The Effect of Pressure Fluid on Bursting of Brittle Materials*

The Second Report ; Bursting of Graphite and Cast Iron

Cylinders under Lateral Fluid Pressure

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In this paper lateral fluid pressure and combined loads of lateral fluid pressure and tension are applied on coated and naked graphite cylinders, and naked cast iron cylinder to study the size effect and the effect of pressure fluid on the bursting of brittle materials, and the following conclusions are obtained ;

(1) On coated and naked graphite cylinders there is no size effect under lateral fluid pressure.

(2) On naked cast iron cylinder there is size effect, and its bursting strength is different depending the kinds of pressure fluids under lateral fluid pressure.

(3) Under combined loads of lateral fluid pressure and tension the bursting strengths of naked cast iron cylinders are different depending on the kinds of pressure fluids as in the case of lateral fluid pressure.

Key Words : Fracture, Lateral Fluid Pressure, Graphite, Cast Iron, Pressure Fluid, Penetration, Experimental Study

1. Introduction

As to the effect of pressure fluid on the bursting of brittle materials, the experimental results on the bursting of cast iron cylinders under internal pressure are already reported in the First Report⁽¹⁾, and it is clear that the leakage pressure of a cylinder which means a pressure at which pressure fluid begins to permeate the outer surface of the cylinder, and the bursting pressures remarkably differ depending on the kinds of pressure fluids and coating or no coating of the inner surface of the cylinder, and that the leakage pressure of the cylinder increases in order of water, turbine oil (#32) and castor oil.

In this paper, to ascertain the effect of pressure fluid on the bursting of brittle materials under internal pressure explained in the First Report, the experimental results are described on cylinders made of cast iron solid bar and electrode bar (graphite bar) under lateral fluid pressure, and the pressure fluids used in this experiment are water, turbine oil (#32) and castor oil. And from these data we study at first the difference of the bursting pressures between coated and

naked graphite cylinders, and the size effect in the bursting under lateral fluid pressure of graphite cylinder, and next we study the size effect in the bursting under lateral fluid pressure of naked cast iron cylinder and the influence of pressure fluid on the bursting of cast iron cylinder. Moreover, we study the bursting of cast iron cylinder under combined loads of lateral fluid pressure and tension to examine the influence of pressure fluid on the bursting in naked cylinder, and also the bursting under stress concentration of cast iron cylinder having a transverse hole of various lengths in the radial direction of the cylinder.

2. Experimental Method

Fig. 1 shows the experimental apparatus for lateral fluid pressure test; in this figure (V) is the pressure vessel, (T) is the test cylinder, the pressure

Fig. 1 Experimental apparatus for lateral fluid pressure test

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Fig. 2 Cast iron solid cylinder for lateral fluid pressure test

fluid is applied with a hand-pump from the outer surface of the pressure vessel and the leakage of the pressure fluid from the clearance between the test cylinder and the pressure vessel is prevented by two "O" rings as shown in the figure. And "l" in Fig. 1 is the interval of two "O" rings, and lateral fluid pressure acts on the outer surface of the cylinder between these "O" rings.

In this lateral fluid pressure test, when the outer surface of the cylinder is coated by a suitable method, pressure fluid does not permeate into the materials, so the stress condition of the cylinder is a biaxial uniform compression. On the other hand, when its outer surface is not coated, pressure fluid permeates into the materials, and the component in the axial direction of lateral fluid pressure acts on the cylinder as a tensile load.

In this paper, two kinds of test cylinders are used for the test under combined loads of lateral fluid pressure and tension; one is a test cylinder illustrated in Fig. 1, and in this case the test cylinder has two chucking parts (C) as shown in the figure, and these chucking parts are fitted to the apparatus for tension test. The other is a test cylinder in Fig. 2. In this cylinder, the "O" ring is set on the outer surface of the cylinder such that its diameter is "d", and a tensile stress σ_p as shown in Eq. (1) is induced in the part of the cylinder with its diameter "d₀", by lateral fluid pressure acting on the cylinder.

$$\sigma_p = \frac{d^2 - d_0^2}{d_0^2} p = \left(\left(\frac{d}{d_0} \right)^2 - 1 \right) p \quad (1)$$

The pressure fluids used in this experiment are water, turbine oil (#32) and castor oil, and in this experiment lateral fluid pressure of the cylinder is increased gradually, and the leakage pressure and the bursting pressure are measured.

