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Behavior of R/C cylindrical shell under lateral load

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Abstract. In this paper, the structural behavior of R/C cylindrical panel is analyzed by experimental results. To avoid the geometric imperfection, R/C shell specimens are made by use of a stiff steel mold. From experimental results, the load carrying behavior of R/C cylindrical panel is presented under an external lateral pressure. Even if R/C shell does not posses geometric imperfections, the inaccuracy of the reinforcement position strongly affects to the ultimate strength and the failure patterns of such shells. To explain these effects, FEM nonlinear analyses are done under the same conditions as those of experiments. The behavior of R/C cylindrical shells are well simulated under the consideration of both the geometric imperfection and several inaccuracies.

Key words: R/C shell; imperfection; experiment; FE Analysis.

1. Introduction

Reinforced concrete (R/C) cylindrical panels are commonly used for industrial plants and storage tanks. R/C cylindrical panel shows large load carrying capacity under lateral distributed external pressure. Especially, these structures are advantageous when the internal compression is predominate status.

R/C cylindrical panel under lateral load has been analyzed experimentally and numerically (e.g. Takayama *et al.* 1990). They reported that the artificially generated geometric imperfection of the shell configuration strongly influences the ultimate strength of the cylindrical shell. However, in the case of the shell experiments without artificial geometric imperfection, both experimental and numerical results are not in good agreement. Because it is difficult to make a model without geometric imperfection and to avoid the inaccurate modeling of the supporting condition in experiment. However, in the case of the cylindrical shell under concentrate loading, it was reported that these imperfections could be avoided by use of steel mold and particular supporting devices (Hara *et al.* 2000).

In this paper, the structural behavior of R/C cylindrical panel, subjected to lateral external pressure, is analyzed by experimental results.

In experimental analyses, R/C cylindrical panels are made by using the steel mold to form the specimens without geometric initial imperfections. Also, in the loading test, R/C cylindrical panel is supported along both meridional edges by the steel ball-hinges to obtain the ideal roller supported

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condition. To realize a quasi uniformly distributed load, the loads are applied by the whiffle tree system. Under such loading condition, the deformation characteristics and the load carrying behaviors are measured.

From experimental results, the load carrying behavior of R/C cylindrical panel is presented under an external lateral pressure. Also, it is pointed out that the inaccurate reinforcing position plays an important role to evaluated the load deflection behavior and the ultimate strength of the R/C cylindrical shells even if the shell possesses no geometric imperfection. To explain the effects of an inaccurate reinforcing position on the behavior of R/C shell panel, FEM nonlinear analyses are performed. Then, it is concluded that the experimental model explains the R/C shell behavior precisely when the inaccuracies mentioned above are taking into account.

2. Analysis model

2.1 Experimental model

In experiment, the stiff steel mold shown in Fig. 1 is used to make the thin R/C concrete shell without geometric imperfection. The steel mold is manufactured by the machining center to control the surface deviation of the specimen within 0.1 mm. The micro concrete of maximum aggregate size 2.5 mm is poured into this mold and is compacted by use of mold vibrator. Fig. 2 shows the R/C

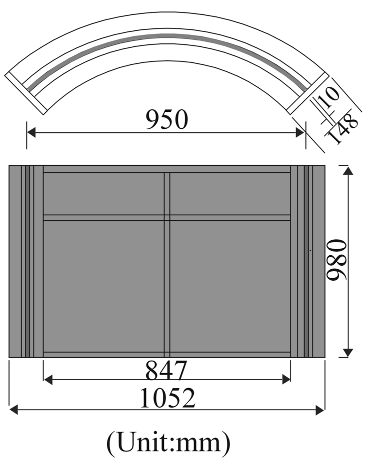

Fig. 1 Steel mold

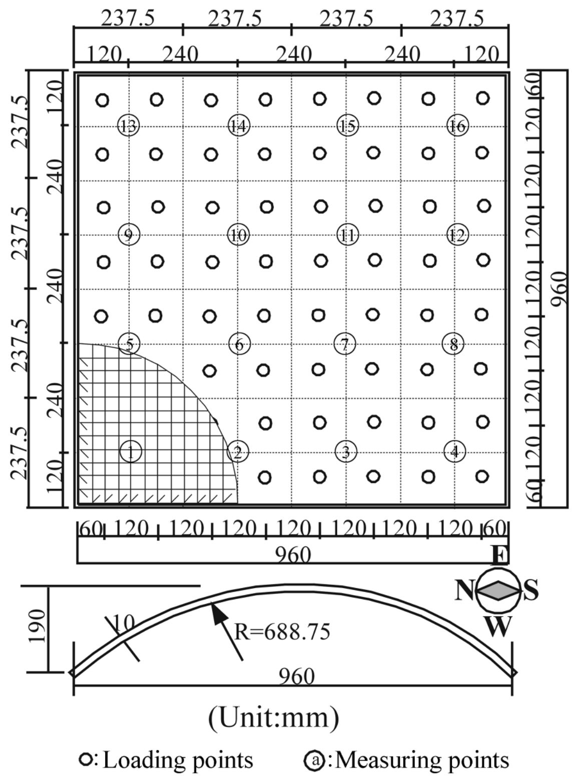

Fig. 2 Experimental model

Table 1 Material properties

Concrete	
Compressive Strength f_c	31.7 MPa
Elastic Modulus E_c	22.9 Gpa
Poisson's Ratio ν	0.21
Tensile Strength f_t	4.33 MPa
Steel	
Yield Stress f_y	449 MPa
Ultimate Strength f_u	521 MPa
Elastic Modulus E_s	200 Gpa
Tangential Modulus E_t	20 Gpa

cylindrical shell panel specimen. The shell panel has the cylindrical shape with 960 mm × 960 mm square plan and has 688.75 mm radius and 10 mm thickness. ϕ0.75 mm stainless wires are used as the reinforcements and are placed in the middle of the shell thickness in both meridional and hoop direction. They are placed in equi-distance 5 mm. Table 1 shows the mechanical properties of the concrete and the reinforcements obtained from standard testing of specimens.

2.2 Loading and supporting system

Fig. 3. shows the loading and the supporting system used in experiment. The cylindrical panel is roller supported along both meridians with steel balls and is free along the hoop direction to obtain

