Effect of Wall Thinning Shape on Combined Torsion and Bending Moments at Plastic Collapse for Pipes

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ABSTRACT. *Wall thinning caused by flow accelerated corrosion is one of the major degradations for piping systems in power plants. Collapse bending moments for pipes with local wall thinning under torsion moments were analysed by finite element modelling at the presence of internal pressure. The wall thinning shapes used in the analyses are two types, rectangular and round in shapes. Plastic deformation behaviours of pipes with these wall thinning were found to be different. Equivalent collapse moments defined as the root of the sum of the squares of the torsion and bending moments at collapse are also different between the rectangular and round shape wall thinning. In case of rectangular shape wall thinning, plastic collapse bending moment decreased rapidly with increasing torsion moment. The equivalent collapse moment is not equal to pure bending collapse moments. On the other hand, the equivalent collapse moment becomes almost constant for the round shape wall thinning if the torsion moment is within the actual plant range. Combined torsion and bending moment at collapse can be estimated by pure bending collapse moment of a pipe with round shape wall thinning.*

INTRODUCTION

Carbon steels are commonly used in piping systems of power plants. Local wall thinning caused by flow accelerated corrosion due to high temperature and high pressure water and steam is one of the major degradations for carbon steel piping systems. Wall thinning became a deep concern to the nuclear power industry with the December 1986 rupture of 24-inch diameter feed water line at Surry Unit 2. On August 9, 2004, rupture occurred at feed water pipe line of Mihama Unit 3.

Therefore, it is important to evaluate the strength of piping undergoing local wall thinning in order to maintain the integrity of the piping systems. Several experimental and analytical studies have been performed with the aim of developing a methodology for evaluating the locally thinned pipes [1, 2].

Applied stresses for piping items in actual power plants are mainly due to internal pressure and bending moment with small torsion moment. Evaluation of plastic collapse bending moment without torsion stress for a cracked pipe is provided by ASME B&PV

Code [3] and JSME FFS Code [4]. Combined bending and torsion moments at collapse for pipes with circumferential crack and local wall thinning are currently being developed by finite element (FE) analyses [5, 6] and its codification is being discussed at the Working Group on Pipe Flaw Evaluation of ASME B&PV Code Committee.

This paper focuses on combined torsion and bending moments at collapse for pipes containing rectangular and round shape local wall thinning, and describes the effect of wall thinning shape on plastic collapse moments. In addition, plastic deformation behaviours for the shapes are revealed.

PLASTIC COLLAPSE MOMONT BY BENDING AND TORSION

Combination of bending and torsion moments for a pipe without a flaw is commonly done by using equivalent moment. Bending and torsion loads are resolved into orthogonal moment components and summed into an equivalent load by vector summation in accordance with the construction code [7]. The equivalent moment M is given by,

$$M = \sqrt{M_x^2 + M_y^2 + M_z^2} \qquad (1)$$

where the equivalent moment M is a resultant moment combining the orthogonal moment components, M_x, M_y and M_z at a given position in a piping system.

Combination of bending and torsion moments for a pipe with a local wall thinning was performed by FE analyses. The equivalent collapse moment M_{eq} is defined as,

$$M_{eq} = \sqrt{M_B^2 + M_T^2} \qquad (2)$$

where M_B is the bending moment and M_T is the torsion moment at collapse, respectively. It has been confirmed that the equivalent collapse moment M_{eq} is almost constant for a cracked pipe subjected to torsion moment corresponding to torsion stress less than 20% of flow stress, where flow stress is given by the average of yield stress and ultimate tensile strength [8 - 10]. That is, M_{eq} is almost equal to the plastic collapse moment for pure bending moment and the plastic collapse of the cracked pipe subjected to combined bending and torsion moments can be estimated by the plastic collapse pure bending moment.

The equivalent collapse moment M_{eq} for a wall thinned pipe is not easy to be described by Eq. 2, because the volume of metal loss is larger and the stiffness of the pipe is smaller compared with a cracked pipe. In this paper, in order to obtain the equivalent collapse moment M_{eq} and check whether the M_{eq} is almost constant for relatively small torsion stress and the plastic collapse can be estimated by the plastic collapse pure bending moment, plastic collapse bending moments with torsion moments for different shape of wall thinning were analysed by FE analysis, as below.

FINITE ELEMENT ANALYSIS FOR WALL THINNING PIPES

Pipe Conditions

Plastic collapse bending moments for 24-in. schedule 80 straight pipes with local wall thinning were calculated for the condition of torsion moment and internal pressure by FE analysis. The model is illustrated in Fig. 1. The pipe outer diameter D_0 is 609.6 mm and the wall thickness t is 30.9 mm. The length of the pipe is eight times of the outer diameter. The wall thinning is located inside of the pipe. The center of the wall thinning is set at pipe mid-length. All of the nodes at one end of the pipe are fixed, and the torsion and bending moments are applied at the other end of the pipe. Internal pressure of 8 MPa, corresponding to hoop stress of 74.9 MPa, is also applied for the pipe.

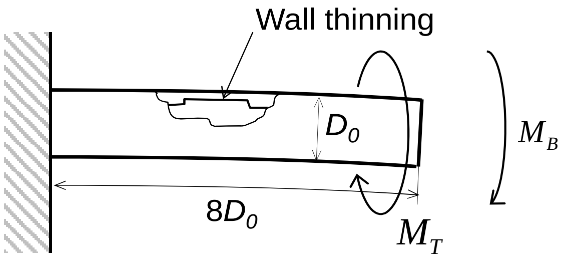


Fig. 1 Model of a locally thinned pipe subjected to bending moment and torsion moment under internal pressure.

Wall Thinning Shape

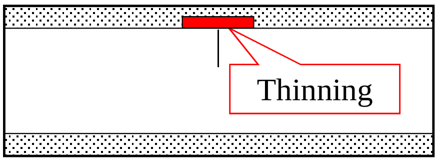
Two types of wall thinning, rectangular and round in shape, as depicted in Fig. 2, were considered in this study. The wall thinning with round shape has been investigated in several studies till now [11, 12]. Recently, it was said that the wall thinning with rectangular shape may give conservative solution [13]. Therefore, in this analysis, the effect of wall thinning shape on collapse moment was investigated.

The wall thinning was located in tensile stress side during the bending load. The wall thinning length, maximum depth and angle in circumferential direction are L, a, and 2θ, respectively. The sizes of the wall thinning in this analyses are $L = D_0$, $a = 0.75t$ and $2\theta = 90^o$ for both rectangular and round shapes.

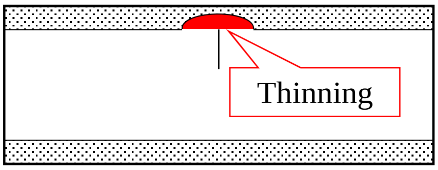
Finite Element Analysis Conditions

FE analysis conditions are given in Table 1. The FE analysis was conducted by ABAQUS standard 6.7-4. Large deformation formulation was invoked in order to obtain plastic collapse moment accurately under large deformation. The material property employed in this paper was assumed to be elastic-fully plastic with the yield strength of 338 MPa, which is identified with the flow stress of the material.

FE mesh for the local wall thinning inside the pipe is shown in Fig. 3. The part with red color shows the wall thinned area. The sequence of the loading is; first pressurizing the pipe to the pressure of 8 MPa, then applying the given torsion moment M_T on the pipe end, finally imposing the bending angle incrementally in small steps and solving the corresponding bending moment, as illustrated in Fig.



(1) Rectangular Shape



(2) Round Shape

Fig. 2 Model of local wall thinning in a pipe.

1. The applied torsion moment was calculated from the corresponding shear stress τ. The relation between the nominal torsion moment M_T and shear stress τ not taking account of the wall thinning is expressed by $M_T = 2\pi R^2 t\tau$, where R is the pipe mean radius. The wall thinning is located such that its center coincides with the plane of the maximum tensile stress due to bending.

ANALYSIS RESULTS

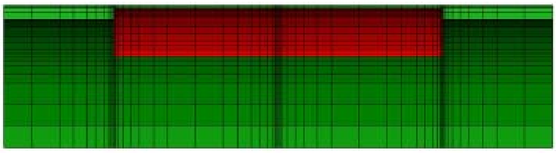
Moment-Deflection Curves and Deformations

Analysis results of bending moments M_b and bending angle θ_b for pipes with rectangular shape wall thinning under torsion stress of τ/σ_f are shown in Fig. 4. It can be seen that, from Fig. 4, the applied bending moment M_b increases with the increasing bending angle θ_b before the maximum bending moment. After the maximum bending moment is attained, the bending moment decreases with the increasing bending angle θ_b. The maximum bending moment corresponds to the plastic collapse moment M_B. The plastic collapse moment decreases with the increasing torsion stresses τ.

