Buckling Analysis for Grid Assembly of PWR Fuel

N. TSUMURA, T. KAWAGOE
Mitsubishi Atomic PowerIndustries, Inc., Kobe, Japan
M. IMAIZUMI, I. KARASAWA
Nuclear Development Corp., Tokaimura, Japan

ABSTRACT

The buckling behavior of PWR fuel grid was investigated by the test with the one cell-wize strap, partial grid and full grid assembly. Also based on the test results, the method to predict the buckling strength by FEM analysis was developed.

1 INTRODUCTION

The grid assembly (grid) of PWR fuel assembly, which supports the fuel rods, impacts with the baffle plate and/or the grid of neighbor fuel assembly in the earthquake and for the higher seismic force than its elastic limit the buckling occurs and the plastic deformation is induced. The buckling force has been obtained by the impact test because of the structural complexity of the gird. However in the development of new grid design and design change, it took long period and much cost to manufacture the test sample (grid) and perform the test. The prediction of the grid buckling force by finite element method (FEM) analysis has been tried to avoid this situation.

2 STRUCTURE OF GRID

Figure 1 shows the typical PWR fuel assembly and the grid supporting the fuel rod. The grid is composed of many perforated straps which are braze or welded at the intersection. Two kinds of cell, those are the fuel rod cell (fuel cell) and thimble cell, exist in a grid. In the fuel cell a fuel rod are supported by two grid springs and four dimples which are formed on the strap. In the thimble cell a guide thimble tube is attached to the grid for the guide of control rod insertion. The grid stiffness is not uniform due to existing two kinds of cell.

3 TEST AND ANALYSIS

Figure 2 shows typical buckling mode of the grid obtained by current impact test. The buckling occurred at the row of the fuel cell. From this, we started the test and analysis at first with a one cell-wize strap and extended to the partial grid.

3.1 1 CELL-WIZE START TEST AND ANALYSIS

The bending and buckling test of one cell-wize grid strap was performed to obtain the equivalent stiffness and the buckling force (figure 3). For comparison the FEM analysis was also performed by ANSYS code (open code for structural and thermal analysis). Analytical model is shown in figure 4.

The test and analytical results are shown in table 1. The moment of inertia were obtained respectively in equation (1) from bending test and Euler's equation (2) from buckling test.

$$I = P\ell^3/3Ed \qquad (1)$$

where
- I : equivalent moment of inertia
- P : applied force
- ℓ : strap length (see figure 3)
- d : deflection
- E : young's modulus

$$P_B = \lambda\pi^2 EI/\ell^2 \qquad (2)$$

where
- P_B : buckling force
- λ : constant for end support

Table 1 Test And Analytical Result of 1 Cell-wize Strap

Case	Test		Euler equ.(2)	FEM Analysis	
	P_B(kg)	I(mm^4)	P_B(kg)	P_B(kg)	I(mm^4)
Bending	-	0.0509*1	-	-	0.0547
Buckling	289*2	-	419	323	-

* average of 3 samples
* average of 4 samples

In table 1, Euler's equation gives much higher buckling force of 419 kg than test result of 289 kg nevertheless the experimentally obtained moment of inertia were used in the evaluation. This would be because Euler's equation is for simple beam and the local buckling deformation cannot be considered. While the FEM Analysis predicted about 12% higher buckling force of 323 kg, it was found one of appropriate method for the estimate of grid buckling force.

3.2 PARTIAL GRID TEST AND ANALYSIS

3.2.1 Test

Although the FEM analysis predicted more realistic buckling force than Euler's equation, it was still question that one cell strap result was enough to estimate the buckling force of the full grid because the structural configulation was much different between one cell-wize strap and the full grid assembly and it was very important to specify the buckling mode in predicting the buckling force. So the further buckling test with partial grid was performed to investigate the following effect on the buckling force.

(1) number of cells
(2) the existence of fuel rod (clad)
(3) thimble cell

Test matrix is shown in table 2 and the test samples cut out from 17 × 17 grid are shown in figure 5.

Table 2 Partial Grid Test Matrix

Sample	Fuel clad	Thimble cell	Buckling force (kg)	
			Test*	FEM Analysis
1×1(1)	x	x	435	530
(2)	O	x	466	582
1×2	x	x	154	130
2×1	x	x	667	780
2×4(1)	O	x	333	341
(2)	O	O	431	441
4×2(1)	x	x	411	333
(2)	O	x	654	735
(3)	O	O	877	913
4×4	O	O	758	735

Sign : O with fuel clad inserted (or thimble cell)
x no fuel clad (or thimble cell)
* average of 3 samples

The buckling forces are also shown in table 2 and figure 6, and the buckling modes were shown in figure 7. The detailed discussions are as follows.

