TITLE:

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CITATION:

SHIBATA, Toshinobu ...[et al]. A Study on the Failure of Partially Thinned Pipes under External Pressure. Memoirs of the Faculty of Engineering, Kyoto University 1979, 41(2): 187-196

ISSUE DATE:

1979-06-30

URL:

http://hdl.handle.net/2433/281102

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A Study on the Failure of Partially Thinned Pipes under External Pressure

By

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(Received December 28, 1978)

Abstract

It is very important to prevent a buckling of thin pipes, such as are in the heat-exchanger system of PWR (pressurized water reactor), which occurs by external pressure. The design code in ASME Sec. III NB considers this point. However, the thickness of the pipe is partially thinned down by the steam-liquid flow in service. In the design step, no consideration has been paid to such a partially thinned down pipe, though much attention should be given to this matter.

In this paper, we discuss the pressure at the failure of the partially thinned pipe under external pressure. Experimental results show that the failure occurs at an unexpectedly small pressure, if the thinned part has some expansion, such as area. Also, the pressure at the failure does not follow the buckling equation given by the elasticity for a thin cylinder.

1. Introduction

In the design of a pipe line system, the internal pressure is an important design factor, but, generally, it is not required to consider the buckling or failure by external pressure. However, in the case of the heat-exchanger, for example, used in the pressurized water reactor (PWR), the pipe lines are loaded with an internal pressure 150 kg/cm^2, and an external pressure 75 kg/cm^2. It is a very important requirement to design the prevention of any buckling or failure by external pressure, if we assume a reactor's accident.

Especially in the steam pipe line of the heat exchanger stated above, it is reported that there have occurred many thinning phenomena (which occurred at the external circumferential surface of pipes), but there has been no report on how strong these partially thinned pipes are for the external pressure.

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In this study, an external pressure test was made on partially thinned pipes and a discussion was made.

2. Test Procedure

2 1 The tested material

The material used for the experiment was a cylindrical pipe specified SGP in JIS G 3425 (whose contents are: P is less than 0.05%, S is less than 0.05%, and C is less than 0.2%). Most of the experiments were done on an as-rolled pipe, but some of the specimens were annealed in a vacuum to be compared with the as-rolled pipe. The conditions of the in-vaccuum-annealing and the mehanical properties of the materials are shown in Table 1, where the mechanical properties were made on No. 11 type specimen specified in JIS Z 2201. The values in the Table are the mean values of three specimens.

2.2 Specimen

After the pipes were machine lathed to an internal diameter 22 mm and an external diameter 26 mm, they were thinned by use of an end-mill as shown in Fig. 1. The partially thinned pipe has three parameters as shown in the figure, *i.e.*, the angle θ, the length L and the thickness t.

The specimen was machined by use of the peripheral cutting edge of the end mill having a diameter 10 mm, and in the circumferential direction, the specimen was rotated by 5° or 10° with the index-head fixed on the table of the milling machine.

Both longitudinal ends of the pipe are soldered with the aluminum plating. Though at high pressure there occurred a depressed deformation on the aluminum plate, there was no leakage or failure at the soldering part.

2.3 The apparatus of loading pressure

For this research a pressure vessel was made, whose design strength is 200 kg/cm² and whose capacity is 6000 cc. The specimen is put into the vessel, and the pressure is

Table 1. Mechanical properties of the specimen.*

Heat treatment	Upper yield point (kg/mm²)	Lower yield point (kg/mm²)	Tensile strength (kg/mm²)	Elongation (%)
As rolled	25.8	—	37.1	40.5
700°C 30 min, Annealing	23.0	21.3	33.0	51.6
900°C 60 min. Annealing	20.1	19.4	31.3	50.0

* JISZ 2201 Type 11 was tested.
* Values show the mean of three specimens respectively.

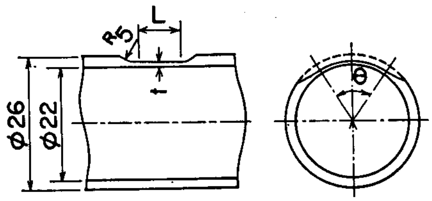


Fig. 1. Test specimen.

loaded by a hand operating pump. The pressure is measured by use of the strain gauge type pressure transducer and is recorded on an X-Y recorder.

When a buckling or an unstable deformation occurs in the specimen pipe in the vessel, the pressure is examined by two methods: one is an audio sound which occurs at the unstable deformation of the test pipe, and the other is the pressure decrease on the recording paper, which is caused by the volume change of the specimen due to the buckling or unstable deformation.