3. Experiment (1)

In Experiment (1) all the solid cylinders are made of graphite bar, and the size effect of graphite solid cylinder is studied under lateral fluid pressure, the experiments being carried out on a cylinder with its outer surface coated and on a naked one; and the pressure fluid used in this experiment is turbine oil (#32).

Fig. 3 Cutting scheme of test cylinder

3.1 Materials for experiment

Graphite used in this experiment is a solid electrode bar of graphitizing material formed by extruding, and its dimensions are 86 mm in outer diameter and 1 m in length. At first, to check the anisotropy of this material internal pressure, compression and lateral fluid pressure tests are carried out on hollow and solid cylinders machined from the axial, the tangential and the radial directions of a graphite solid bar as shown in Fig. 3. Tables 1, 2 and 3 show the mean values of these experiments, there was no anisotropy in the tensile strength σ_b obtained from the bursting pressure of internal pressure test shown in Table 1 and in the compressive strength σ_c shown in Table 2, but there was anisotropy in the bursting pressure p_b obtained from lateral fluid pressure test shown in Table 3. So the solid cylinders for lateral fluid pressure test used thereafter in this study were machined from the axial directions of graphite solid bars.

3.2 Pressure ~ strain diagram

To obtain the pressure ~ strain relation of graphite under lateral fluid pressure, lateral fluid pressure test was carried out on three kinds of naked cylinders with diameters 20, 28 and 45 mm. Fig. 4 shows the pressure-strain relations of graphite cylinders, lateral fluid pressure p and tensile strain ϵ_a of graphite being taken on ordinate and abscissa respectively, and tensile strain in this case was calculated from the

Table 1 Internal pressure test (Graphite)

Materials	σ_b	MPa
Axial Direction	7.4	7.7
Tangential Direction	8.2	
Radial Direction	7.6	

Table 2 Compression test (Graphite)

Materials	σ_c	MPa
Axial Direction	47.5	47.7
Tangential Direction	47.8	
Radial Direction	47.9	

Table 3 Lateral fluid pressure test (Graphite)

Materials	p_b MPa
Axial Direction	17.0
Tangential Direction	10.1
Radial Direction	10.1

Fig. 4 Pressure ~ strain relations under lateral fluid pressure
(Naked graphite solid cylinder)

difference in the readings of two dial gages which were set at the both ends of the test cylinder. The pressure ~ strain relations of each cylinder coincide very well up to the bursting point of the cylinder, b ; the tensile strain up to the bursting point of this graphite is about 0.2 % ; and this value also coincides with that under tension for the same material.

3.3 Experimental result on naked cylinder

Fig. 5(a) shows a naked solid cylinder for lateral fluid pressure test, (T) is graphite cylinder, (A) is aluminium solid cylinder, and such aluminium solid cylinders are attached with a nitrocellulose adhesive to both ends of graphite cylinder to prevent the leakage of pressure fluid. The percentage of voids of graphite is about 30 %, and pressure fluid flows out from both ends of the cylinder through these voids ; therefore if we do not attach these aluminium solid cylinders to graphite cylinder, the pressure will not increase. And the leakage of pressure

(a) Naked cylinder

(b) Coated cylinder

Fig. 5 Graphite solid cylinder

Table 4 Lateral fluid pressure test (1)
(Naked graphite cylinder)

NO	d _o mm	P _b MPa		P _b MPa
1	5	17.8	15.7	17.4
2	8	17.1	16.6	16.7
3	12	17.2	18.5	18.0
4	20	15.5	17.3	16.5
5	28	16.0	16.3	15.3
6	45	16.3	16.2	17.2
7	60	15.8	15.0	15.3

fluid from the clearance between the pressure vessel and the test cylinder shown in Fig. 1 is prevented by two "O" rings fitted to aluminium cylinders shown in Fig. 5(a).

Table 4 gives the experimental result of naked graphite solid cylinder in lateral fluid pressure test, and the outer diameters of test cylinders were changed variously as shown in the table. The mean values of the bursting pressures of the cylinders, $\bar{P}_b$, were almost equal, and there was no size effect recognized in this experiment.

