Available online at www.sciencedirect.com
ScienceDirect
International Journal of Pressure Vessels and Piping 84 (2007) 545–559
INTERNATIONAL JOURNAL OF Pressure Vessels and Piping
www.elsevier.com/locate/ijpvp

Use of local and global limit load solutions for plates with surface cracks under tension

Y. Lei*

British Energy Generation Ltd, Barnett Way, Bamwood, Gloucester GL4 3RS, UK

Received 13 July 2006; received in revised form 25 April 2007; accepted 25 April 2007

Abstract

Some available experimental results for the ductile failure of plates with surface cracks under tension are reviewed. The response of crack driving force, J, and the ligament strain near the local and global limit loads are investigated by performing elastic-perfectly plastic finite element (FE) analysis of a plate with a semi-elliptical crack under tension. The results show that a ligament may survive until the global collapse load is reached when the average ligament strain at the global collapse load, which depends on the uniaxial strain corresponding to the flow stress of the material and the crack geometry, is less than the true fracture strain of the material obtained from uniaxial tension tests. The FE analysis shows that ligament yielding corresponding to the local limit load has little effect on J and the average ligament strain, whereas approach to global collapse corresponds to a sharp increase in both J and the average ligament strain. The prediction of the FE value of J using the reference stress method shows that the global limit load is more relevant to J-estimation than the local one.

Keywords: Global limit load; Local limit load; Semi-elliptical crack; Surface crack

1. Introduction

When performing a structural integrity assessment using the R6 procedure [1], the limit load of a defective component is one of the most important inputs, and is used to define L_r, a parameter that measures the proximity to plastic collapse. Elastic–plastic fracture is assessed via the reference stress J-estimation approach [2]. The reference stress is proportional to L_r and hence the limit load is also a key parameter in assessment against fracture.

For a part-through defect, the limit load may be defined according to either the behaviour of the overall plastic deformation of the defective structure (global limit load) or that in the crack ligament (local limit load) [3]. A global limit load is the load at which the load-point displacement becomes unbounded and is relevant to failure of the whole structure. A local limit load corresponds to a loading level at which gross plasticity occurs in the crack ligament and may be relevant to ligament fracture. The local limit load is always less than or equal to the global limit load for a cracked structure and, therefore, can yield a conservative result in an assessment. However, sometimes it gives an unduly conservative result. In the R6 procedure before 2006, the use of the global limit load for part-through cracks was not generally supported, unless detailed calculations for particular cases were performed. Behind this restriction were two concerns. The first was possible ductile failure of the crack ligament, which might fail much earlier than the whole structure; the second was about ligament fracture, i.e. J at the crack tip corresponding to the smallest ligament might increase much faster than that at other positions after the ligament yields. This restriction has been relaxed in the current R6 procedure, for particular geometries and loadings, following investigations performed in the last decade. This paper addresses validation in support of the change in the R6 procedure.

In 1983, Miller [4] experimentally investigated the ductile failure of ligaments in plates with surface cracks under tension. Together with other available experimental results,

*Tel.: +44 1452 652285.
E-mail address: yuebao.lei@british-energy.com

0308-0161/$ - see front matter
doi:10.1016/j.ijpvp.2007.04.008

Nomenclature

a	crack depth of a surface crack
A_{net}	net-section area in crack plane
c	half-length of a surface crack
d	crack centre opening displacement of an elastic plate with a central through-wall crack under pure tension
d_1	parameter used in the limit load equation for a rectangular surface crack
d_3	parameter used in the limit load equation for a semi-elliptical surface crack
E	Young's modulus
E_1	plastic modulus for the bi-linear material
J	J-integral
J_e	elastic J
l	ligament thickness, $=t-a$
L	half-length of plate
L_r	measure of proximity to plastic collapse
L_r^{max}	material property defining the cut-off on the failure assessment diagram
n	strain-hardening exponent of a Ramberg–Osgood material
N	tensile load
N_{fexp}	load corresponding to ligament failure, load obtained from the experiment
N_{LG}	global limit load for tensile force
t	thickness of the plate
W	half-width of the plate
α	a/t
α_m	material constant for a Ramberg–Osgood material
β	c/W
ε	strain
ε_{ftrue}	true fracture strain of material
ε_{lig}	average ligament strain
ε_p	plastic strain
ε_{ref}	reference strain
ε_y	yield strain or normalising strain
δ	crack tip opening displacement at the deepest point of a surface crack
Δ	load-point displacement
ϕ	a/c
γ	global-based crack area ratio, $=ac/(Wt)$
φ	angle defining the position along the crack front of a semi-elliptical surface crack
ν	Poisson's ratio
σ	stress or remote stress applied to the plate
σ_f	flow stress
σ_{fexp}	ligament failure stress obtained from the experiment
σ_{ref}	reference stress
σ_L	limit stress
σ_{LG}	global limit stress
σ_{LL}	local limit stress
σ_u	ultimate stress of the material
σ_y	yield stress or 0.2% proof stress
ζ	local-based crack area ratio, see Appendix A

he concluded that the global limit load was more relevant to ductile failure of the ligament than the local limit load. However, there were still a small number of plates that failed at lower load levels than the corresponding global limit loads. In 1986 and 1988, Miller [5,6] reviewed published calculations of J for surface defects in plates under tension and found that the global limit load gave better reference stress J estimates than did the local limit load. Chell [7] later obtained a similar result from his investigation. Recently, Lei [8–10] performed detailed 3-D J and limit load finite element (FE) analysis for semi-elliptical surface cracks in plates under tension, bending and combined tension and bending. The results show that a global-based limit load expression gives the best prediction of the FE J results. The 3-D FE analyses for semi-elliptical cracks in plates under tension performed by Kim et al. [11] led to the same conclusion. It seems that the information accumulated is leading to greater confidence in the use of the global limit load in structural integrity assessments. However, direct experimental evidence showing the responses of J and plastic deformation in the crack ligament to ligament yielding is still lacking.

In this paper, the available experimental data are reviewed first to find out the reason why ligament failures took place before the global limit load was reached in some cases. Elastic-perfectly plastic FE analysis for a plate with a deep semi-elliptical crack under tension is then described to show the plastic deformation behaviour of the crack ligament and the relationship between the global or local limit load and J values. Guidance for using the global limit load in structural integrity assessments is proposed following the discussion.

2. Review of available experimental data

Table 1 summarises 43 ductile fracture tests for surface flaws in plates under tension performed by Miller [4,12] and Connors and Hellen [13]. The test materials were mild steels and the material properties at the test temperature are given in Table 2. The plate geometry for the tests is illustrated in Fig. 1. The surface flaws were introduced into the plates using a spark erosion method. Two types of surface flaws were tested, rectangular and part-circular (Fig. 2). The tests were conducted under pure tension with fixed grips. Therefore, the plate-end rotation may be assumed to be zero and the global limit load, N_{LG}, based on flow stress, may be estimated by the net-section yielding condition, i.e.

$$N_{LG}(\sigma_f) = A_{net}\sigma_f, \quad (1)$$