Study of Spherical Steel Shell Buckling

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ABSTRACT

Buckling test and linear buckling analysis were performed on the spherical steel shell structure. In general, measured buckling loads are less than the values obtained by analysis and the knock-down factors are usually defined as the ratios of the experimental buckling loads to the analytical values. The knock-down factors derived from the study are as follows:

For horizontal direction: 0.47 ∿ 0.57
For vertical direction : 0.40 ∿ 0.60

The allowable buckling stress can be evaluated by using a knock-down factor and a safety factor. A simple and practical method for evaluating the allowable buckling stress for spherical shell has been proposed as a result of the study.

1. INTRODUCTION

The buckling evaluation method has been already clearly specified for the cylindrical shell and is widely in use, however the method for the spherical shell has not necessarily been clearly defined and the available experimental data for the buckling evaluation are still insufficient in Japan.

Buckling test and analysis were performed in order to establish the basis for the evaluation of a spherical shell under seismic loads. Figure 1 shows the flow of the present study.

It is rather difficult to estimate the buckling stress only with analysis because of complicatedness of the buckling phenomenon which is not the outcome of a stable equilibrium. That necessitates both experimental and analytical approaches for the evaluation. Comparisons were made between experimental buckling loads and analytical ones and therefrom the knock-down factors (reduction coefficients), which were defined as the ratios of the former values to the latter, were derived. The allowable buckling stresses for the spherical shell are evaluated by multiplying the analytical values by the knock-down factors and a safety factor. Those allowable stresses are to be compared with the shell stresses imposed by seismic loads in the confirmation of the integrity of the shell under seismic conditions.

2. BUCKLING TEST

2.1 Outline of the Test

It is generally known that a spherical shell is imposed by three different buckling modes, shear, meridional and circumferential buckling modes, as shown in Figure 2. These three modes of buckling take place, as shown in Figure 3, in the following load cases;

Horizontal loading: Shear, meridional and circumferential mode,
Vertical compression loading: Meridional mode,
Vertical tension loading: Circumferential mode.

All of the above buckling modes were considered in the design of the test arrangement with the static load and the load-displacement relation, the buckling loads and the buckling modes were investigated.

(1) Test model and arrangement

Figure 4 shows the basic dimensions of the model and the arrangement of the test facility is shown in Figure 5. The inner diameter and thickness of the steel shell model are 1120mm and 0.7mm, respectively. The lower part of the models were rigidly fixed on the base plate and the load was statically applied at the center of the top flange.

(2) Test conditions

The test conditions are shown in Table 1. The test matrix was determined in view of the loading directions (horizontal, vertical and their combination) and corresponding buckling modes. Five cases of test were conducted and two models were tested in every case.

(3) Measured items

The following items were measured in every test case;

Initial imperfection
Load
Displacement
Strain
Buckling mode, etc.

2.2 Test Results

Table 2 summarizes the results of the tests together with the analytical results. The experimental buckling loads in the horizontal and vertical directions are $5 \sim 7$ tons and $13 \sim 19$ tons, respectively.
The cases No.1 through No.6 in Table 2 are horizontal load cases. All of the three buckling modes took place in these tests: meridional buckling in case 1 and 5, circumferential buckling in cases 2 and 6, and shear buckling in cases 3 and 4. This variation of buckling mode can be attributed to the effects of the initial imperfection as well as the thickness of the model shell. And further, buckling load values of each mode shall be considered nearly equal. The cases No.7 and 8 are vertical compression load cases where only meridional buckling mode was observed. The cases No.9 and 10 are vertical tension load cases and only circumferential buckling mode was observed as expected.

3. ANALYSIS

Linear buckling analysis was carried out with a finite element method in order to derive the knock-down factors under the same load conditions as in the tests. An axisymmetric shell FEM program was used for the calculation. The spherical shells analyzed are perfect ones with the same thickness value as the measured. The analysis results are shown in Table 2. The horizontal and vertical buckling loads obtained by analysis are $10 \sim 12$ tons and $29 \sim 37$ tons, respectively. The analysis for the horizontal load cases resulted in only shear buckling mode and for the vertical load cases the same results as of the tests were obtained.

4. BUCKLING EVALUATION METHOD

The knock-down factors have been derived as the ratios of the measured buckling loads to those values obtained by the analysis. The values range from 0.47 to 0.57 for the horizontal direction, and from 0.40 to 0.60 for the vertical direction. The minimum values of the knock-down factor for each direction, which are shown in Table 3, are used together with a safety factor in the evaluation of the allowable buckling stresses. As the safety factor, 1.5 is assumed from the engineering point of view. Equation (1) given in Figure 5 has been proposed for the buckling evaluation of a spherical shell on the basis of the ratios of the shell stress to the allowable buckling stress. The equation requires that the linear combination of the ratios in the horizontal and the vertical directions with the knock-down factors and the safety factor as the combination coefficients should be equal to or less than 1.

5. CONCLUSION

The buckling test and analysis were performed on the spherical steel shell structure, which resulted in the knock-down factors for the horizontal and vertical directions. On the basis of the test and analysis results, a simple buckling evaluation equation for the spherical shell has been proposed.

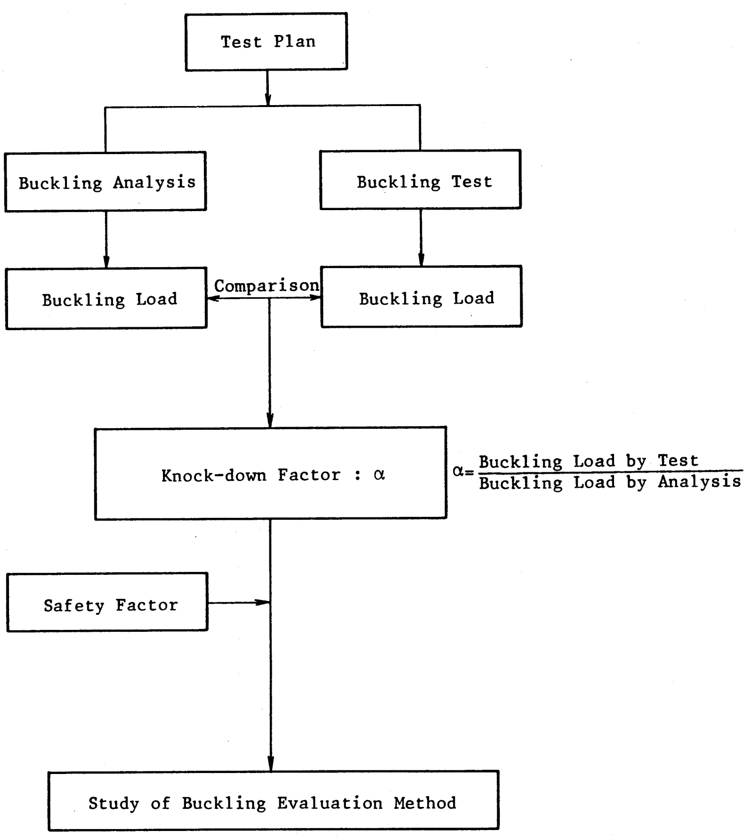


Fig. 1 Buckling Test Flow Chart

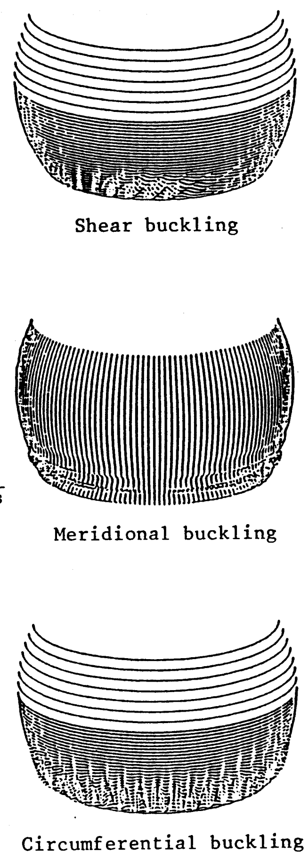


Fig. 2 Buckling Mode

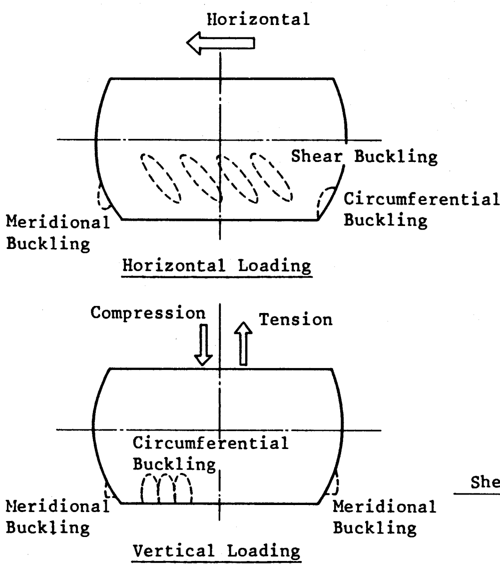


Fig. 3 Buckling Mode of Each Load Condition

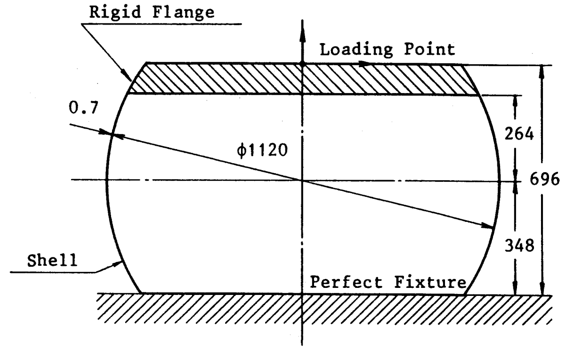


Fig. 4 Basic Specification of Test Model

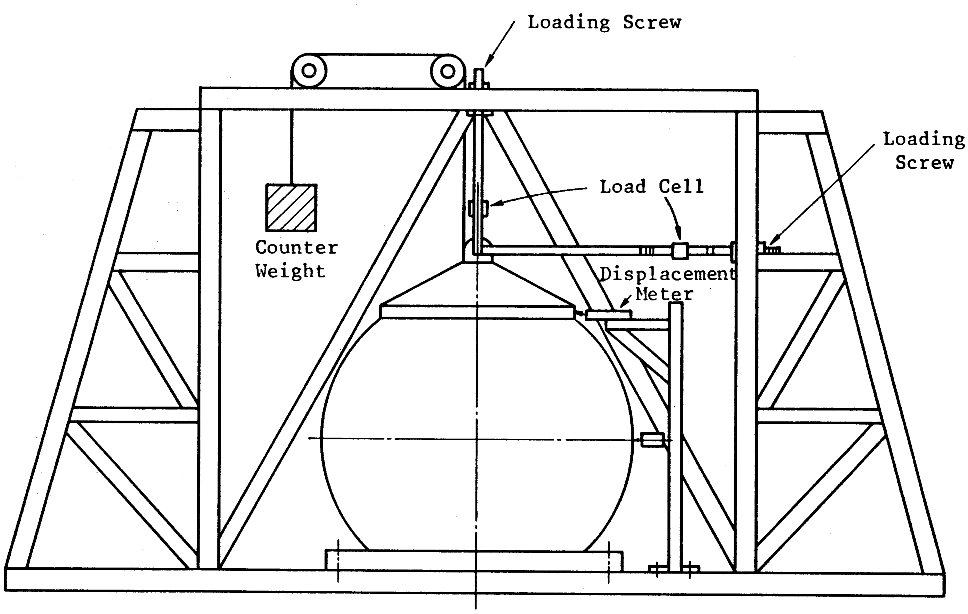
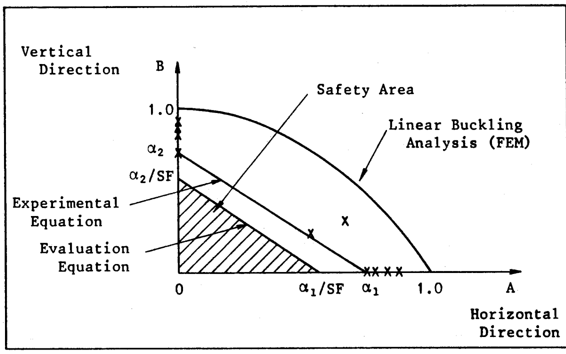