Effect of Number of Cell

The effect of horizontal number of the cell can been seen in the comparison 1 × 1 to 2 × 1 without the fuel clad inserted and 2 × 4 to 4 × 4 with fuel clad inserted and a thimble cell. The buckling force is nearly proportional to number of the vertical strap.

The effect of vertical number of the cell is presumed as that of the beam length in Euler's buckling equation (2) and then the buckling force of the grid would be in inverse proportion to a square of number of cell. It is followed by the relation of 1 × 1 to 1 × 2 without fuel rod inserted and a thimble cell. However the decrease of the buckling force in 4 × 4 is much less than expected with comparison to 4 × 2 with fuel clad inserted and thimble cell. It stay about 11%. This is because the buckling occurred in upper half of 2 cell rows without thimble cell and the buckling mode of 4 × 4 was similar to 4 × 2. From this results, the buckling of the grid should be discussed with the buckling mode.

Effect of Fuel Clad

The comparison between with and without fuel clad inserted gives the effect of the fuel clad in 1 × 1 and 4 × 2 test. The buckling force of the grid with fuel clads increased to that without it and its effect was larger in 4 × 2 than 1 × 1.

By inserting the fuel clad into the grid cell, it contacts to the grid springs and dimples and the structural line induces horizontally and vertically. As the result, the horizontal line supports laterally the strap at the mid point of the cell and the vertical line shares some of the applied force to the grid. This could be reason why the buckling force increased with fuel clads inserted. It is easily understood that the contribution of its effect per one strap increased with the grid cell number.

Effect of Thimble Cell

The higher buckling force with a thimble cell was obtained to without it in the 2 x 4 and 4 x 2 test. This is because the thimble tube attached the grid strengthen the grid cell. It is understood from the fact that the thimble cell hardly deformed as shown in figure 7 (d), (g) and (h), and had an effect on the buckling mode. For example, the similar buckling mode of 4 x 4 was obtained in comparison to that of 4 x 2 nevertheless the vertical number of cells increased.

3.2.2 Analysis

The buckling analysis of the partial grid was performed to support the consideration mentioned above, to study the applicability of FEM analysis and to make a model predicting the buckling force of a full grid assembly. Figure 8 show a typical analytical model in which the grid strap was simulated by beam element. The moment of inertia was adjusted to that by the bending analysis of one cell-wize strap. The slant beams were attached to simulate the condition with a fuel rod inserted and thimble tube.
The buckling forces by analysis are shown in table 2 in comparison to the test results and the buckling modes are shown in figure 9. The analytical buckling force was good agreement with the beam theory in the number of cells, that is, the buckling force was proportional to the horizontal number of cells and inversely to a square of the vertical number of cells. Then the equivalent buckling forces were predicted for the similar buckling modes as the test results. Although the FEM analysis showed higher buckling force than the test in the small partial grid (1 x 1, 1 x 2, 2 x 1) and equivalent ones in the larger partial grid (2 x 4, 4 x 2, 4 x 4). This would be because the grid was strengthened with increasing the cell structurally.

The partial grid model was extended to the full model of the grid assembly. The buckling force of 2895 kg was predicted in the analysis in comparison to 2810 kg in the test. Figure 10 shows the typical buckling mode in the analysis, which was also agreed with the test result.

4 CONCLUSION

The grid buckling behavior was investigated by the tests with one cell-wize straps, partial grids and full assemblies. And based on test results, the FEM analytical model was developed and it was considered enough applicable to predict the buckling force of the grid and very effective in the initial stage of the new grid design and design change.

