International Journal of Pressure Vessels and Piping 146 (2016) 65–73

Contents lists available at ScienceDirect

International Journal of Pressure Vessels and Piping

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

A framework for estimating residual stress profile in seam welded pipe and vessel components Part II: Outside of weld region

Shaopin Song, Pingsha Dong*

Welded Structures Laboratory, Department of Naval Architecture and Marine Engineering, University of Michigan, Ann Arbor, MI 48109, USA

ARTICLE INFO

Article history:
Received 3 August 2015
Received in revised form
21 July 2016
Accepted 24 July 2016
Available online 28 July 2016

Keywords:
Residual stresses
Finite element
Long seam welds
Pipe and vessel welds
Residual stress profile
Fitness-for-service
Membrane and bending decomposition
Curved beam

ABSTRACT

Part I of this study has identified two key parameters (r/t ratio and characteristic heat input $\widehat{Q}$) that dominate important through-thickness residual stress distribution characteristics, with which a residual stress profile estimation scheme has been developed for weld region, i.e., at weld centerline and weld toe. In Part II, we present an analytical model for achieving residual stress profile estimation for through-thickness sections away from the weld region in seam welded pipe and vessel components. A curved beam bending theory based model is analytically constructed through an assembly of two parts: One is weld fusion zone region and the other is the rest of the component section along circumferential direction. The final assembly of the two parts leads to a closed form solution to both axial (longitudinal) and hoop (transverse) residual stress components as a function of circumferential angular position away from weld toe. The effectiveness of the full-field residual stress estimation scheme is demonstrated by comparing with finite element modeling results over a broad range of 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 and welding heat input.

1. Introduction

When performing fracture mechanics based FFS assessment for longitudinal seam welded components for potential failures such as those described in Refs. [1–6], through-thickness residual stress profiles at both weld location and some distance away from weld are often required. Although cracking often originates at weld in seam welded components [1–5], its subsequent growth behavior once outside of a weld region can be strongly influenced by residual stress distributions at some distance away from weld. Such a phenomena phenomenon can be seen in the wide spread stress corrosion cracking observed in a 304 stainless steel seam welded pipe [6]. The extent of residual stresses away from weld in seam welded pipe and vessel components have been shown to depend upon component radius to thickness ratio (r/t) [7–11] and heat input [8–10], as confirmed by the large number of parametric analyses discussed in Part I [12]. However, there exists little guidance on residuals stress profile determination for location at some distance away from seam weld in existing FFS Codes and Standards [13–15].

As a case in point, both BS 7910 [13] and R6 [14], seam weld transverse residual stress profile (transverse to weld) remains the same over a circumferential distance of 1.5W from weld centerline, where W is seam weld width. Beyond 1.5W, no information is given in BS 7910 while a linear reduction to zero over a distance estimated based on 1D heat transfer and general thermodynamic equations in R6 [14]. It should also be noted that both BS 7910 [13] and R6 [14] do not recognize r/t ratio effects on residual stress profiles, resulting in the same residual stress profiles as those for describing plate butt welds. API 579 [15] recommends that residual stress profiles at weld can be extended over a circumferential distance in terms of $\sqrt{rt}$, based on a best fit of upper bound of all finite element results over all r/t ratios and heat inputs performed at that time [16]. Therefore, depending upon which FFS procedure is used, there can be significant differences in through-thickness residual stress profile prescriptions at a distance away from weld region, from no information given in BS 7910 [13] to linear variation to zero stress over a small circumference distance in R6 [14] to quadric variation over a circumferential distance in terms of $\sqrt{rt}$ in API 579 [15]. The current work represents an attempt in addressing some of

* Corresponding author.
E-mail address: dongp@umich.edu (P. Dong).

