FATIGUE CRACK GROWTH ANALYSIS USING THE BOOTSTRAP S-VERSION FINITE ELEMENT MODEL

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SUPERVISOR’S DECLARATION

We hereby declare that we have checked this thesis and in our opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Master of Science.

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I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

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ABSTRAK

Kelesuan adalah sumber paling biasa disebalik kegagalan struktur mekanikal yang menyumbang kepada kecederaan dan kerugian dalam industri. Di samping itu, pemilihan bahan, geometri, pemprosesan dan tegasan baki menghasilkan ketidakpastian dan mod kegagalan yang berlaku dalam bidang kejuruteraan. Masalah berterusan dalam analisis pengiraan, di mana model yang kompleks, seperti permukaan retak tiga-dimensi mungkin memerlukan darjah kebebasan yang banyak dalam analisis. Variasi dalam parameter pertumbuhan retak lesu menghasilkan keputusan berselerak. Oleh itu, analisis yang wajar diperlukan untuk menyelesaikan ketidakpastian. Objektif utama penyelidikan ini adalah untuk membangunkan satu model ketidakpastian dalam analisis pertumbuhan retak lesu. Tujuannya untuk mengenal pasti taburan kebarangkalian pertumbuhan retak dan faktor keamatan tegasan untuk masalah permukaan retak. Ramalan faktor keamatan tegasan (SIF), pertumbuhan permukaan retak dan jangka hayat lesu dinilai dengan pengiraan empirikal dan hasil eksperimen sebelumnya. Satu plat dengan ketebalan terbatas mempunyai retak permukaan dan bebanan rawak yang berterusan di analisis menggunakan kaedah kebarangkalian Model Unsur Terhingga versi-S Bootstrap (BootstrapS-FEM). BootstrapS-FEM adalah pengembangan dari Model Unsur Terhingga (FEM) yang biasa. FEM telah dikemaskinikan dengan jaringan halus (versi-*h*), peningkatan urutan polinomial (versi-*p*), hasil gabungan versi *h-p* dipanggil sebagai model unsur terhingga versi-S. Kaedah persampelan semula bootstrap digunakan untuk analisis kebarangkalian, kemudian dimasukkan ke dalam model unsur terhingga versi-S, dan disebut sebagai BootstrapS-FEM untuk mendapatkan strategi persampelan berkesan. Parameter pertumbuhan retak lesu dihasilkan oleh proses persampelan data sampel sedia ada dengan penggantian dalam taburan normal dan lognormal. SIF dikira berdasarkan kaedah penutupan retak maya (VCCM). Pertumbuhan retak lesu dikira berdasarkan model Paris dan kriteria Richard. BootstrapS-FEM kemudiannya disahkan dengan pengiraan SIF, pertumbuhan retak permukaan, ramalan jangka hayat lesu dan taburan saiz cacat awal. Proses pengesahan dibandingkan dengan kerja eksperimen sebelumnya. Sumbangan utama penyelidikan ini adalah untuk membangunkan analisis kebarangkalian dengan menggunakan kaedah persampelan semula bootstrap untuk model unsur terhingga versi-S. Fornula ketidakpastian dalam analisis ini dibentangkan dengan keupayaan untuk model taburan pertumbuhan retak permukaan. Ramalan SIF disebabkan oleh beban ketegangan menggunakan BootstrapS-FEM bersetuju dengan penyelesaian Newman-Raju dalam jarak 0.5% – 10% ralat peratusan. Ramalan jangka hayat lesu untuk lenturan tiga-titik dan empat-titik oleh BootstrapS-FEM dibandingkan dengan hasil eksperimen sebelumnya dalam jarak 5% – 17% ralat peratusan. Ralat ini boleh diterima untuk tujuan ramalan dimana kurang dari 20%. Oleh itu, ramalan dengan menggunakan BootstrapS-FEM menunjukkan hasil yang lebih baik dibandingkan dengan konsep deterministik terhadap hasil eksperimen sebelumnya. BootstrapS-FEM meramalkan pertumbuhan retak permukaan untuk lenturan tiga-titik dan empat-titik yang diwakili dua tanda pantai. Ramalan itu dianggap boleh diterima berdasarkan tren dan hadnya. Jadual waktu pemeriksaan menunjukkan jangka hayat sebelum kegagalan bencana bermula dengan menggunakan kaedah reka bentuk berdasarkan taburan saiz cacat awal lognormal. BootstrapS-FEM menunjukkan penyelesaian masalah ketidakpastian dalam analisis lesu dimana semua keputusan mungkin dipertimbangkan. Ramalan SIF, jangka hayat lesu, pertumbuhan retak permukaan telah disahkan dan dianggap sebagai julat yang boleh diterima. BootstrapS-FEM boleh dilanjutkan lagi untuk mod patah campuran dengan beban amplitud yang berubah-ubah dalam persekitaran yang tidak menentu.

