Experimental and Numerical Tests for Buckling Characteristics of Spacer Grids in PWR Fuel Assembly

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ABSTRACT

This study contains the buckling tests and finite element analysis for small size grid samples and full size spacer grids. The buckling tests and finite element analysis were performed to evaluate the buckling characteristics of PWR spacer grids. The buckling tests were performed for the full size spacer grids and small size grid samples having several different number of rows and columns of grid. Eigenvalue buckling analyses were also performed by a finite element method using ANSYS program and the results were compared with experimental test results. Based on the test and analysis results, the correlation between the buckling strength of the full size spacer grid and that of small size grid samples were derived. As a result, the buckling strength of the full size spacer grid can be predicted by the buckling strength of small size grids and it can be used for the selection of a new grid model among various proposed ones considering buckling strength during the development of new grid design.

INTRODUCTION

The spacer grids of PWR fuel support the fuel rods along their length and maintain the lateral spacing between the rods throughout the design life of the fuel assembly. The fuel rod of the 17X17 type fuel assembly considered in this study is supported at six points within each grid cell by a combination of springs and dimples. Each grid is composed of interconnected array of slotted grid straps, that are welded at the intersections to form a lattice-like plate structure[1]. The spacer grid impacts with the baffle plate and/or spacer grid of neighboring fuel assembly during the seismic and LOCA(Loss of Coolant Accident). The spacer grid should maintain the lateral spacing between the rods under both the operational and the accident loading conditions, such as seismic and LOCA, to maintain the coolability of the reactor core geometry[2]. The impact test of spacer grid has been performed at an operating temperature to verify the requirements for accident conditions.

It is well known that buckling strength varies principally with strap thickness and weld penetration but also with spring and dimple shapes, cell windows etc[3]. When developing new spacer grids, various proposed models may be tested with small size samples before fabricating full size prototype model. In this study, the buckling tests and finite element analyses for small size grid samples and full size spacer grids were performed to evaluate the buckling characteristics of PWR spacer grids. The buckling tests were performed for the full size spacer grids and the small size grid samples having several different number of spacer grid cells, e.g. 1X1, 1X2, 1X3, ... , 1X17, 2X1, 2X2, ... , 2X17, 3X17 etc. Numerical analyses were also performed by a finite element method using ANSYS program[4] and the results were compared with the experimental test results.

Based on the test and analysis results, the correlation between the buckling strength of the full size spacer grid and that of small size grid samples were derived. The static buckling strength of the full size spacer grid can be predicted by the buckling strength of small size grid specimens and numerical analysis results and it can be used for selection of a new grid model among various proposed ones considering buckling strength. It is shown that the critical buckling strength of spacer grids having same number of row increases linearly as the number of column increase, while the critical buckling strength of spacer grids having same number of column rapidly decrease as the number of row increase. Also, the buckling modes of each specimen that has different number of cells were characterized. The buckling modes of each spacer grid specimen were quite different depending on the configuration of the spacer grid specimen. Each spacer grid specimen has its own buckling mode depending on its configuration but the typical failure mode of grid was a rotational failure at the welded position of grid strap intersects.

BUCKLING OF RECTANGULAR PLATE

The differential equation of plate buckling under the action of in-plane forces N_x, N_y, and N_{xy} can be written by

$$D\left(\frac{\partial^4 w}{\partial x^4}+2\frac{\partial^4 w}{\partial x^2 \partial y^2}+\frac{\partial^4 w}{\partial y^4}\right)=N_x\frac{\partial^2 w}{\partial x^2}+N_y\frac{\partial^2 w}{\partial y^2}+2N_{xy}\frac{\partial^2 w}{\partial x \partial y} \tag{1}$$

$$\text{with } D = \frac{Et^3}{12(1-\nu^2)}$$

When a simply supported rectangular plate is subjected to uniaxial in-plane forces N_x, letting $N_y = N_{xy} = 0$, the differential equation of plate bending, Eq. (1), reduces to

$$D\left(\frac{\partial^4 w}{\partial x^4} + 2\frac{\partial^4 w}{\partial x^2 \partial y^2} + \frac{\partial^4 w}{\partial y^4}\right) + N_x \frac{\partial^2 w}{\partial x^2} = 0 \tag{2}$$

