THE EFFECT OF SUPPORT CONDITION ON MECHANICAL BEHAVIOR OF FREE-FORMED REINFORCED CONCRETE SHELLS

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1. Introduction

Free-formed shells, that have less bending moments under dead load, have rational and beautiful shapes. A number of free-formed reinforced concrete shells have been developed by Isler, using the hanging method and other methods [1]. The investigations of the free-formed shell have been performed by Isler [2], Kollegger [3], and Saitoh [4], etc. And shape finding methods of free-formed shell have also been investigated analytically by Ramm [5], Ohmori [6], and Yoshinaka [7], etc.

Failure behaviors of free-formed reinforced concrete shells are affected by various factors; boundary conditions, loading conditions, initial imperfections, material nonlinearity, etc. The authors have conducted several experiments on the free-formed reinforced concrete shells over a few years, and presented the results of the experiments at IASS symposiums in Stuttgart (‘96) and Singapore (‘97),[8], [9]. In these Experiments, the effect of loading mode and rise-span ratio to the behavior of the free-formed shells has been discussed.

In this paper, the effect of boundary conditions on the failure behaviors of free-formed reinforced concrete shells was investigated. The three models with different tie-beam stiffness were tested, and the results of them were compared with analytical results. The shape of the testing model with 80 cm span, 16 cm rise and 8 mm thickness was obtained by numerical shape finding process.

2. Shape Finding Procedure

Finite element method considering the geometrically nonlinear was used as shape finding method. A flat square membrane with pin supports on the corner was discretized into isoparametric, degenerated nine node shell elements, as shown in fig. 1. The dimensions of the membrane were 80 x 80 cm plan and 8 mm thickness. During the shape finding process, the material of the membrane was assumed to maintain linear elastic behavior.

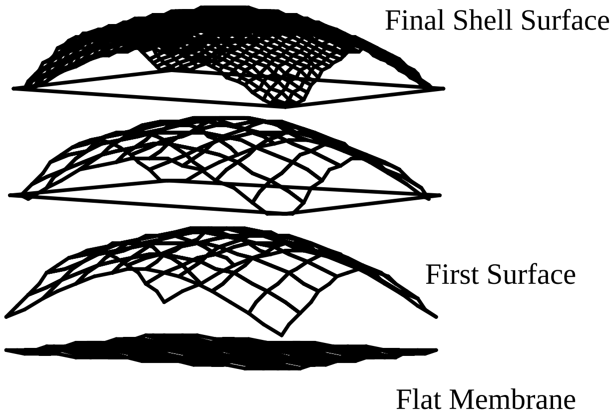


Fig.1 shape finding process

At first, uniform distributed load was increased step by step, until the displacement at the center of the membrane reached 16 cm (= 20 percent of the span). And then the areas of the deformed elements were estimated. The analysis was repeated again under the modified load in proportion to the estimated areas. Finally, the obtained surface was made smooth using the parametric spline function.

