International Journal of Mechanical Sciences 133 (2017) 704–719

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

Crack arrest behavior of central-cracked stiffened plates under uniform tensions

Xingling Huang[a,b], Yinghua Liu[a,*], Xiangbing Huang[b], Yanwei Dai[a]

[a] Department of Engineering Mechanics, AML, Tsinghua University, Beijing 100084, China
[b] Department of Naval Architecture, Naval University of Engineering, Wuhan, Hubei Province 430033, China

ARTICLE INFO

Keywords:
Crack arrest
Stiffened plate
Three-dimensional stress intensity factor
Relative stiffness
Out-of-plane bending

ABSTRACT

The magnitude and distribution of three-dimensional stress intensity factor are affected by out-of-plane bending and loading modes in stiffened plates, and the influences are studied externally under uniform tensile stresses. Based on theoretical analysis of linear elastic fracture mechanics, crack propagation behavior is investigated with three-dimensional finite element method. The crack arrest effects of stiffeners and the influences of out-of-plane bending are analyzed in three typical stiffened plates. Then relative stiffness is proposed to reflect the difference of crack arrest effects of the stiffeners, and mathematical models are developed for the fracture parameters of stiffened plates. Lastly, the effects of loading modes on crack propagation are discussed. The results indicate that stiffened plates generally have better crack arrest effects than flat (unstiffened) plates, and the relative stiffness, location, integrity and load sharing of the stiffeners play significant roles in crack arrest behavior. In some situations, the influence of out-of-plane bending cannot be negligible and should be considered carefully.

1. Introduction

Stiffened plates are important structural components, and generally composed of metal plates reinforced by stiffeners which are designed to deal with various loading conditions. For the advantages of light weight as well as high strength and stiffness, stiffened plates are widely employed in industrial applications. However, failures of the structures usually happen as a result of the propagation of cracks which initiate in the plates or stiffeners. Consequently, the crack growth behavior of stiffened plate is more complicated than that of flat (unstiffened) plate which has been studied by lots of researchers [1–7]. It is thus necessary to investigate the crack arrest effects of stiffeners and the crack propagation characteristics in stiffened plates.

In recent years, linear elastic fracture mechanics has been used extensively for predicting fractures in brittle materials, and one of the fundamental parameters is stress intensity factor (SIF), which is used to determine the crack growth life as well as the critical crack length. Geometry correction function (GCF), being called the beta factor in some references, is considered as the non-dimensional SIF. It accounts for geometry effects and is usually used in fracture analysis. The effects of width and length on SIFs have been analyzed in cracked plates and the GCFs can be found in published literatures [8,9]. Admittedly, the SIFs of cracked stiffened plates are also affected by the stiffeners' type, size, location, etc. And these influences should be taken into account during crack propagation analyses.

Several kinds of stiffeners (i.e. riveted, integral, welded, bonded, etc.) are usually utilized in engineering fields, and the fracture analyses of stiffened plates have been conducted extensively since some solutions were given by Greif and Sanders [10], Kanazawa et al. [11], Poe et al. [12] and Isida [13]. Boundary collocation method was employed to derive the solutions of SIFs in the earlier work [14]. On the other hand, displacement compatibility method, for its simplicity and efficiency, was used widely to obtain the analytical solutions of SIFs by a number of authors [15–19]. Furthermore, the SIFs were also determined theoretically using Airy stress function, Reissner's plate theory, complex stress function and other methods [20–25]. The analytical approach allows parametric studies of the problem, but it usually needs some simplification of the complex geometries or loading conditions.

Compared with analytical approach, experimental approach is a more straightforward way to investigate the fracture phenomena [26–30], especially when the analytical approach fails to provide reliable solutions. Nevertheless, experiment is time consuming and enormously expensive sometimes. For this reason, it is generally conducted on a small series of specimens for verification or other purposes, and usually in combination with analytical or numerical approaches.

* Corresponding author.
E-mail addresses: huang-xl14@mails.tsinghua.edu.cn (X. Huang), yhliu@tsinghua.edu.cn, yhliu@mail.tsinghua.edu.cn (Y. Liu), hxb_wh@163.com (X. Huang), daiyw13@mails.tsinghua.edu.cn (Y. Dai).

https://doi.org/10.1016/j.ijmecsci.2017.09.040
Received 27 May 2017; Received in revised form 5 September 2017; Accepted 24 September 2017
Available online 25 September 2017
0020-7403/

Nomenclature

Symbol	Description
a	half crack length
A_s	cross section area of stiffeners
C_i	coefficients in polynomial equation
d_s	half distance between stiffeners
E	Young's modulus of the plate
E_s	Young's modulus of the stiffener
H	plate height
h_s	stiffener height
I_x	moment of inertia about x axis for stiffened plate
J	domain integral
K	mode-I stress intensity factor
K_M	stress intensity factor induced by σ_M
K_{max}	maximum stress intensity factor along plate thickness direction
K_{mid}	stress intensity factor at the mid-plane
K_Q	stress intensity factor induced by Q
M	additional moment of out-of-plane bending
Q	longitudinal shear force acting on the plate by stiffeners
R^2	regression coefficient
S_λ	relative stiffness
t	plate thickness
t_s	stiffener thickness
W	plate width
z'	distance from the calculated location to the neutral plane of stiffened plate
ν	Poisson's ratio
β	geometry correction function
β_{2D}	two-dimensional geometry correction function of flat plate
β_{3D}	three-dimensional geometry correction function derived from β_{2D}
β_{mid}	geometry correction function at the mid-plane
β_{max}	maximum geometry correction function along plate thickness direction
β_p	geometry correction function of corresponding flat plate
$\Delta\beta$	increment from β_{mid} to β_{max} in stiffened plate
$\Delta\beta_s$	crack arrest effect of the stiffener
$\Delta\beta_{sp}$	crack arrest effect of stiffened plate
$\delta_{\beta max}(i)$	difference of β_{max} between situations in a case
σ	remote tensile stress
σ_M	additional stress induced by out-of-plane bending
σ_{Mmax}	maximum additional tensile stress induced by out-of-plane bending