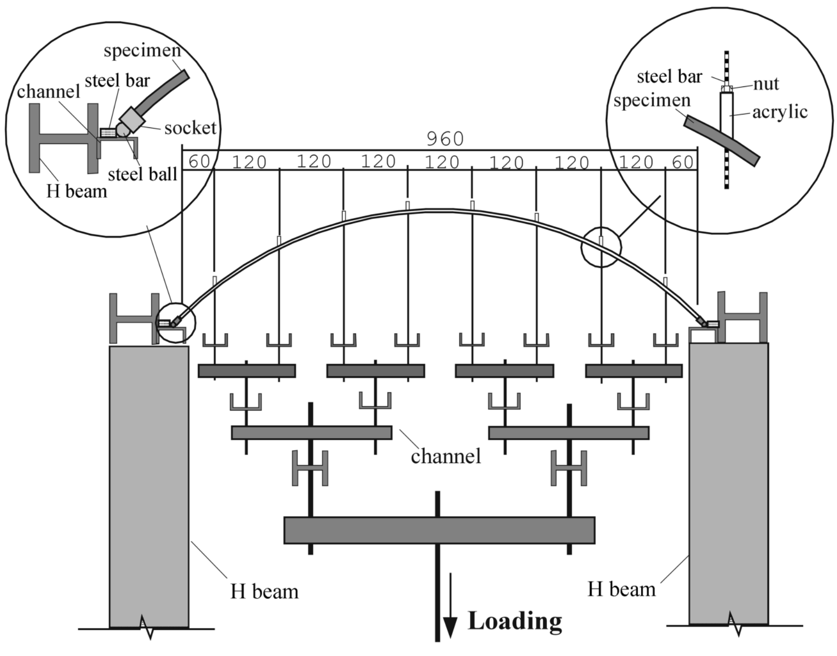

Fig. 3 Loading and supporting system

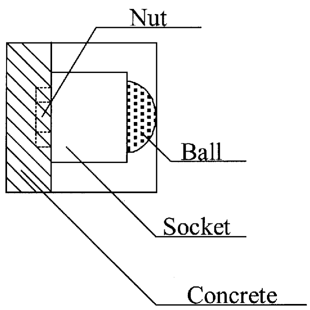

Fig. 4 Supporting ball

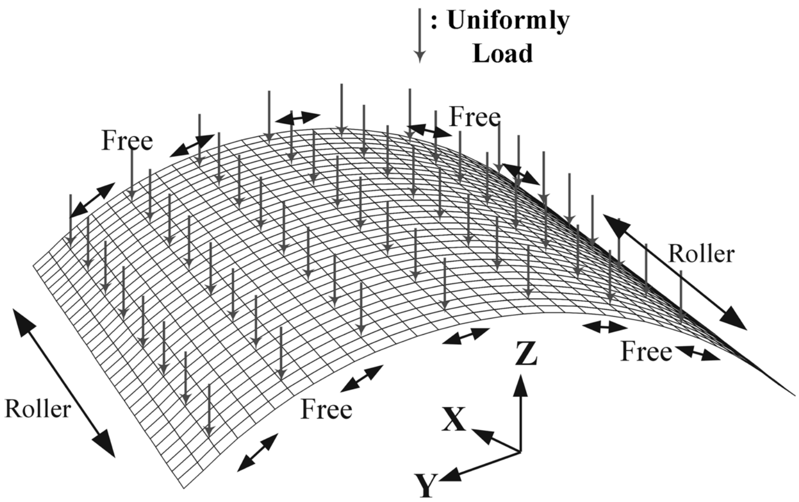

Fig. 5 Numerical model

the ideal supporting condition. The detail of roller support is shown in Fig. 4. The steel ball is placed in the steel socket and these sockets are attached to the shell meridians. Each spacing between these supporting devices is 2 cm. From these devices and the supporting system, R/C shell specimen can move freely in meridional direction but is fixed in hoop direction. The lateral load is applied by whiffle tree system (see Fig. 3). The 64 loading points are represented in Fig. 2 with circle (o). These applied loads are balanced by the whiffle tree system. The root of whiffle tree is connected to the servo actuator jack and is controlled by displacement increment. In Fig. 2, the circled number denotes the number of displacement transducers to measure the displacements of the R/C shell panel. Conceptual loading and supporting conditions are shown in Fig. 5.

3. Experimental results

3.1 Load deformation relation

Fig. 6 and Fig. 7 show the load displacement relation of the R/C cylindrical shell panel. The

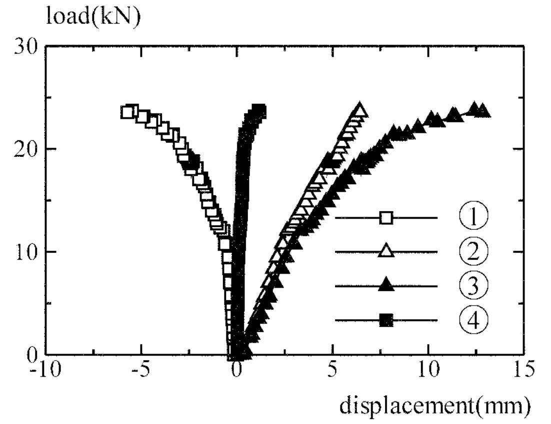

Fig. 6 Load displacement relation (Experiment: hoop direction)