3. Test Results and Discussions

3.1 The buckling equation of thin cylindrical pipe

The external pressure at the buckling of a thin cylindrical pipe or cylindrical vessel is given by[1)~3)]

$$P_{cr}=\frac{E}{4(1-\nu^2)}\left(\frac{t}{r}\right)^3 \tag{1}$$

where E: Young's modulus

ν: Poisson's ratio

t: thickness of pipe or vessel

r: radius of pipe

which is solved by a plane stress problem as a solution of an infinitely long ring. In this equation, the effect of the length of the pipe is not considered. The buckling pressure, when the external pressure acts on radial and longitudinal directions, is given by Von Mises[4)] as following,

$$P_{cr}=\frac{Et}{r}\cdot\frac{1}{n^2+(\pi r/L)^2/2}\cdot\left\{\frac{1}{[n^2(L/\pi r)^2+1]^2}+\frac{t^2[n^2+(\pi r/L)^2]^2}{12r^2(1-\nu^2)}\right\} \tag{2}$$

where n: is the buckling order number

L: is the length of pipe.

When the length L is infinitive, the critical pressure P_{cr} is proportional to $(t/r)^3$, but is not equal to Eq. (1), because in Eq. (1) the longitudinal pressure is not considered.

3.2 The buckling equation of a partially thinned pipe

Both Eqs. (1) and (2) do not represent the critical pressure for the partially thinned pipe. In this section we will try to find such an equation with the help of experimental data. The factors causing the buckling or the unstable deformation are considered to be the dimension of the partially thinned part (*i.e.*, the length L, the angle θ, and the thickness t), the pipe diameter $2r$, and the properties of material (E, ν, and σ_y). However, in this research a uni-dimensional pipe is used, so E, ν, r, and σ_y can be neglected in the discussion.

Considering a pipe with only a small thinned part, under the assumption that the shear stress of the material has charge of all the external pressure, the critical pressure is presumed in relation to the angle θ as following,

$$P_c \propto A + 1/\theta. \tag{3}$$

Though the constant A is a function of the length L and thickness t, it is assumed for simplicity that A is a first order function of only t. And, the pipe is fractured at even $\theta=0$, as the thinned part exists. Therefore, we replace $\theta+\theta_0$ instead of θ, and so Eq. (3) becomes

$$P_c \propto At + 1/(\theta+\theta_0). \tag{3'}$$

In the same way, and by the analogy from Eq. (2), the critical pressure can be written in relation to the length L as following,

$$P_c \propto Bt + 1/(L+L_0)^2. \tag{4}$$

From these discussions, the buckling pressure Pc of a partially thinned pipe is represented as a function of L, θ, and t by

$$P_c = P_0 t^{\alpha} \{1/(\theta+\theta_0) + At\} \{1/(L+L_0)^2 + Bt\} \tag{5}$$

The constant θ_0 and L_0 are determined by expanding the partially thinned area from the thickness t to $1.1t$, *i.e.*,

$$\theta_0 = 5° \text{ and } L_0 = 6\text{ mm}.$$

These values were proven to be reasonable by the observation of the deformed specimen. The constants A and B are independently obtained by use of the least square method; that is, in order to obtain A, the data where t and L are constant, and to obtain B, t and θ are constant. Using all the tested data, the constants P_0 and α are obtained by use of the least square method. The result is shown by

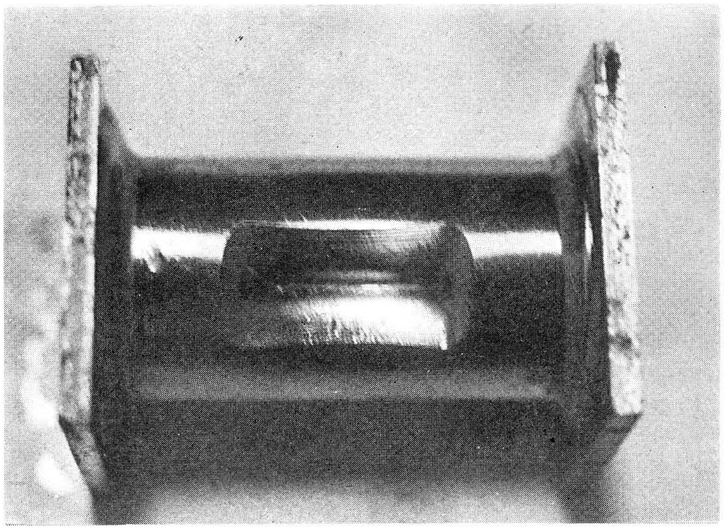
$$P_c = 3.89 \times 10^4 \times t^{-0221} \left\{ \frac{1}{\theta+5} + 0.672\, t \right\} \left\{ \frac{1}{(L+6)^2} + 0.0157\, t \right\} \tag{6}$$

where P_c: buckling pressure in kg/cm²
t: thickness of thinned part in mm
L: length of thinned part in mm
and θ: angle of thinned part in degree.