The minimum critical load can be obtained by solving Eq. (2) as follows [5] :

$$(N_x)_{cr} = \frac{4\pi^2 D}{b^2} \tag{3}$$

where, $(N_x)_{cr}$: Critical Compressive Load per Unit Distance,
D : Flexural Rigidity, E : Elastic Modulus, ν : Poisson's Ratio
b : Width of the Plate, t : Thickness of the Plate,

The above equation is applicable to the simply supported rectangular plate subjected to uniaxial in-plane forces. In case of spacer grid strap, the geometrical shape and boundary conditions are somewhat different from the rectangular plate that is considered in Eq. (2). Several windows and slots exist for spring and dimples on the strap of spacer grid. It can be said that the boundary conditions are the combination of simply supported and clamped conditions. Therefore, the above equation cannot be directly used for the study of grid buckling analyses, but it is presumed that the buckling strength is proportional to third power of plate thickness and second power of plate width. In this study, the buckling strength of grid strap was calculated using commercial finite element program, ANSYS 5.6 and the results were compared with the buckling strengths from the static buckling tests.

STATIC BUCKLING TESTS AND RESULTS

Five full size spacer grids and fifty small size grid samples were prepared for the static buckling test. The full size spacer grids are sectioned into small size grid samples. Table 1 shows the number of small size grid samples and full size spacer grids used in static buckling test. The configuration of test setup is shown in Figure 1. Figure 2 shows the shape of small size grid samples and full size spacer grids. The mechanical properties for the spacer grid straps are given in Table 2. The buckling test for small size grid and full size grid were performed using universal test machine. The compressive loads acting on the grids were measured as a function of deflection during the buckling test. The buckling loads are summarized in Table 3 and the buckling modes are shown in Figure 2. The buckling load of grids as a function of the number of columns for the case of 1, 2, 3, and 17 rows are shown in Figure 3. Figure 4 shows the buckling load of grids as a function of the number of rows for the case of 17 columns.

EIGENVALUE BUCKLING ANALYSIS AND RESULTS

The finite element analyses were performed to identify the effect of the number of rows and the number of columns on the buckling load of full size grid and small size grid samples having several different number of spacer grid straps. The eigenvalue buckling analyses were carried out for the buckling characteristic of spacer grid straps by using ANSYS 5.6[4]. The geometrical dimensions of spacer grid straps for analytical model are shown in Figure 5. The finite element models were generated for 1, 2, 3, 4, and 5 straps in vertical direction and 1, 2, 3, 4, and 5 straps in horizontal direction. The finite element model is consists of 4 node quadrilateral elastic shell elements, SHELL63. Each cell of the models consists of 1,545 elements and 1,773 nodes. Figure 6 shows the shape of small size grid strap models and boundary conditions that is used for the eigenvalue buckling analyses. The eigenvalue buckling analyses were performed for the grid strap models. Table 4 shows the buckling load of plate having several different number of spacer grid straps. The eigenvalue buckling strength as a function of the number of cells are shown in Figure 3 and 4. The buckling modes of 1, 2, 3, 4, and 5 cell models in vertical direction are shown in Figure 7. The buckling modes of 1, 2, 3, 4, and 5 cell models in horizontal direction are same as that of 1, 2, 3, 4, and 5 cell models in vertical direction.

DISCUSSIONS

The Effects of the Number of Row and Column

Figure 3 shows the buckling load of grids as a function of the number of columns for the case of 1 and 2 rows. It is shown that the critical buckling strength of spacer grids having same number of row increases linearly as the number of column increases. The buckling strength of small size grid is proportional to the number of horizontal cells and inverse proportional to the number of vertical cells as shown in Table 3 and Figure 3. Figure 4 shows the buckling load of grids as a function of the number of rows for the case of 17 columns. The effects of the number of rows on the buckling strength of spacer grids were more sensitive for the case of smaller number of rows and the effects are decreased as the number of rows increase. It is evaluated that there are some transition number of rows that buckling strength is not inverse proportional to the number of vertical cells in relation to the buckling mode.