Fig. 5 Test Installation



$A = \frac{\text{Calc. membrane stress}}{\text{Calc. buckling stress}}$ for horizontal loads

$B = \frac{\text{Calc. membrane stress}}{\text{Calc. buckling stress}}$ for vertical loads

α_1 = Knock-Down-Factor for horizontal loads only (0.47)

α_2 = Knock-Down-Factor for vertical loads only (0.40)

Linearized equation from the experiments:

$$B = \frac{-\alpha_2}{\alpha_1} A + \alpha_2 \dashrightarrow \frac{A}{\alpha_1} + \frac{B}{\alpha_2} = 1$$

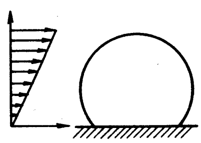
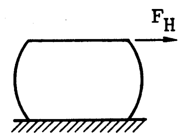
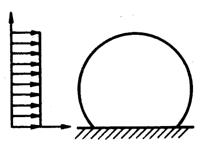
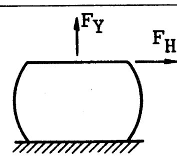
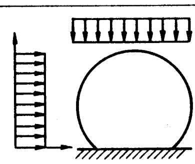
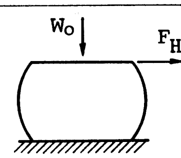
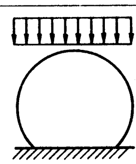
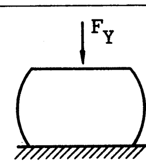
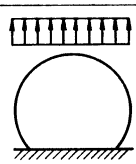
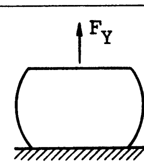
Evaluation equation considering a safety factor SF:

$$\frac{SF}{\alpha_1} A + \frac{SF}{\alpha_2} B \leq 1 \quad (1), \text{ i.e.}$$

$$\frac{1.5}{0.47} A + \frac{1.5}{0.40} B \leq 1$$

Fig. 6 Buckling-Evaluation-Diagram

Table 1 Test Matrix

No.	Load Condition				Remark
	Actual Plant		Test Model		
1	Horizontal		Horizontal		α_1
2	Horizontal		Combination (Horizontal + Vertical)		α_1
3	Combination (Horizontal + Vertical)		Combination (Horizontal + Vertical)		α_1 α_2
4	Vertical Compression		Vertical Compression		α_2
5	Vertical Tension		Vertical Tension		α_2

α_1 : K.D.F. at horizontal direction
α_2 : K.D.F. at vertical direction

Table 2 Buckling Test and Analysis Result

No.		Buckling Load by Test (Ton)			Buckling Load by Analysis (Ton)			Knock-down Factor
		Horizontal	Vertical		Horizontal	Vertical		
			Compression	Tension		Compression	Tension	α
1	A	5.5	-	-	11.8	-	-	0.47
	B	5.5	-	-	9.7	-	-	0.57
2	A	6.6	-	1.7	12.3	-	3.1	0.54
	B	5.3	-	1.3	9.7	-	2.4	0.55
3	A	4.3	4.0	-	12.7	37.3	-	Horizontal: 0.34 Vertical : 0.11
	B	6.3	5.0	-	10.0	29.1	-	Horizontal: 0.63 Vertical : 0.17
4	A	-	12.9	-	-	32.5	-	0.40
	B	-	15.2	-	-	28.7	-	0.53
5	A	-	-	19.2	-	-	36.7	0.52
	B	-	-	18.5	-	-	30.6	0.60

Table 3 Knock-down Factor

Load Direction	Knock-down Factor
Horizontal	0.47
Vertical Compression	0.40
Vertical Tension	0.52