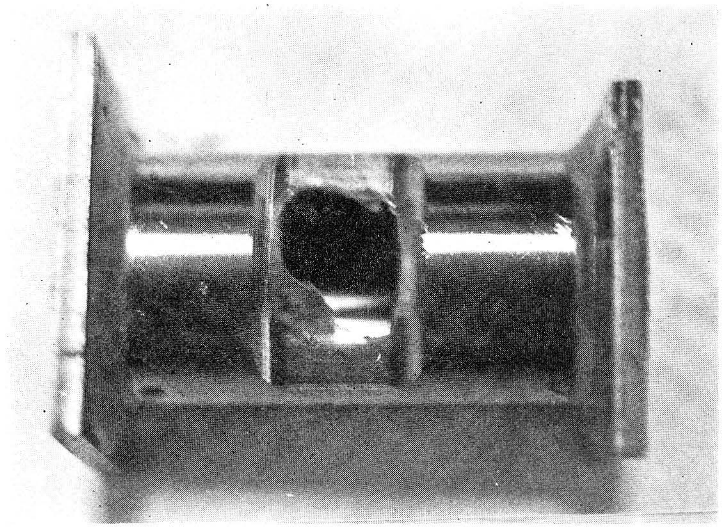
The value $\alpha=1$ is estimated from equations (1) and (2), but the calculated value is $\alpha=-0.221$, which is not so different from the presumed value by experiments.

3.3 Experimental results.

Photo 1 shows two examples of pipes deformed by external pressure. The dimensions and pressures at buckling are shown in the photo. By increasing the external pressure, the specimen is unstably deformed by buckling and then fractures (*i.e.*, a small



(a) $L=20$ mm $\theta=10°$ $t=0.52$ mm $P_e=130$ kg/cm^2



(b) L=10 mm $\theta=70°$ $t=0.17$ mm $P_e=33$ kg/cm^2

Photo 1. Examples of pipe failured by external pressure.

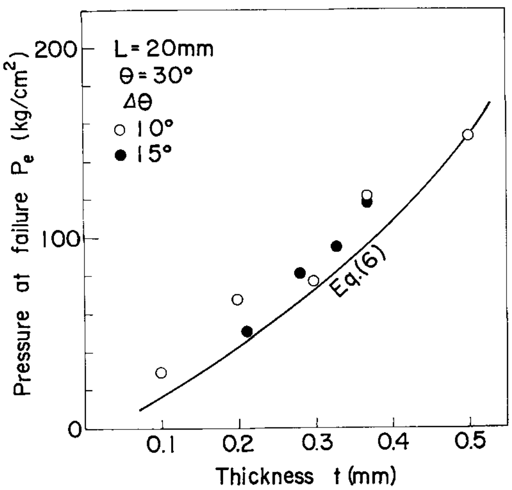


Fig. 2. The effffect of the angle of index-head part on the results.

pin hole is made, or a shearing fracture occurs at the thinned part). The unstable deformation and the opening of a small pin hole occurred at pressure 130 kg/cm² on the specimen shown in Photo 1(a). On the specimen shown in Photo 1(b), at pressure 33 kg/cm² the deformation occurred, but the shearing fracture occurred within the range of 33 to 45 kg/cm². It is difficult generally to specify the pressure when the shearing fracture occurred or when the small pin hole was made. Therefore, hereafter, we will only the pressure when buckling occurs in the specimen or when there is unstable deformation.

Fig. 2 shows the effect of the rotation angle of the index-head on the buckling pressure. The solid line in the figure is the value calculated from Eq. (6). As we can say

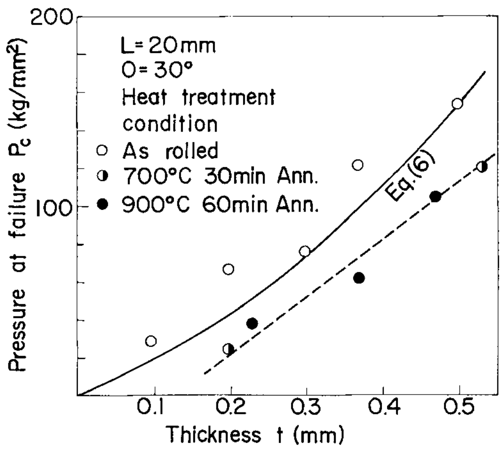


Fig. 3. The effect of the heat treatment on the result.

