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A numerical analysis based on *M*-integral about the interaction of parallel surface cracks in an infinite plate

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ABSTRACT

Multiple cracks have been widely observed in pressure vessels and structure components. When multiple cracks approach each other, the interaction between them could affect the stress field around the cracks. So multiple cracks should be taken into account simultaneously because the interaction could change the stress intensity factor (SIF) of the cracks. In ASME Boiler and Pressure Vessel Code Section XI, a flaw combination criterion is provided for interacting parallel surface cracks. However, the criterion for the offset distance does not consider the influence of crack size on the magnitude of the interaction and is only given by an absolute value. In present paper, firstly, SIF for parallel surface cracks is evaluated as a function of the crack front position, relative position, aspect ratio and relative size by numerical analysis based on *M*-integral. And the influence of the interaction on SIF is quantified. It is shown that the crack front position, relative position between two cracks, aspect ratio and relative size are important parameters to determine the interaction between parallel surface cracks. Secondly, the new combination criteria for the offset distance are proposed for the fracture evaluation based on analysis results.

1. Introduction

Multiple cracks have been widely observed in pressure vessels and structure components in the past few decades. And the initiation of multiple cracks is very common in material failure, such as stress corrosion cracking [1,2] and fatigue [3–6]. So the accurate stress analysis of these components containing multiple cracks and the evaluation of fracture parameters are needed for reliable estimation of the residual fracture strength and crack growth rates. When multiple cracks approach each other, the interaction between them could affect the stress field around cracks. Therefore, the stress intensity factor of multiple cracks changes with the magnitude of the interaction. It is significant to investigate changes of SIF in the fracture assessment because SIF is the key parameter for evaluating the integrity of cracked structures.

Many numerical analysis methods have been used to investigated the SIF of interacting multiple cracks, including the body force method (BFM) [7,8], the finite element method (FEM) [9], the finite element alternating method (FEAM) [10–12], and the boundary element method (BEM) [13,14]. Furthermore, some researches have experimentally investigated the problem of multiple cracks in different situations. For example, Soboyejo et al. [15] has experimentally investigated the interaction and coalescence of surface cracks subjected to bending loads. And Liu and Saka [16] studies the 2-D and 3-D multiple cracks which are arbitrary oriented surface cracks using the direct current potential drop technique. These results show that SIF of interacting multiple cracks will be magnified when they approach each other. The SIF for coplanar multiple cracks in structures has been investigated by many researchers [17–24]. And these researches reveal that the influence of the interaction on SIF is not only dependent on the relative location among multiple cracks, but also on the shape, size of multiple cracks and so on.

The interaction between non-coplanar multiple cracks also has been investigated by some researchers. For example, Moussa et al. [25] reveals the influence of the relative positions among non-coplanar surface cracks on the interaction intensity by FEM. Kamaya and Nishioka [26] researches the growth of parallel surface cracks with dissimilar sizes by S-version FEM and the result shows that the relative size is an important parameter to determine the interaction between parallel surface cracks.

In structure components, multiple cracks are often observed to be close to each other, so the influence of the interaction on SIF need to be considered for defect assessment. In the current fitness-for-service codes for defect assessment, such as ASME Boiler and Pressure Vessel Code Section XI [27], API 579-1/ASME Fitness-for-service [28], JSME Fitness-for-service Code [29] and Chinese assessment standard GB/T

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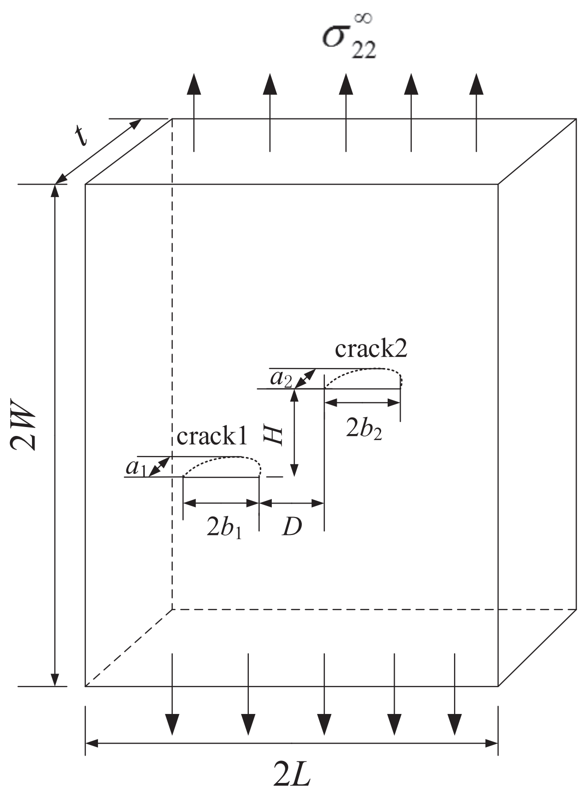

Fig. 1. Geometry of a plate containing parallel surface cracks.