Fig. 6(a) shows a burst naked cylinder, and the bursting of the cylinder occurred on a cross section perpendicular to the axial direction of the cylinder.

3.4 Experimental result on coated cylinder

Fig. 5(b) shows a solid cylinder with its outer surface coated. (T) is graphite cylinder, (A) is aluminium cylinder, and the coating of the cylinder was carried out with a nitrocellulose adhesive, and two "O" rings to prevent the leakage of pressure fluid were setting on the coated parts.

Table 5 gives the experimental result of coated graphite solid cylinder, the mean values of the bursting pressures of cylinders, $\bar{P}_b$, were almost equal and there was no size effect recognized in this case just as in naked cylinder.

Fig. 6(b) shows a burst coated graphite solid cylinder.

4. Experiment (2)

In this experiment bursting tests of

d_o = 20.04 mm, p_b = 16.5 MPa

(a) Naked cylinder

d_o = 20.02 mm, p_b = 48.0 MPa

(b) Coated cylinder

Fig. 6 Bursting of graphite solid cylinder

Table 5 Lateral fluid pressure test (2)
(Coated graphite cylinder)

NO	d_0 mm	P_b MPa				P_b MPa
1	5	47.1	49.0	48.0	48.5	48.2
2	8	48.0	47.1	48.5	48.5	48.0
3	12	48.0	48.5	46.6	47.5	47.7
4	20	45.6	48.5	46.1	48.0	47.1
5	28	46.1	46.6	46.6	46.1	46.4
6	45	49.0	45.1	50.0	-	48.0
7	60	48.0	50.0	51.0	-	49.7

solid cylinders machined from a cast iron solid bar of FC 10 were carried out, and the size effect of cylinders was studied. The experiment was carried out on naked cylinder, and the pressure fluid used in this experiment was turbine oil (#32).

4.1 Materials for experiment

Cast iron solid bars used in this experiment were ten bars of the same casting and the dimensions of a bar were 110 mm in outer diameter and 1 m in length.

To check the anisotropy of this material lateral fluid pressure test was carried out on naked cylinder by the same method as used for graphite, there was no size effect, and the mean value of the bursting pressure was $p_b = 159$ MPa. Therefore, all the test cylinders used in this experiment were machined from the axial direction of cast iron solid bar.

In Experiment (2) the bursting test was also carried out on naked cylinder having a transverse hole in the radial direction. We analyze at first the experimental results on naked solid cylinder having no transverse hole.

4.2 Experimental result of cylinder having no transverse hole

Fig. 7(a) shows a cast iron solid cylinder having no transverse hole, and the outer diameters of the test cylinders were changed variously from 5 mm to 53 mm as shown in Fig. 8. Fig. 8 shows the relation between the bursting pressure p_b and the outer diameter d_0 of the cylinder. The bursting pressures of the cylinders

Fig. 7 Cast iron solid cylinder

Fig. 8 Lateral fluid pressure test (1)
(Cast iron solid cylinder)
(having no transverse hole)

were constant in the range of the outer diameters of the cylinders more than 20 mm, and there was no size effect. But, in the range of the outer diameters of the cylinders less than 20 mm, the bursting pressures of the cylinders fell as the outer diameter of the cylinder decreased, and size effect was recognized.

Fig. 9(a) shows a burst cast iron cylinder having no transverse hole under lateral fluid pressure.

4.3 Experimental result of cylinder having a transverse hole

Fig. 7(b) shows a cylinder having a transverse hole in the radial direction, the diameters of the transverse holes, $2a$, being 1 mm and 2 mm, and the lengths of the transverse holes, C , being changed variously in the range of $C = 0 \sim 20$ mm as shown in Fig. 10.

Fig. 10 shows the $p_b \sim C/d_0$ relation, where C/d_0 is the ratio of the length of the transverse hole to the outer diameter of the cylinder, and in the range of C/d_0 less than 0.5 the bursting pressures of the cylinders fall as the length of the transverse hole increases, but the bursting pressures of the cylinders are almost constant in the range of C/d_0 more than 0.5.

Fig. 9(b) shows a burst cast iron cylinder having a transverse hole.