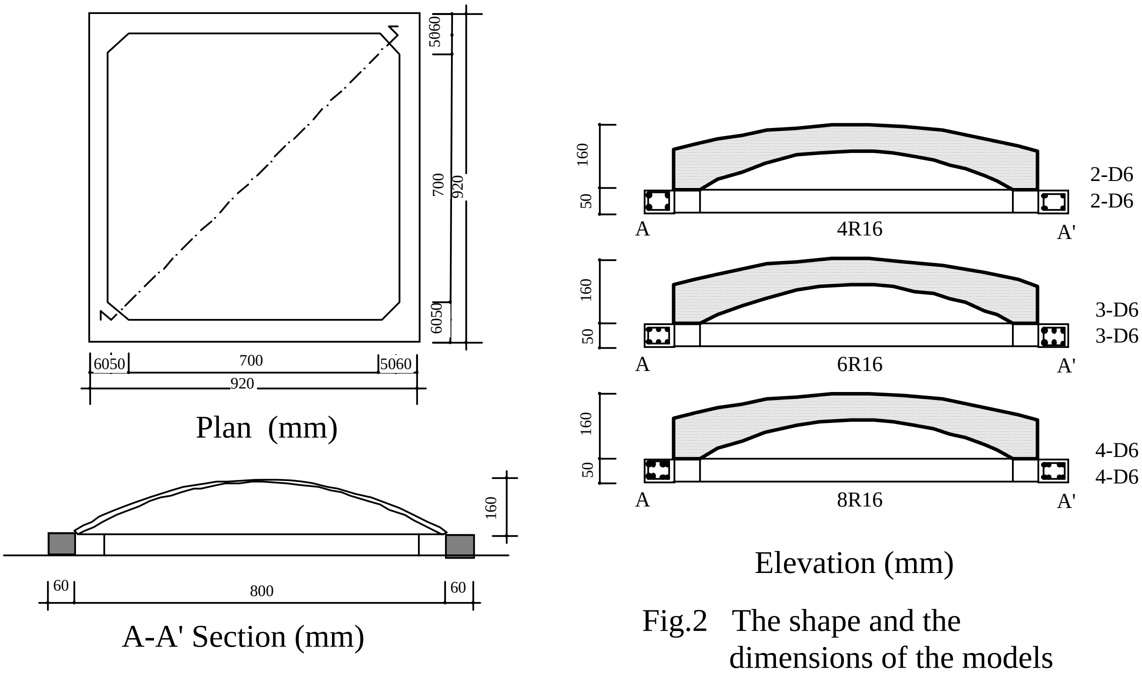
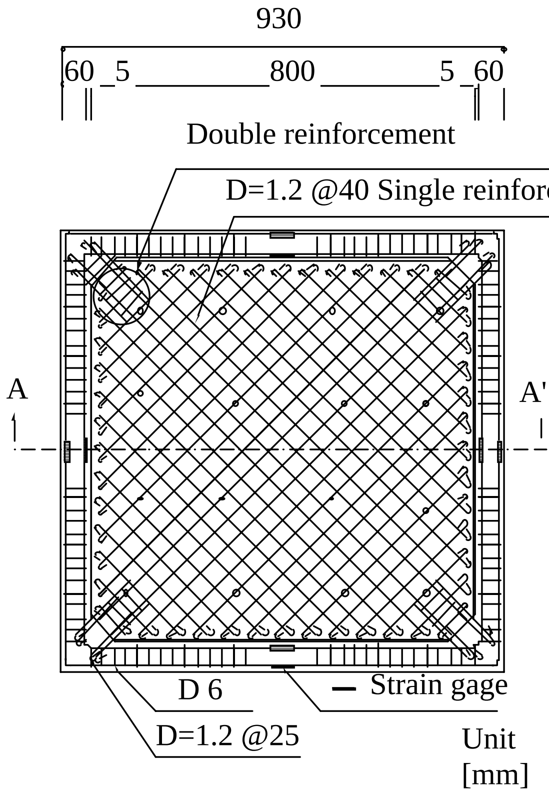


Fig.2 The shape and the dimensions of the models

3. Experimental Program

Fig. 2 gives the shape and the dimensions of the model. The shell thickness was designed as 8 mm at center part of the shell and increased gradually to 16 mm at the corner. And the corners were connected each other by the tie-beam that was reinforced concrete beam with 5x6 cm section. The stiffness of the tie-beam was controlled by the number of the reinforcement steels(diameter = 6.0 mm), as shown in fig. 3.



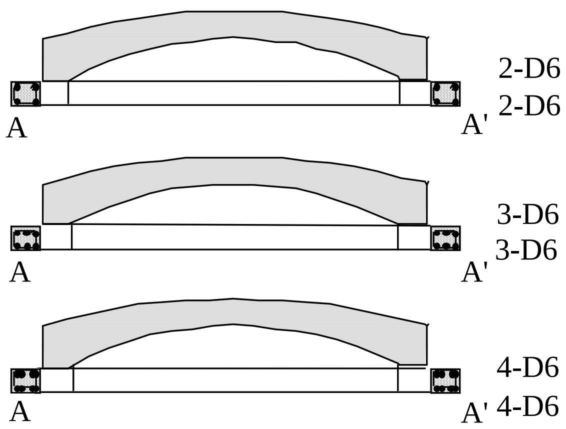


Fig.3 Steel Arrangement and Testing models

Single-layer of reinforcement steels (diameter = 1.2 mm) were arranged in diagonal direction in the shell part. In the thick part at the corner, however, double-layer of steels were arranged. The slender steel(1.2 mm) had the yield strength of 440 MPa and Young's modulus of 251 GPa, and another steel(6.0 mm) had 424 MPa yield strength, 214 GPa Young's modulus.

