over contact interface. FFDP evaluation using maximum principal-shear stress approach is observed to be more appropriate for three dimensional problems

Keywords: Contact stress; dovetail interface; fretting fatigue; fretting fatigue damage parameter; ruiz criteria; slip.

1. Introduction

Fretting is a phenomenon occurring between two surfaces having relative oscillatory motion of small amplitude [1]. Fretting damage occurs on the surfaces of contacting components that are clamped together and are subjected to vibration or change in contact conditions due to the nature of loading, although the clamped bodies are nominally at rest relative to each other. Fretting fatigue occurs whenever a small amplitude oscillatory motion (10-50 μm) between two contacting bodies subjected to contact loading is combined with an applied cyclic load, and leads to reduction in fatigue properties. Field failures have been reported during service at the contact interface due to fretting [2], as fretting aspects were not taken into account in the early design of mechanical systems. Fretting fatigue failures are observed in mechanical systems and assemblies, such as dovetail, flanges, pins or fasteners bearing on hole, spring washers, leaf spring and coil springs, keys in

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keyways of shaft, spline assembly, gears, wheel bosses on shafts, collars and bushes, etc. used in aircraft, power plant, automotive, locomotive, nuclear, orthopaedic and other engineering applications. As a consequence, fretting fatigue damage assessment and life estimation is gaining importance in the recent times, to ensure structural integrity requirements and optimization of mechanical systems and assemblies.

Different methodologies such as multiaxial fatigue [3] and fracture mechanics approach [4, 5] and empirical approach are being studied for assessing fretting fatigue damage and fretting fatigue life prediction. However a robust and simple universal design parameter involving few fretting parameters to identify crack location and prediction of fretting fatigue life is yet to be developed; this is due to complex nature of fretting damage and synergistic interaction of many parameters involved in fretting. Ruiz et al [6] proposed fretting fatigue damage parameters involving stresses and slip amplitude at contact interface, and demonstrated the same in two-dimensional analysis of dovetail interface. Simplistic nature of the Ruiz parameter encourages its use in design optimization of mechanical assemblies involving contact interface. Often the complex three dimensional problems are assumed to be two dimensional plane stress/strain problem with a compromise on results. Recent advancements in computational power and numerical techniques overcome the simplification of three dimensional problem into two dimensional problem, and directly solve many three dimensional problems to produce high fidelity results. Hence the extension of Ruiz criterion for evaluation of fretting fatigue damage for three dimensional problems is important and would improve the fretting fatigue damage assessment and life estimation.

The present study extends the Ruiz criterion for assessing the fretting fatigue damage in three dimensional problems. Two different approaches are proposed for the evaluation of composite fretting fatigue damage parameter. This paper also reports application of these approaches for evaluation of FFDP on a three dimensional dovetail interface.

2. Extension of Ruiz criterion for a 3D problems

Mechanism of fretting fatigue mainly involve three stages; a) crack initiation due to fretting, b) crack propagation under the combined influence of contact loads due to fretting and bulk loads and c) crack propagation under the influence of bulk load only. Fretting is the main driver behind the first two stages of mechanism.

Ruiz developed two criterion for assessing fretting damages on two dimensional model of dovetail interface and used them for correlating with fretting fatigue life estimated through experimental results. The first criterion emphasized that the primary surface damage driving factors are relative slip and contact shear stress at the interface. It considered the frictional work done at the surface is the main cause for surface damage and crack initiation due to fretting. This has been denoted as Fretting Damage Parameter (FDP). Hence the fretting damage parameter which is a function of relative slip (δ) and the contact shear stress (τ) at the interface was expressed as below.

$$\textit{Fretting damage parameter } (\kappa_I) = \tau.\delta \qquad (1)$$

The second criterion considered that the crack growth is governed by the maximum stress in tangential (σ_{tan}) direction at the interface. It takes into account the frictional work done at the interface and stress in tangential direction at the interface and hence a composite Fretting Fatigue Damage Parameter (FFDP) was defined as the product of frictional work and stress in tangential direction. This essentially means that the empirical Fretting Fatigue Damage Parameter accounts for first two stages of fretting mechanism which HAS significant influence on the fretting fatigue life. Fretting effect does not play critical role in third stage which involves crack growth due to bulk load. FFDP characterizes the severity of fretting fatigue damage and probability of crack initiation location. The composite fretting fatigue damage parameter was expressed as below.

$$\textit{Fretting fatigue damage parameter } (\kappa_{II}) = \sigma_{\tan}.\tau.\delta \qquad (2)$$

The contact interface lies on a line for the two dimensional problem. Typical three dimensional problems involve area contact interface which results in slip in two directions and six stress components at the interface. Consideration of appropriate stress components and slip is essential to arrive at a meaning a meaningful FFDP for three dimensional problem. Vidner and Leidich [7] indicated the use of principal stress (σ_I) in place of σ_{tan}, for two dimensional problems, because of uni-dimensionality of Ruiz's formulation. The current study considers two approaches to incorporate the three dimensional effect in FFDP (κ_{II}) evaluation.

