Combined Torsion and Bending Moments at Collapse for Pipes with Circumferentially Through-Wall Crack

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ABSTRACT. *Pressurized piping items in power plants may experience combined torsion and bending moments during operation. Currently, there is a lack of guidance in flaw evaluation procedures for combined loading modes of pressure, torsion and bending loads. Recently, collapse bending moments for pipes under torsion moments were analysed by finite element modelling. Equivalent moments defined as the root of the sum of the squares of the torsion and bending moments are shown to be equal to pure bending moments for various diameter pipes containing circumferentially part-through cracks. This paper focuses on behaviour of plastic collapse moments for pipes with circumferential through-wall cracks using finite element analysis, and describes the behaviour of the equivalent bending moments for flaw evaluation procedures, referring part through cracked pipes.*

INTRODUCTION

Piping items in power plants may experience internal pressure, bending and torsion loads during operation. When cracks detected in piping items are assessed by using ASME Boiler and Pressure Vessel Code Section XI [1] or JSME S NA1-2008 [2]. These Codes provide evaluation procedure for predicting plastic collapse loads for cracks in pipes subjected to internal pressure and bending moment under fully plastic conditions. Torsion load is not included in these Codes.

A guidance including the torsion moment is currently developed for pipes with circumferential part-through wall cracks. It is reported that combined bending and torsion moments at collapse can be estimated by pure bending moments, when the combined bending and torsion moments are given by the equivalent moment defined as the root of the sum of the squares of the torsion and bending moments [3-5].

An evaluation method for predicting plastic collapse moments for pipes with local wall thinning is also developing by authors. The plastic collapse bending moment under torsion moment can be estimated by pure bending moment within certain sizes of local wall thinning [6].

This paper focuses on combined torsion and bending moments at collapse for pipes containing circumferential through-wall crack, and shows validity of the equivalent moment at plastic collapse for circumferential through-wall crack, referring the equivalent moment for part- through wall cracks.

PLASTIC COLLAPSE MOMONT BY BENDING AND TORSION

Combination of bending and torsion moments for a pipe with a circumferential part-through crack was performed by FE (finite ekement) analyses. The equivalent collapse moment M_{eq} is defined as,

$$M_{eq} = \sqrt{M_B^2 + M_T^2} \qquad (1)$$

where M_B is the bending moment and M_T is the torsion moment at collapse, respectively. The equivalent moment M_{eq} is almost constant for a part through cracked pipe subjected to torsion stress less than 20% of flow stress, where flow stress is given by the average of yield stress and ultimate tensile strength. The M_{eq} is equal to pure bending moment at collapse for a pipe with a part-through crack.

In order to obtain the equivalent moment M_{eq} for through-wall cracked pipes, plastic collapse bending moments with torsion moments are analysed by FE analysis, as below.

FINITE ELEMENT ANALYSIS FOR WALL THINNING PIPES

Analytical Conditions

Plastic collapse bending moments for 24-in. schedule 80 straight pipes with circumferential through-wall cracks were calculated under 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 larger than the outer diameter. The crack is located at the centre of the pipe length. All of the positions 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 is also applied for the pipe, where 8 MPa correspond to hoop stress of 74.9 MPa.

The crack is located in tensile stress side during the bending load. The crack depth and angle are a, and 2θ, where through-wall crack depth is $a = t$.

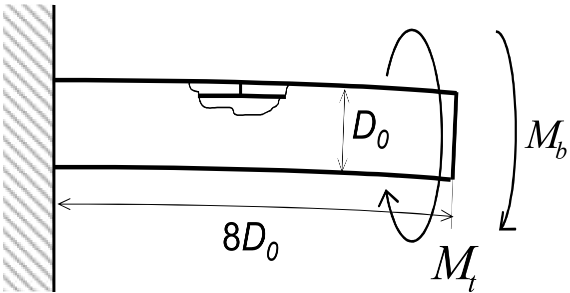

Fig. 1 Model of a cracked pipe receiveing bending moment and torsion moment under internal pressure.