Buckling Mode

The buckling modes of small size grid and full size grid specimens are shown in Figure 2 and the buckling modes for the analytical models are shown in Figure 7. Each spacer grid specimen has its own buckling mode depending on its configuration but the typical failure mode of grid was a rotational failure at the welded position of grid strap intersects. The buckling modes of 1 row grids, 1X1, 1X2, 1X3, 1X4 and 1X5, and 2 row grids, 2X1, 2X2, 2X3, and 2X9, are same as the first mode of the each analytical model for 1 row and 2 row grids as shown in Figure 2 and Figure 7 for the 1 to 3 vertical row models except 1X17 model. It is evaluated that the buckling mode of 1X17 specimens should be same as that of 1X1, 1X2, 1X3, 1X4 and 1X5 grids. However, there was some horizontal sliding at the upper end of the vertical strap of 1X17 specimen during buckling test. As a result of the sliding, the buckling strength was decreased compare to the expected buckling strength of 1X17 specimen and the buckling mode was different from the same kind of specimens such as 1X1, 1X2, 1X3, 1X4 and 1X5. There were three different kind of buckling modes for the full size grids as shown in Figure 2. The buckling strengths are 1,965 lbs, 1,771 lbs, 1,452 lbs for buckling mode 1, 2, 3 of full size grids, respectively. Most of full size grids were buckled with buckling mode 3. The buckling mode 3 was same as the buckling mode of beam with clamp boundary conditions at both ends. And, the buckling strengths of full size grid were lowest value when the grid buckled with mode 3. Based on the evaluation of buckling strength and mode shape of 17X17 grids, the buckling strength of grids should be considered with the buckling mode of grids.

Prediction of Buckling Strength

Based on the test and analysis results, the correlation between the buckling strength of the full size spacer grid and that of small size grid samples were derived as shown in Figure 3 and 4. The buckling strength of small size grid that has several number of horizontal cell can be predicted using that of unit cell grid that has the same number of vertical cells as shown in Figure 3. And, the buckling strength of small size grid that has several number of vertical cell can be also predicted using that of unit cell grid that has the same number of horizontal cells as shown in Figure 4. As a result, the static buckling strength of the full size spacer grid can be predicted by the buckling strength of small size grid specimens and numerical analysis results and it can be used for the selection of a new grid model among various proposed ones considering buckling strength during the development of new grid design.

CONCLUSIONS

The buckling tests and finite element analysis for small size grid samples and full size spacer grids were performed to evaluate the buckling characteristics of PWR spacer grids. The buckling tests were performed for the small size grid samples having several different number of spacer grid cells and the full size spacer grids. Numerical analyses were also performed by a finite element method using ANSYS program and the results were compared with experimental test results. Based on the test and analysis results, the correlation between the buckling strength of the full size spacer grid and that of small size grid samples were derived.

(a) The buckling strength of small size grid is proportional to the number of horizontal cells and inverse proportional to the number of vertical cells as shown in Table 3 and Figure 3.
(b) It was shown that the buckling modes of the small size grid that has the same number of vertical row were same.
(c) The buckling strength of small size grid that has several number of horizontal cell can be predicted using that of unit cell grid that has the same number of vertical cells. And, the buckling strength of small size grid that has several number of vertical cell can be predicted using that of unit cell grid that has the same number of horizontal cells.

Table 1. Test Matrix of Small Size and Full Size Grids

Items		Quantity (EA)
Small Size Grids	1 ROW (1X1, 1X2, 1X3, 1X4, 1X5, etc.)	26
	2 ROW (2X1, 2X2, 2X3, 2X9, etc.)	20
	3 ROW (3X17)	4
Full Size Grids	17 ROW (17X17)	5

Table 2. Mechanical Properties of Grid Strap

Items	Values
Young's Modulus (at 70°F, psi)	14.3×10^6
Posion Ratio	0.3
Yield Strength, 0.2% (Minimum, psi)	43,000
Ultimate Tensile Strength (Minimum, psi)	55,000

Table 3. Static Buckling Test Results

Grid Type	Buckling Strength (lbf)	Grid Type	Buckling Strength (lbf)
1X1	659	2X1	304
1X2	982	2X2	448
1X3	1,315	2X3	654
1X4	1,634	2X9	1,697
1X5	1,931	2X17	3,509
1X17	4,577	3X17	2,663
-	-	17X17	1,618

(Note) Buckling strengths are the average of 3 to 5 samples.