2.1. Summation approach

To account for the fretting effects in two directions over the contact surface, summation approach is proposed. This approach considers summation of fretting damage parameters evaluated for two slip directions. The composite fretting fatigue damage parameter is independently calculated for two slip directions (along *x* and *y* shown in Fig. 2c) over the contact interface and the summation of these two direction FFDPs are considered as the overall FFDP. Fretting fatigue damage parameter based on summation approach is expressed as:

$$\kappa_{II}^{xy} = \kappa_{II}^{x} + \kappa_{II}^{y} \tag{3}$$

Where,

$$\kappa_{II}^{x} = \sigma_{xx}.\tau_{xz}.\delta_{x} \tag{4}$$

$$\kappa_{II}^{y} = \sigma_{yy}.\tau_{yz}.\delta_{y} \tag{5}$$

2.2. Maximum principal-shear stress approach

The other approach considers the use of maximum principal stress in place of σ_{tan} and replacement of shear stress *(τ)* with maximum shear stress considering all the stress components. Fretting fatigue damage parameter based on combined maximum principal-shear stress is expressed as:

$$\left(\kappa_{II}^{PS} \right) = \sigma_{1}.\tau_{\max}.\delta_{res} \tag{6}$$

Where σ_I is the maximum principal stress, τ_{max} is the maximum shear stress and δres is the resultant of slip in two directions (*x* and *y* shown in fig. 3c) over the interface. Peak value of cyclic stress response and cyclic slip amplitude are considered in the FFDP evaluation.

3. Application of 3D Ruiz criteria to a dovetail interface

A typical bladed-disc with skewed dovetail interface, shown in Fig.1, is considered for the application of the extended Ruiz criterion for three dimensional problems. The skewed dovetail interface experiences significant stress gradient and contact condition variation along axial direction, in addition to radial and tangential directions. 3D analysis is essential for the problem, as 2D analysis would result in significant compromise in the results accuracy. Figure 2 shows the details of finite element modeling developed for this study, and the 3D finite element procedure followed for the study could be referred in ref [8]. Contact stresses and slip (relative displacement) at the interface are computed from the finite element analysis results, with reference to coordinate system indicated in Fig. 2c., for evaluation of FFDP.

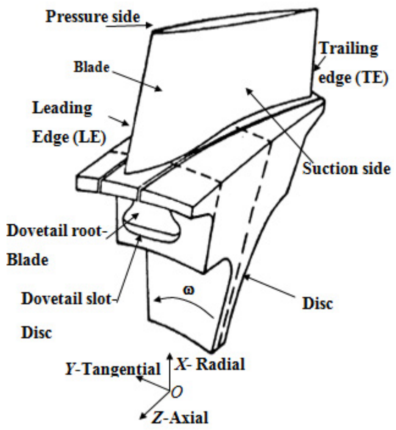

Fig. 1. Typical aero-engine rotor sector with dovetail interface.

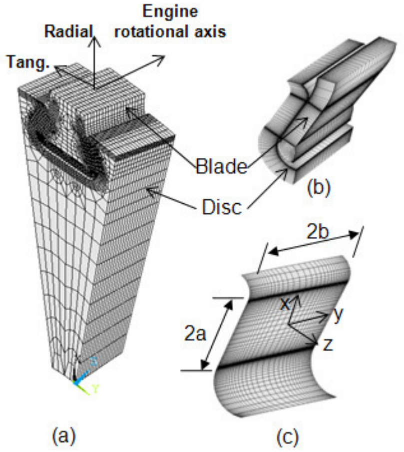

Fig. 2. Finite element model of (a) global model, (b) sub-model (c) contact elements at interface with reference coordinate for FFDP calculation.

Summation approach calculates the FFDP at each nodes at the interface for *x* and *y* direction and added to arrive at the total FFDP at each node location, as per eq. (3). FFDP for *x* and *y* direction is calculated using eq. (4) and eq. (5) respectively. FFDP distribution over pressure side dovetail interface is shown in fig.3. Maximum principal-shear stress approach considers the maximum principal stress, maximum shear stress and resultant slip at each node of the interface for evaluating the FFDP at each node, as per eq. (6). Resultant slip is calculated from computed slip in *x* and *y* direction using finite element analysis results. FFDP distribution over pressure side dovetail interface is shown in fig. 4.

