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Predicting Fracture in Steel Structures

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ABSTRACT: Now a day the railway transport infrastructure in Ethiopia is the major issues in relation to the development of the country. To strengthen this infrastructure, related researches must be conducted at the beginning of the construction of the sector. This paper which mainly concerned about the analysis of crack propagation of rail due to vertical wheel load is done to predict the initiated crack growth rate under different load conditions. The objective of this research is to analyze propagation of initiated crack and determine its growth rate under different load conditions and to identify the maximum axle load used, which is basic to justify the way of crack propagation near to the contacting interface. A design axle load of 25ton (ERC) and 22.5tons and 20tons are assumed for the calculation of Stress Intensity factors. A wheel of S1002 profile and a UIC60 rail profile are modeled using CatiaV5R19 software. The models are assembled and imported to Ansys 15.0 release workbench and then to Ansys APDL to simulate wheel/rail contact. The material properties of rail steel are taken and a side crack model is made to simulate crack propagation of railroad rail taking only the vertical load from wheel. The cracked plate is assumed as it is taken from a cracked rail. Then, initiated cracks of different sizes are taken and tensile stress loads are applied on each crack length. The analysis is done taking into account the theories of Linear Elastic Fracture Mechanics. The analysis is based on numerical and analytical methods. For numerical methods, the analytical stress intensity factor KI is calculated using a formula given by (Ewalds and Wanhill, 1989). The analytical method uses Ansys KCALC (Displacement extrapolation method) based on the stress and strain plane conditions. Both results are compared with the numerical results. The tensile loads which take in to account the effects of the dynamic magnification of the vertical wheel load show higher SIF and the life cycle the cracks under these cases are shorter.

KEYWORDS: Crack Propagation, Crack Growth Rate, Linear Elastic Fracture Mechanics, Wheel-Rail Contact Geometry

I. INTRODUCTION

Failure of steel structures triggered by fracture is a much-feared situation across various engineering disciplines. Beginning with the Liberty Ship fractures in the 1940s (Sheldon 2010) that catalyzed the initial development of fracture mechanics as a field of study, catastrophic structural failures are periodic reminders of the consequences of fracture. Prominent examples include the fracture of the Alexander Kielland drilling rig in 1980 (Almar-Naess et al. 1984) resulting in 123 deaths, and steel building fractures during the 1994 Northridge and 1995 Kobe earthquakes. Because some of these earlier fractures occurred outside the realm of civil infrastructure, fracture mechanics initially evolved within the mechanical, aero-space, and nuclear engineering disciplines. Within civil engineering, fracture was largely addressed through prescriptive detailing or through design checks in which applied stresses (calculated through classical strength of materials-type approaches) were checked against empirical stress capacities (American Welding Society 2015). The Northridge and Kobe earthquakes underscored the problems with these empirical approaches, providing impetus for studying fracture within a context specific to civil (especially earthquake) engineering. This resulted in adaptation of existing methodologies to civil engineering (Barsom and Rolfe 1999), as well as the development of new models and methods (Kanvinde and Deierlein 2007) that address problems peculiar to civil (structural) engineering, e.g., earthquake-induced ultralow-cycle fatigue (ULCF). The subsequent evolution of fracture mechanics within structural engineering has been influenced by various factors including (1) its application scenario, e.g., sharp versus blunt cracked components, monotonic versus cyclic loading, and limited versus extensive

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yielding within the component; (2) computational resources available at the time of its development; and (3) established trade practices and standards for material testing and characterization. Not surprisingly, fracture mechanics sometimes appears to be a patchwork of competing theories and methodologies whose suitability for addressing structural fracture under various conditions is somewhat unclear. In view of this, the primary objective of this report is to present fracture prediction approaches from a structural engineering standpoint with consideration of the following factors: (1) application scenario, (2) trade-offs between expense and accuracy, (3) limitations and areas for refinement, and (4) improvements to professional practices to enable more effective fracture simulation.

1.1 Motivation

A general overview of fracture in steel structures, describing the responsible micro mechanisms across multiple scales. The subsequent section outlines methodologies for fracture prediction, recognizing that all ultimately seek to characterize common physical mechanisms, albeit in varying contexts and at different scales, such that these methods are suited for different application scenarios. The next section examines scenarios (materials, loading types, geometry) common to structural engineering and the suitability of the different fracture models to address them.

1.2 Background

The report then summarizes limitations of the state of the art as they pertain to structural engineering, outlining areas for improvement in the modeling methods themselves and in professional practices that are necessary to fully leverage these methods. Finally, noteworthy applications of fracture mechanics are discussed to illustrate its growing acceptance in professional practice. The focus of the report is to review the state of the art for predicting fracture in civil steel structures, and not the state of the art of fracture mechanics itself. This is an important distinction because the former is subject to subjectivities in material characterization owing to trade practices, as well as a relative lack of resources (compared to other disciplines and applications) for effective application of some of the most advanced fracture mechanics approaches. Consequently, the report emphasizes approaches that are practical for structural engineering while discussing the advanced models to provide fuller context.