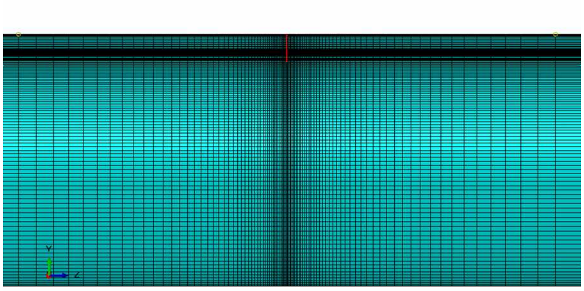

Fig. 2 FE mesh break dwon of a circumferential cracked pipe.

Pure torsion moment under internal pressure of 8 MPa was also calculated for circumferentially cracked pipe. Torsion moment was applied at the end of the pipe end, and the applied moment-torsion angle and the maximum torsion moment were obtained by FE analysis.

Calculation conditions for the FE analysis are tabulated in Table 1. The FE analysis was conducted by ABAQUS standard v.6.7-4. Large deformation formulation is invoked in order to obtain plastic collapse moment accurately under large deformation. The material employed in this paper is elastic-fully plastic stress-strain curve with the yield strength of 372 MPa, which is identified with the flow stress of the material.

Sequence of Loading

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, and finally the bending moment was imposed by incremental rotation of the moment of the remote end, as illustrated in Fig. 1. The applied torsion moment is 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 crack is expected by $M_T = 2\pi R^2 t\, \tau$, where R is the pipe mean radius. The crack is located such that its center coincides with the plane of the maximum tensile stress due bending.

Table 1 Calculation conditions for FE analysis.

Program	ABAQUS 6.7-4
Stress strain curve	Elastic-fully plastic
Geometrical non-linearity	Considered
Yield stress, $\sigma_y = \sigma_f$	372 MPa
Young's modulus, E	200 GPa
Strain hardening, H	0
Internal pressure (Hoop stress)	8 MPa (74.9 MPa)
Crack depth, a/t	0.5, 0.75, 1.0
Crack angle, 2θ	90°, 135°

CALUCULATION RESULTS

Moment-Deflection Curves and Deformations

Calculation results of bending moments M_b and bending angle θ_b for pipes with circumferential cracks under constant torsion stress of τ/σ_f and internal pressure of 8 MPa are calculated by FE analysis. In case of part-through crack of $a/t = 0.75$ and $2\theta = 90^\circ$, the relationship between the M_b and the θ_b is shown in Fig. 3. As shown in Fig. 3, the applied bending moment M_b increases with increasing bending angle θ_b, and attained the maximum bending moment. After the maximum bending moment, the bending moment decreases with increasing the bending angle θ_b. The maximum bending moment corresponds to the plastic moment M_B. The plastic moments M_B decrease with increasing the torsion stresses τ.

The relationship between the applied bending moment and bending angle for through-wall cracked pipe were obtained by FE analysis. Figure 4 shows the load-displacement curves for pipes with circumferential through-wall cracks of $2\theta = 90^{\circ}$. The plastic bending moment M_B decreases with increasing torsion stress τ, as the same behaviour of Fig. 3. In case of through-wall cracks, the values of collapse bending moments M_B are small and the values of bending angles θ_b are large, compared with

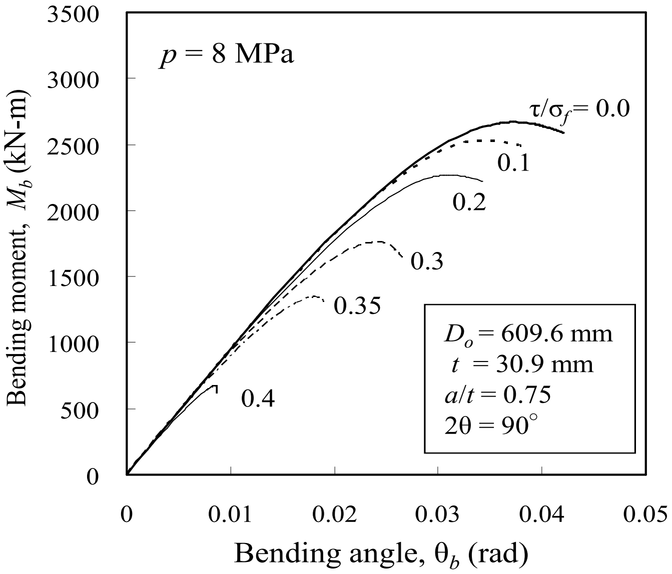

Fig. 3 Load-displacement curves for pipes with part through cracks of $2\theta = 90^{\circ}$.

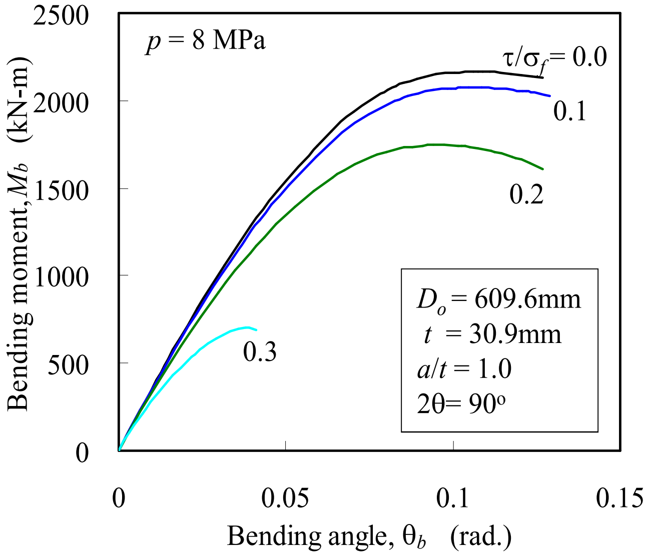

Fig. 4 Load-displacement curves for pipes with through-wall crack of $2\theta = 90^{\circ}$.

those in Fig. 3.

Effect of Torsion on Bending Moment

The plastic collapse bending moment M_B for a circumferentially cracked pipe decreases with increasing torsion stress τ, as shown in Figs. 3 and 4. Figures 5 and 6 depict the relationship between the plastic collapse bending moments M_B and the torsion

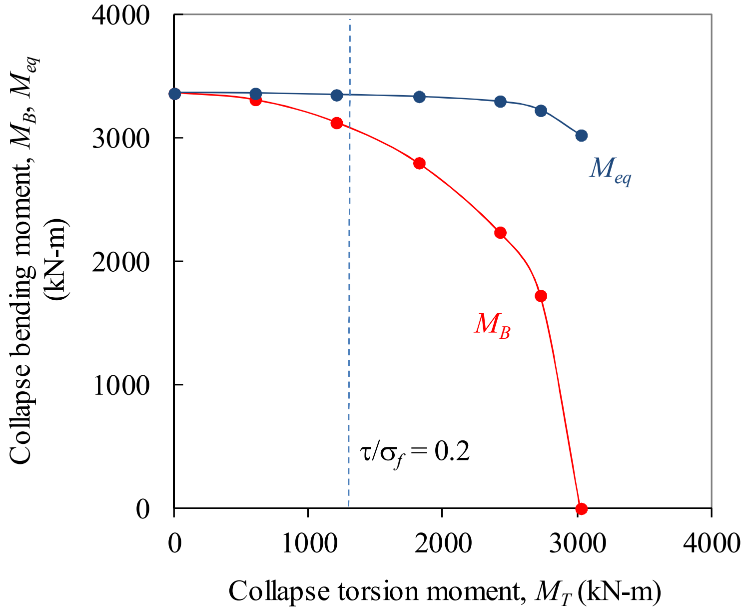

Fig. 5 Plastic collapse bending moment M_B and equivalent moment M_{eq} for pipes with crack of $a/t = 0.5$ and $2\theta = 90^o$.

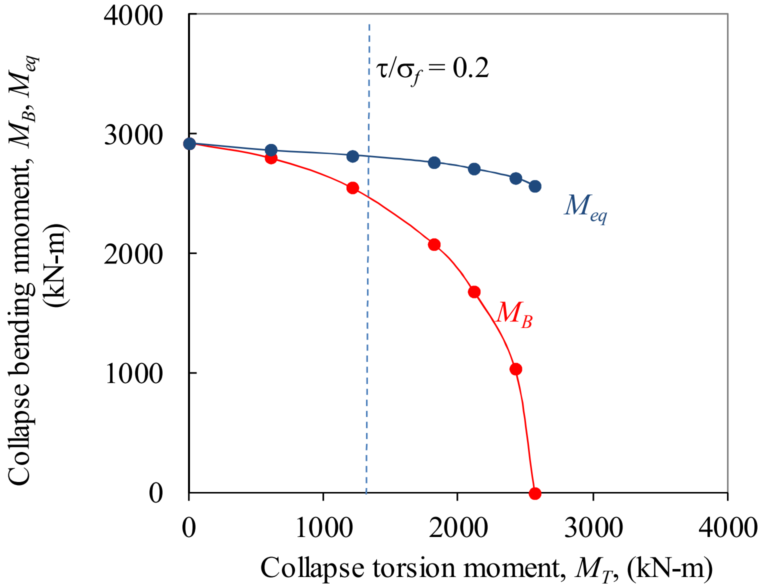

Fig. 6 Plastic collapse bending moment M_B and equivalent moment M_{eq} for pipes with cracks of $a/t = 0.75$ and $2\theta = 90^o$.

moments M_T for pipes with part through cracks of $a/t = 0.5$ and 0.75. Figure 7 shows the relationship between M_B and M_T for pipes with through-wall cracks. When $M_T = 0$, the bending moment is a pure bending moment, that is $M_B = M_{B0}$. When $M_B = 0$, the moment is a pure torsion moment M_{T0}, which was obtained by FE analysis under the conditions of the same material properties and crack sizes.

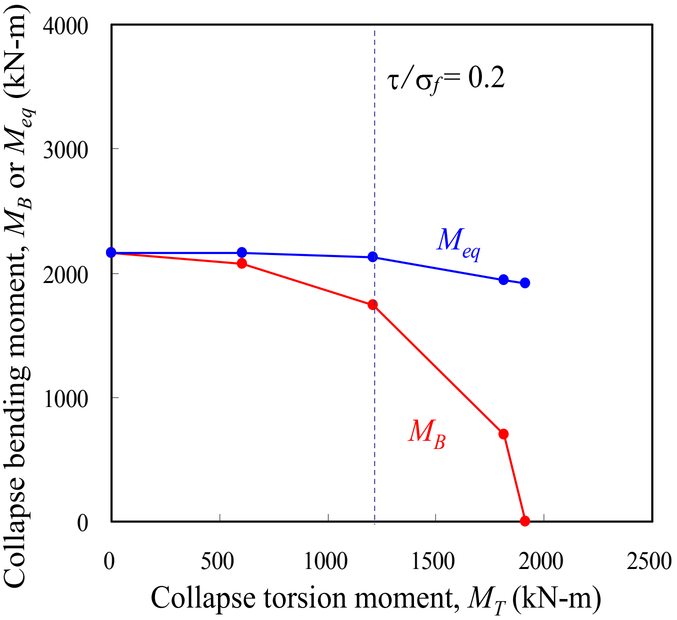

Fig. 7 Plastic collapse bending moment M_B and equivalent moment M_{eq} for pipes with cracks of $a/t = 1.0$ and $2\theta = 90^\circ$.