$d_0 = 20.03$ mm, $p_b = 173$ MPa

(a) Cylinder having no transverse hole

$d_0 = 20.02$ mm, $2a = 2$ mm, $C = 10$ mm,

$p_b = 113$ MPa

(b) Cylinder having a transverse hole

Fig. 9 Bursting of cast iron cylinder (1)
(FC 10)

Fig. 10 Lateral fluid pressure test (2)
(Cast iron solid cylinder)
having a transverse hole)

5. Experiment (3)

In Experiments (1) and (2) the bursting tests under lateral fluid pressure were carried out on solid cylinders made of cast iron and graphite by using turbine oil, and we studied the size effect of the cylinder.

In Experiment (3) bursting tests of cast iron solid cylinders were carried out under lateral fluid pressure by using water, turbine oil (#32) and castor oil as pressure fluid, and the size effect of the cylinder was investigated under these pressure fluids, and also the influence of pressure fluid on the bursting of cast iron cylinder was studied. Moreover, the bursting test of cast iron cylinder under the combined loads of lateral fluid pressure and tension was carried out.

5.1 Materials for experiment

The materials used in this experiment were cast iron solid bars of FC 10 and FC 20, and the dimensions of cast iron bars were 75 mm in outer diameter and 540 mm in length. On these materials lateral fluid pressure tests were carried out to check the anisotropy of material by using the solid cylinder machined from three directions of a solid bar as shown in Fig. 3 as in Experiment (2). Tables 6, 7 and 8 give the chemical compositions, the tensile strength σ_b and the compressive strength σ_c of this material.

5.2 Lateral fluid pressure test

In this experiment the size effect and the influence of pressure fluid on the bursting of cast iron cylinders were studied by using solid cylinders with outer diameters changed from 4 mm to 50 mm, and water, turbine oil and castor oil as pressure fluid.

Fig. 11 shows the $p_b \sim d_0$ relations of cylinders. Even in every pressure fluid, in the range of small outer diameters of the cylinders, the bursting pressures fall as the outer diameter decreases. But, in the range of the outer diameters larger than 20 ~ 30 mm the bursting pressures are

Table 6 Chemical compositions of cast iron
(Weight percent)

Materials	T.C.	Si	Mn	P	S
FC 10	3.42	2.06	0.48	0.187	0.066
FC 20	3.35	1.87	0.41	0.049	0.052

Table 7 Tensile strength of cast iron

Materials	d_0 mm	σ_b MPa	$\bar{\sigma}_b$ MPa
FC 10	14	99	103
FC 20	14	192	188

Table 8 Compressive strength of cast iron

Materials	d_0 mm	σ_c MPa	$\bar{\sigma}_c$ MPa
FC 10	15	409	425
FC 20	15	679	660

constant, and there is no size effect. The bursting pressures of the cylinders are greater in order of water, turbine oil and castor oil, and a remarkable effect of pressure fluid is recognized in the bursting pressures of the cylinders.

Fig. 12 shows burst cast iron cylinder under lateral fluid pressure; when pressure fluid is castor oil, a few cracks occur in the tangential direction of the cylinder except on the final fracture surface.

5.3 Experiment under combined loads of lateral fluid pressure and tension

In this experiment the effect of pressure fluid on the bursting pressure of the cylinder was studied under the combined loads of lateral fluid pressure and tension. The cylinder used in this experiment was a naked cast iron solid cylinder of the outer diameter $d_0 = 25$ mm, it was made of FC 20 and the pressure fluids were water, turbine oil and castor oil. In these experiments three types of cylinders were used, i. e., types A, B and C. A cylinder of type A is the same cylinder as used in Experiments (1) and

Fig. 11 Effect of pressure fluid on
bursting of cast iron cylinder(1)
(Lateral fluid pressure)

(2). One of type B is a cylinder shown in Fig. 2, in this cylinder d is larger than d_0 as shown in the figure; if lateral fluid pressure acts on the cylinder, the stress condition of the parallel part becomes a combined stresses of lateral fluid pressure and tension, and the tensile stress σ_p in this case can be expressed by Eq. (1). And one of type C is a cylinder having two chucking parts (C) shown in Fig. 1; when the parts (C) are attached to the testing machine, in addition to lateral fluid pressure an axial stress σ_w will be induced in the parallel part of the cylinder.