1.3 Objectives

1. Modeling 3D Finite Element for wheel/rail rolling contact.
2. Modeling an initiated crack for a rail steel
3. Fine meshing technique in crack tip region is used to achieve both computation efficiency and accuracy.
4. Analyzing the crack propagation of rail (caused by wheel load) and
5. Predicting life of initiated crack of rail under different wheel load cases
6. Analyzing the stress distribution around crack tip of crack initiated rail steel by using elastic-plastic FEA.
7. Calculating stress intensity of crack tip and its fracture mode
8. Discussing the possible influence on crack propagation

1.4 Scope of the Project Work

Fracture is an extreme limit state in steel structures, often precipitating structural failure or serious loss of function. Methods to predict fracture in civil structures include traditional approaches developed in other disciplines (mechanical or aerospace engineering) subsequently adopted in structural engineering, as well as approaches to characterize earthquake-induced fractures originating within civil engineering. Developed over nearly six decades, the state of the art is composed of theories and models that address fracture over multiple scales and are targeted toward disparate application scenarios.

II. LITERATURE REVIEW

1. The fracture performance of steel wires for civil, engineering applications remains a major concern in civil engineering construction and maintenance of wire reinforced structures. The need to employ approaches that simulate micromechanical material processes which characterizes fracture in civil structures has been emphasized

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recently in the literature. However, choosing from the numerous micromechanics-based fracture models, and identifying their applicability and reliability remains an issue that still needs to be addressed in a greater depth. Laboratory tensile testing and finite element tensile testing simulations with the shear, ductile and Gurson-Tvergaard-Needleman's micromechanics based models conducted in this work reveal that the shear fracture model is an appropriate fracture model to predict the fracture performance of steel wires used for civil engineering applications. The need to consider the capability of the micromechanics-based fracture model to predict the "cup and cone" fracture exhibited by the wire in choosing the appropriate fracture model is demonstrated. [1]

2. Current design codes for fire resistance of structures are based on isolated member tests subjected to standard fire conditions. Such tests do not reflect the behaviour of a complete building under either normal temperature or fire conditions. Many aspects of behaviour occur due to the interaction between members and cannot be predicted or observed in tests of isolated elements. Performance of real structures subject to real fires is often much better than that predicted from standard tests due to structural continuity and the provision of alternative load paths. This paper reports on the results of a collaborative research project (Tensile membrane action and robustness of structural steel joints under natural fire, European Community FP5 project HPRI—CV 5535) involving the following institutions: Czech Technical University (Czech Republic), University of Coimbra (Portugal), Slovak Technical University (Slovak Republic) and Building Research Establishment (United Kingdom). It consists of an experimental programme to investigate the global structural behaviour of a compartment on the 8-storey steel-concrete composite frame building at the Cardington laboratory during a BRE large-scale fire test, aimed at the examination of the temperature development within the various structural elements, the corresponding (dynamic) distribution of internal forces and the behaviour of the composite slab, beams, columns and connections. [2]
3. The Northridge and Kobe earthquakes demonstrated that fracture is an important mode of failure in steel moment connections during earthquakes. Investigations conducted since these earthquakes revealed important limitations of traditional fracture mechanics in characterizing ductile crack initiation under large-scale yielding which is more likely in post-Northridge connections with smaller flaws and tougher materials. Micromechanical models that capture the fundamental mechanisms of ductile crack initiation can predict fracture even in situations of widespread yielding. This paper discusses one such model the Stress Modified Critical Strain (SMCS) model, and its applications to realistic connection situations. The paper introduces the model and then describes a series of finite element analyses used to calibrate and apply the model to situations such as bolt-hole and Reduced Beam Section (RBS) type connection tests. It is observed that due to the relatively flat stress-strain contours in these specimens, the SMCS model can be applied using a relatively coarse mesh, indicating that the micromechanical models may be feasible for widespread use in fracture prediction. The SMCS model predicts fracture with good accuracy. The paper then describes the use of the SMCS models to transfer results between experiments, based on two different configurations of the bolt-hole experiments, where the conditions for fracture in either situation are observed to be identical when in fact the loading configuration is different. The paper concludes by referencing a larger study by the author that focused on micromechanical models for predicting low-cycle fatigue in structures during earthquakes. It is briefly noted that the micromechanical models such as the SMCS can be relatively free from assumptions and virtually extended to any loading/stress-situation because they aim to capture the fundamental mechanism of failure. [3]
4. This paper presents a simple criterion to predict the failure of steel structures due to the interaction effect of fracture and fatigue which is termed as extremely-low cycle fatigue (ELCF) failure. The criterion has been obtained from further simplification of available cyclic void growth model (CVGM). Initially the simplified ELCF fracture criterion is clearly presented and associated ELCF fracture prediction methodology is also indicated. The simplified criterion is then employed to determine ELCF fracture of some structural models. Hence verification of the simplified criterion is confirmed by comparing the results with previous criterion based estimations. Then the simplified criterion is applied to predict the ELCF fracture of a reduced beam section specimen. Finally, study