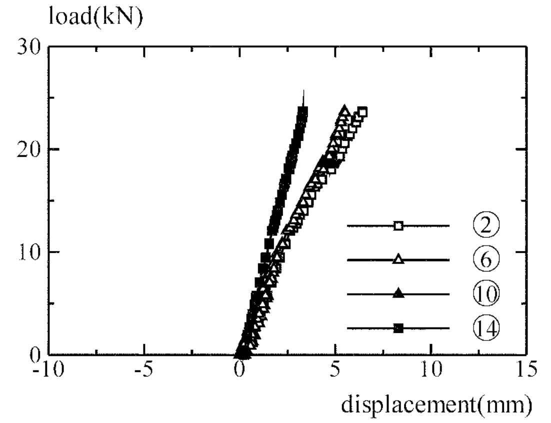

Fig. 7 Load displacement relation (Experiment: meridional direction)

abscissa and the ordinate denote the displacement at each point shown in Fig. 2 and the applied loading, respectively. The loading conditions are the equivalent distributed load mentioned in previous section. R/C shell is made without initial geometric imperfection using the stiff steel mold and is supported by ideal roller hinges composed of steel balls and sockets to prevent the friction at supports. Fig. 6 shows the displacements at several measuring points along the hoop direction. The circled number denotes the measuring points as shown in Fig. 2. The positive and the negative displacements show the vertical displacement downward and upward, respectively. If the cylindrical panel has complete configure without geometric imperfection, the deformation mode of the cylindrical panel may show the symmetric deformation about central meridian under symmetric loading. However, in spite of avoiding geometric imperfection using stiff steel mold, R/C shell panel specimens does not deform to the symmetric configuration. On the other hand, Fig. 7 shows the load displacement relation at several measuring points along the meridional direction. From Fig. 7, the deformation tendencies along with the meridian is similar. Therefore, R/C shell denotes the same deformation mode through the hoop direction at any cross section of the meridional direction so that the R/C cylindrical panel behaves as like as an arch structure with wide arch width .

3.2 Influence of inaccurate reinforcing position

To investigate the causes of an unsymmetric deformation pattern of R/C shell panel along with the hoop direction, we assumed that the deviation of the reinforcement position from the middle surface of the shell plays an important role. Therefore, the reinforcement position of whole shell surface is measured after experimental tests. Fig. 8 shows the distribution of the reinforcement position from the middle surface of the shell. In Fig. 8, the positive and the negative amount of deviation denotes the downward and the upward deviation from the middle surface, respectively. From these measuring of the shell surface, the configuration of the panel has not geometric imperfection mentioned above. However, the reinforcing position has deviations from the middle surface of the cylindrical panel considering such imperfections. To explain the effects of the inaccurate reinforcing position on the behavior of R/C shell, some numerical analyses are done by FEM (Hara *et al.* 1996, 2000).