Table 4. Eigenvalue Buckling Analysis Results

Vertical No. of Straps	Buckling Strength (lbf)			Horizontal No. of Straps	Buckling Strength (lbf)	
	Mode 1	Mode 2	Mode 3		1 Row	2 Row
1	416.68	920.52	1206.4	1	416.68	199.29
2	199.29	535.21	598.47	2	833.36	398.72
3	178.35	195.03	438.85	3	1250.04	598.15
4	169.39	187.85	197.52	4	1666.72	797.16
5	149.04	168.99	190.64	5	2083.40	996.45

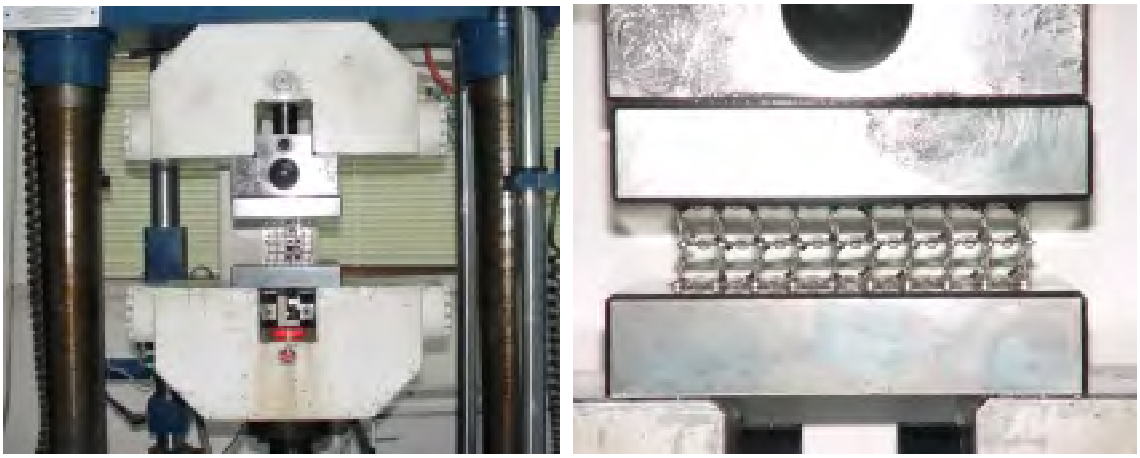


Fig. 1. Configuration of Test Setup

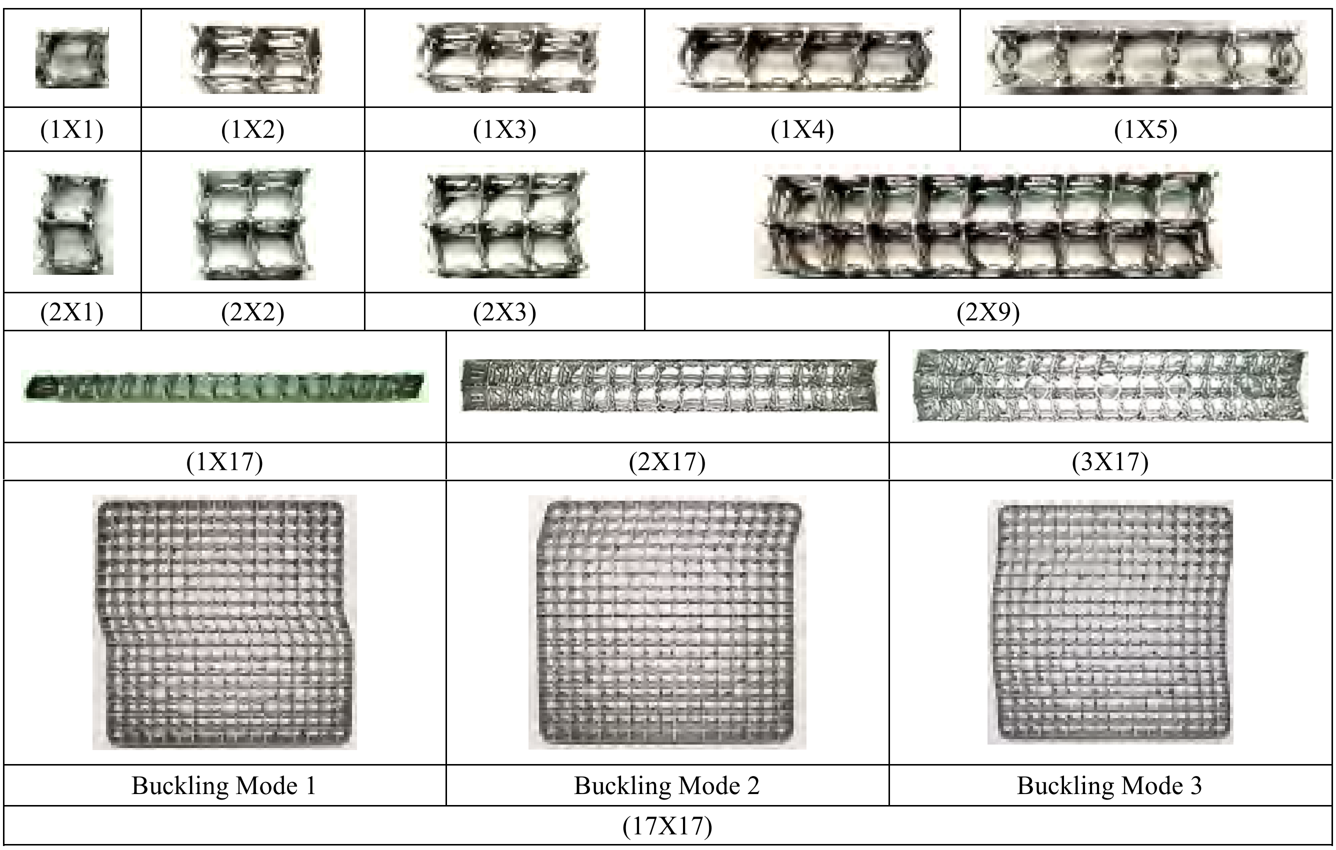


Fig. 2. The Shapes and Buckling Modes of Small Size and Ful Size Grids

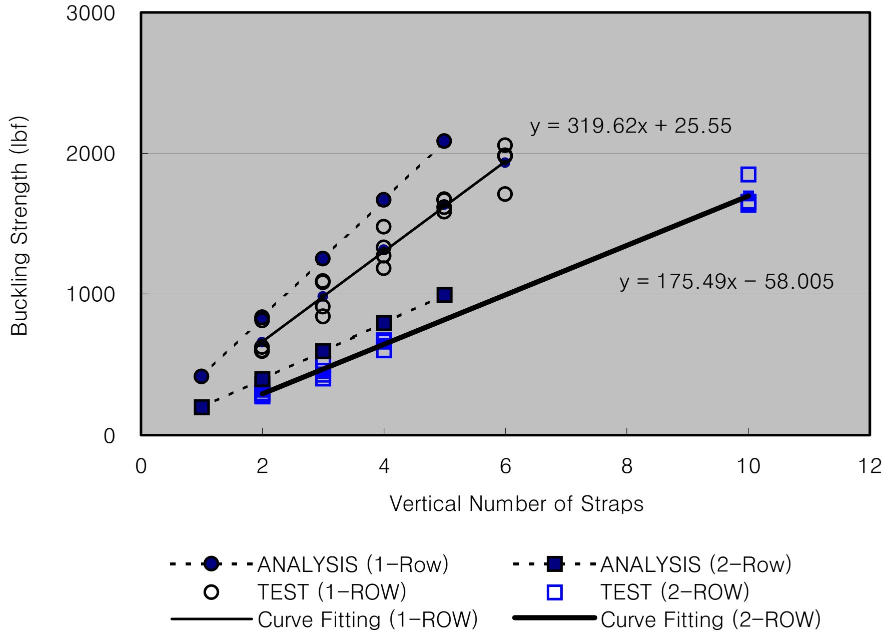


Fig. 3. Buckling Strength as a function of the Number of Straps
(Number of Straps = Number of Columns + 1)