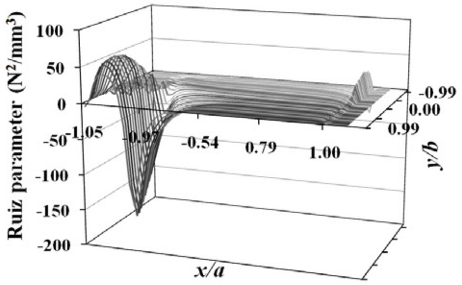

Fig. 3. Summation approach based FFDP distribution.

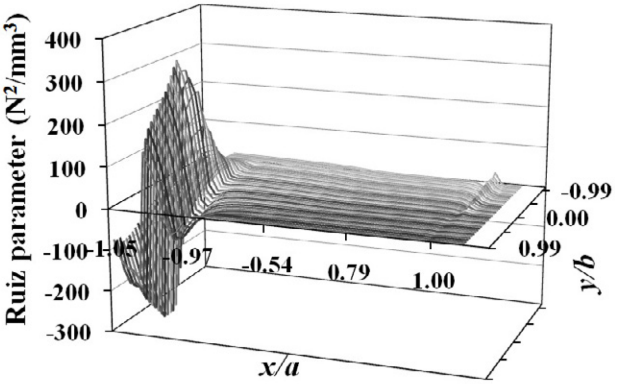

Fig. 4. Maximum principal-shear stress based FFDP distribution.

4. Results and discussion

The summation approach and principal stress approach show the similar FFDP distribution pattern. Both the approach indicates the peak FFDP occurs at the same location. Higher level of FFDP is observed near the contact edges of a dovetail interface compared to the interior zone of interface. Positive value of the FFDP is critical for crack initiation, as cracks occur at peak tensile tangential stress location, as observed in an experimental investigation [6]. The FFDP distribution over the pressure side shows that the crack initiation is expected at the trailing side-bottom contact edge of disc, for the skewed dovetail. A work of Barlow and Chandra [9] indicated a crack at one side of contact edge of blade dovetail interface, when a rotor was subjected to accelerated mission endurance test (AMET). A good agreement between failure location at dovetail interface and peak FFDP computed from this work was observed, though complete results correlation could not be made in this work.

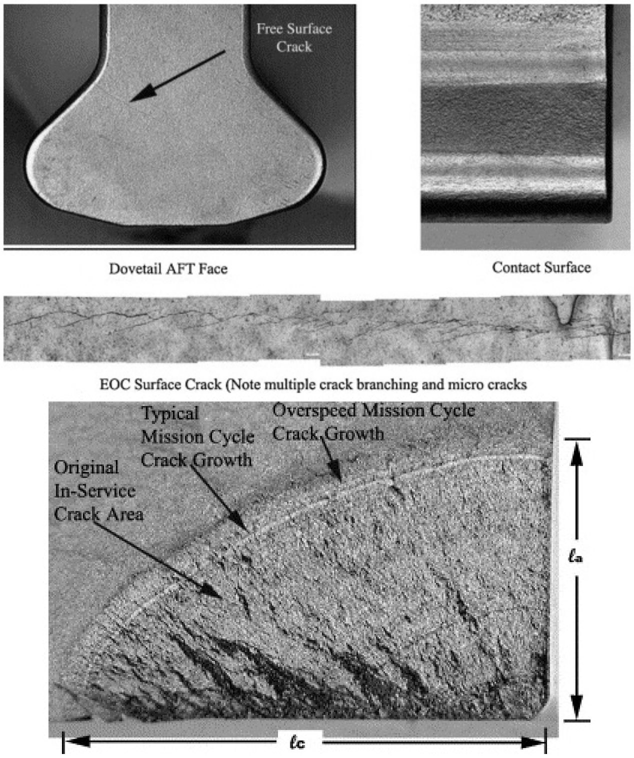

Fig. 5. Fretting fatigue cracks on a dovetail interface (Barlow and Chandra, 2005).

The principal stress based approach is observed to be more appropriate for three dimensional analysis as (i) it considers the maximum shear stress and maximum principal stress over the interface, which are critical for fretting crack initiation and propagation mechanism and (ii) it uses the effective stress in a three dimensional problem. Three dimensional FFDP arrived from the extended Ruiz criteria can be used as an input for optimization of mechanical systems and assemblies, incorporating fretting aspects in the design. High FFDP locations over the interface to be considered as fretting fatigue critical location.

5. Conclusion

Two approaches have been proposed for assessing FFDP by extending the Ruiz criterion for three dimensional problems. FFDP estimation from Maximum principal-shear stress approach is observed to be more appropriate for three dimensional problems and could be used to identify the fretting fatigue critical location. Experimental validation of these approaches is suggested. Three dimensional FFDP based on extended Ruiz criteria can be used as an input for design optimization of mechanical systems and assemblies that incorporates fretting aspects in the design.

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