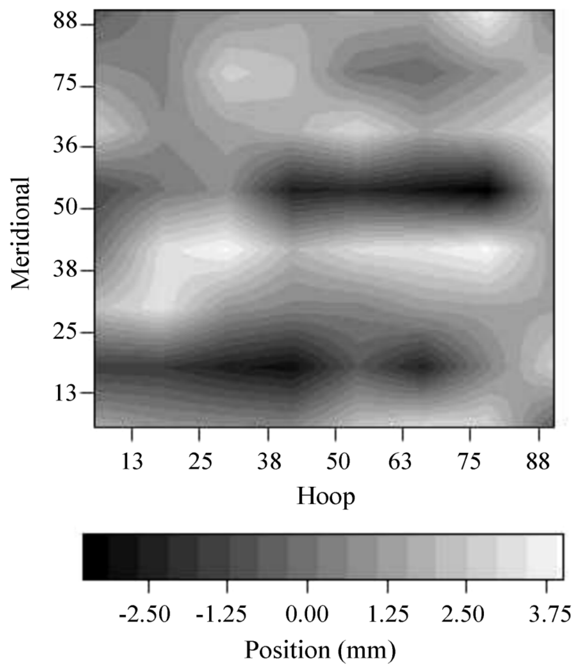

Fig. 8 Reinforcing cover from the mid surface

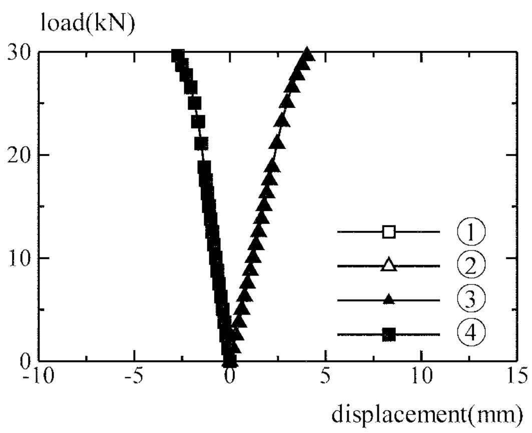

Fig. 9 Load displacement relation (Numeric: ignoring inaccurate reinforcement position)

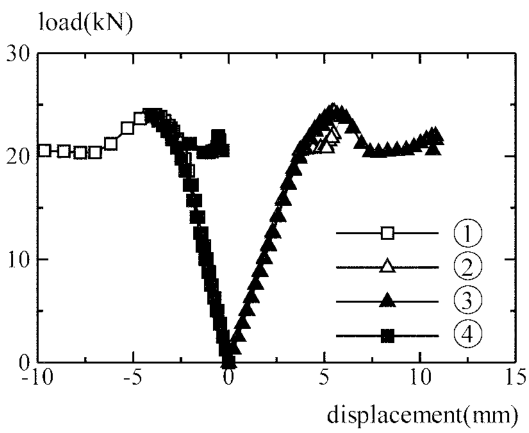

Fig. 10 Load displacement relation (Numeric: considering inaccurate reinforcement position)

Fig. 9 shows the numerical load displacement relation of the cylindrical panel along the hoop direction. In this case, the reinforcements are assumed to be placed in the middle surface of the R/C shell panel. Therefore, it is assumed that there is no deviation of the reinforcement position from the middle surface. The examined points are the same as shown in Fig. 6. The load displacement relation shows symmetric characteristics along with the hoop direction. However, from the comparison between Figs. 6 and 9, the deformation patterns of both results are not similar and the ultimate strength in Fig. 6 is higher than experimental results in Fig. 9.

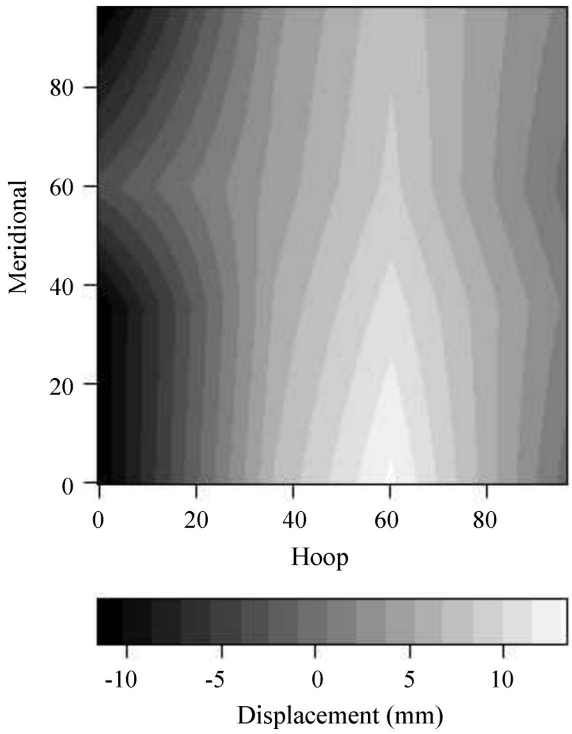

Fig. 11 Deformation pattern (Experiment: P = 24 kN)

To overcome these discrepancies, the deviation of reinforcing position is introduced into the numerical analyses. Fig. 10 shows the load displacement relation under the same condition as those of Fig. 9. However, the reinforcing positions are defined based on the measuring results (see Fig. 8). Comparing the results of Fig. 10 with that of Fig. 6, the load displacement relation of Fig. 10 agrees well with the experimental results shown in Fig. 6. Also, the ultimate strength of both Figs. 10 and 6 does not show any differences but agrees well. In addition, both results show unsymmetric deformation patterns.

Fig. 11 shows the deformation pattern obtained by experimental analysis under lateral load P = 24 kN. In Fig. 11, the positive and the negative displacement denote the downward and the upward direction, respectively. The left part from the middle meridian of the shell deforms upward. On the other hand, the right part of the shell deforms downward. The deformation pattern agrees well with numerical results.

3.3 Cracking patterns on the shell surfaces

Fig. 12 shows the cracking patterns of the specimen numerically and experimentally. The left side and the right side of the figure denote the cracks from numerical and experimental results, respectively. Also, the upper and the lower side of the figure denote the cracks on upper and inner surface of the model, respectively. Cracks occurred on both upper surface of the left from the central meridian and lower surface of the right. Because the shell deformation patterns are shown in both Fig. 11.

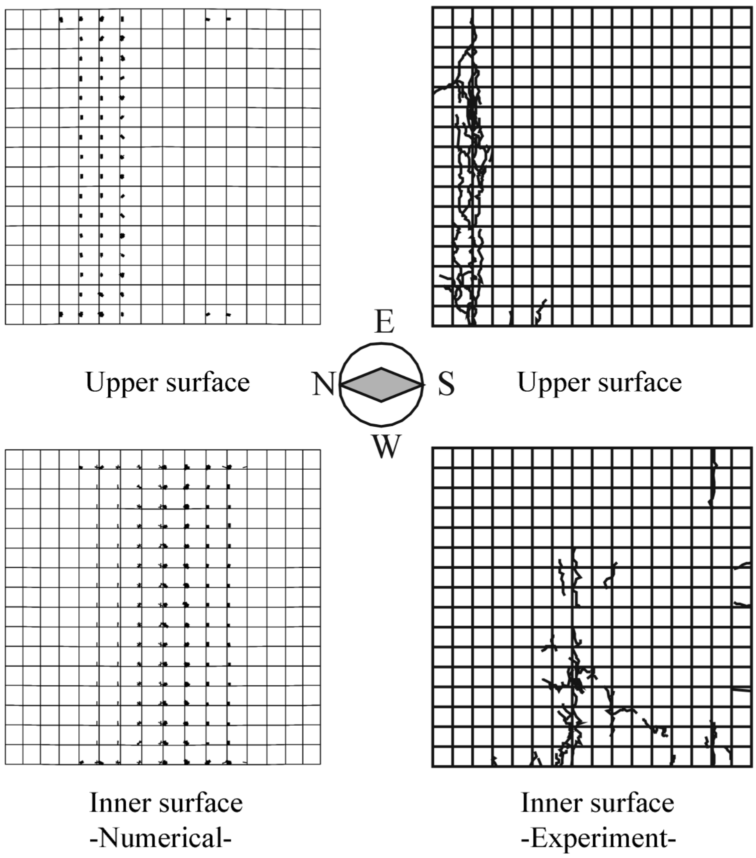

Fig. 12 Crack pattern

4. Conclusions

In this paper, the structural behavior of R/C cylindrical shell panel is analyzed by experimental results focused on the relation between deformation properties and the geometric imperfection caused by the deviation of the reinforcing position. In experimental analysis, the shell is made without any geometric imperfection and the loading test is performed using the particular supporting devices to match with the numerical condition. From experimental results, the load carrying behavior of R/C cylindrical panel is presented under an external lateral pressure. Also, the cracking patterns and the ultimate strength of the R/C cylindrical panels are examined. From experimental results, following conclusions are obtained:

1. The imperfection effects, arisen from the deviation of the reinforcing position from the designed one, play an important role for R/C shell deformation and ultimate strength as well as crack patterns.
2. To evaluate the behavior of R/C shell panel, it is important to consider the effects of the inaccurate position of the reinforcement and the realistic R/C shell behavior is presented when the imperfection effects based on such causes are taken into consideration in the numerical analyses.

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