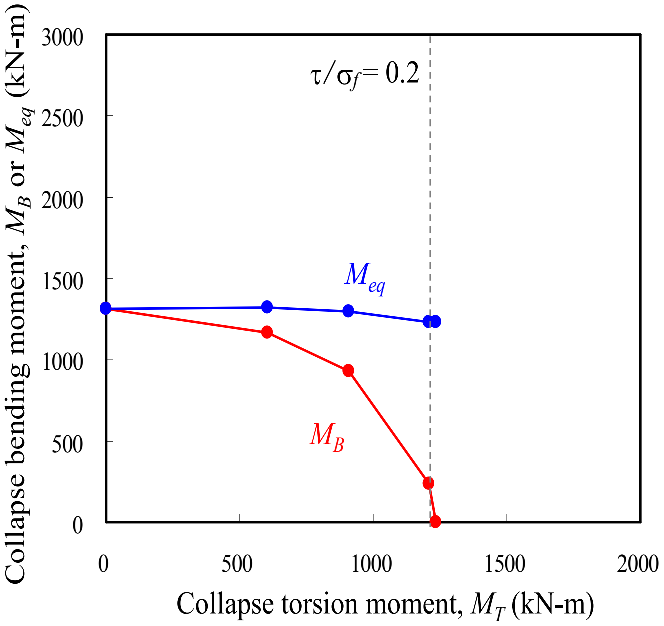

Fig. 8 Plastic collapse bending moment M_B and equivalent moment M_{eq} for pipes with cracks of $a/t = 1.0$ and $2\theta = 135^\circ$.

Pure bending moment M_{B0} at collapse for a cracked pipe can be estimated by limit load criteria provided by ASME Section XI and JSME Codes [1, 2]. In addition, there are lots of experimental data of M_{B0} performed by bending tests. The moments M_{B0} obtained in this calculations are not compared with those obtained by the limit load criteria and experimental data. This is because the calculation herein employed the elastic full- plastic stress strain curve.

Plastic collapse bending moment M_B for pipes with part through cracks of $a/t = 0.5$ and 0.75 decreases with increasing torsion moment M_T, as shown in Figs. 5 and 6. It is also obtained that the M_B for pipes with through-wall cracks of $2\theta = 90^o$ and 135^o decreases with increasing M_T, as shown in Figs. 7 and 8. The decreases of the M_B between the part through and through-wall cracks are resemblance, although the values of the M_B are different.

EQUIVALENT MOMENTS FOR PIPES WITH CRACKS

Equivalent moments M_{eq} given by Eq. 1 are shown in Figs. 5 and 6 for part through cracked pipes with $a/t = 0.5$ and 0.75 and $2\theta = 90^o$. The moments M_{eq} are almost flat, but slightly decrease, when the M_T are small. When M_T is large, the M_{eq} becomes small.

In case of through-wall crack, the M_{eq} were obtained as shown in Figs. 7 and 8, for pipes with $a/t = 1.0$ and $2\theta = 90^o$ and 135^o. The value of the M_{eq} for through-wall cracked pipe is small, compared with those for part through cracked pipes with the same crack angle of $2\theta = 90^o$ as, shown in Figs. 5, 6 and 7. The M_{eq} for the pipes with through-wall crack of $2\theta = 90^o$ and 135^o are almost constant in the entire range of M_T.

The torsion moments in power plants are generally small at many positions in piping systems. Based on plant design stress survey, 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. 5 to 8, as $\tau/\sigma_f = 0.2$.

The M_{eq} for pipes with part through and through-wall cracks retains almost constant with increasing the torsion moment M_T in the range of torsion stress of $\tau/\sigma_f = 0.2$, where the difference of the equivalent moment M_{eq} against pure bending moment M_B is within 10 % of the pure bending moment. That is, the M_{eq} is almost equal to M_{B0}. This means that combined bending and torsion moments at collapse can be estimated by pure bending moment for through-wall cracked pipes, as the same manner with part through cracked pipes.

CONCLUSION

Plastic collapse moments for pipes with through-wall cracks 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, plastic collapse bending moments decrease with increasing torsion moments for through-wall cracked pipes. Equivalent moments are almost constant against the torsion moments in the torsion stresses of actual plant range.

This means that the plastic collapse bending plus torsion moments together with internal pressure can be estimated by the pure bending moment for circumferentially through-wall cracked pipes, as the same with part through cracked pipes.

REFEENCES

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