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tends to conclude that the simplified criterion produces reasonable accurate prediction to ELCF fracture of steel structures where magnitude of triaxiality remains relatively constant. [4]

5. The crack spacing of reinforced concrete structures has a major influence on structural performance. The fracture energy criterion of crack formation was employed to predict the crack spacing of concrete based on the linear elastic fracture mechanics. This method employs analytical derivation of three dimensional axisymmetric elastic mechanics problems. The simplified solution for a direct tension specimen with a single rebar at the center is derived and both the fracture mechanics criterion as well as the strength criterion is put forward to predict the crack spacing of reinforced concrete members. The influence of concrete strength to the crack spacing is also well explained by this method. Data analysis of classical test results implies a proof for employing fracture mechanics criterion instead of the strength criterion. [5]
6. Steel bridges play an important role in the transportation system of many countries. To ensure that bridges are structurally sound, engineers monitor their performance, which is known as structural health monitoring. Historical evidence indicates that bridge damage is pervasive and that the service life of bridges is decreasing. To manage safety and costs, engineers must be able to accurately predict the service life of bridges. A statistical method to predict service life for steel bridges is presented, which can assist bridge engineers, bridge owners, and state officials in the objective assessment of deteriorated bridges for retrofit or replacement. Timely repair and retrofit of bridges increase their safety levels and decrease costs. A nonparametric statistical approach based on the bootstrap method for stress analysis for fatigue life prediction of steel bridge components is proposed. The bootstrap provides a simple approach for the reproduction of the extremely complex probability distribution of measured strain data. It is completely automated numerical method which requires no theoretical calculations and it is not based on the asymptotic results. The service life index is introduced which quantifies the fatigue life of steel bridges under daily traffic loads. A regression model is developed for the prediction of remaining service life of steel bridges using a service life function. The predicted remaining service life derived from the function can contribute to effective management of steel bridges. [6]
7. Fatigue is a localized and progressive process in which structural damage accumulates continuously due to the repetitive application of external loadings such as vehicles for steel bridges, winds for high-rise buildings, waves for offshore platforms, and temperature for turbine engines, while these applied loadings may be well below the structural resistance capacity. This kind of process is extraordinarily dangerous because a single application of the load would not create any abnormal effects, whereas a conventional structural stress analysis might lead to a conclusion of safety that does not exist. Over a long period of time, the strength and serviceability modes of failure have been well investigated in the professional engineering communities. However, as one of the most critical forms of damage and principal failure modes for steel structures, fatigue is still less understood in terms of the cause of formation and failure mechanism. It is therefore essential to seek novel methodologies and develop advanced technologies for seizing the fatigue phenomenon and conducting reliable assessment of fatigue damage status of steel bridges which serve as vital components in the transportation infrastructure of a nation. [7]

III. METHODOLOGY

3.1 Materials of Wheel and Rail

Railroad rails are grouped according to their standards, strength, grade, quality and length. The rail steel qualities can be distinguished in to two categories.

- Normal steel quality, with an ultimate tensile strength of 700-900MPa.
- Hard steel quality, used mainly on curves, and crossings etc. with an ultimate tensile strength of 900-1200MPa.

Depending on their requirements, the chemical compositions of rail steels have great varieties of Carbon, Manganese, Chromium and Silicon contents. Since the rails have to withstand the impact load, friction and stress of

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freights, they should have sufficient strength, hardness, toughness and good welding performance. However a large increase in rail mechanical strength may result in brittle failure and as a result a further increase is not desirable.

3.2 Wheel-Rail Contact

The general conditions considered during the wheel rail contact simulation are the assumption of the Hertz contact theory. The common Hertz assumptions are:

- Isotropic and homogenous material
- no friction (Hertz wrote that the surfaces of both bodies had to be completely smooth)
- both bodies were considered as half-spaces
- The contact is elastic

When two bodies (wheel and rail) are in contact, stresses and strains appear. A large force from the first body (wheel) is transferred to the second body (rail) through a small contact region of about 1cm^2

Wheel rail contact regions can be classified as shown in the above figure:

- Region A** - wheel tread -rail head contact: this contact zone is most common contact region with lower contact stress.
- Region B** -wheel flange- rail gauge corner: this contact zone is much smaller contact area and more severe; higher contact stresses and wear rates occurs.
- Region C** - wheel and rail outer sides contact: this contact zone is least likely contact region with high contact stress, and undesirable wear lead to incorrect steering of wheelset

3.2.1 Wheel-Rail Contact Stresses

The forces arising between wheel and rail contact generate contact stresses in a local volume of the two bodies. The most well-known calculation model for this local stresses is the Hertzian one. Hertzian model describes the local stresses with good accuracy for the most common wheel-rail contact problems. This model also provides a good understanding of general contact phenomena. Although Hertzian theory is valid only for elastic contacts it can be useful far beyond that. Limited plasticity will not affect the contact stresses very much.

3.2.2 Hertzian Contact

When a wheel and a rail are brought into contact under the action of the static wheel load, the contact area and the pressure distribution are usually determined using the Hertz theory [6]. In Hertz contact theory, no plastic deformation in the contact patch is assumed, and the radii of the curvature of wheel and rail profiles in the contact patch are assumed to be constant. According to Hertz theory, the normal pressure is distributed as an ellipsoid over the elliptic contact area. The distribution of the contact pressure in this elliptical area represents a semi-ellipsoid

Load Case	Remote Pressure [Mpa]	Crack length							
		a=10mm		a=12mm		a=14mm		a=16mm	
		KI [MPa]	da/dN [m/cycles]	KI [MPa]	da/dN [m/cycles]	KI [MPa]	da/dN [m/cycles]	KI [MPa]	da/dN [m/cycles]
1	153.28	42.25	3.34E-4	51.44	4.12E-3	62.25	1.25E-2	75.2	3.13E-2
2	247.7	68.27	1.98E-2	83.13	4.96E-2	100.6	1.16E-1	121.52	2.64E-1
3	138	38.03	-6.88E-4	46.32	1.72E-3	56.04	7.06E-3	67.7	1.9E-2
4	222.94	61.45	1.17E-2	74.82	3.06E-2	90.54	7.27E-2	109.38	1.67E-1
5	122.625	33.8	-1.41E-3	41.16	4.21E-5	49.8	3.26E-3	60.16	1.05E-2
6	200.08	55.15	6.4E-3	67.15	1.83E-2	81.26	4.47E-2	98.16	1.04E-1

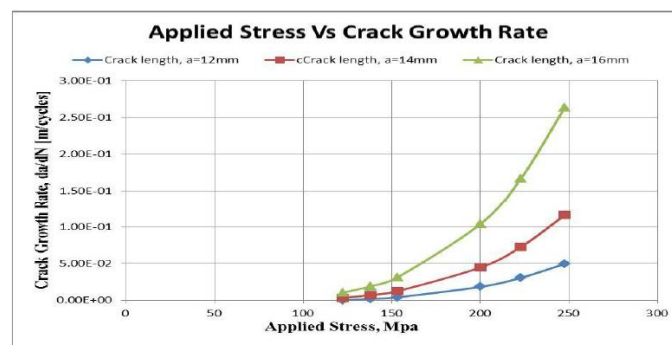
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From table 4.4 above, we will see that the crack growth rate increases with the increases in the stress intensity factor. For crack length of 10mm, the stress intensity factor under the application of tensile loads of 138MPa and 122.625MPa is less than the fracture toughness of the material. The crack growth rate under these conditions is negative which means that the life of crack under the application of this loads are infinite or the crack is stable.



Graph 4.5: Applied Stress vs Crack Growth Rate.

IV. CONCLUSION

From this study, it has been observed that the Stress Intensity Factor, SIF value increases with increase in crack length and the crack propagates when the SIF is greater than critical value i.e. fracture toughness of the material. When the stress intensity is less than the fracture toughness of the material the crack is stable and the life of the crack is infinite. Assuming the strain plane condition for estimation of the stress intensity factor, only the life of crack length, $a=10\text{mm}$ is infinite when a tensile load of 122.625MPa is applied on it. Because, the SIF based on strain plane condition is $37.14 \text{ MPa(m)}^{1/2}$, which is less than $41 \text{ MPa(m)}^{1/2}$, the assumed fracture toughness of the chosen material. For the rest of other cases, the calculated SIF is greater than the fracture toughness of the material and therefore, the cracks are propagating under the application of the above loads. When the stress plane condition is used for the estimation of the stress intensity factor, the life of crack length $a=10\text{mm}$ is infinite under the application of tensile loads of 138MPa and 122.625MPa. The results show that the cracks under dynamically magnified loads with higher speeds are worse (case 2, case 4 and case 6) for each crack length. The stress plane results show that the 2D model results are reasonable to compare with the numerical results. To check the failure criterion the stress plain conditions can be used as these results shows the maximum value for each stress intensity factor, KI for mode –I.

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