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Paper 270

A Study of the Structural Design of a Bottle with Vacuum Insulation

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Abstract

In this paper the indicators that are necessary for the optimal design of stainless steel vacuum insulation bottles are considerd. For the strength of the bottle, the critical strength of the outer cylinder depends on the shape parameters (the ratios between the height and diameter, and the diameter and thickness of the bottle). It was found that the relationship between the critical strength and the shape parameters is useful for the design of the outer cylinder. We prove this result by conducting experiments with three kinds of bottles.

Keywords: stainless steel, vacuum insulation, bottle, cylinder, critical strength, shape parameter.

1 Introduction

Vacuum insulation bottle (hereinafter called as bottle) has a double structured cylindrical container vessel as shown in Figure 1, the space between the inner cylinder and the outer cylinder there is a vacuum layer. By providing a vacuum layer to the tube between the inside and outside, the vacuum layer intercept the heat conduction from the inside to the outside of the container and also having high heat insulation against cold storage object was stored in the container. Containers with such a mechanism have been used as a container and carry drinking water. The increasing demand of bottle efforts, enhance the performance of the bottle came to be actively carried out. There is a weight saving of the bottle as a part of it. There is a benefit not only convenient to carry by weight saving, leading to the reduction of resources used. The disadvantage is there is a defect, such as to cause other problems such as cracks and wrinkles during processing by a thin layer of thickness due to the weight saving of the bottle, deformation occurs in the bottle after production, as shown in Figure 2. Therefore, the optimal design of plate thickness corresponding to the shape of the bottle has begun to be asked. However, at present it is difficult to achieve in the design of the plate thickness by reducing weight limit, because they rely on know-how that has no clear indicators in the design of the bottle. Therefore, it is necessary to find a design guideline for determining the optimal thickness and shape of the bottle.

The purpose of this study is to consider indicators that are necessary for the optimal design for vacuum insulation bottle. Experiments were conducted to determine the strength against the pressure load in order to study the parameters that are valid for the bottle design, to demonstrate its effectiveness. These verification of strength against the pressure from these bottles, made a proposal towards the surface structure for optimum design for the bottle.

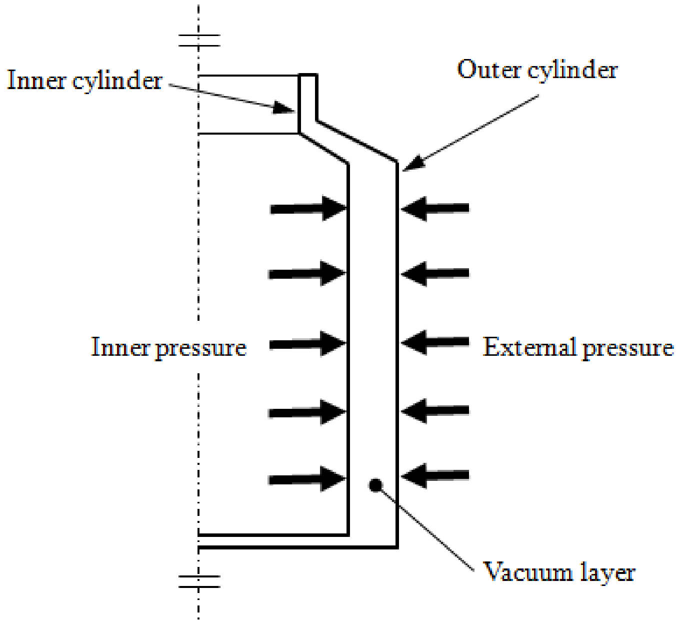


Figure 1: Section of the bottle


Figure 2: Deformed bottle

2 Analysis

2.1 Analytical model

In this study, we used nonlinear structural analysis LS-DYNA ver.971 made by Livermore Software Technology Corp. In order to examine the strength of the bottle by loading pressure, we created the double cylinder model reproducing the structure of the bottle [1]. This model consists of outer cylinder body, outer cylinder bottom, inner cylinder body, and inner cylinder bottom. They are all shell elements. Table 1 and Figure 3 show the geometry and the boundary condition of an analytical model. D1 and L1 are diameter and height of outer cylinder, respectively. Also, D2 and L2 are them of inner cylinder, respectively. L1 and L2 are heights of cylinder bodies excluding oral regions of the bottles. Each thickness of inner and outer cylinder body is taken as same value. It was varied among 0.1 to 0.35mm. The thickness of the bottom part is set constant at 0.4mm.

