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Limit loads for un-cracked and circumferential through-wall cracked pipe bends under torsion moment considering geometric nonlinearity

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A B S T R A C T

This paper is dedicated to providing a detailed plastic collapse load analysis for un-cracked and circumferential through-wall cracked pipe bends under torsion moment by three dimensional FE methods considering geometric nonlinearity. For un-cracked pipe bends results show that radius-to-thickness is the main factors affecting the plastic collapse load. For cracked pipe bends the weakening factor decreases with increasing crack length, and the decreasing rate exhibits three typical stages which performs a similar trend with that in bending case. Although the weakening factor in plastic collapse load shows the similar variation based on geometric nonlinearity with that based on geometric linearity change, the limit load solutions based on geometric linearity fail to be used in prediction for torsion load based on geometric nonlinearity. So estimating limit load solutions by FE method are proposed, which shows a better choice compared with the past solutions. Furthermore the effect of yield strain is considered with the normalized parameter proposed to represent this weakening effect of yield strain on torsion moment. Results show that pipe parameters bend radius-to-radius and crack length have little impact on the weakening parameter, however radius-to-thickness have an obvious impact on the weakening parameter, which increases with decreasing weakening parameter. Results also show that radius-to-thickness has a great impact on the ovality deformation, while bend radius-to-radius hasn't. Therefore geometry effect is significant for a high yield strain value and a high radius-to-thickness value.

1. Introduction

Pipe bends (or elbows) are commonly used components in a piping system, which is widely used in petroleum, chemical and nuclear power industries [1]. For pipe bends with or without crack defects, limit load and plastic collapse load solutions are available in the literature [2–5]. Among these severe factors the geometric nonlinearity effect known as GNL could significantly influence plastic behavior of pipe bends [6], and it is important to accurately capture the elbow deformation under bending loading [7]. Research in the past has identified that a change in geometry of the pipe dimensions due to large deformation assumptions will have an influence on stresses of pipe bend. The total loading will change as a result of the change in pipe diameters and the cross section area with GNL considered [8]. Compared to those of straight pipes, plastic limit load analysis of pipe bends is complicated not only due to more geometric variables involved, such as the bend radius and angle, but also due to the geometric nonlinearity effect. Pipe bends are more flexible than straight pipes with similar dimensional parameters due to the complex deformation they exhibited under bending loads. Pipe bends tend to show different mechanical properties as the interaction of geometrical nonlinearity and material nonlinearity when they are under bending and torsion moment [9].

Due to the self weight, valve weight, fluid weight in addition to heat expansion in the pipe system bending and torsion moment should not be overlooked. The stress caused by bending moment and torsion moment is often greater than membrane stress only by pressure. Pipe bends normally have higher loading capacity under torsion moment than those under bending capacity for both un-cracked and cracked pipe bends, except for the cases when the pipe bends are thick-walled and have long bend radius, because in these cases the pipe bends may recover to straight pipes in elastic-plastic mechanical behaviors showing higher bending capacity instead. It is interesting to find out the distinction in the torsion load. The past researches show that GNL has some influences on the limit load. Unfortunately research for pipe

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Nomenclature

t	thickness of pipe bend
L	length of attached straight pipe
r	mean radius of cross section
R	bend radius of pipe bend
λ	bend characteristic of pipe bend
θ	crack length
E	Young's modulus
μ	Poisson's ratio
σ_s	yield stress
ε_s	yield strain
k	a normalized parameter
W	the weakening factor
M	bending moment
M_o	limit bending moment for un-cracked pipe bends
M_L	limit bending moment for cracked pipe bends
M_o^S	limit bending moment for straight pipes
T	torsion moment
T_o	limit torsion moment for un-cracked pipe bends
T_L	limit torsion moment for cracked pipe bends

Abbreviations

TES	twice-elastic slope
FE	finite element
GNL	geometry nonlinearity

bends under torsion load considering the geometry change is still lacking. This paper is dedicated to providing a detailed limit load analysis for un-cracked and circumferential through-wall cracked pipe bends under torsion moment using three dimensional FE methods based on geometric nonlinearity.

