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On residual stress prescriptions for fitness for service assessment of pipe girth welds

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ABSTRACT

This paper aims to provide a detailed assessment of some of the existing residual stress profiles stipulated in widely used fitness-for-service assessment codes and standards, such as BS 7910 Appendix Q and API 579 RP Annex E, by taking advantage of some comprehensive residual stress studies that have recently become available. After presenting a case study on which residual stress measurements are available for validating finite element based residual stress analysis procedure, residual stress profiles stipulated in BS 7910 for pipe girth welds are selected for detailed evaluation by comparing residual stress distribution characteristics shown in parametric finite element results. A shell theory based full-field residual stress profile estimation scheme is then presented to illustrate how an improved estimation of residual stress profiles can be achieved in light of some of the deficiencies in BS 7910 and API 579 identified in this study.

1. Introduction

When performing fitness-for-service assessment (FFS) on welded components, residual stress information is essential for computing fracture driving force using fitness-for-service codes and standards or recommended practices such as BS 7910 (recently superseded by BS 7910:2013) [1], R6 [2], FITNET [3], and API 579 RP-1/ASME FFS-1 [4]. Residual stress prescriptions in these procedures are mostly developed based upon the interpretation of experimental measurements on selected components and/or finite element based parametric residual stress solutions with a level of conservatism being built in Refs. [5,6]. All above mentioned residual stress prescription procedures to date may be categorized as a product of one of the following two approaches:

(1) Based upon a polynomial curve fit of residual stress measurements on selected welded components [1–3], and supplemented with finite element residual stress results [e.g., Ref. [5]] by taking an upper bound: One major advantage of this approach is the simplicity of resulting residual stress profiles for use in practice. However, it has been well-established that both heat input and component geometry such as pipe or vessel radius to thickness ratio (or r/t) can have significant effect on residual stress distributions [6–8]. For the former, most of the FFS procedures [e.g., Refs. [1–3]] introduce a grouping scheme in terms of linear welding heat input level (with a unit of J/mm) by defining low, medium, and high input levels normalized by wall thickness [1–3]. For the latter, a sufficient guidance seems not available to distinguish r/t ratio effects on residual stress distributions in pipe and vessel components. Both BS 7910 [1] and R6 [2] only consider wall thickness effect in a normalized linear heat input definition, while API 579 RP-1/ASME FFS-1 [4] explicitly incorporate thickness term in residual stress formulation up to a thickness of about 50 mm.
(2) Based upon finite element parametric stress analysis results validated experimentally on selected components and mechanics-based characterization of key controlling parameters governing residual stress distributions [4]: With this approach, a welding linear heat input related parameter, i.e., characteristic heat input intensity with a unit of J/mm^3, and component geometry (r/t) are treated as continuous

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Nomenclature and abbreviation

C_p	specific heat, J/kg °C
d_p	distance from the weld toe to the boundary of plastic zone, mm
E	Young's modulus, GPa
e	2.718
F_w	welding induced shrinkage force, N
I	welding current
K	a material constant, N mm/J
M_0	ring moment, N mm
$\dot{q}$	linear heat input, J/mm
Q_0	ring force, N
r	mean radius of pipe, mm
t	thickness of pipe, mm
u	welding travel speed, mm/s
V	welding voltage
W	weld width, mm
x	distance measured from inner surface, mm
α	coefficient of thermal expansion, °C^{-1}
η	welding heat input efficiency
ρ	density, kg/mm^3
$\sigma^r(x)$	residual stress, MPa
σ_i^r	residual stress value at inner surface, MPa
σ_o^r	residual stress value at outer surface, MPa
σ_Y	yield strength, MPa
σ_{YB}	yield strength of base material, MPa
σ_{YW}	yield strength of weld material, MPa
$\sigma_{x,b}$	decomposed bending component of transverse residual stress, MPa
$\sigma_{\theta,m}$	decomposed membrane component of longitudinal residual stress, MPa
$\sigma_{\theta,b}$	decomposed bending component of longitudinal residual stress, MPa
DHD	deep hole drilling
FEA	finite element analysis
ID	inner diameter
OD	outer diameter
WCL	weld centerline
WT	weld toe