Fig. 13 shows the relation between axial stress σ_a acting on the parallel part and lateral fluid pressure p_b at the bursting point of the cylinder under combined loads, the experimental values of types A, B and C being indicated by the marks of $\circ$, $\odot$ and $\bullet$ (Type A), the marks $\ominus$, $\ominus$ and $\bullet$ (Type B), and the marks $\odot$ and $\bullet$ (Type C). The $p_b \sim \sigma_a$ relations of the cylinders rise in order of water, turbine oil and castor oil as in the experimental result under lateral fluid pressure shown in Fig. 11. These experiments made clearer the effect of pressure fluid on the bursting of cast iron cylinder. And the bursting of the cylinder under these combined loads occurs on a cross section of the cylinder that is almost perpendicular to the axial

 $d_0 = 10.07 \text{ mm}, p_b = 123 \text{ MPa}$

 $d_0 = 49.98 \text{ mm}, p_b = 142 \text{ MPa}$
 (a) Water

 $d_0 = 10.10 \text{ mm}, p_b = 206 \text{ MPa}$

 $d_0 = 49.97 \text{ mm}, p_b = 216 \text{ MPa}$
 (b) Turbine oil (#32)

 $d_0 = 10.10 \text{ mm}, p_b = 243 \text{ MPa}$

 $d_0 = 49.97 \text{ mm}, p_b = 284 \text{ MPa}$
 (c) Castor oil

Fig. 12 Bursting of cast iron cylinder(2)
 (FC 10)

direction of the cylinder just as the bursting under only lateral fluid pressure shown in Fig. 12.

6. Considerations on experimental results

Explanations on the bursting of the cylinders made of graphite and cast iron under lateral fluid pressure have been made, and now discuss on these experimental results by comparing them with those of the bursting of cast iron cylinders under internal pressure in the First Report.

6.1 Experiment (1)

At first, we discuss the anisotropy of graphite used in this experiment. To check the anisotropy of this graphite, internal pressure test, compression test and lateral fluid pressure test were carried out on this material, and the anisotropy of graphite was recognized only in lateral fluid pressure test. The voids of graphite used in this experiment, as already explained, were about 30%; in lateral fluid pressure test of naked cylinder, pressure fluid permeated into these voids; the component of the axial direction of pressure oil acts on graphite cylinder as a tensile load. By this tensile load, the cylinder burst on a cross section that is perpendicular to the axial direction of the cylinder. Thus if there is anisotropy in graphite, and the cylinders machined from the axial, the tangential and the radial directions burst on cross sections that are perpendicular to the axial direction of the cylinder, the anisotropy will appear in lateral fluid pressure test. On the contrary, in internal pressure and compression tests the cylinders do not burst on a cross section that is perpendicular to a specific direction as in lateral fluid pressure test, so it is considered that the bursting stresses in these tests are constant as if there were no anisotropy. From these considerations it seems that

Fig. 13 Effect of pressure fluid on bursting of cast iron cylinder(2)
 (Combined loads of lateral fluid pressure and tension)

lateral fluid pressure test is the most suitable test to check the anisotropy of porous materials such as graphite.

Next, we discuss the size effect in lateral fluid pressure test of naked graphite cylinder. Under lateral fluid pressure, pressure fluid permeates into the voids in the material, and the component of the axial direction of this pressure fluid acts on the test cylinder as a tensile load. Moreover, graphite cylinder is only supported by two "O" rings as shown in Fig. 1, so a bending moment does not act on the cylinder. Consequently, the cylinder bursts under uniform tensile stress, and the size effect does not appear under such uniform stress. This coincides very well with the experimental result of simple compression test of brittle materials⁽²⁾ and that of internal pressure test of cast iron thin-walled cylinder in the First Report⁽¹⁾.

The pressure fluid under lateral fluid pressure does not permeate into the material of coated cylinder; lateral fluid pressure acts in the tangential and the radial directions of the cylinder, so the stress condition in this case is a biaxial uniform compression. On the bursting of brittle materials under biaxial uniform stress⁽³⁾ one of the authors has already studied, and is clear that this bursting strength coincides with the compressive strength of the same material. Of course, even in this report there is no size effect recognized in coated graphite cylinder under lateral fluid pressure only, the mean value of the bursting pressures of the cylinders being $p_b = 47.9$ MPa, and this coincides with the compressive strength of graphite shown in Table 2, $\sigma_c = 47.7$ MPa. And the fact that there is no size effect in coated graphite cylinder under lateral fluid pressure is the reason why the stress condition in this case is a biaxial stress, and this coincides with the experimental result under simple compression of brittle materials⁽²⁾.