2. Review

2.1. Geometry parameters of pipe bends

The geometry of a pipe bend is shown in Fig. 1. The bend angle is considered to be 90°, and the straight pipe attached to pipe bend is long enough ($L > 4r$) to ignore the end effects on limit loads [10]. R is the bend radius of pipe bends, t is the thickness of pipe bends, and r is the mean radius of cross section, θ is the crack length.

2.2. Limit loads for pipe bends under torsion moment based on geometric linearity

2.2.1. Un-cracked pipe bends

A detailed stress analysis is conducted in our recently published work [11] showing that in the geometrical bending section combined bending and torsion moment effects exist at the same time, and these combined effects also spread along attached straight pipes for as long as $3r$ length in axial direction of straight pipes. Meanwhile a new expression predicting limit torsion moment is proposed

$$T_o/M_o^S = 1.0682(r/t)^{-0.3114}(R/r)^{0.1787} \quad (1)$$

Seen in Fig. 2, where,

$$M_o^S = 4r^2 t\sigma_s \quad (2)$$

Results in Fig. 2 show that the limit loads increase with increasing r/t and R/t, and r/t is the main parameter influencing the limit loads.

Eq. (2) denotes the limit loads for straight pipes with the same dimension of pipe bends, σ_s is the material yield stress, T_o is the limit load for a pipe bend under pure torsion moment.

2.2.2. Cracked pipe bends

Based on the FE results, the following approximate limit load solutions for circumferential through-wall cracked pipe bends under torsion moment are proposed [12].

For cracks at extrados

$$W = \begin{cases} \min\{1.0,\ \exp(-5.299(\theta/\pi)^2 + 1.208(\theta/\pi))\} & \text{Upper bound} \\ \min\{1.0,\ \exp(-4.6837(\theta/\pi)^2 + 0.3322(\theta/\pi))\} & \text{Lower bound} \end{cases} \quad (3)$$

$$W = \begin{cases} \min\{1.0,\ \exp((0.0648R/r - 5.0842)(\theta/\pi)^2 & r/t = 5 \\ \quad + (-0.1318R/r + 1.1307)(\theta/\pi))\} & \\ \min\{1.0,\ \exp((-0.0023R/r - 5.484)(\theta/\pi)^2 & r/t = 10 \\ \quad + (-0.1008R/r + 1.4491)(\theta/\pi))\} & \\ \min\{1.0,\ \exp((0.2027R/r - 4.3561)(\theta/\pi)^2 & r/t = 20 \\ \quad + (0.0482R/r + 0.8878)(\theta/\pi))\} & \end{cases} \quad (4)$$

Seen in Fig. 3.

And for cracks at intrados

$$W = \begin{cases} \min\{1.0,\ \exp(-5.9699(\theta/\pi)^2 + 1.2239(\theta/\pi))\} & \text{Upper bound} \\ \min\{1.0,\ \exp(-4.7239(\theta/\pi)^2 + 0.1423(\theta/\pi))\} & \text{Lower bound} \end{cases} \quad (5)$$

$$W = \begin{cases} \min\{1.0,\ \exp((0.0344R/r - 4.6775)(\theta/\pi)^2 & r/t = 5 \\ \quad + (-0.0925R/r + 0.6411)(\theta/\pi))\} & \\ \min\{1.0,\ \exp((0.0098R/r - 5.6447)(\theta/\pi)^2 & r/t = 10 \\ \quad + (-0.084R/r + 1.1403)(\theta/\pi))\} & \\ \min\{1.0,\ \exp((-0.0636R/r - 6.2715)(\theta/\pi)^2 & r/t = 20 \\ \quad + (-0.0437R/r + 1.4392)(\theta/\pi))\} & \end{cases} \quad (6)$$

Seen in Fig. 4.

where W is the weakening factor written as

$$W = T_L/T_o \quad (7)$$

The weakening factor W is evaluated to express the loading capacity for pipes and pipe bends containing defects [1,13,14]. Results in Fig. 3 and Fig. 4 show that the weakening factor decreases with increasing crack length, while the decreasing rate exhibits three typical stages.

It should be emphasized that these estimated solutions for pipe bends under torsion load are all based on geometric linearity. Research on torsion loads considering the geometry change is extremely required for engineering structure assessment.