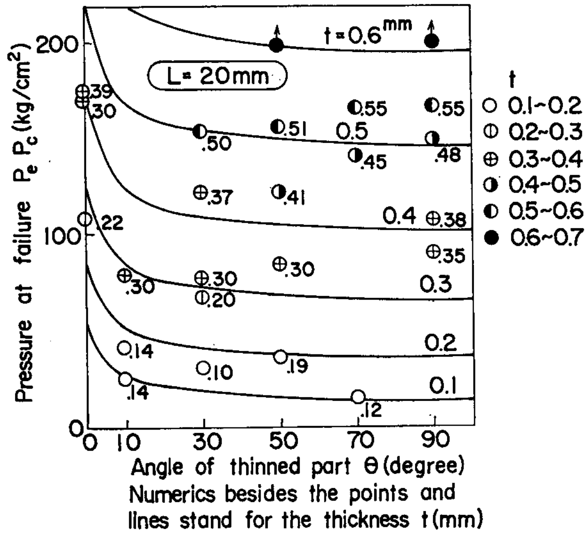


Fig. 4. The effect of the angle thinned part on the result.

that there is no effect of the rotation angle of the index-head on the result, we will discuss the result obtained on the specimen with the rotation angle $\Delta\theta=10°$ of the index-head in the following section of this paper.

In Fig. 3, the effect of the heat treatment on the results is shown. The buckling pressure is fairly lessened by the annealing, and this is considered to be caused by increasing the ductility of the materials as shown in Table 1. As the material in service is used in a rolled state, we discuss only the results on the as-rolled-material.

3.4 The comparison of the experimental results with Eq. (6)

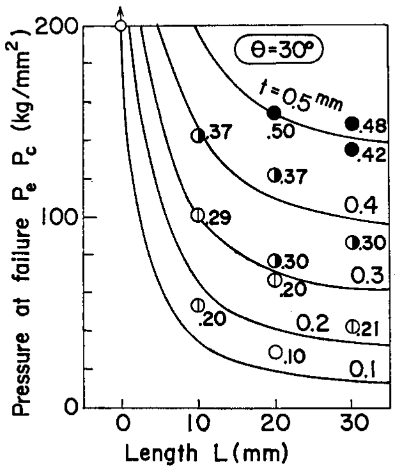


Fig. 5. The effect of the length of the thinned part on the result.

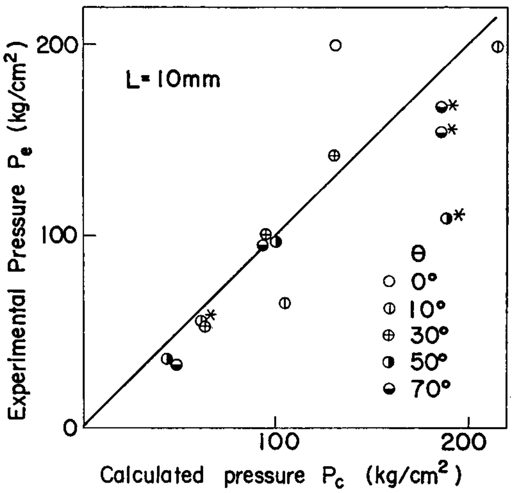


Fig. 6. Comparison of experimented results with calculated ones.

The test results, compared with Eq. (6) obtained in section 3.2, are shown in Figs. 4~8. The experimental conditions are written in the figures. In Figs. 4, 5, and 8, the solid lines stand for the values obtained from Eq. (6). If the scatter of the experimental data are taken into consideration, Equation (6) represents the test results very well.

3.5 Comparison of Eq. (6) with Miki's experimental results

Miki has reported[5] the strength of the internally and the externally pressurized heat-exchanger pipe made of Inconel 600. The specimen form used in his experiment

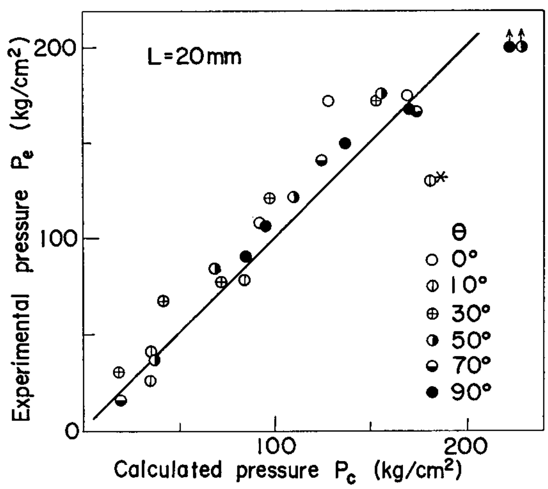


Fig. 7. Comparison P_e with P_c. (l=20 mm)