6.2 Experiment (2)

At first, we discuss the size effect in lateral fluid pressure test of naked cast iron cylinder. The voids in cast iron are very few as compared with graphite, so in this case of lateral fluid pressure acting on the cylinder, pressure fluid permeates through the outer surface of the cylinder into the material. And if there are no remarkable defects in the material, it seems, this pressure fluid goes concentrically into the material. For this reason the bursting of the cylinder in this case occurs under a uniform tensile load induced by the component of the axial direction that permeates into the material. When the material bursts under uniform tensile load, there is no size effect recognized as mentioned already in this report. In fact, in lateral fluid pressure test of naked cast iron cylinder shown in Fig. 8 there was no size effect evident in the range of the outer diameters of the

cylinders more than 20 mm. But, in the range of the outer diameters of the cylinders less than 20 mm in Fig. 8, the bursting pressure of the cylinder falls, as the outer diameter of the cylinder decreases; and size effect is evident in this range. This is the reason why the effective area of the cross section of the cylinder becomes small. There are many voids in the outer surface of the cylinder made of such cast iron like FC 10, and if we consider that these voids are constant for a specific material, the effective area of the cylinder excluding these voids which sustains actually the tensile load, decreases, as the outer diameter of the cylinder decreases. On the other hand, the tensile load induced by pressure fluid into the material is constant, having no relation to these voids. For this reason the bursting pressure of the cylinder falls as the outer diameter of the cylinder decreases in the range of comparatively small outer diameters of the cylinders, and this phenomenon appears as a kind of size effect.

Next, the bursting of the cylinder having a transverse hole in the radial direction is discussed. From the experimental result shown in Fig. 10, next conclusions can be drawn.

(1) When the depth of a transverse hole is extremely small, the hole does not affect the bursting of the cylinder.

(2) The bursting pressure of the cylinder decreases as the depth of the transverse hole increases.

(3) While the depth of the transverse hole is larger than the radius of the cylinder, the bursting pressure of the cylinder is almost constant.

When the depth of the transverse hole is small, the bursting pressure of the cylinder having a hole is nearly equal to that of the cylinder having no hole because there are many surface defects on outer surface of the cylinder corresponding to the transverse hole of the cylinder, and this phenomenon coincides with the experimental results on the bursting of the cylinder⁽⁴⁾ and the plate⁽⁵⁾ under stress concentration. Perfect explanations for the second and the third conclusions we can not give, because a stress analysis of the cylinder having a transverse hole in its radial direction has never been carried out. But, these experimental results can be explained qualitatively by a cutting surface under lateral fluid pressure of a cylinder having a transverse hole made of polymethyl metacrylate (PMMA)⁽⁶⁾. Namely, observing the cutting surface of PMMA cylinder having a transverse hole, in the range of the depths of the transverse hole smaller than the radius of the cylinder, we see its maximum stress occurs at the tip of the transverse hole. On the other hand, in the range of its depths larger than the radius of the cylinder, its maximum stress occurs in the neighbourhood of the center of the transverse hole. Thus

in the former range the tensile load induced by the pressure fluid flowing the transverse hole increases, and the cross sectional area that sustains this tensile load decreases, so the bursting pressure of the cylinder falls. On the other hand, in the latter range the bursting of the cylinder occurs in the neighbourhood of the center of the cylinder, and this bursting is symmetric about the center of the cylinder, and the bursting pressure of the cylinder in this case occurs under uniform tensile stress, so its value is constant. Next, considering the relation between the inner diameter of the transverse hole of the cylinder and its bursting pressure, in the range of small depths of the transverse hole under tensile load occurs at the tip of its hole as mentioned already, so the diameter of the cylinder does not affect its bursting pressure. But, in the range of depths of the cylinder larger than the radius of the cylinder, the tensile load induced by lateral fluid pressure increases as the transverse hole of the cylinder becomes big, so the bursting pressure of the cylinder falls as the transverse hole of the cylinder becomes big. The results of these observations coincide with the experimental results shown in Fig. 10.