http://dx.doi.org/10.1016/j.ijpvp.2016.07.010
0308-0161/

Nomenclature

d_p	distance from the weld toe to the boundary of plastic zone, mm
M_0	moment at the weld toe, N mm
M	moment along circumference as a function of angle θ, N mm
N_0	normal force at the weld toe, N
N	normal force along circumference as a function of angle θ, N
n_p	number of weld passes
R	variable in pipe radial direction varying from inner radius r_i to outer radius r_o, mm
r	mean radius of a pipe, mm
r_i	inner radius of a pipe, mm
r_o	outer radius of a pipe, mm
t	pipe thickness, mm
σ_m	membrane component of residual stress, MPa
σ_b	bending component of residual stress, MPa
$\sigma_{s.e.}$	self-equilibrating component of residual stress, MPa
$\overline{\sigma}_m$	dimensionless membrane component of residual stress
$\overline{\sigma}_b$	dimensionless bending component of residual stress
$\overline{\sigma}_{s.e.}$	dimensionless self-equilibrating component of residual stress
σ_T	transverse residual stress, MPa
$\sigma_{T,m}$	membrane component of transverse residual stress, MPa
$\sigma_{T,b}$	bending component of transverse residual stress, MPa
$\sigma^0_{T,m}$	membrane component of transverse residual stress at weld toe, MPa
$\sigma^0_{T,b}$	bending component of transverse residual stress at weld toe, MPa
σ_L	longitudinal residual stress, MPa
$\sigma_{L,m}$	membrane component of longitudinal residual stress, MPa
$\sigma_{L,b}$	bending component of longitudinal residual stress, MPa
$\sigma^0_{L,m}$	membrane component of longitudinal residual stress at weld toe, MPa
$\sigma^0_{L,b}$	bending component of longitudinal residual stress at weld toe, MPa
σ_R	radial residual stress, MPa
υ	Poisson's ratio

Abbreviations

FEA	finite element analysis
FFS	Fitness-for-Service
ID	inner diameter
OD	outer diameter
SV	Single V
WCL	weld centerline
WT	weld toe

the inconsistencies in seam weld residual stress profiles brought forth in the above discussions by introducing an analytical framework with which residual stress distributions away from seam welded components can be constructed.

As a sequel to Part I [12] in which a functional form of residual stress profile has been proposed and proven effective for weld region, Part II focuses upon the development of a mechanics based framework for extending the residual stress profile away from weld until it vanishes. To do so, a curved beam bending model is introduced to analytically describe circumferential variation of the residual stress profile beyond weld region in seam welded components. The validity of the analytical approach is then examined by comparing with finite element modeling results for seam welded components with different component geometries (r/t), thicknesses (t), and heat inputs. The results have demonstrated that a full-field residual stress profile estimate can be indeed achieved with the proposed approach for weld region (see Part I [12]) and away from weld region. Finally, the full-field seam weld residual stress profile estimation scheme is demonstrated using a longitudinal seam welded component on which material, component geometry, joint type, as well as welding parameters are given, as typically presented to a fracture mechanics analyst in practice, for which he or she must determine a residual stress profile before commencing any fitness for service calculations.

2. A curved beam bending model

As illustrated in Part I [12], membrane and bending content in a given through-thickness residual stress distribution are principally dominated by two key parameters, i.e., component geometry (r/t) and characteristic heat input ($\widehat{Q}$). Through-thickness self-equilibrating residual stresses are mostly confined within weld region, which can be taken into account through a set of consistency conditions as described in Part I [12]. This is because through-thickness self-equilibrating residual stress has been shown to be dominated by pass sizes, pass sequence, and joint preparation etc. [11,17,18]. Along this line of thinking, it should be reasonable to hypothesize that through-thickness membrane and bending stresses away from weld region may be modeled as internal forces in an equivalent curved beam model subjected to shrinkage force exerted by weld region. Indeed, as demonstrated in the following sections, such a formulation is not only feasible, but also proven to be effective for a full range of pipe geometries and welding procedures considered in this investigation.

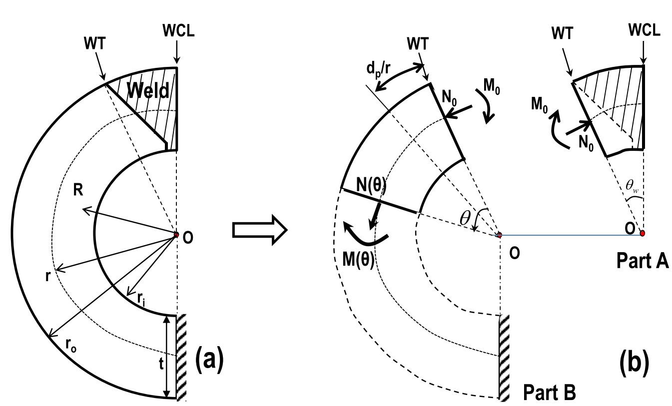

Fig. 1. Definition of curved beam bending model for estimating residual stress profile at locations away from weld: (a) Half cross section of a seam welded component, and (b) Curved beam bending model with two-part assembly (Part A: weld region, and Part B: curved beam representing the rest of seam welded section including a plastic zone depth with an angular span of d_p/r from weld toe).