19624-2004 [30], the influence of the interaction on SIF is taken into account conservatively by the combination rule. However, because of the complexity of the interacting phenomenon, it is pointed out that many combination rules are excessively conservative and need to be revised based on the evaluation of the intensity of the interaction [31–34]. So some investigations [35–37] have tried to revise the current combination rules and reduce the conservativeness. In ASME Boiler and Pressure Vessel Code Section XI, parallel surface cracks are treated and combined as a single crack when their relative distance satisfies the criteria (schematically shown in Fig. 1):

$$D \leqslant \max(0.5a_1, 0.5a_2) \quad (1)$$

$$H \leqslant 12.5\ \text{mm} \quad (2)$$

The depth of the combined single crack is equal to the depth of the deeper of parallel surface cracks and the surface length is equal to the sum of the ligament length of neighboring crack tips and length of parallel surface cracks.

In the criterion of Eq. (1), the horizontal distance D is defined as a function of crack depth, but the offset distance H in the criterion of Eq. (2) is absolute value 12.5 mm. The criterion of Eq. (2) is unreasonable because the parallel surface cracks are combined as a single crack although little interaction when the sizes of parallel surface cracks are very small compared with 12.5 mm; besides when the sizes of surface cracks are large, the interaction is not considered even though the interaction between cracks is large. So the criterion for the offset distance H need to be revised.

The analysis of parallel surface cracks has not attracted much attention. And the influence of various parameters on the intensity of the interaction has not been systematically studied. So in present paper, firstly, parallel surface cracks in an infinite plate subjected to remote tension loading perpendicular to the crack faces are parameterized investigated. SIF for parallel surface cracks is evaluated as a function of the crack front position, relative position, aspect ratio and relative size by numerical analysis based on M-integral. And the influence of the interaction on SIF is quantified. And then, based on the evaluation for the influence of the interaction on SIF of parallel surface cracks, an alternative criterion for the offset distance H is proposed and verified.

2. Calculation procedure

2.1. Model

Fig. 1 shows the plate containing parallel surface cracks. For convenience, the parallel surface cracks are numbered as crack1 and crack2. Crack1 is always the larger of two cracks if they have dissimilar sizes. Half-length and depth of crack1 are b_1 and a_1 respectively. And they are b_2 and a_2 for crack2. Half crack length and crack depth are represented by b and a respectively when two cracks are identical. In Fig. 1, the relative distance of two cracks is defined by offset distance H and horizontal distance D. The cracks are located on a plate which length is $2W$, width is $2L$ and thickness is t. And according to analysis in present paper, the size of the plate is set to $W \geq 8(2b_1 + D + 2b_2)$, $L \geq 5(2b_1 + D + 2b_2)$ and $t \geq 5(a_1 + a_2)$. So the plate is large enough that the cracks can be regarded as located in an infinite plate. In all analysis, Young's modulus, $E = 210{,}000$ MPa and Poisson's ratio, $\nu = 0.3$ are assumed. The plate is applied to a remote uniform tension stress of magnitude σ_{22}^{∞}.

In the analysis, wedge elements are used by collapsing one side of each brick element around the crack front to improve SIF calculation accuracy. The mid-side nodes of such wedge elements are shifted to quarter-point positions, as shown in Fig. 2, to reproduce the theoretical square-root singularity of the stress field. The cracked mesh is generated as shown in Fig. 3.

2.2. M-integral for SIF determination

The M-integral, which is also known as interaction integral, was first developed by Yau et al. [38] and Wang et al. [39] from J-integral as a way to extract the stress intensity factors for three fracture modes from the global energy release rate. In present paper, M-integral is extended to three dimensions to calculate SIF of parallel surface cracks in the plate on the basis of their work.

Numerically M-Integral is similar to J-Integral and it can be used to

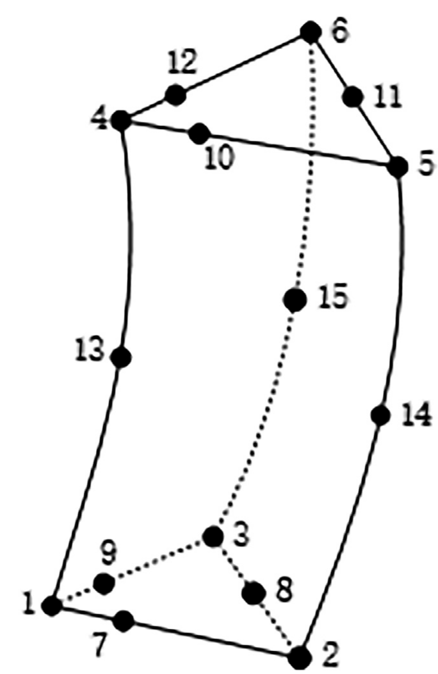

Fig. 2. Wedge quarter-point element.