A study has already been made on the bursting of cast iron solid cylinder having a transverse hole under tension⁽⁷⁾, and this experimental result coincides very well with Experiment (2) of this paper.

6.3 Experiment (3)

At first, we deal with the size effect on the bursting pressure of naked cast iron cylinder made of FC 10. As shown in Fig. 11 the size effect in the bursting due to lateral fluid pressure of cast iron cylinder, just as in Experiment (2), is different with the borderline at 20 ~ 30 mm of the outer diameter of the cylinder; there is no size effect in the range of the outer diameters of the cylinder larger than 20 ~ 30 mm. And the mean bursting pressure p_b of each pressure fluid is 147 MPa for water, 219 MPa for turbine oil and 261 MPa for castor oil, the bursting pressure ratios of turbine oil and castor oil in the case that the bursting pressure in water being 1.00 are 1.49 and 1.78 respectively. On the other hand, the bursting pressure of the cylinder under each pressure fluid falls as the outer diameter of the cylinder decreases. As these size effects are similar to those explained in Experiment (2), the explanation for these size effects is omitted here.

Next, the discussing is on the experimental result of naked cast iron solid cylinder made of FC 20 under combined loads of lateral fluid pressure and tension. In Fig. 13 showing these experimental results, the experimental data on ordinate indicate the bursting pressures of the cylinders when only lateral fluid pressure acts; these

bursting pressures of the cylinders, p_b , for the pressure fluids of water, turbine oil and castor oil are 212 MPa, 307 MPa and 381 MPa, respectively. And the bursting pressure ratios when the pressure fluids are turbine oil and castor oil are 1.45 and 1.80, as in lateral fluid pressure test of FC 10, putting the bursting pressure under water as 1.00, and these bursting pressure ratios coincide with 1.49 and 1.78 of FC 10, respectively.

A study has already been made on the bursting of naked solid cylinders made of glass and marble under lateral fluid pressure⁽⁸⁾; the bursting pressure ratios of the cylinders made of glass and marble when the bursting pressure are constant are 1.8 and 2.7 for glass, and 1.3 and 2.2 for marble, putting the bursting pressure of the cylinder under water as 1.0. From these experimental results it is clear that the effect of the pressure fluid on the bursting of the cylinder is also different depending on the kinds of the materials.

As mentioned above, the effect of pressure fluid on the bursting under lateral fluid pressure of cast iron cylinder is similar to that under internal pressure of cast iron cylinder and it is greater in order of water, turbine oil and castor oil. And under internal pressure, pressure fluid permeates the outer surface of the cylinder when the pressure fluids are water and turbine oil, but when the pressure fluid is castor oil the pressure fluid does not permeate the outer surface of the cylinder even in a cylinder of the same dimension. The same phenomenon mentioned here can be observed in the bursting under lateral fluid pressure; a few crack lines develop in the tangential direction on the outer surface of the cylinder except on the final bursting surface when the pressure fluid is castor oil, and such cracks of the tangential direction can not be observed when the pressure fluids are water and turbine oil. From these experimental results it is understood that the mechanisms of the bursting of the cylinders under internal pressure and lateral fluid pressure differ, as the bursting pressure increases.

As the explanation for the bursting under lateral fluid pressure is done in the above, we consider now the bursting of cast iron cylinder under the combined loads of lateral fluid pressure and tension. If tensile load acts in the axial direction of the cylinder, the pressure fluid permeates into the materials easily. So lateral fluid pressure at the bursting point, p_b , falls as the axial stress σ_a increases. And the $p_b \sim \sigma_a$ relations under each pressure fluid converge to the point A in abscissa which indicates the tensile strength of cast iron shown in Table 7 ($\sigma_b = 195$ MPa). Moreover, the bursting pressures of the cylinders under the same axial stress are greater in order of water, turbine oil and castor oil; and

Table 9 Lateral fluid pressure test of cast iron cylinder (FC 20)

Pressure fluid	Viscosity	d ₀ mm	P _b MPa			
Water (H ₂ O)	1.0 cp	20	225	235	245	240
Alcohol (C ₂ H ₅ OH)	1.2 cp	20	225	201	221	-

the effect of pressure fluid on the bursting of the cylinder under the combined loads is similar to that of internal pressure in the First Report and that of lateral fluid pressure shown in Fig. 13 of this paper.

