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A full-field residual stress estimation scheme for fitness-for-service assessment of pipe girth welds: Part II – A shell theory based implementation

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ABSTRACT

With the two key controlling parameters identified and their effectiveness demonstrated in Part I of this study series for constructing a continuous residual stress profile at weld region, a classical shell theory based model is proposed in this paper (Part II) for describing through-thickness residual stress distributions of both axial and hoop components at any axial location beyond weld region. The shell theory based model is analytically constructed through an assembly of two parts: One represents weld region and the other represents the remaining component section away from weld. The final assembly of the two parts leads to a closed form solution to both axial and hoop residual stress components as a function of axial distance from weld toe position. The effectiveness of the full-field residual stress estimation scheme is demonstrated by comparing with a series of finite element modeling results over a broad range of pipe weld geometries and welding conditions. The present development should provide a consistent and effective means for estimating through-thickness residual stress profile as a continuous function of pipe geometry, welding heat input, as well as material characteristics.

1. Introduction

In addition to weld region (e.g., weld centerline and weld toe locations) as discussed in Part I [1], needs often arise for describing residual stress distributions away from weld region, where residual stresses can be significant when a through-thickness axial residual stress distribution exhibits a "global bending" type as illustrated by Dong [2,3]. As recently discussed by Dong et al. [4], there exists little guidance in current structural integrity assessment procedures [5–7] for estimating through-thickness residual stress profile as a function of distance away from weld region. For instance, API 579 RP-1/ASME FFS-1 [5] only provides a single curve based upper-bound estimate of axial and hoop variations over axial distance from weld region (in terms of $\sqrt{rt}$) for all cases of girth welds, even though some recent investigations [2–4,8–10] has clearly illustrated that both pipe r/t ratio and heat input, among others, can have a significant impact on axial variation of residual stresses away from weld. Similar to API 579 RP-1/ASME FFS-1 [5], R6 Sec. IV.4 [6] only proscribes a single curved based linear variation over axial distance for hoop residual stress components, while no information is provided for axial residual stress components. BS7910:2013 [7] does not provide any information on the dependency of through-thickness residual stress profile on axial distance away from weld region, except stating that the stipulated profiles are applicable within 3*W* region with respect to weld centerline, where *W* represents weld width.

As a sequel to Part I [1], this paper presents a shell theory based formulation for generalizing key findings reported in Part I so that through-thickness residual stress profile can be estimated not only within weld region, but also at any position away from the weld region until residual stresses completely vanish. This paper starts with a two-part shell model in which the first part represents weld region and second part represents the rest of the component section. As an integral of the two-part shell section assembly process, an estimation scheme on plastic deformation depth measured from weld fusion boundary is developed based on a one dimensional (1D) thermoplasticity model. Then, the

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Nomenclature and abbreviations

A_p	plastic zone size, mm^2
A_w	weld fusion zone size, mm^2
C_p	specific heat, J/(Kg K)
D	flexural rigidity
d_p	plastic deformation depth measured from the weld fusion boundary, mm
E	Young's modulus, GPa
F_p	circumferential shrinkage force, N
M_x	axial bending moment, N mm
M_θ	hoop bending moment, N mm
N_x	axial shear force, N
N_θ	hoop shear force, N
$\widehat{Q}$	characteristic heat input density or intensity, J/mm^3
r	radius to pipe mid-thickness
r_w	molten weld deposition size, mm
S_y	yield strength, MPa
t	pipe thickness, mm
t_{hold}	hold time used in 2D FE model, sec
ΔT	temperature difference (usually from room temperature to melting temperature), °C
ΔT_y	temperature to reach yield magnitude on heating in fully constraint condition, °C
w	radial deflection, mm
W_p	equivalent plastic zone width, mm
α	thermal diffusivity, mm^2/sec
α_T	coefficient of thermal expansion,/K
$\sigma(x)$	residual stress, MPa
σ_m	membrane component of the residual stress, MPa
σ_b	bending component of the residual stress, MPa
$\sigma_{s.e}$	self-equilibrating component of the residual stress, MPa
$\sigma_{x,b}$	bending component of axial residual stress, MPa
$\sigma_{\theta,m}$	membrane component of hoop residual stress, MPa
$\sigma_{\theta,b}$	bending component of hoop residual stress, MPa
$\sigma_{\theta,m}^{ave}$	membrane component of hoop residual stress at weld centerline, MPa
$\sigma_{\theta,m}^{0}$	membrane component of hoop residual stress at weld toe, MPa
$\sigma_{\theta,b}^{0}$	bending component of hoop residual stress at weld toe, MPa
$\sigma_{x,b}^{0}$	bending component of axial residual stress at weld toe, MPa
λ	time, sec
ρ	density, Kg/mm^3
DV	Double V
FEA	finite element analysis
FFS	fitness-for-service
ID	inner diameter
NG	Narrow Groove
OD	outer diameter
SV	Single V
WCL	weld centerline
WT	weld toe

shell deformation problem can be solved by considering the first part of the shell model being subjected to circumferential shrinkage force and axial bending moments that are already established in Part I [1] of this two-part paper series. As a result, the assembly of the two-part shell deformation problem provides a complete description of through thickness axial and hoop residual stress distributions at any position along axial direction away from weld toe. Validations are then performed against finite element calculations for a large number of pipe and vessel configurations, including different joint preparations, heat inputs, and materials.

2. Shell theory based estimation scheme

In Part 1 [1], by decomposing through-thickness residual stress distributions into three parts, i.e., membrane, bending and self-equilibrating, two key controlling parameters in terms of component geometry (r/t) and characteristic heat input ($\widehat{Q}$) have been identified in view of their unique influences on membrane and bending content in a residual stress distribution. Both parts have been shown to contribute significantly to fracture driving force [11–13] than self-equilibrating part in a given through-thickness residual stress distribution. The effects of self-equilibrating part are limited to small crack regime (e.g., when crack size is 0.1 t–0.2 t) even if with comparable peak value with that of the membrane and bending parts [11–13]. Furthermore, as far as residual stresses at some distance away from weld are concerned, it can be argued that only membrane and bending parts are operative while self-equilibrating part remains local to a weld area [11–13]. With such considerations, a classical shell theory based solution should provide a reasonable functional description of through-wall membrane and bending stress distributions under prescribed loading conditions in terms of forces and moments generated by weld zone against the rest of the shell body. Indeed, as demonstrated in the following sections, such a formulation is not only feasible, but also effective for a full range of pipe geometry and welding procedures considered in this investigation.

2.1. Formulation

In the context of shell theory, it is assumed that residual stress distributions in a girth-welded cylindrical component can be modeled as an assembly of two part shell sections, as shown in Fig. 1. Part A represents an equivalent plastic zone width along the shell mid-thickness while Part B represents the rest of the component section, as shown in Fig. 1. The interactions between the two parts are through a ring shear force Q_0 in radial direction and a ring moment M_0. The ring force (consistent with line force definition with a unit of, e.g., N/mm) can be related to hoop shrinkage force F_p induced by plastic zone (Part A) position on the shell mid-thickness, as:

$$Q_0 = \frac{F_p}{2r} = \frac{\sigma_{\theta,m}^{ave} \cdot W_p \cdot t}{2r} \quad (1)$$

In Eq. (1), W_p represents the equivalent plastic zone width situated on shell mid-surface, as shown in Fig. 1b, in which d_p stands for the depth of plastic zone beyond weld fusion zone and its estimation method is to be given in the next section. Here, it is assumed that the plastic zone boundary at mid-thickness (Fig. 1b) is approximately aligned with weld toe position at OD.