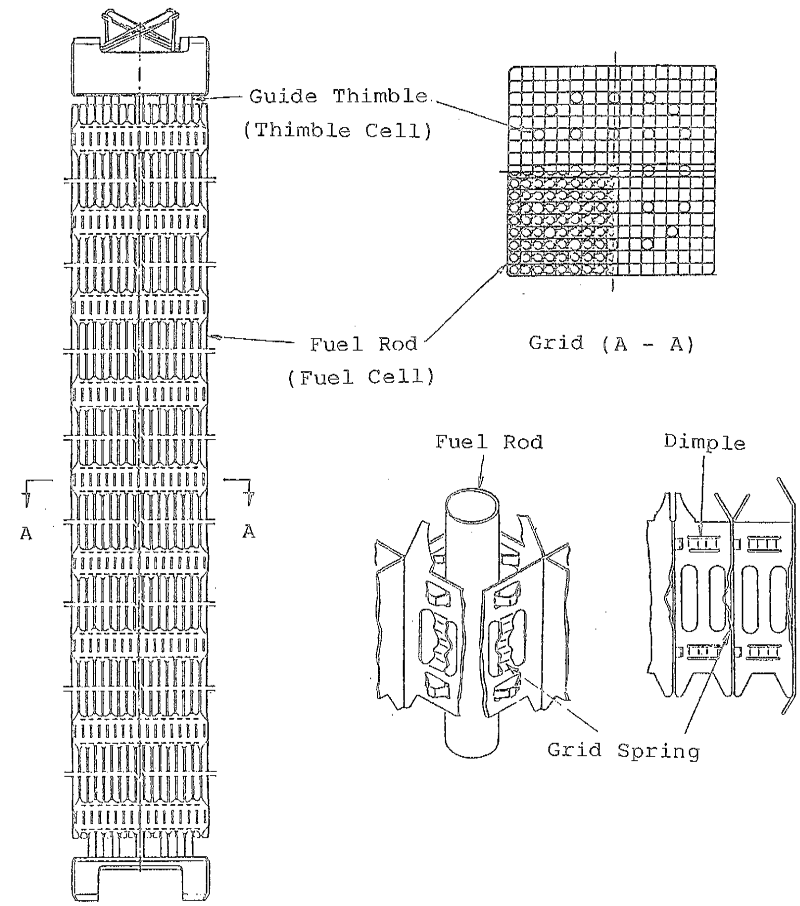


Fig. 1 PWR Fuel Assembly and Grid

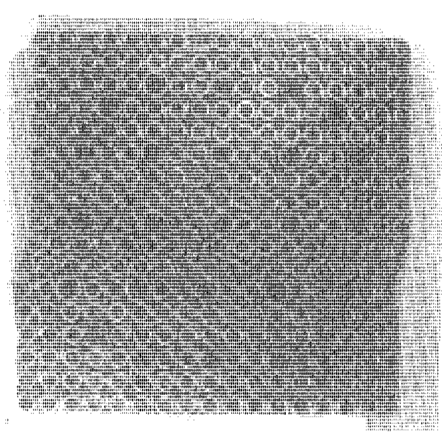
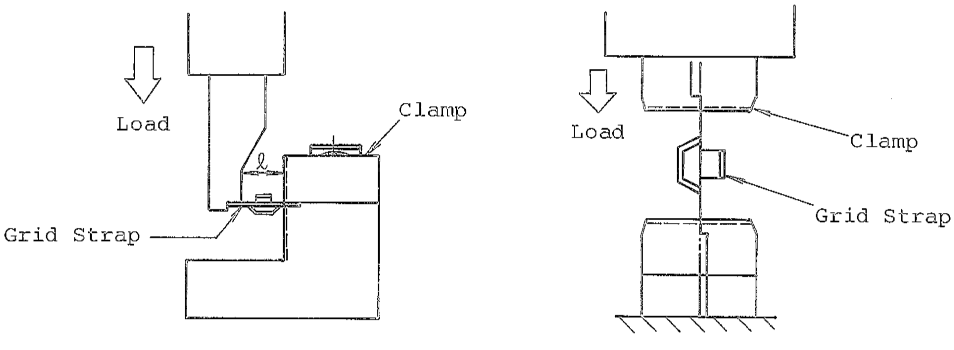