Analytical model		D1 [mm]	L1 [mm]	D2 [mm]	L2 [mm]
B1	a	56	106	52	88
	b		157		136
	c		204		183
B2	a	60	160	56.6	131.65
	b		200		171.15
	c		240		211.65
B3	a	67	120	62.4	84.65
	b		168		133.65
	c		217		182.65

Table 1: Dimension of double cylinder model

Metal	Mass density ρ [g/cm3]	Young's modulus E [GPa]	Yield stress σ [MPa]	Poisson ratio
sus304	8.03	197	205	0.3

Table 2: Material property in analysis

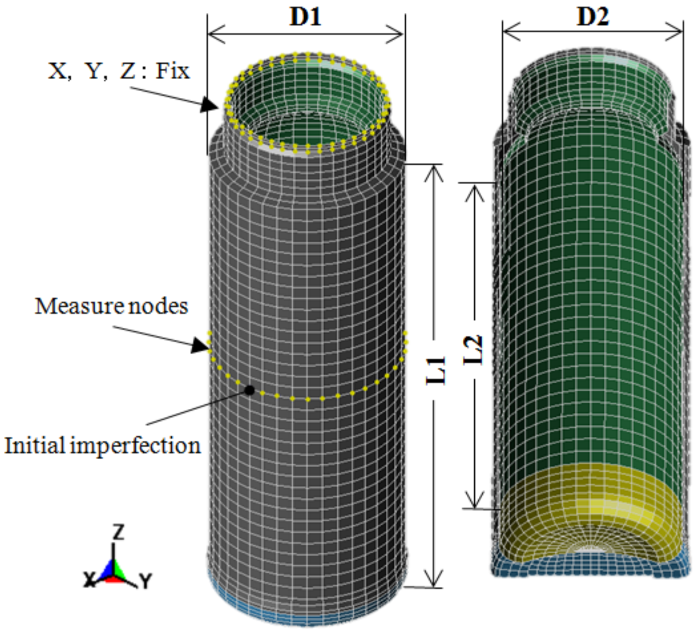


Figure 3: Geometry and boundary condition of double cylinder model

2.2 Analytical condition

In boundary condition, the nodes which are joining sections of inner and outer cylinder were fixed to X, Y, and Z axial direction. The space between the inner and outer cylinder in double cylinder model was presupposed the atmosphere, and pressure was loaded on the whole inner and outer cylinder caused by the differential pressure between the external. The volume elasticity of the fluid was set to 1.4×10^5 Pa and the mass density of it was $1.293 kg/m^3$. Moreover, the initial imperfection is given to the analytical model as a starting point of deformation [2]. In initial imperfection, a node of the coordinates of point was (x=D1/2, y=0, z=L1/2) and had -0.01mm at X axial displacement. In order to confirm deformation of the model, the amount of displacement was outputted, which is making the nodes on the circumference in the height of the middle of the model into the point of measurement. Table 2 shows the material property of sus304 and elastic perfectly plastic solid was used in this analysis.

3 Experiment

3.1 Material under the test or Specimen

Sus304, austenitic stainless steel was used for material under the test. Thickness of specimen was 0.2 to 0.4mm. First, the plate was processed into 42 to 50mm steel pipe diameter, and carried out the tube expansion by bulge processing which is one of the manufacturing processes of the bottles. Tube expansion average by bulge processing is 1.22 to 1.32. Table 3 and Figure 4 show the shape and size of the specimen used in this experiment. The specimens E1, E2, and E3 corresponds to B1-b, B-2-b, and B3-a of the analytical model to Section 2, respectively. The both ends of the specimen were reinforced with the epoxy resin, and sealed the inside. The experiment was conducted 3 times for thickness of each specimen. Figure 5 shows material property of the specimens. This is the result of obtaining by a quasi-static tensile test.