The concrete of the model was made using normal Portland cement and 1.2 mm maximum size aggregate. The names of the models and material properties of concrete are given in tab. 1. The name gives the number of the reinforcement steels in the tie-beam, i.e., the model 4R16 has four reinforcement steels. And R16 means the rise 16 cm. The shell thickness of the models are also given in tab. 1. And it indicates that the real thickness was considerably thick than the designed value.

Table.1 Properties of concrete and shell thickness

Model	Compressive strength (MPa)	Tensile strength (MPa)	Young's modulus (GPa)	Poisson's ratio	Thickness (mm)	
					Design	Real
4R16	32.5	2.99	21.9	0.17	8.00	10.9±1.9
6R16	33.4	3.14	20.9	0.19	8.00	9.48±1.31
8R16	30.7	2.98	21.2	0.18	8.00	10.4±1.3

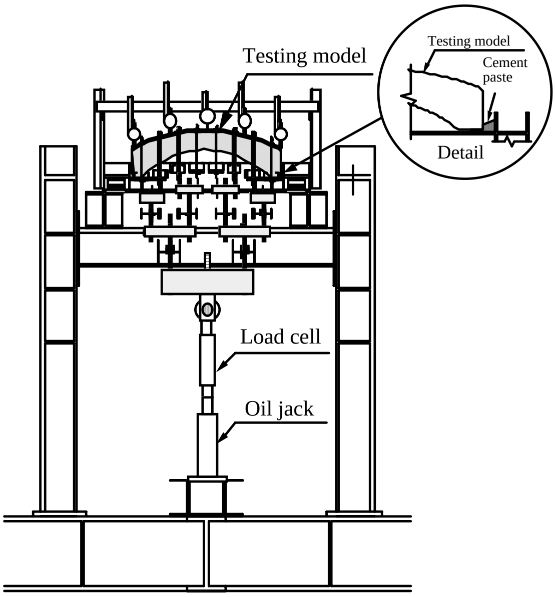


Fig.4 Testing Apparatus

Fig. 4 shows the tournament system testing apparatus. Loads were applied monotonically in the incremental manner until the model reached the failure state. The friction between tie-beam and apparatus was removed by Teflon sheets.

4. Finite Element Analysis

Analyses were performed considering geometrical and material nonlinearity. The layered degenerated shell element was used to simulate the response of free-formed reinforced concrete shell. The reinforcement steels were treated as steel layers with equivalent thickness. Each steel layer was assumed to have a uniaxial behavior resisting only the axial force in the bar direction. Each element, which was Heterosis element with nine nodes, consisted of eight concrete layers and two steel layers, as shown in fig. 5. The elements in the part of double-layered reinforcements had four steel layers.

Fig. 6 shows the finite element mesh used in this analysis. The model, which was divided into 34 elements, is a half of the model considering the symmetry. The stiffness of the tie-beam was represented by the elastic spring equivalent to the reinforcement steels in the tie-beam at the supporting points. The dimensions of the models, material properties and loading conditions, used in

