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The study of weld strength mismatch effect on limit loads of part surface and embedded flaws in plate

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ABSTRACT

Strength mismatching between weld metal and parent material is common in pressure vessel and piping industry. To carry out the fracture assessment of weld defects, it is required to accurately estimate the reference stress or limit load for the flawed section. Weld strength mismatch introduces complexity in determination of the limit load. Although it is acceptable to use the weaker material properties in the assessment, it can be overly conservative. Industrial standards R6 and BS7910 provide the methods for weld strength mismatch, but no limit load ratio solutions are available for semi-elliptical surface and embedded flaws which are the most common cracks in pressure vessels and pipework. It is useful to understand whether the existing limit load ratio solutions in R6 and BS7910 can be used for part surface and embedded flaws. This paper reviews the assumptions used in the existing reference stress solutions and discusses its suitability for mismatch conditions. The effects of weld strength mismatch on limit loads of the part surface and embedded flaws are studied using 3D elastic-plastic finite element analyses. The results are compared with the R6 and BS7910 solutions. The validity of the handbook solutions of through-wall flaws for part surface and embedded flaws in plate and the effects of weld strength mismatch and weld strip width on limit loads are discussed.

1. Introduction

In most welded structures, weld metal and parent material have strength mismatch. The weld metal is typically stronger than the parent metal (overmatching) as the welding procedure qualification generally requires that the weld strength should not be lower than the parent material, but there are instances where the weld metal has lower strength than the parent (undermatching).

In order to carry out engineering critical assessment (ECA) of a defective weld in pressure vessels and piping, it is required to accurately estimate the limit load or reference stress, but mismatch causes difficulty in calculations. It is acceptable to use weaker material properties in ECA, but it can be overly conservative. On the other hand, weld metal overmatching parent material may potentially increase limit load and allowable flaw size, which could be a benefit from overmatching. It is necessary to understand the effect of weld strength mismatch on ECA, particularly on the limit load, of defective weld in pressure vessels and piping.

For homogeneous structures, closed form reference stress or limit load solutions are well established in relevant flaw acceptance assessment standards, such as BS7910 [1], R6 [2] and API579-1 [3]. The results of some studies [4,5] on the effect of strength mismatch had been incorporated into R6 and BS7910. However, there are no solutions available for semi-elliptical surface and embedded flaws, which are the most common cracks in pressure vessel and piping welds. Finite element analysis (FEA) is often used for calculating the limit loads for a surface or embedded flaw with weld strength mismatch, but this is time consuming. It is worth investigating if the existing handbook solutions can be used to estimate the limit load for mismatched weldment with a surface or embedded flaw.

In addition, limit load ratio solutions in R6 and BS7910 are based on the net section yield or global collapse assumption, while most reference stress and limit load solutions for surface or embedded flaw for homogeneous structures are based on ligament or local collapse criterion.

In this paper, it is studied that if mismatch limit load ratio solutions of a through-wall flaw in plate given in BS7910 (or R6) can be used for a surface or embedded flaw in plate. It starts from a review of the net section yield assumption (NSYA) of reference

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Nomenclature

a	surface flaw depth; embedded flaw half width; through-wall flaw half length
A_r	net section area
B	plate thickness
c	half length of embedded and surface flaws
F	tensile load
F_e^p, F_e^w	limit load made of parent material, limit load made of weld metal
F_e^m	limit load of mismatch structure
h	weld strip half width
L_r	load ratio of applied load divided by limit load
M	mismatch ratio, $M = \sigma_Y^w/\sigma_Y^p$
P, P_L	external load, limit load
P_m	primary membrane stress
p	flaw deepest point ligament size
W	plate total width
ψ	weld strip normalized ligament size, $\psi = (W/2\text{-}a)/h$, ($\psi < 1$ for wide weld and $\psi > 1$ for narrow weld)
σ_{ref}	reference stress
σ_Y, σ_Y^p, σ_Y^w	material yield strength, parent material yield strength and weld yield strength

stress solutions in above standards to identify its suitability for mismatch conditions. General effect of mismatch on limit load is then studied for fusion line part surface and embedded flaws in plate using elastic-plastic FEA with different weld strip widths. The FEA results are compared with the mismatch solutions given in BS7910 and R6, and the validity of the handbook solutions for part surface and embedded flaws in plate is discussed.