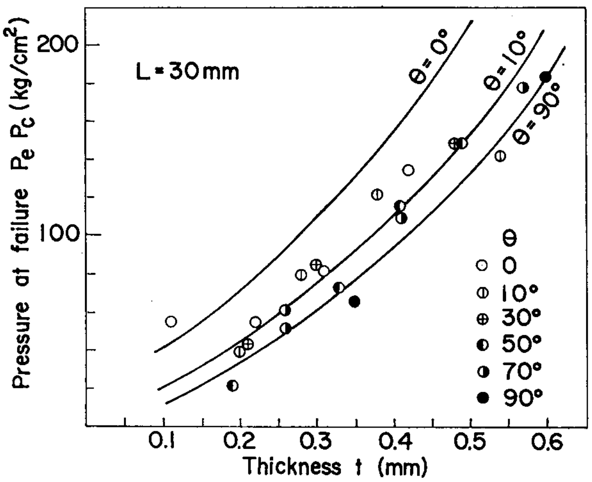


Fig. 8. Effect of thickness at thinned part on the result.

is shown in Fig. 9. We redraw his results, especially the results by the external pressure, in Fig. 10. Miki stated that partially thinned pipes are fractured at over 200 kg/cm². However, his experimental conditions are limited to $\theta=0°$ and $t=0$ mm as shown in Fig. 9, so that his conclusion can not be said to be right. As shown in Figs. 4~8, if the partially thinned part expands from $\theta=0°$, and $t=0$ mm to a certain finite value of

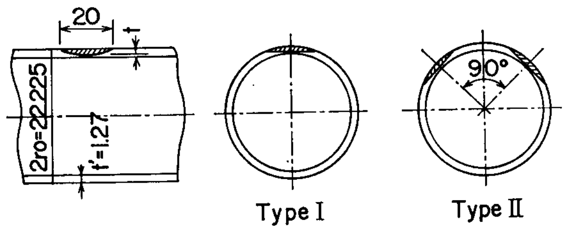


Fig. 9. Test specimen in Miki's experiment[5] (shadowed parts were thinned out).

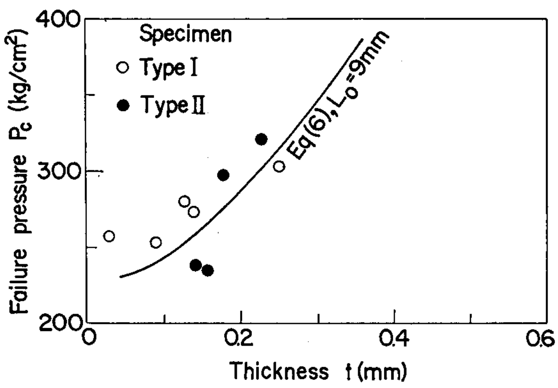


Fig. 10. Miki's experimental result.

θ and t (not equal to 0), the external pressure when such partially thinned pipes fracture decreases to a lower value than 200 kg/cm^2.

Miki's values are smaller than those calculated by Eq. (6), which is, we consider, caused by the differences of the thickness of the original pipe, and the radius of curvature at the shoulder of the thinned part, *i.e.,* Miki's specimen is more deformable than ours. The solid line in Fig. 10 is drawn using L_0=9 mm instead of L_0=6 mm in Eq. (6), and it is found that the equation obtained from our test results can be applied very well to his results.

4. Conclusion

In order to obtain the deformability of a partially thinned pipe by external pressure, we made a series of experiments using the length of the thinned part L, the angle θ, and the thickness t as parameters. The following conclusions were obtained.

(1) The elastic equation of the buckling for the thin cylindrical pipe cannot be applied to a partially thinned pipe.

(2) We induced an equation to give the pressure for the partially thinned pipe, which showed good coincidence with the test results. The critical pressure for the thin cylindrical pipe is in proportion to t^3 by elasticity, but by our experimental results, the critical pressure for the partially thinned pipe is proportional to $t^{1.78}$.

(3) If the thinned part has some expansion, the pipe will easily have unstable deformation by a very small external pressure. Therefore, much precaution should be given to the pipe-management.

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