functions uniquely prescribing through-thickness residual stress distribution in terms of membrane and bending content in pipe/vessel girth welds. A through-thickness self-equilibrating distribution is introduced to capture welding procedure related contribution to the residual stress profile such as Double-V and Single-V joint preparations as well as pass sequence effects. The main advantage of this approach is that the resulting residual stress profile is continuous in terms of its membrane and bending content as a function of heat input and component geometry (r/t). This approach also recognizes the fact that it is the membrane and bending components that play a significantly dominant role in fracture driving force determination than self-equilibrating component in a residual stress distribution [4,6,7]. However, one drawback is that as such, residual stress profile determination procedure requires more input parameters and a slightly more involved representation of the self-equilibrium function in form of both sinusoidal and logarithmic functions in API 579 RP-1/ASME FFS-1 [4].

Recognizing the major differences in above two approaches and resulting residual stress profiles, the authors of this paper feel it should be informative to compare or contrast some of the existing residual stress profiles stipulated in above mentioned fitness for service assessment procedures in light of some recent findings from a number of comprehensive studies on residual stresses [8–17].

This paper will be focused upon residual stress prescriptions on pressure vessel/pipe girth welds. It starts with a brief description on residual stress profiles for pipe girth welds provided in the new version of BS 7910 [1]. The reason for this is that almost identical residual stress profiles have been used by R6 [2] and FITNET [3], except a minor difference in specifying residual stress variation in pipe axial direction. Furthermore, API 579 RP Annex E is currently being updated, most likely following BS 7910:2013 approach [1]. Then, a finite element based case study on a P91 heavy section girth weld [9,10] on which some detailed residual stress measurement data are available will be performed. The case study provides a quantitative comparison among the residual stress profiles prescribed in BS 7910, predicted by finite element method, and measured experimentally. A series of parametric finite element analysis results will then be presented to examine the residual stress profiles in BS 7910 under various prescribed conditions at a later section. Both transverse residual stresses (perpendicular to the weld) and longitudinal residual stresses (parallel to the weld) will be examined in detail. Finally, a framework for developing consistent residual stress profiles is presented along the same line as used in 2007 API 579 RP-1/ASME FFS-1 [4], but with a major improvement in consistency and applicability in a wider range of r/t ratio and wall thickness. Therefore, some of the major deficiencies identified in some of the existing residual stress prescriptions given in Refs. [1–4] can be effectively removed.

2. Residual stress profiles in BS 7910 and R6

BS 7910 Appendix Q [1] and R6 Sec IV.4 [2] provide the same set of analytical formulas describing through-thickness residual stress distribution in pipe or plate butt welds under as-welded conditions. For circumferential girth welds, residual stress profiles are summarized below.

2.1. Longitudinal residual stress

The longitudinal residual stress (parallel to the weld) is prescribed as a linear function of the position (x) through the thickness of pipe wall as follows:

$$\sigma^r(x) = \sigma_i^r + \left(\sigma_o^r - \sigma_i^r\right)\left(\frac{x}{t}\right) \tag{1}$$

where σ_i^r and σ_o^r are residual stress values at the inner and outer surface of pipe, respectively. Here, x is the distance measured from inner surface to the position of interest and t is the thickness of pipe. Residual stress values at the inner and outer surfaces are given by the following equations:

$$\begin{aligned} &\sigma_o^r = \sigma_Y \\ &\sigma_i^r = \sigma_Y && \text{for } t \le 15 \text{ mm} \\ &\sigma_i^r = \sigma_Y[1.0 - 0.0143(t-15)] && \text{for } 15 < t \le 85 \text{ mm} \\ &\sigma_i^r = 0 && \text{for } t > 85 \text{ mm} \end{aligned} \tag{2}$$

where σ_Y takes on either the value of either base metal yield strength σ_{YB}, or weld metal yield strength σ_{YW}, as,