ABSTRACT

Fatigue is the most common source behind failures of mechanical structures which is expected to contribute in injuries and financial losses in industries. In addition, materials selection, geometry, processing and residual stresses produce uncertainties and possible failure modes in the field of engineering. The problems may remain in computational analysis, which is a complex model, such as a three-dimensional surface crack which may require many degrees of freedom during the analysis. The variations in the fatigue crack growth parameters produce scatter results. Therefore, a reasonable analysis is required to solve the uncertainties. The main objective of this research work is to develop a model for uncertainties in fatigue crack growth analysis. The purpose is to identify a probabilistic distribution of crack growth and stress intensity factors for surface crack problems. The prediction of stress intensity factor (SIF), surface crack growth and fatigue life are evaluated with the empirical calculation and previous experimental results. A finite thickness plate with surface cracks subjected to random constant amplitude loads was considered for the fracture analysis using a Bootstrap S-version Finite Element Model (BootstrapS-FEM). The BootstrapS-FEM is an expansion of the standard finite element model (FEM). The FEM was updated with a refined mesh (*h*-version), an increased polynomial order (*p*-version), and the combination of the *h*-*p* version which is known as the S-version finite element model. A bootstrap resampling method is utilized for probabilistic analysis, then embedded in the S-version finite element model, and it is called as BootstrapS-FEM in order to obtain an effective sampling strategy. The fatigue crack growth parameters are generated by a resample process from an existing sample data with replacement in normal and lognormal distributions. The SIF is calculated based on the virtual crack closure method (VCCM). The fatigue crack growth is calculated based on Paris' law and Richard's criterion. The BootstrapS-FEM is then verified for SIF calculation, surface crack growth, prediction of fatigue life and initial flaw size distribution. The validation process is compared to previous experimental work. The major contribution of this research is for the development of a probabilistic analysis by using bootstrap resampling method for the S-version finite element model. The formulation of uncertainties in this analysis is presented with the ability to model the distribution of the surface crack growth. The forecast of SIFs due to tension loading by using BootstrapS-FEM agreed well with the Newman-Raju solution with percentage errors within range of 0.5% – 10%. The prediction of fatigue life for three-point and four-point bendings by BootstrapS-FEM was well-compared with previous experimental results within range from 5% – 17% of percentage errors. These errors were acceptable for purpose of prediction which are less than 20%. Thus, the predictions by using BootstrapS-FEM shows a better results to compare with the deterministic concept against previous experimental results. The BootstrapS-FEM predicted the surface crack growth for three-point and four-point bendings represented with two beach marks. The predictions were considered acceptable based on its trend and bounds. The interval inspections schedule were represented for lifetime before the catastrophic failure begins by using the design method based on the lognormal initial flaw size distribution. The BootstrapS-FEM was shown to resolve the problem of uncertainties in fatigue analysis where all possible results were considered. The prediction of SIF, fatigue life, surface crack growth were validated and considered as an acceptable range. The BootstrapS-FEM can be further extended for a mixed mode fractures subjected to variable amplitude loadings in an uncertain environment.

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