As the physical factors of pressure fluid concerning the bursting of brittle materials like cast iron and graphite, the viscosity, the molecular size, the surface tension, the wetness and so on are conceivable, and it is not yet estimated synthetically how these factors affect the bursting of the material. The viscosities of castor oil, turbine oil and water are 986 cp, 72 cp and 1 cp respectively, and it is clear that these viscosities affect greatly the bursting of the materials. And to check the effect of the molecular size on the bursting of cast iron, we carried out lateral fluid pressure test on cast iron hollow cylinder made of FC 20 by using water and alcohol whose viscosities are nearly equal to each other. According to Table 9 showing the experimental results, the bursting pressures of the cylinders are nearly equal despite the fact that the molecular size of water is greater than that of alcohol.

In this study, the size effect of cast iron cylinder has been investigated assuming that pressure fluid permeates into the material. But, in brittle materials like glass it is not likely that pressure fluid permeates into the material, and it would be better to consider for explanation that so called "Reibinder Effect" that the strength of a material becomes weak when pressure fluid directly touches the surface of the material. The effect of pressure fluid on the bursting of the cylinder under lateral fluid pressure will not be clarified unless the bursting mechanism of the cylinder can be understood including the experimental result of internal pressure test. We are now studying these mechanisms under various loads.

7. Conclusions

In this paper, we carried out bursting tests under lateral fluid pressure on graphite and cast iron cylinders and under the combined loads of lateral fluid pressure and tension on cast iron cylinder to study the size effect in the bursting of graphite and cast iron cylinders, and also we studied the effect of pressure fluid on these burstings.

From these bursting tests, it is made clear that the bursting pressure is constant and there is no size effect in naked and coated graphite cylinders, and that the bursting pressure of coated graphite cylinder coincides with the compressive strength of graphite. On the other hand, in naked cast iron cylinder there is no size effect in the range of larger outer diameters of the cylinder, just as in graphite cylinder; but as the outer diameter of the cylinder increases, the size effect can appear, and the bursting pressure falls as the outer diameter of the cylinder increases. And these bursting pressures are different depending on the kinds of pressure fluids, these pressures being greater in order of water, turbine oil and castor oil, just as the bursting under internal pressure on cast iron cylinder in the First Report. The bursting test on coated cast iron cylinder under these loads was not carried out, because its bursting pressure was very high, and we could not find any suitable coating material which withstood the bursting pressure.

For the effect of pressure fluid on the bursting of brittle materials, various qualitative explanations are given about the bursting under internal pressure in the First Report and under lateral fluid pressure in this paper, but there are many factors involved in these burstings as mentioned in this paper, and the bursting mechanism is not clear. The bursting mechanisms are now under investigation, so the result of investigation will be reported in the Third Report including quantitative analyses of the experimental results in the First and the Second Reports.

References

- (1) Nagai, F., Matsukura, T. and Sato, Y., Bulletin of the JSME, Vol. 26, No. 215 (1983), p. 739.
- (2) Nagai, F., et al., Jour. Materials Sci. Soc. Japan (in Japanese), Vol. 12, No. 1-2 (1975), p. 56.
- (3) Sato, Y., Trans. Japan Soc. Mech. Engrs. (in Japanese), Vol. 39, No. 320 (1973), p. 1096.
- (4) Sato, Y. and Arai, H., Trans. Japan Soc. Mech. Engrs. (in Japanese), Vol. 34, No. 267 (1968), p. 1871.
- (5) Sato, Y., et al., Trans. Japan Soc. Mech. Engrs. (in Japanese), Vol. 46, No. 406, A (1981), p. 557.
- (6) Sasajima, K., et al., Trans. Japan Soc. Mech. Engrs. (in Japanese), Vol. 48, No. 425, C (1982), p. 131.
- (7) Nagai, F., et al., Pre-print Japan Soc. Mech. Engrs. (in Japanese), No. 780-13 (1978), p. 39.
- (8) Sato, Y. and Mori, T., Jour. Materials Sci. Soc. Japan (in Japanese), Vol. 15, No. 1 (1978), p. 50.