Fig. 2 Typical Buckling Mode of Grid



(a) Bending Test (b) Buckling Test

Fig. 3 1 Cell-Wize Strap Test Concept

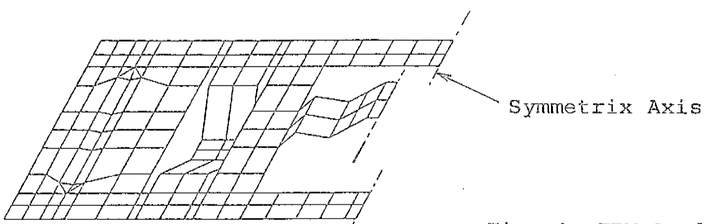


Fig. 4 FEM Analytical Model

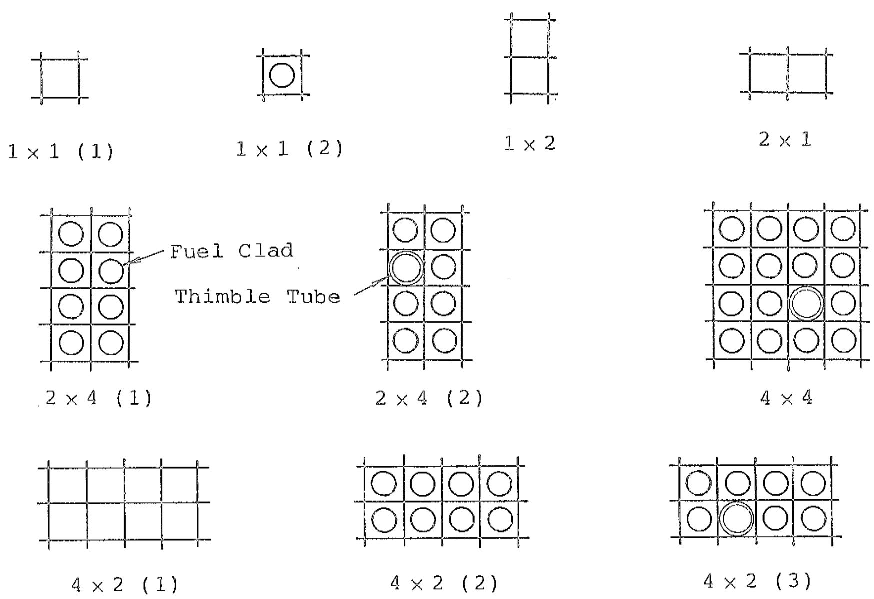


Fig. 5 Configulation of Partial Grid

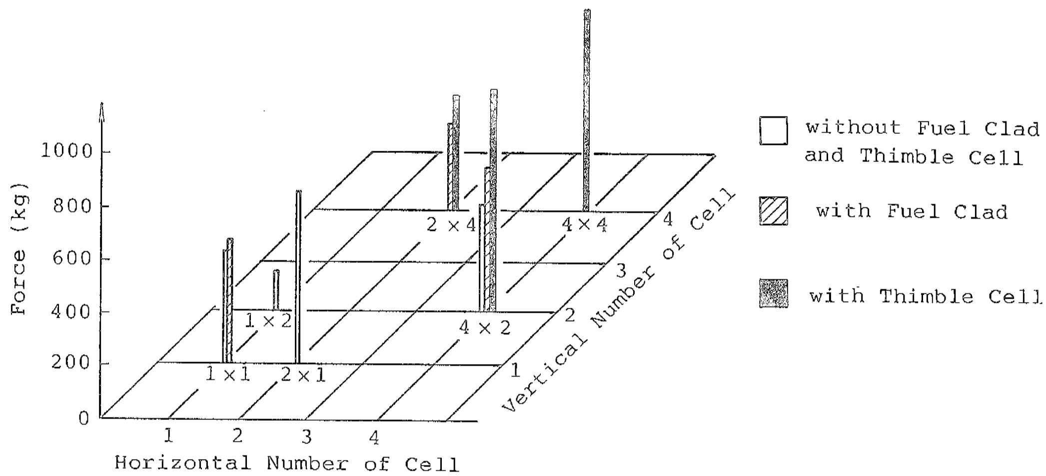
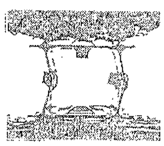
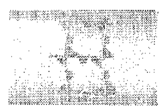


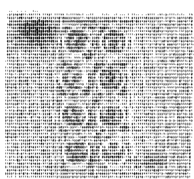
Fig. 6 Buckling Force in Partial Grid Test



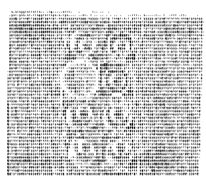
(a) 1 × 1



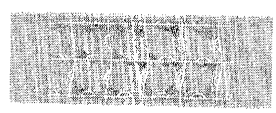
(b) 1 × 2



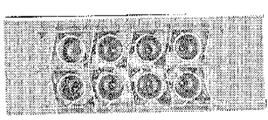
(c) 2 × 4 (1)



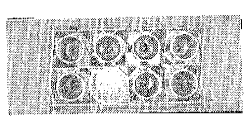
(d) 2 × 4 (2)



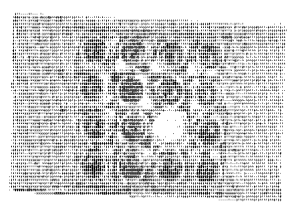
(e) 4 × 2 (1)



(f) 4 × 2 (2)



(g) 4 × 2 (3)