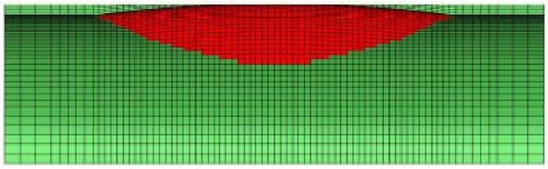
Table 1 FE analysis conditions.

Program	ABAQUS 6.7-4
Stress strain curve	Elastic-fully plastic
Geometrical non-linearity	Considered
Yield stress, $\sigma_y = \sigma_f$	338 MPa
Young's modulus, E	203 GPa
Strain hardening, H	0
Internal pressure (Hoop stress)	8 MPa (74.9 MPa)

The deformation behaviour of the pipe containing rectangular wall thinning shape without torsion stress is also shown in Fig. 4, with the color contour of equivalent plastic strain. Small bulging due to internal pressure can be seen at the entire area of the wall thinning, before applying bending moment. At the maximum bending moment, deformation mainly occurs at the corners of the wall thinning edges, as expected. After the maximum bending moment, the deformation at the corner of the wall thinning becomes large and the deformation pattern of the pipe looks a kink.



(1) Rectangular shape



(2) Round shape

Fig. 3 FE mesh for a pipe with local wall thinning.

In case of pipe with round shape wall thinning, relationship between the bending moments M_b and the bending angle θ_b is shown in Fig. 5. The applied bending moment M_b increases with the increasing bending angle θ_b before the maximum bending moment M_B. After the maximum bending moment is attained, the bending moment gradually decreases with the increasing bending angle θ_b. The plastic collapse bending moments M_B decrease with the increasing torsion stresses τ. The plastic collapse bending moments for pipes with round wall thinning are larger than those for rectangular wall thinning.

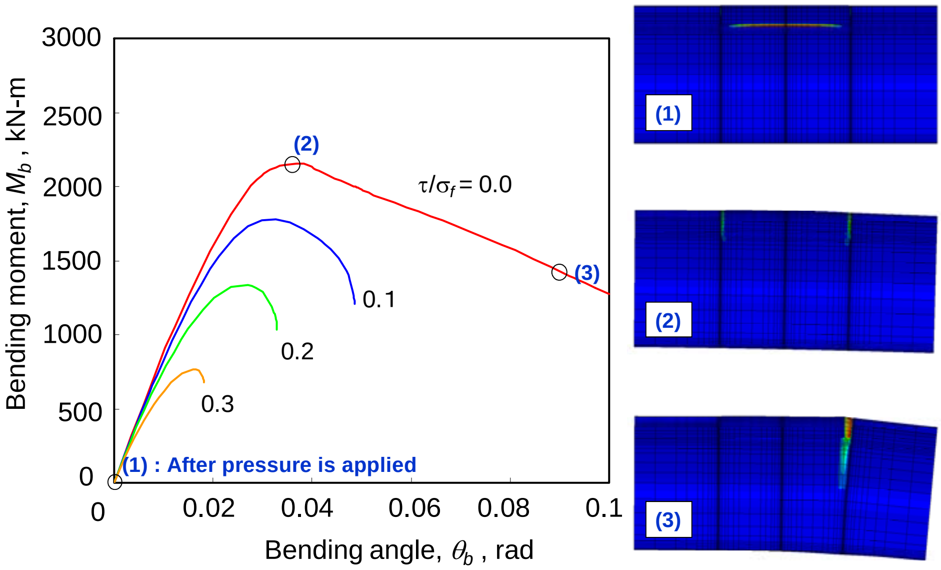


Fig. 4 Collapse bending moment and deformation for a pipe with rectangular wall thinning of $L/D_0 = 1.0$, $a/t = 0.75$ and $2\theta = 90^{\circ}$.

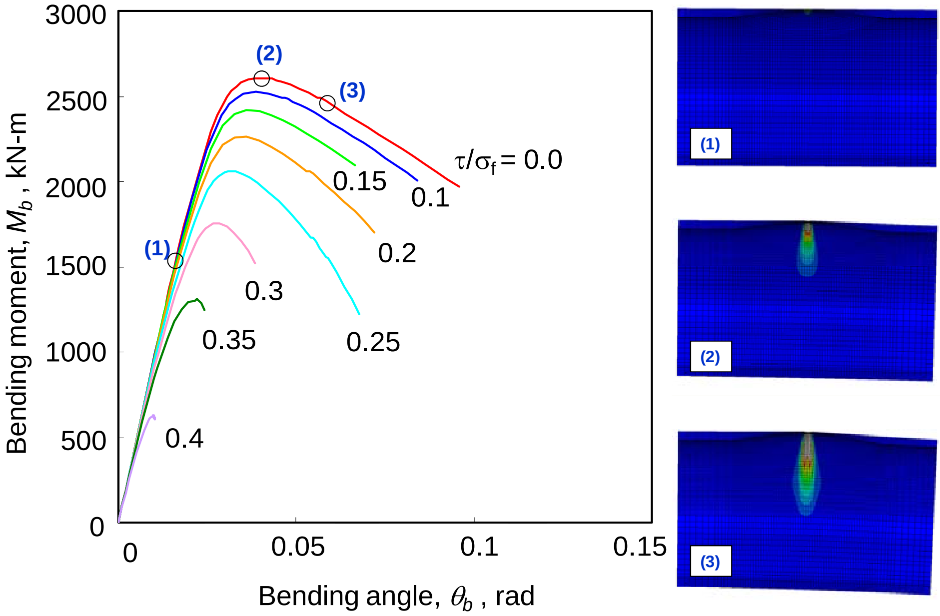


Fig. 5 Collapse bending moment and deformation for a pipe with round wall thinning of $L/D_0 = 1.0$, $a/t = 0.75$ and $2\theta = 90^{\circ}$.

Plastic deformation behaviour for pipe without torsion stress is also shown in Fig. 5 for round wall thinning. The maximum deformation occurs always at the deepest point of the round wall thinning. Due to the difference of deformation behaviour and volume of metal loss, the plastic collapse bending moments M_B for pipes with round wall thinning became larger compared with those for pipes with rectangular wall thinning. Although the plastic collapse moment for rectangular wall thinning is conservative, rectangular shape is an unrealistic geometry from the view point of actual phenomena.

Effect of Torsion on Bending Moment

The plastic collapse bending moment decreases with the increasing torsion moment, as shown in Figs. 4 and 5. Figures 6 and 7 show the relationship between the plastic collapse bending moment M_B and the collapse torsion moment M_T for pipes with the rectangular shape and the round shape wall thinning, respectively. The plastic collapse moments for pure torsion M_{T0} were also obtained by FE analyses under the conditions of the same material properties and wall thinning sizes. The wall thinning lengths, depths and angles are the same as $L/D_0 = 1.0$, $a/t = 0.75$ and $2\theta = 90^o$.

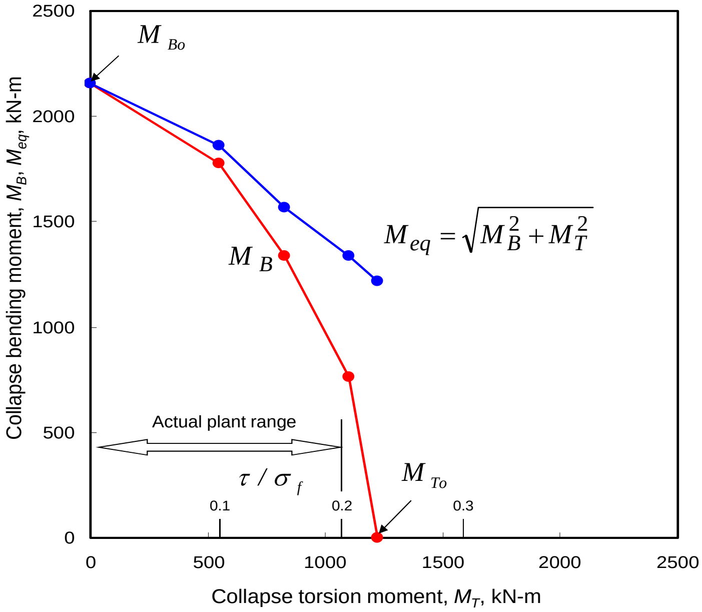


Fig. 6 Plastic collapse bending moment M_B and equivalent moments M_{eq} for a pipe with rectangular wall thinning of $L/D_0 = 1.0$, $a/t = 0.75$ and $2\theta = 90^o$.

When there is no torsion moment, the plastic collapse bending moment M_B becomes the plastic collapse pure bending moment M_{B0} and when the bending moment is zero, the plastic collapse bending moment becomes the plastic collapse pure torsion moment M_{T0}. The torsion moments in power plants are generally small at many positions in piping systems. Based on plant design stress survey [10], it is sufficient to limit the torsion stress τ up to 20% of the flow stress σ_f. The plant torsion actual range is illustrated in Figs. 6 and 7, as actual plant range.