2. Review of handbook reference stress solutions

To determine the proximity to plastic collapse, load ratio L_r is required in ECA. Both reference stress and limit load can be used to calculate the load ratio L_r, as defined below.

$$L_r = \frac{\sigma_{ref}}{\sigma_Y} = \frac{P}{P_L(a, \sigma_Y)} \tag{1}$$

The limit load $P_L(a,\sigma_Y)$ depends on geometry, flaw size and material yield strength.

R6 and BS7910 provide reference stress or limit load solutions of part surface and embedded flaws in homogeneous plate or curved shell. The net section yield assumption (NSYA) is used to derive the reference stress. It is assumed that flawed section plastically collapses when the stress in the flawed section reaches the material yield strength. For a component subject to tensile load, the reference stress is equal to the external load divided by the net area and the limit load is equal to net area times the material yield strength.

For a semi-elliptical surface flaw in a homogeneous plate, the reference stress σ_{ref} can be determined by equation P.9 of BS7910. Provided that bending stress is negligible, equation P.9 is simplified to

$$\sigma_{ref} = \frac{P_m}{1 - \alpha''} \tag{2}$$

where,

$\alpha'' = (2a/B)/(1 + B/c)$ for $W > 2(c + B)$, a wide plate;

$\alpha'' = (a/B)(2c/W)$ for $W < 2(c + B)$, a narrow plate;

From the formulae above, it can be seen that, for narrow plate ($W < 2(c + B)$), the reference stress is equal to the tensile load divided by the net cross-section area, i.e. $\sigma_{ref} = F/(BW\text{-}2ac)$, so it meets the NSYA. However, wide plate reference stress does not meet the NSYA. Note that the reference stress is discontinuous at $W = 2(c + B)$. This indicates that the ligament collapse assumption might be used for wide plate solution which can be overly conservative for deep flaws when α'' is close to 1.0.

For an embedded flaw in plate under tension only, the reference stress can be calculated as per equation P.11 of BS7910 presented below

$$\sigma_{ref} = P_m \frac{\alpha'' + \left[(\alpha'')^2 + (1 - \alpha'')^2 + 4p\alpha''/B\right]^{0.5}}{(1 - \alpha'')^2 + 4p\alpha''/B} \tag{3}$$

where,

$\alpha'' = (2a/B)/(1 + B/c)$ for $W > 2(c + B)$, a wide plate;
$\alpha'' = (2a/B)(2c/W)$ for $W < 2(c + B)$, a narrow plate

For a plate with weld strength mismatch under tension, BS7910 and R6 only provide limit load ratio solutions for through-wall flaw or double edge flaw. The limit load ratio solutions for a through-wall flaw in a plate is based on the limit load solution given in equation (4) below for plane stress and homogeneous structure.

$$F_e^P = 2B\left(\frac{W}{2} - a\right)\sigma_Y^p \tag{4}$$

Both equations (2) and (4) meet the NSYA for narrow plate. When converting a surface flaw to an equivalent through-wall flaw with the same net area, both equations provide the same limit load. This suggests that using an equivalent flaw length the through-wall flaw solution can be used for part surface or embedded flaw in a mismatched weldment.

3. Limit load ratio solutions for mismatch

In terms of mismatch, it is necessary to clarify two technical terms first—mismatch ratio $M = \sigma_Y^w/\sigma_Y^p$ and limit load ratio F_e^m/F_e^p. The former is a ratio of the weld metal yield strength σ_Y^w over the parent material yield strength σ_Y^p. The latter is a ratio of the mismatch structure limit load F_e^m over the limit load F_e^p of a homogeneous parent material. In this paper, mismatch effect is only studied for fusion line (interface) central flaw in plate under tension.

Since the FEA plate model used in this study is in plane stress condition, the limit load ratio solutions for a through-wall flaw in plate at weld fusion line for plane stress are presented below.

For undermatching ($M < 1$), the limit load ratios are

$$\frac{F_e^m}{F_e^p} = M\{1.095 - 0.095\exp[(M-1)/(0.108M)]\} \quad \text{for } \psi << 1 \text{ (R6 uses this one for all } \psi) \tag{5}$$

$$\frac{F_e^m}{F_e^p} = M \quad \text{for } \psi >> 1 \tag{6}$$

For overmatching ($M > 1$), the limit load ratios are: