International Journal of Mechanical Sciences 88 (2014) 100–109

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

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

Limit loads for pipe bends under combined pressure and out-of-plane bending moment based on finite element analysis

Jian Li, Chang-Yu Zhou *, Ji-Lin Xue, Xiao-Hua He

School of Mechanical and Power Engineering, Nanjing Tech University, Nanjing 211816, China

ARTICLE INFO

Article history:
Received 18 October 2013
Received in revised form
29 July 2014
Accepted 31 July 2014
Available online 7 August 2014

Keywords:
Pipe bends
Out-of-plane bending moment
Internal pressure
Limit loads
Finite element analysis

ABSTRACT

In present work, limit loads for pipe bends under combined internal pressure and out-of-plane bending moment have been investigated systematically via finite element simulation based on both small displacement analysis and large displacement analysis. By normalized methods, a wide range of non-dimensional parameters were considered and limit bending moment expression has been suggested which shows that r/t is the main factor affecting the limit bending moment. In addition, the effect of internal pressure on the limit loads was studied in detail which is significant for thin walled pipe bends. It is found that yield strain ε_0 has an obvious effect on limit load based on large displacement analysis. According to the finite element results, practicable engineering assessment equations of limit loads have been proposed for pipe bends under combined loads. These proposed equations are validated with experiment data and also justified to be a good choice for limit loads assessment.

1. Introduction

Pipe bends or elbows are considered to be the crucial components in pressure piping system which are widely used in petroleum, chemical and nuclear power industries [1]. Pipe bends can usually change the direction of pipeline, and are subjected to complex loads such as internal pressure, bending moment, torsion and their combinations caused by heat expansion [2]. They also play an important role through the local deformation to release system energy [3]. Therefore it is important for pipe bends to maintain the structure integrity of piping system. In addition, accidents may occur in power plants due to the complex loads, and great loss will be brought on account of the weak part of pipe bends. So the research on limit loads for pipe bends under combined pressure and out-of-plane bending moment is of great significance.

In practice, pipe bends tend to show different mechanical properties as the interaction of geometrical nonlinearity and material nonlinearity when they are under bending moment or combined internal pressure and bending moment. Over the years, a great number of studies have been carried out to investigate the limit load of pipe bends including theoretical analysis, finite element simulation [4,5] and experimental based validations [6,7]. Many researches emphasize on in-plane bending moment [8–11].

Hashem et al. [12–14] have performed analyses on pipe bends subjected to pure out-of-plane bending moment or combined internal pressure with out-of-plane bending moment, and discussed the limit loads of pipe bends based on small displacement analysis, large displacement analysis and the effect of internal pressure under combined loads, and obtained some valuable solutions. In their work, the effect of attached straight pipe has been omitted in FE model, and elbow element chosen from the ABAQUS library may exhibit some error for thick pipe bends [15]. At the same time their work lack of supplying estimated equations of limit loads.

In present paper, both small displacement analysis and large displacement analysis including geometric and material nonlinearity are adopted, and the limit load analysis for pipe bends under combined internal pressure and out-of-plane bending moment is carried out thoroughly by means of three-dimensional nonlinear finite element simulation. This object is trying to further study the limit load of pipe bends subjected to complex load conditions.

2. Finite element analysis

2.1. Geometry parameters of pipe bends

The dimension parameters of pipe bends are listed in Table 1. 16 models are chosen for the calculations, which contain 4 different bending radiuses and 4 different wall thicknesses. The bend angle is considered to be 90°, and the straight pipe attached to pipe bend is long enough ($L > 3r$) to ignore the end effects on limit loads [16].

* Corresponding author. Tel./fax: +86 25 58139951.
E-mail address: changyu_zhou@163.com (C.-Y. Zhou).

http://dx.doi.org/10.1016/j.ijmecsci.2014.07.012
0020-7403/© 2014 Elsevier Ltd. All rights reserved.

Nomenclature

t	thickness of pipe bend
P_L	limit pressure for pipe bend under combined loads
L	length of attached straight pipe
M_L	limit bending moment for pipe bend under combined loads
r	mean radius of cross section
R/r	relative bend radius,
R	bend radius of pipe bend
r/t	relative thickness
λ	bend characteristic of pipe bend
P_o^S	limit pressure for straight pipe
D_{max},	maximum outside diameter,
M_o^S	limit bending moment for straight pipe
M_o^{exp}	pure experiment limit bending moment for pipe bends under out-of-plane bending moment
D_{min},	minimum outside diameter,
D	nominal diameter
C	percent ovality
M_L^{exp}	experiment limit bending moment for pipe bends under combined loads
E	Young's modulus
μ	Poisson's ratio
M_O^{FE}	FE data for combined out-of-plane and internal pressure
σ_0	yield stress
M_{IC}^C	limit bending moment from Eq. (21)
M_{IO}^C	limit bending moment from Eq. (22)
ε_0	yield strain
M_{IC}^K	limit bending moment from Eqs. (24) and (25)
I	cross-sectional moment of inertia
M_{IO}^K	limit bending moment from Eqs. (26)–(28)
R_C	correlation coefficient
M_O^{PR}	limit bending moment from Eq. (29)
p	normalized internal pressure
P	internal pressure
P_o	limit pressure for pipe bend
M	bending moment
M_o	pure limit bending moment for pipe bend

Abbreviations

LPF	load proportionality factor
TES	twice-elastic slope
FE	finite element

This length is set to be 1000 mm. The bend characteristic of pipe bend is defined as λ, where λ can be represented as:

$$\lambda = \frac{Rt}{r^2} = \frac{(R/r)}{(r/t)} \tag{1}$$

2.2. Finite element model

The finite element analysis is performed by ABAQUS code [17]. As depicted in Fig. 1, in the left plane of pipe end, fixed constraint is applied. In the right plane of pipe end, a Multi-Point Constraint (MPC) is applied to the nodes. A single node is set up at the center of right plane, and a rigid beam will be formed by connecting this single node to the nodes of right end plane, then a bending moment can be applied to the single node directly. Internal pressure is applied as a uniform distributed load on the internal surface of model, in addition with equivalent axial tension stress applied at the right plane of pipe end.

Table 1
Dimension parameters of pipe bends.

Dimensions (mm × mm)	R (mm)	λ	R/r	r/t
Φ323.9 × 7.15	338.05	0.096	2.13	22.15
Φ323.9 × 14.3	338.05	0.202	2.18	10.83
Φ323.9 × 21.45	338.05	0.317	2.24	7.05
Φ323.9 × 28.6	338.05	0.443	2.29	5.16
Φ323.9 × 7.15	438.05	0.125	2.77	22.15
Φ323.9 × 14.3	438.05	0.261	2.83	10.83
Φ323.9 × 21.45	438.05	0.411	2.90	7.05
Φ323.9 × 28.6	438.05	0.575	2.97	5.16
Φ323.9 × 7.15	538.05	0.153	3.40	22.15
Φ323.9 × 14.3	538.05	0.321	3.48	10.83
Φ323.9 × 21.45	538.05	0.505	3.56	7.05
Φ323.9 × 28.6	538.05	0.706	3.64	5.16
Φ323.9 × 7.15	638.05	0.182	4.03	22.15
Φ323.9 × 14.3	638.05	0.381	4.12	10.83
Φ323.9 × 21.45	638.05	0.598	4.22	7.05
Φ323.9 × 28.6	638.05	0.837	4.32	5.16

The material used is assumed to be elastic-perfectly plastic, and non-hardening J_2 flow theory is used within ABAQUS. The Young's modulus E=210,000 MPa, Poisson's ratio μ=0.3 and yield stress σ_0=200 MPa. A normalization method is used in order to reflect the geometry characteristics of pipe bends including R/r, r/t and λ which have been mentioned above [7–11]. A 20 node quadratic brick reduced integration element (C3D20R) is used, as shown in Fig. 2. A mesh convergence has been analyzed for a coarse mesh model in present work with 11,200 elements and a fine mesh model with 16,800 elements. The limit load difference between two models is less than 0.01% for a pipe bend subjected to pure bending load, where r/t=5.16, R/r=4.32. Obviously, present mesh is adequacy and can satisfy with FE calculation. The Riks option is adopted to avoid the difficulty of convergence in finite element analysis. For combined internal pressure and bending moment, loading is applied by two steps. The pressure load is applied in the first step. In the second step, the bending moment is applied in a proportion. To acquire comprehensive limit loads of pipe bends, the present work considers both small and large displacement analysis to investigate the limit loads.

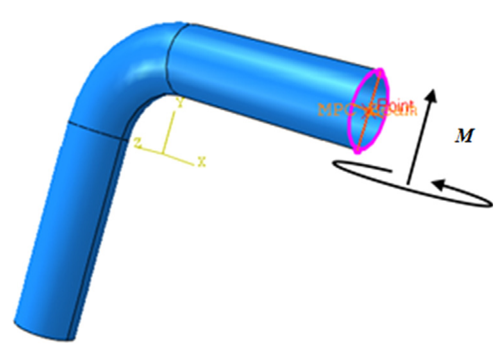

Fig. 1. Finite element model with boundary conditions.