Test specimen	D [mm]	L [mm]
E1	56	157
E2	60	200
E3	67	120

Table 3: Dimension of test specimen

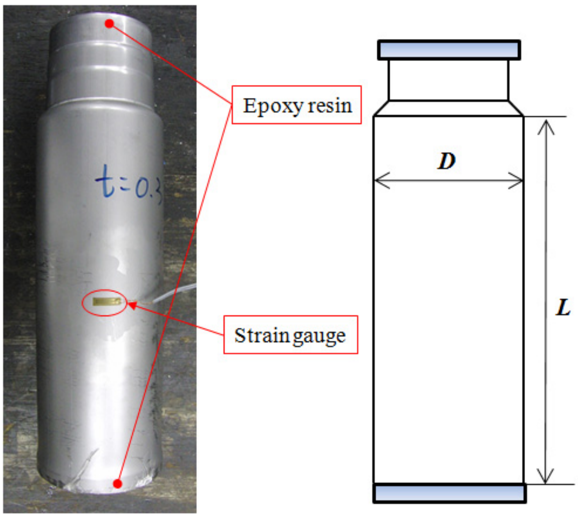


Figure 4: Test specimen

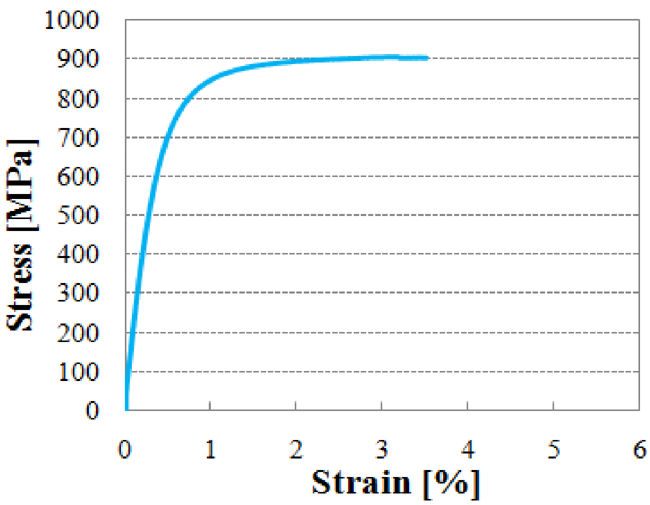
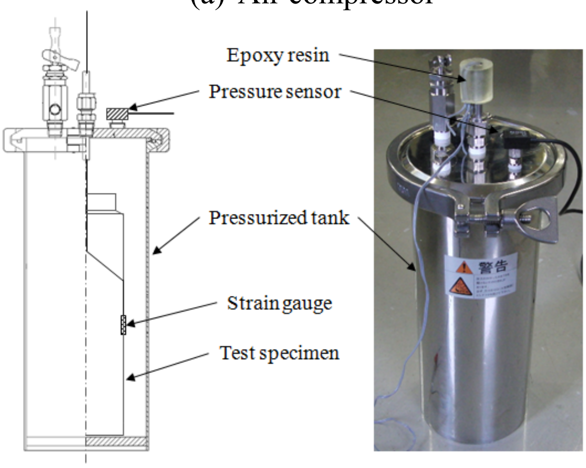


Figure 5: Material property of sus304 after tube expansion process

3.2 Test method

In the experiment, equal pressure was loaded to the cylinder side and height direction of specimens, and the pressure at the time of deformation of specimen body part was measured [3]. In order to perform pressure loading to specimens, they were installed in the pressurized tank (LIQUID SYSTEM Corporation/ SVF-1027) and the inside of a container was pressurized using the air compressor (ANEST IWATA Corporation/ CS-175PB). The regulator was used for adjustment of air pouring into the tank, and the pressure sensor (KEYENCE Corporation/ AP-V41A) was used for measurement of the pressure in the tank. In order to judge the deformation amount of specimens, the strain gauge was stuck in the circumference direction of the central height of specimen body part. It was assumed that specimens carried out plastic deformation to the amount of distortion reaching to 0.1%, and the pressure at the time was measured. In order to secure the sealing state in the pressurized tank in measurement with the strain gauge, the penetration joint and the stainless steel tube were attached to the pressurized tank, and the code of the strain gauge was laced in the stainless steel tube and the one side was hardened by the epoxy resin. Figure 6 shows experimental apparatus.

(a) Air compressor



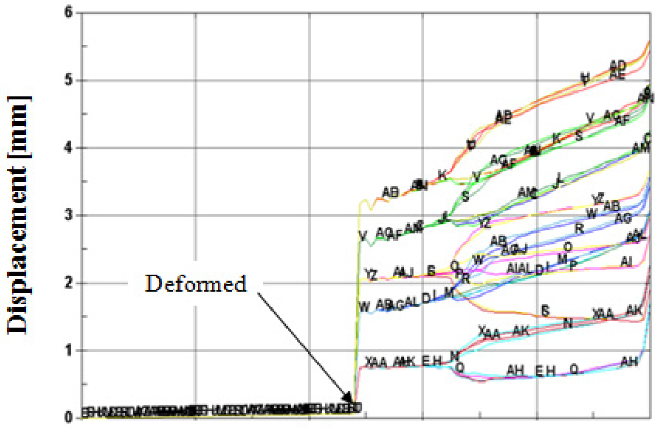
(b) Set of the pressurized tank

Figure 6: Experimental apparatus

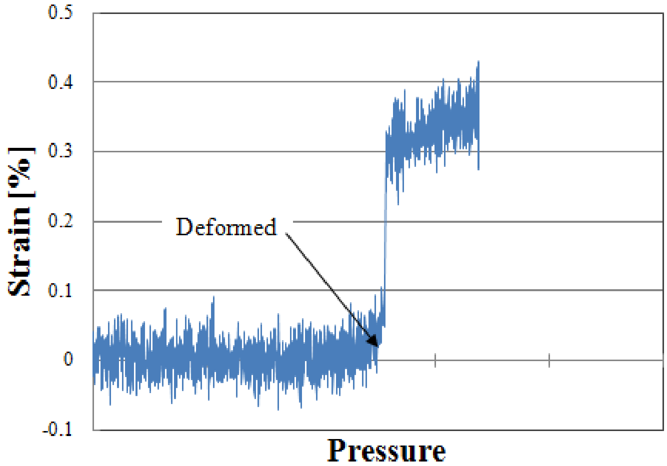
4 Result and discussion

4.1 Verification of the deformation phenomenon by pressure load

It observes about the double cylinder model and the deformation phenomenon of the specimens which it is pressured. Deformation behaviour and configuration of analytical models and specimens in the experiment are compared, and the deformation phenomenon in analysis is evaluated. Figure 7 and Figure 8 show the deformation phenomenon by pressure load in analytical model B2-b (Table 1) and specimen E2 (Table 2). When a value of pressure loading is reached, it turns out that the analytical model is changing rapidly. Also it was found that it is crushed from four directions in deformed configuration. Since the same result was obtained also in the experiment, even if the deformation phenomenon by the pressure of double cylinder model compares with actual deformation phenomenon, it can be said that high reproducibility is shown.



(a) Model B2-b of analysis



(b) Specimen E2 of experiment

Figure 7: Deformation behavior by pressure loading

(a) Model B2-b of analysis (b) Specimen E2 of experiment

Figure 8: Deformation shape by pressure loading

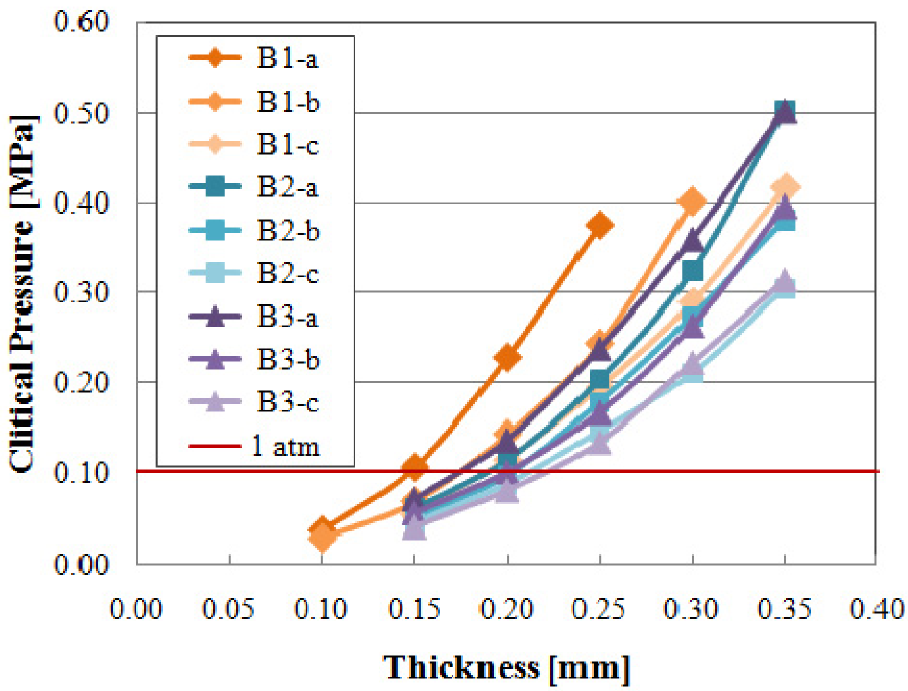


Figure 9: Analytical result of critical pressure

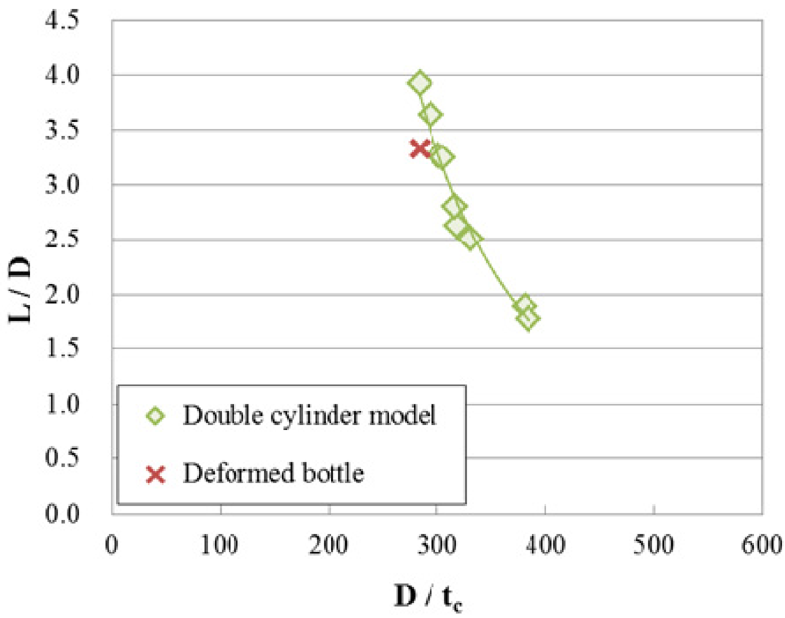


Figure 10: Comparison with double cylinder model and deformed bottle

4.2 Shape parameter in the double cylinder model

It verifies about the relation of strength and shape parameter by pressure load in double cylinder models. The pressure in front of deformation is defined as critical pressure. Figure 9 shows the relation between critical pressure and board thickness in double cylinder models. About the strength of the bottle, define a critical thickness $\boldsymbol{t_c}$ that the bottle can maintain the shape, if it is loaded the determinate external pressure. A value of the pressure here is 0.1MPa (1atm). It is known that for the cylindrical container which receives external pressure, the ratios of height and diameter, and diameter and thickness of the bottle will affect a collapsing phenomenon [4, 5]. Critical thickness is computed from Figure 9, and what was arranged by shape parameter is shown in Figure 10. Also, the bottle which the deformation phenomenon actually produced is henceforth called bottle P. It is found that the graph which shows strength by external pressure in double cylinder models is very close to the plot which shows the shape data of bottle P. The relation of strength and shape of bottles which are shown by a shape parameter (L/D, D/t_c) can say that it is very effective to outer cylinder design of bottles.

4.3 Validity of shape parameter to bottle design

An experiment proves the relation of strength and shape parameter, which are obtained from numerical analysis, of outer cylinder of bottles. Figure 11 shows the relation of critical pressure and thickness in the specimens E1, E2, and E3 (Table 2) and analytical model B1-b, B-2-b, and B3-a (Table 1), it is the respectively same shape. It is found that critical pressure and board thickness of each analytical model and specimen show the same tendency with the almost same value. The critical thickness of outer cylinder under the pressure of 1MPa (atm) is computed. An approximate expression is drawn from the plot of the result obtained from each specimen in the experiment, critical thickness is computed, and it collects using shape parameter. Figure 12 shows what compared the result obtained from experiment and numerical analysis. Since the relation between shape parameter and strength obtained from experiment and numerical analysis is almost in agreement, it can be said that the relation between shape parameter and strength in double cylinder model was proved.

Here, it is verified that the plot of shape data in bottle P exists in the domain which makes strength enough. Figure 13 shows critical thickness in analytical model B2-b and the specimen E2 of the same shape as bottle P, and it is compared in detail. Although critical pressure in analysis and experiment is almost in agreement like the result shown in Figure 11, it is found that there may be a difference with analysis and experimental value depending on specimens. Table 4 shows comparison with critical pressure for every specimen and an analysis result. It is found that specimens which the difference about 0.02MPa produces between analysis value and experimental result exist. As this cause, it is possible that thickness distribution, circularity, processing history, etc. in actual bottles have influenced strength [6]. It is because they cannot be taken into consideration by numerical analysis. Since thickness of bottle P is 0.22mm, critical pressure by numerical analysis serves as 0.127MPa, and it is thought that deformation does not produce on analysis. However, when the big differences (0.02MPa) which produced in comparison with analysis value of critical pressure checked by experiment is taken into consideration, critical pressure in shape of bottle P does not almost have a difference with atmospheric pressure, and it can be said that there is a possibility of enough that deformation phenomenon will produce. If this difference can be taken into consideration about design strength, it will be thought that the validity of shape parameter to bottle outer cylinder design can be improved further.

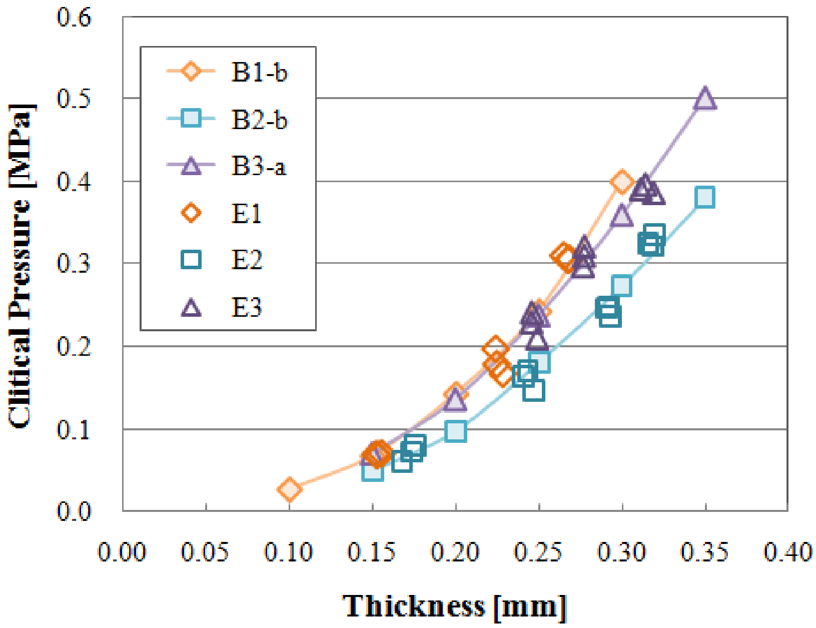


Figure 11: Comparison with analytical and experimental result

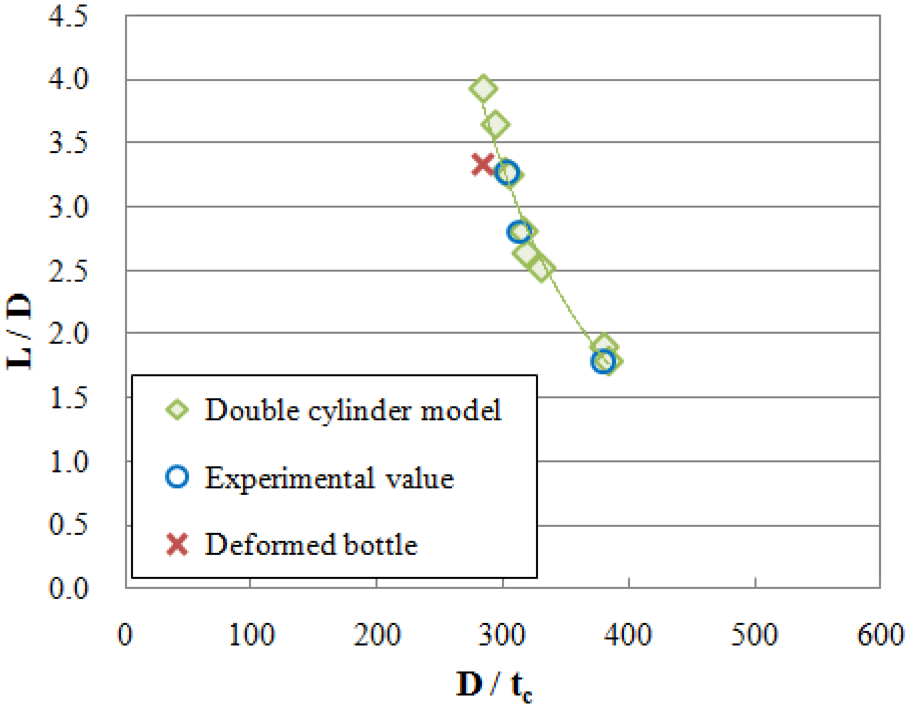


Figure 12: Shape parameter of analytical and experimental result

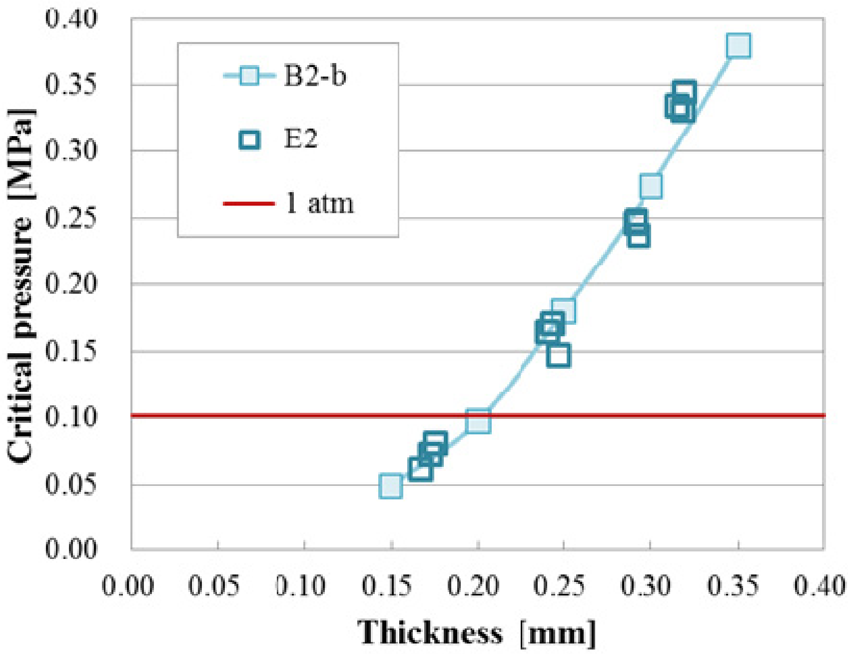


Figure 13: Comparison with analysis of B2-b and experiment of E2

Test specimen E2		Thickness of specimen [mm]	Critical pressure [MPa]		Difference between the Experiment and Analysis values [MPa]
			Experiment	Analysis	
Thickness of steel plate t = 0.4 mm	1	0.320	0.345	0.316	0.029
	2	0.316	0.335	0.308	0.027
	3	0.319	0.332	0.314	0.018
Thickness of steel plate t = 0.35 mm	1	0.293	0.237	0.261	0.024
	2	0.292	0.249	0.259	0.010
	3	0.291	0.247	0.257	0.010
Thickness of steel plate t = 0.3 mm	1	0.241	0.164	0.162	0.002
	2	0.247	0.147	0.172	0.026
	3	0.243	0.171	0.166	0.004
Thickness of steel plate t = 0.2 mm	1	0.175	0.081	0.070	0.011
	2	0.173	0.072	0.068	0.005
	3	0.168	0.061	0.062	0.001

Table 4: Difference between the experiment and analysis values of test specimen E2

5 Conclusion

As verification of the validity to outer cylinder design of bottles in relation to the strength and shape parameters by applying pressure loading to the outer cylinder of bottles, numerical analysis was conducted using a double cylinder model reproducing the bottle structure. Experiments were conducted in order to prove the result.

Concerning the deformation phenomenon produced in the outer cylinder of the bottles, the deformation behaviour and shape could be checked in the numerical analysis and experiments. By conducting numerical analysis using a double cylinder model, the relationship between shape parameters and the strength of the outer cylinders of the bottles was obtained, and it was found that it is very effective for outer cylinder design of bottles. Since the same results were obtained from the numerical analysis (compared to the experiment) for the double cylinder model it was demonstrated that the outer cylinder design of the bottles using shape parameters is effective.

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