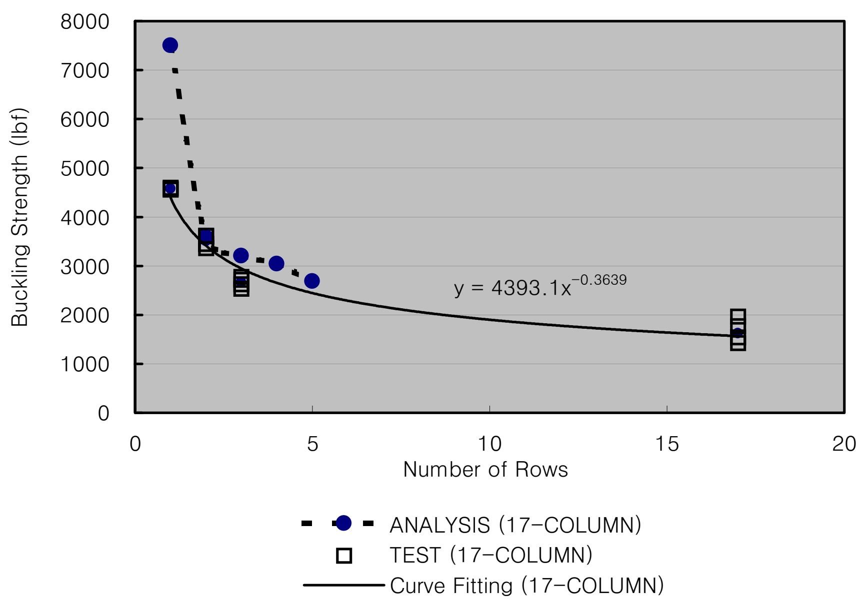


Fig. 4. Buckling Strength as a function of the Number of Rows

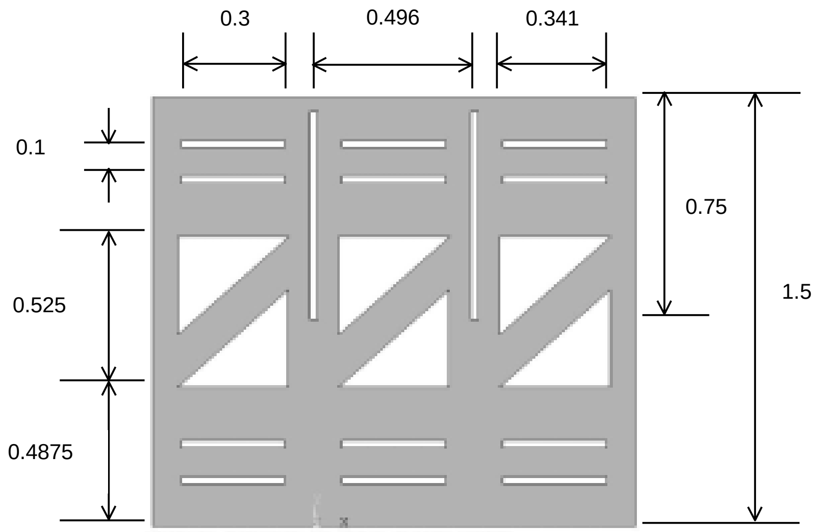
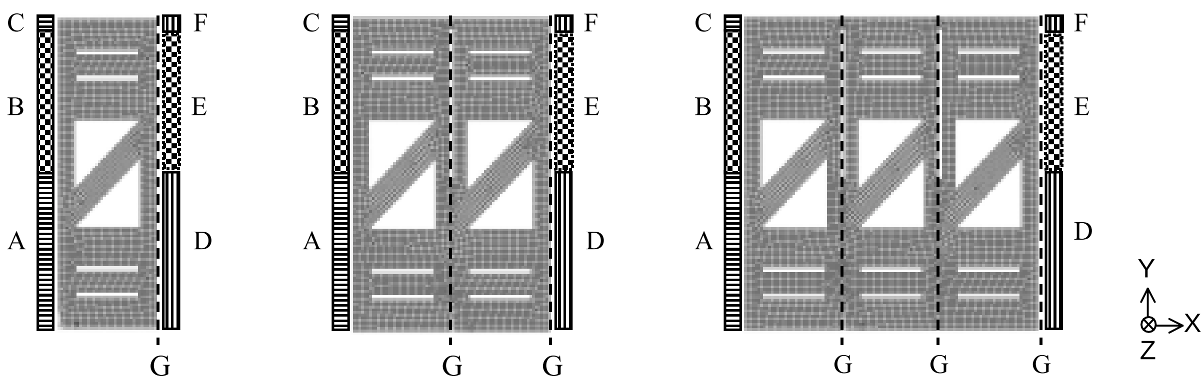