Plastic collapse bending moment M_B for a pipe with rectangular wall thinning decreases rapidly with the increasing torsion moment M_T, as shown in Fig. 6. On the other hand, the plastic collapse bending moment M_B for a pipe with round shape wall thinning decreases gradually with the increasing torsion moment M_T, as shown in Fig. 7. The difference of decrease of the M_B between the rectangular and round shapes is inferred from plastic deformation behaviours. In case of the rectangular wall thinning, there are severe strain concentrations at the corners of rectangles. These strain concentrations facilitate the progress of plastic deformation. At the maximum bending moment, deformation of the pipe occurs kinks at the corners of the wall thinning. In case of the round wall thinning, the strain concentration at the center of wall thinning is less severe and the values of the collapse bending moments M_B are higher compared with the pipe containing rectangular wall thinning.

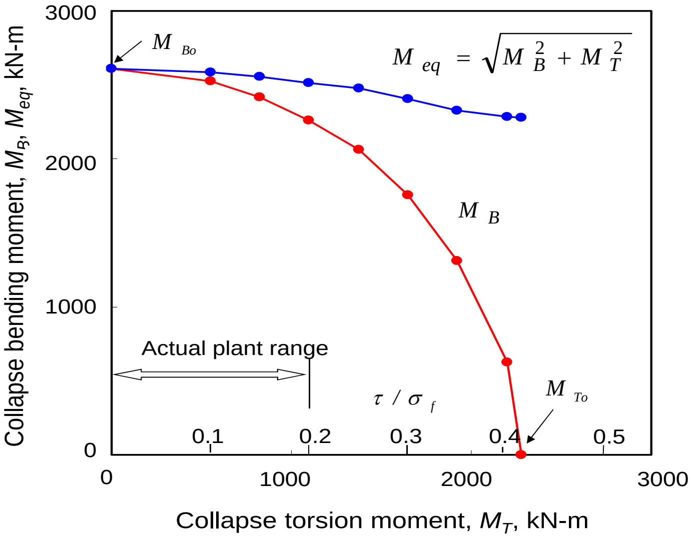


Fig. 7 Plastic collapse bending moment M_B and equivalent moments M_{eq} for a pipe with round wall thinning of $L/D_0 = 1.0$, $a/t = 0.75$ and $2\theta = 90^{\circ}$.

EQUIVALENT MOMENTS FOR PIPES WITH LOCAL WALL THINNING

Equivalent collapse moments M_{eq} given by Eq. 2 are shown in Figs. 6 and 7 for rectangular and round shape wall thinning. The M_{eq} for a pipe with the rectangular shape wall thinning decreases significantly with the increasing torsion moment M_T. On the contrary, the M_{eq} for a pipe with round shape wall thinning retains almost constant with the increasing torsion moment M_T in the torsion stress of actual plant range, where the difference of the equivalent collapse moment M_{eq} against plastic collapse pure bending moment M_B is within 10 %. That is, the equivalent moment M_{eq} is defined to be constant [11] and the M_{eq} can be used as M_{B0}. That is, M_{eq} is almost equal to M_{B0}. Combined bending and torsion moments at collapse can be estimated by the plastic collapse pure bending moment.

The Eq. 2 can be applied for wall thinning pipe under the some limitations of wall thinning. Applicable area of wall thinning for Eq. 2 is described in Ref. [12] considering the wall thinning length, depth and angle. When the wall thinning geometry is rectangular in shape, Eq. 2 is not applicable, although the shape is unrealistic.

CONCLUSION

Plastic collapse moments for pipes with rectangular and round shape wall thinning subjected to combined bending and torsion moments in the presence of internal pressure were investigated by FE analyses.

As the results of the FE analysis, deformations of the pipes with rectangular wall thinning are larger than those with round shape wall thinning, although the rectangular wall thinning is an unrealistic shape. In addition, plastic collapse bending moments decrease rapidly with increasing torsion moments for rectangular shape wall thinning, and equivalent collapse moments consisted on bending and torsion moments decrease with the increasing torsion moments. On the other hand, in case of round shape wall thinning, plastic collapse bending moments decrease gradually with the increasing torsion moments, and the equivalent collapse moments are almost constant against the torsion moments in the torsion stresses of actual plant range. The plastic collapse of the pipes subjected to combined bending and torsion moments in the presence of internal pressure can be estimated by the plastic collapse pure bending moment for a given round wall thinning sizes.

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