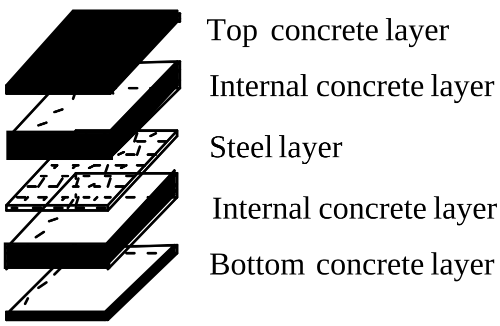


Fig.5 Layer Model

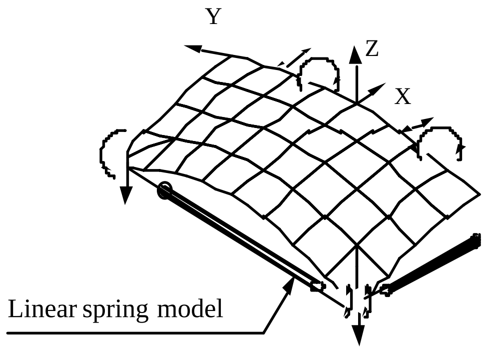


Fig.6 Finite element mesh

this analysis, were same as those of the experimental models.

5. Results of Analyses and Experiments

Tab. 2 gives the names and the ultimate loads of all models. It is recognized in this table that the ultimate loads of the models in the experiments were close to each other and to the analytical results. The most stiffened model (8R16) , however, had lower ultimate load than other models, because it had a thinner part than surroundings at one corner. It was recognized that the ultimate load of free-formed concrete shell was considerably affected by the shell thickness.

Table.2 Ultimate loads of models

Model	Experiment P(kN)	Analysis P(kN)	Ex/An
4R16	94.9	76.0	1.25
6R16	96.7	81.0	1.19
8R16	77.6	78.0	0.99

Fig. 7 shows the load-displacement curves of all models. The stiffness of the model (8R16) with high tie-beam stiffness was relatively high than those of the models with lower tie-beam stiffness. The effect of the support condition was clear in the stiffness of the model.

The comparison of analytical and experimental results of load-displacement curves of the models is given in fig. 8. It shows the good agreement in the tendency of the stiffness of the models.

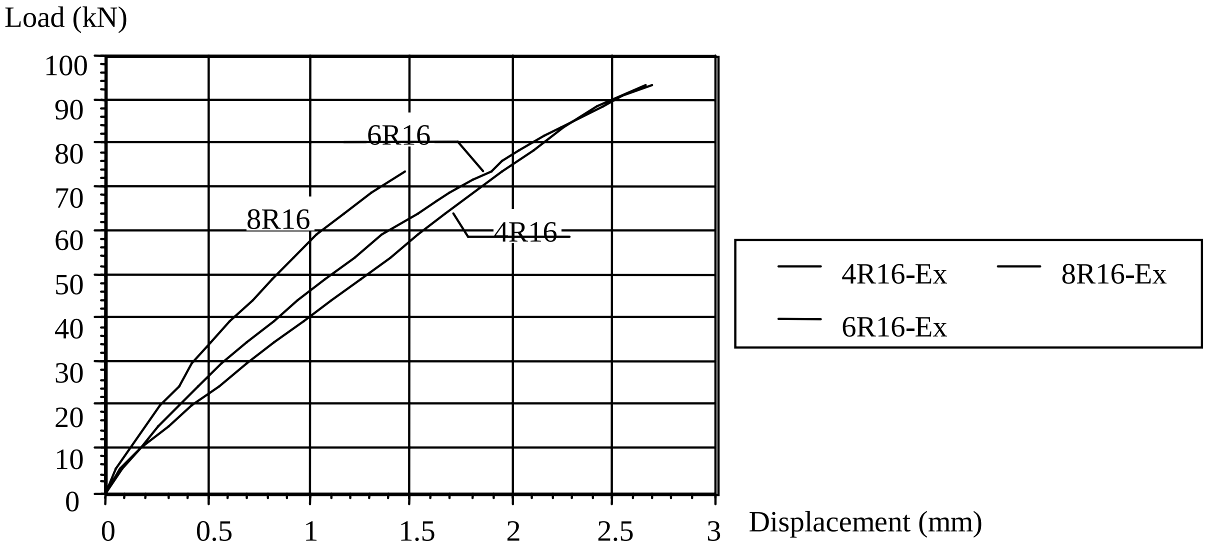


Fig.7 Load-Displacement Relations of Experimental Models

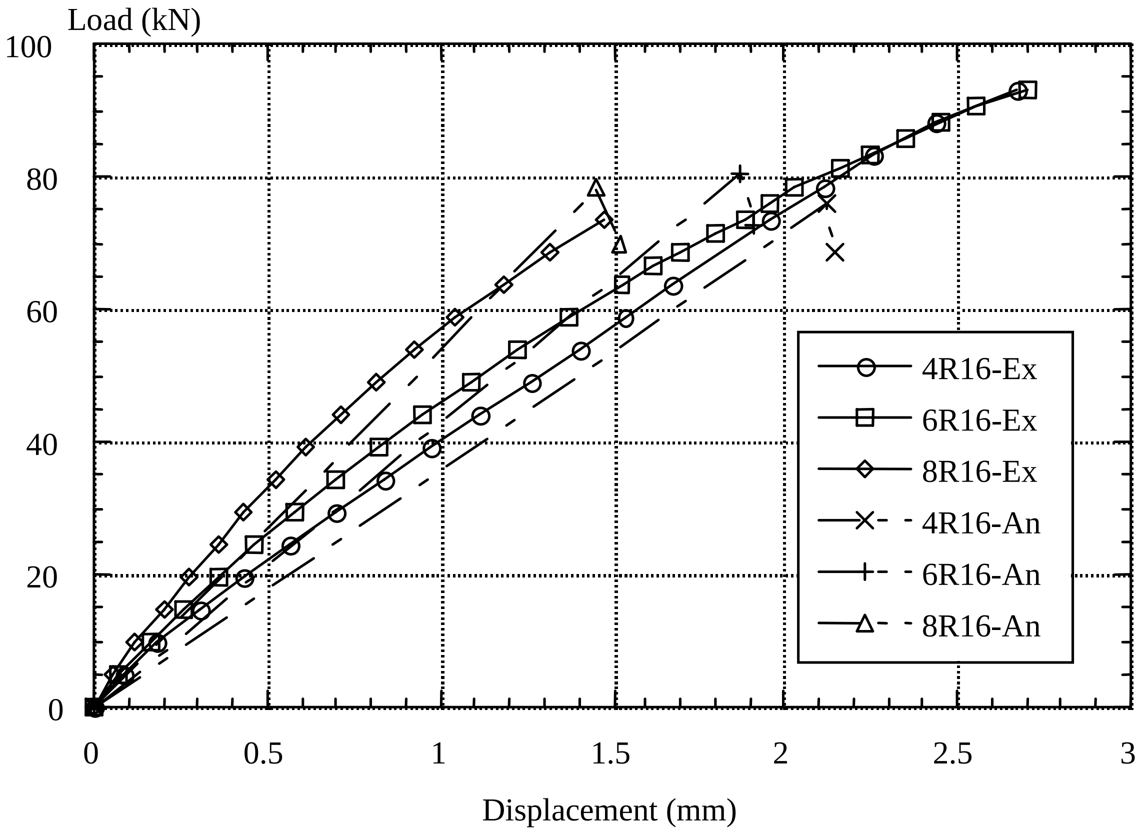


Fig.8 Load-Displacement Relations of Analytical and Experimental Models

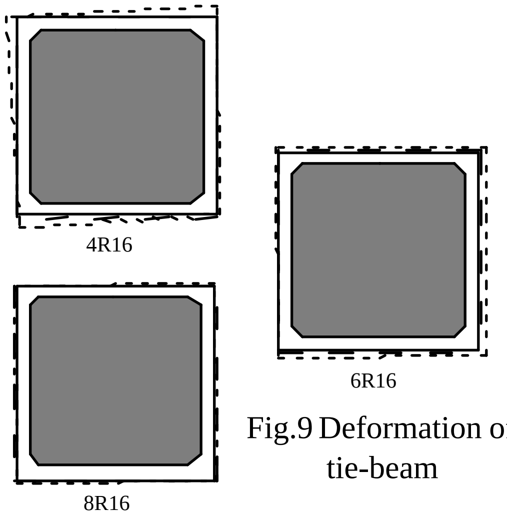


Fig.9 Deformation of tie-beam

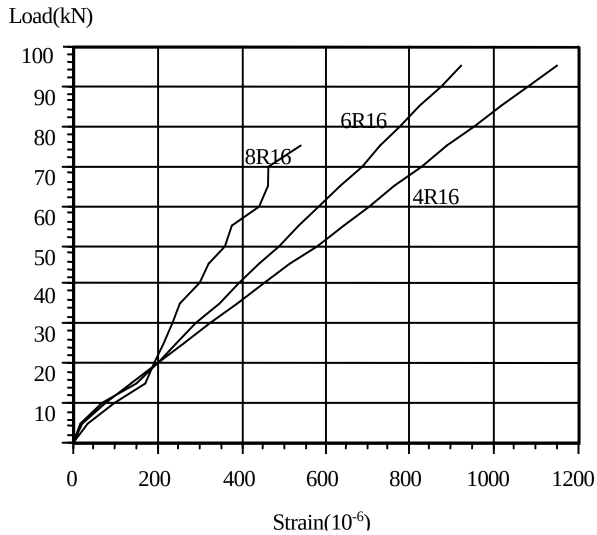


Fig.10 Load-Strain Relationship

Fig. 9 shows the mode of horizontal deformation of the tie-beam. It is recognized that the deformation increased as the stiffness of the tie-beam reduced. And the load-strain relation of the reinforcement steel in the tie-beam is given in fig. 10. The same tendency is recognized in this figure. And fig. 10 also shows that the reinforcement steels in the tie-beam remained the elastic state.

Fig. 11 shows the crack patterns of the testing models after failure. In all testing models, a part near the supporting point at the corner was folded or dimpled suddenly. Some of the long diagonal cracks, however, occurred after failure.

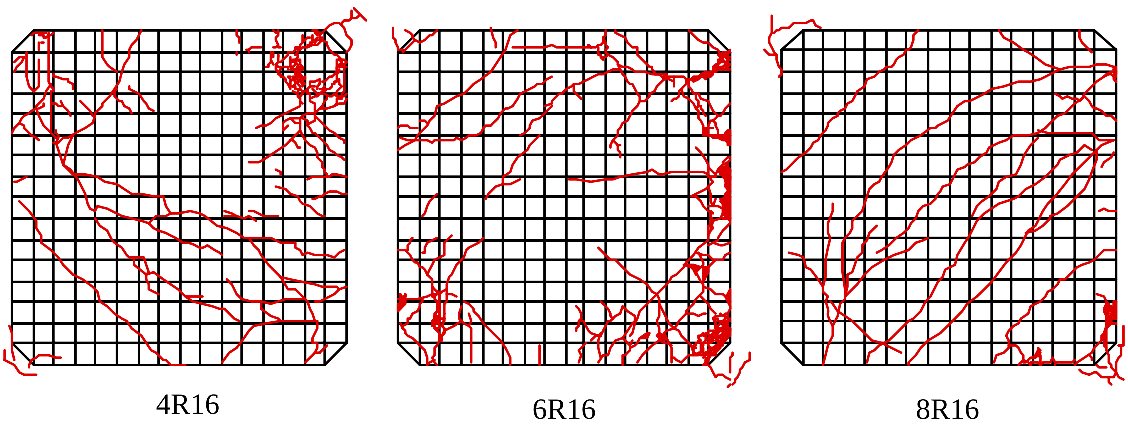


Fig.11 The Crack Patterns

6. Conclusions

Buckling behaviors of free-formed reinforced concrete shell were investigated experimentally and analytically on the effect of the tie-beam stiffness, support condition. These results indicate that the stiffness of the free-formed concrete shell is considerably affected by the tie-beam stiffness. In these models, however, the load capacity of the shell was not so affected by the tie-beam stiffness. The deviation between the analytical results and the experimental results suggests that the buckling behaviors of free-formed reinforced concrete shell are also affected considerably by the shell thickness.

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