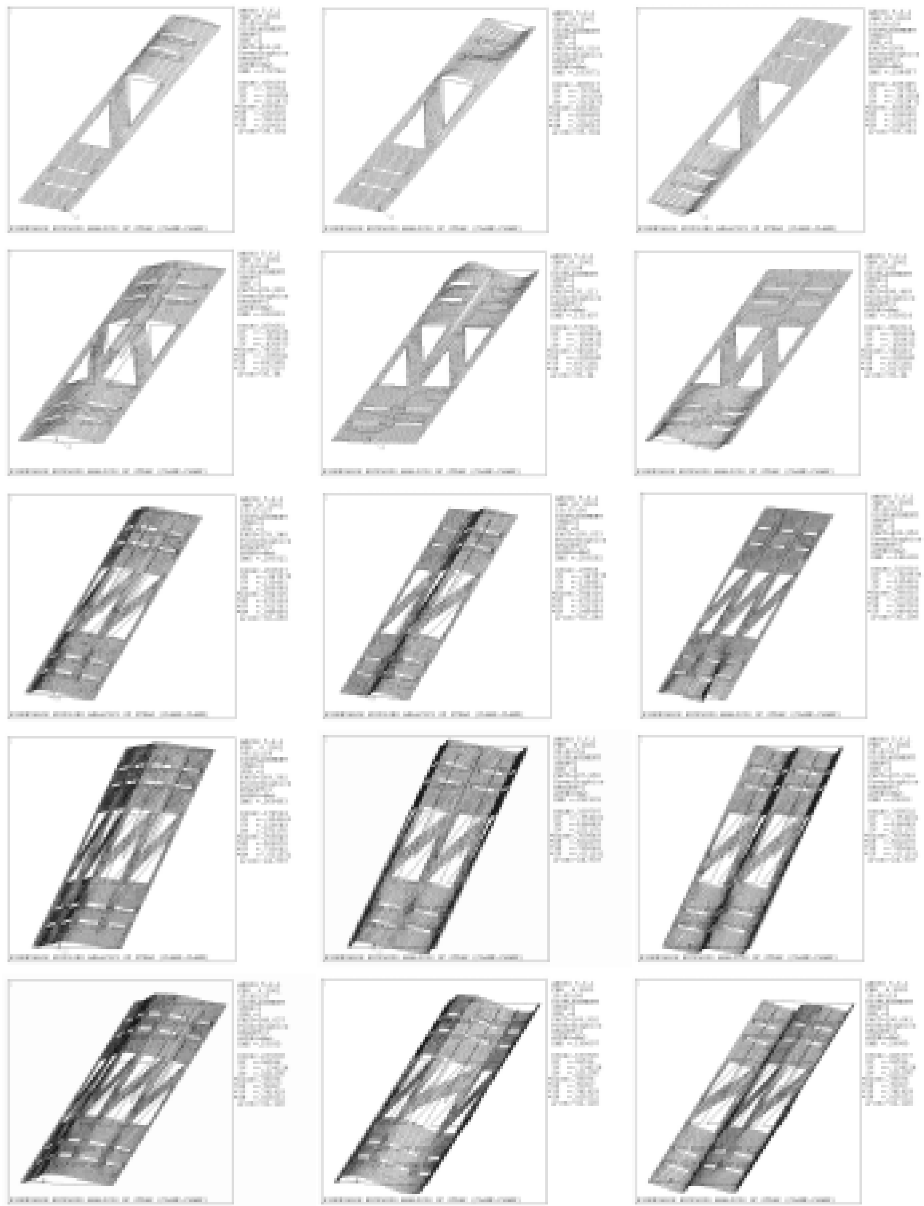
Fig. 5. Geometrical Dimensions of Strap Model (unit : inches)



(a) 1-Cell Strap Model (b) 2-Cell Strap Model (c) 3-Cell Strap Model

A : Ux=Uy=Uz=Rx=Ry=Rz=0, B : Ux=Uy=Uz=0,
C : Ux=Uy=Uz=Rx=Ry=Rz=0, D : Uy=Uz=Rx=Ry=Rz=0,
E : Uy=Uz=0, F : Uy=Uz=Rx=Ry=Rz=0,
G : Displacement Coupling with Ux

Fig. 6. Finite Element Models and Boundary Conditions



(a) 1-Cell Strap Model

(b) 2-Cell Strap Model

(c) 3-Cell Strap Model

(d) 4-Cell Strap Model

(e) 5-Cell Strap Model

Fig. 7. Buckling Modes of Analytical Models

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