Abbreviation	Description
2D	Two-dimensional
3D	Three-dimensional
DSC-SP	Double symmetrical central stiffened plate
DSE-SP	Double symmetrical edge stiffened plate
FE	Finite element
FEM	Finite element method
GCF	Geometry correction function
SC-SP	Single central stiffened plate
SIF	Stress intensity factor

Finite element method (FEM) is widely used to discuss fracture behavior of stiffened plates because of high efficiency and low cost. Numerical simulations of crack growth were conducted at different loading conditions [31–33], and the SIFs were usually calculated directly in FEM programs for various materials [34–38]. In view of crack propagating in the plate and stiffeners simultaneously, GCFs were derived at a combination of different cracks sizes in numerical analyses [39]. The comparisons of damage-tolerances for riveted, integral, welded and bonded stiffened plates were carried out by Nesterenko [40] and Zhang et al. [41,42] with experiments and FEM.

In order to reduce the nodal degrees of freedom and save computational time, several techniques were developed in numerical simulations. For instance, the global-local modeling technique [43] and the finite element/alternating method (FEAM) [44], were introduced to cope with complex cracked structures. However, most previous work focused on two-dimensional (2D) plane problems, or performed three-dimensional (3D) finite element (FE) analyses based on shell or plate elements.

Few 3D solutions of SIFs for cracked stiffened plates have been reported in the literatures. By means of 3D FEM, Kwon et al. [45], Wu [46] and Garcia-Manrique et al. [47] obtained the characteristics of 3D stress fields in central-cracked flat plates and CT specimen. By use of 3D brick or solid elements, Chung et al. [48] studied the SIFs of skin/stiffener structure with inclined cracks, Abd-Elhady [49] evaluated the mode I SIFs in cracked plates with welded cover plates, and Tsouvalis et al. [50] studied the fatigue behavior of cracked steel plates reinforced by composite patch. Llopart et al. [51] investigated the influences of stringer geometry on mode I SIF with simplified 3D models. Moreira et al. [52], Labeas et al. [53] and Evans et al. [54] studied crack growth behavior in stiffened plates with 3D models, and presented a variety of useful information respectively.

When the stiffeners are attached to only one side of the plate, out-of-plane bending occurs in stiffened plate externally under uniform tensile stresses. To the authors' knowledge, the effect of out-of-plane bending on crack growth was neglected or not considered by former researchers. Moreover, the influence of loading modes (e.g. different loading ratios between the stiffeners and the plate) was not investigated too. These factors will influence the magnitude and distribution of 3D SIF, and should be discussed. To this end, the crack arrest behavior of central-cracked one-side stiffened plate (denoted as stiffened plate for brevity) is studied with theoretical derivation and 3D FEM in the present work.

The paper is structured as follows. First, the SIFs of stiffened plates are analyzed theoretically in linear elastic fracture mechanics. Then, 3D FEM is employed to conduct crack propagation analyses in three kinds of stiffened plates. Next, the crack arrest effects of stiffeners and the influences of out-of-plane bending are investigated at different situations. In the sequence, a parameter is presented to summarize the crack arrest performances of stiffeners, and empirical equations are developed for the GCFs and the crack arrest performances of stiffened plates. Finally, the influences of loading modes on crack growth are discussed.

2. Problem description and methodology

2.1. Central-cracked structures description

There are two kinds of central-cracked structures studied in the paper. The first is a flat plate with a through-the-thickness crack, and it is used for the validations of 3D FEM and the results reported in previous references. The second is a stiffened plate with a similar central crack, which will be deeply studied in the following paragraphs.

The flat plate and the coordinate system are defined in Fig. 1. The geometric parameters are as follows: $H/W=1$; $t/W=0.01$, 0.02 and 0.05; and normalized crack lengths $2a/W=0.1$, 0.2, …, 0.9. The flat plate is subjected to uniform tensile stresses σ on its ends.

The stiffened plate is made up of a plate and stiffeners which are symmetrical about the central-plane (yoz) of the plate, and the configuration is shown in Fig. 2. The plate's ends are under uniform tensile stresses σ, and the stiffeners' ends are free in the model. The geometric parameters of the plate are kept constant: $H/W=1$ and $t/W=0.02$, while the stiffeners vary in number, location and size (i.e. height h_s and thickness t_s). There are many types of stiffened plates because of a combination of stiffeners' number and location (i.e. half distance between stiffeners d_s), but three typical stiffening configurations are considered: