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A comparative study of fatigue inspection methods

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Abstract

Bridges are inspected, regularly or otherwise, for fatigue cracks using a variety of different methods. However, for all of these methods, inspection does not necessarily imply detection due to a number of factors including the inspector's experience and the physically inherent limitations of the method. Consequently, traditional inspection methods do not have a limitless capacity for crack detection. As fatigue is a phenomenon involving crack growth over time, application of a particular method will have a time-dependent probability of detecting a crack. In this paper, crack growth, as this may be observed in a typical bridge fatigue detail, is quantified using fracture mechanics and the performance of four different inspection methods over time is compared in terms of their probability of detection. Although the results presented here are pertinent to the particular type of bridge detail and loading conditions, fracture mechanics may also be applied to a wide variety of different details in order to compare detection capabilities at different time instances.

Keywords: Fracture mechanics; Bridges; Welded details; Inspection; Fatigue

1. Introduction

It has long been recognised that cracks in metallic structures initiate and grow under the application of repeated stresses, a phenomenon which is generally known as fatigue [1]. In welded components the crack development or initiation stage is very short, due to pre-existing cracks [2]. As bridge details are generally subjected to a large number of small amplitude stress cycles, high-cycle fatigue becomes an important consideration, a fact which has long been recognised in a number of design codes [3]. However, although modern bridges are designed for fatigue with a life expectancy of 120 years [3], the generally ageing UK bridge stock, the continuously increasing bridge traffic and, in the case of riveted bridges, the necessity to extend in some cases their useful lives beyond the 120-year mark, may raise the issue of possible fatigue inspections. Furthermore, visual inspections, accidental or otherwise, may also result in crack discovery, leading to a series of questions regarding the extent of damage in other parts of the bridge and the methods that may be successfully employed to ascertain this.

A bridge owner has at his disposal a wide variety of methods that may be used to inspect a particular part of a bridge. Each method is based on a number of underlying physical principles, which also limit its detection capability. This capability also depends on the operator's experience, the conditions under which the inspection takes place, the nature of the crack (surface or buried), the condition of the inspected surface, etc. Therefore, an existing crack may or may not be detected with a certain probability. Clearly, large cracks will be detected more easily by even the most inexperienced operators, while smaller cracks may be missed altogether. As a means of quantifying the detective capability of a particular inspection method, it is customary to plot the probability of detection (PoD) as a function of the crack size. Although such PoDs provide a good first indication of how successful the method is, they do not provide any clear information on how likely a fatigue crack is to be detected at different time instances. This likelihood is of course a function of how fast cracks grow, which in turn depends not only on the material properties and magnitude of applied stresses but also the type of detail within which the crack grows.

In this paper, a cover plate termination fatigue detail is selected as a suitable case study. The fatigue crack is assumed to be located at the toe of the transverse weld and it is assumed to grow, subject to bridge loading, in a manner prescribed by the Paris–Erdogan model [4]. Material crack growth parameters and crack sizes are treated as random and at different times the

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Nomenclature

$\mathbf{a}$	Crack depth
$\mathbf{a}_d$	Detectable crack depth
$\mathbf{a}_f$	Fatigue crack depth
$\mathbf{a}_{\text{in}}$	Initial crack depth
a_L	Crack depth corresponding to inspection method's cut-off
b	Plate thickness
c	Half crack width
f	Probability density function (subscript indicates the variable)
$\mathbf{m}$	Paris exponent
t	Time
t_{insp}	Time to inspection
x_0, x_1	PoD fitting parameters
$\mathbf{C}$	Paris crack growth parameter
$E[\,]$	Expectation operator
F, G	Functions
L	Cover plate length
M_m	Newman–Raju geometry factor
N	Number of applied cycles
N_a	Annual number of applied cycles
PD	Time-dependent probability of crack detection
PoD	Probability of crack detection
S_r	Stress range
Y	Geometry factor
W_{cp}	Cover plate width
W_f	Flange width
θ	Weld toe angle
ζ, λ	Parameters of lognormal distribution (subscript indicates the variable)
μ	Mean value (subscript indicates the variable)
$\Gamma(\,)$	Gamma function
ΔK	Stress intensity range
ΔK_{thr}	Threshold stress intensity range

probabilities of detection for four typical inspection methods are obtained. For the example studied here, it is found that, although beyond a certain stage all methods tend to the same detective capability, which is equal to 1, prior to this, significant differences in the performances may be observed.

2. Analysis

2.1. General fatigue considerations

Under constant amplitude sinusoidal loading of stress range S_r, the rate at which the crack grows may be conservatively approximated through the well-known Paris–Erdogan [4] model for crack growth

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C(\Delta K)^m \tag{1}$$

where a is the crack depth, C and m are experimentally determined material parameters also termed the Paris parameters, N is the number of applied cycles and ΔK, which is the stress intensity range, is given as

$$\Delta K = S_r Y \sqrt{\pi a}. \tag{2}$$

In Eq. (2), Y is a non-dimensional function of the geometry, that is, it is a function of the normalised crack depth, normalised crack width and various other normalised geometric parameters. The conservatism of Eq. (1) arises from the fact that it only describes a portion of the entire crack growth curve pertaining to relatively high ΔK values. At lower ΔK values, a change in slope, on a $\mathrm{d}a/\mathrm{d}N$ versus ΔK log–log plot, which is observed experimentally in most metallic materials, results in considerably lower crack growth rates for the same ΔK value. Further conservatism is introduced by ignoring the existence of ΔK_{thr}, the threshold parameter, which forms a lower cut-off to crack growth. Consequently, as bridge loading is associated with a very large number of small stress ranges and accompanying ΔK values, some of which would be below the threshold, solution of Eq. (1) would in general underestimate the fatigue life [5].

For variable amplitude loading, Eq. (1) may be solved, to a first-order approximation, for the unknown number of cycles N required to propagate the crack from a_{in} to a_f leading to [6]

$$N = \frac{1}{CE[S_r^m]} \int_{a_{\text{in}}}^{a_f} \frac{\mathrm{d}a}{(Y\sqrt{\pi a})^m} \tag{3}$$

where E denotes the expectation operator. In general, fatigue life estimation using fracture mechanics involves the solution of two, coupled, Paris-type differential equations [5,7,8]. These equations provide crack growth descriptors in two directions. However, by assuming a constant crack depth/width ratio throughout the entire fatigue process, and incorporating this into the expression for Y, Eq. (3) may be viewed as an approximate solution to the problem. Within the context of the previously stated assumptions, Eq. (3) essentially provides a relationship between the number of cycles N and any final crack depth a_f. The former may be readily converted into time (t) through the annual number of applied cycles N_a, assumed here to be constant over time. At any given time t, a_f becomes random since in general C and m are random. The parameter a_{in} is also random and may be seen in welded details to represent the crack depth associated with the as-welded condition. Therefore, by virtue of Eq. (3),

$$\mathbf{a}_f = F(t, S_r, \mathbf{C}, \mathbf{m}, \mathbf{a}_{\text{in}}) \tag{4}$$

where bold faced characters are used in what follows to denote random variables.

2.2. Inspection

Cracks of a certain size can be detected with a certain probability. For a given inspection method, operating