(h) 4 × 4

Fig. 7 Buckling Mode in Partial Grid Test

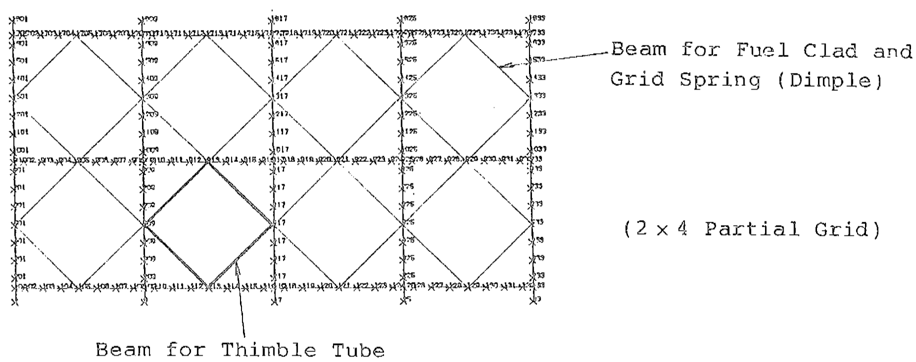


Fig. 8 Typical FEM Analytical Model for Partial Grid

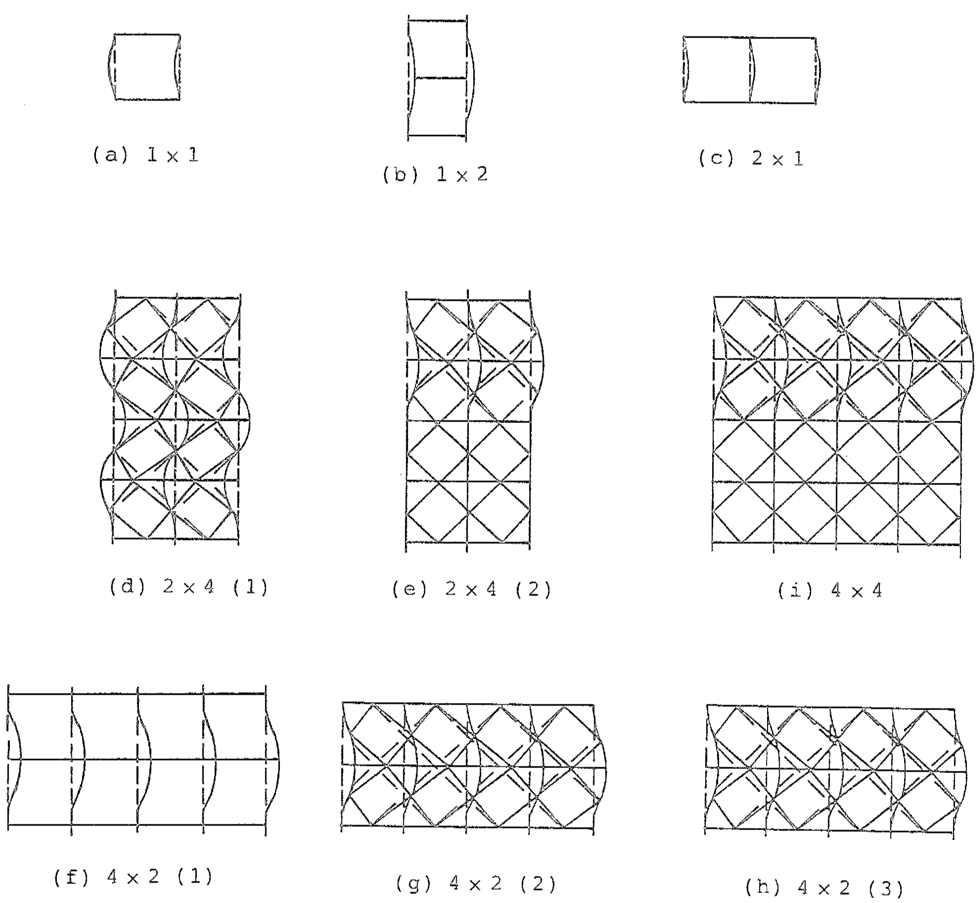


Fig. 9 Buckling Mode of Partial Grid in FEM Analysis

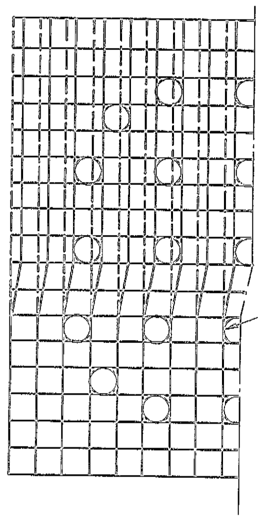


Fig. 10 Typical Buckling Mode of Full Grid in FEM Analysis