Finite Element Analysis of Optimized H Shape Spring in a Nuclear Fuel Spacer Grid by using Contact Definition*

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Abstract
The primary role of the grid springs in a spacer grid is to hold the fuel rods in an appropriate position using a friction force and to prevent the fuel rods from dropping during a normal reactor operation. Spring force decreases as the fuel burn-up increases since the spring stiffness is degraded by the high temperature and irradiation effects in a reactor core. So this phenomenon has to be considered when the initial spring force of a grid spring is being determined. To check whether a spring has a suitable spring force, characterization tests of a spring are conducted. In this paper, an analytical verification work, a FE model using contact definitions, is established for predicting the spring stiffness without any spring test. Finally, the test and analysis results are carefully compared to check the availability of a finite element model for investigating the spring characteristics at an in-grid boundary condition.

Key words: Spring Characterization Test, Ingrid Boundary Condition, Optimized H Type Grid Spring, Spacer Grid

1. Introduction
A spacer grid (SG), one of the most important components of a nuclear fuel assembly, is composed of horizontal/vertical straps, which are crossed to form an egg crate-like structure (1). It constitutes the skeleton of a fuel assembly together with guide thimbles and a top and bottom nozzle. The primary role of a SG is to hold fuel rods in an appropriate position between a top and bottom nozzle as well as adjacent fuel rods. Also, the SG prevents a lateral force by a seismic vibration and LOCA blowdown, maintains a fuel rod’s space under accidental and operational loads, promotes a mixing of a coolant and maintains the guide tubes straight so as not to interrupt a control rod insertion.

Horizontal/vertical straps have springs and dimples that contact a fuel rod. A fuel rod can be positioned due to a friction force from the springs and dimples. When a fuel rod is inserted into a spacer grid, the springs and dimples of the SG are displaced to some extent in the normal direction, that is, the axial direction of a fuel rod, which is termed as ‘initial interference’. Initial interference plays an important role to prevent the fuel rods dropping during a reactor operation. The stiffness of a spring is very difficult to predict because of existing initial interference and it depends on the spring shape and the dimensions of a spring, such as the thickness of a strap, the width and the fillet radius of a spring. Also the spring force decreases as the fuel burn-up increases since the elastic modulus is degraded by...
the high temperature in a reactor and the accompanying irradiation effects \(^{(2)}\). These phenomena should be considered when the initial spring force (i.e. initial interference depth) between a fuel rod and a SG is being determined. When a certain initial spring force is determined for a fuel design, the shape and the interference of a spring should be determined tentatively and manufactured. And then, spring tests are conducted. Finally, the characteristics of a spring, i.e. the curve of displacement versus force, are obtained. The spring stiffness obtained from the curve is checked to assess whether it is acceptable in a comparison with the design values. This test is called a ‘characterization test’. The obtained test data is used to determine the design of a spring \(^{(3)}\).

In this paper, a spring analysis method to obtain a spring characterization curve is established without characterization tests. Although a specimen for spring characterization tests is a 16by16 SG, the FE model of a 5by5 partial SG is used in this study due to the movable constraints of the loading bar. Finally, the results of the tests and analysis are compared to verify the usability of the proposed simulation.

2. Spring characterization test

2.1 Test specimen

The specimen is a 16by16 SG made of Zircaloy-4. SG is composed of horizontal, vertical and outer straps. Each strap has a few springs and dimples. Because the thickness of the horizontal and vertical straps (i.e. inner straps) is different from the thickness of the outer straps, the spring characterizations of the inner and outer straps are distinct. Also a dimple is usually much stiffer than a spring. In this paper, the spring characterization rather than the dimple characterization on the inner straps is the focal point of the test and analysis.

2.2 Apparatus

A universal tensile testing machine (UTM) is used for applying a compression to the spring \(^{(4)}\). A data acquisition system and a personal computer are used for logging the load and the displacement on a line. For the spring characterization test, the fixture and loading bar are illustrated in Fig. 1.

![Fig. 1 Schematic drawings of the fixture and the loading bar](image)

The fixture clamps four outer surfaces of the space grid and is placed on the lower crosshead of the UTM. The spring characterization test for a specimen is conducted in four zones, such as the A, B, C, and D zones, rotated in a clockwise direction due to the movable distance constraint of the loading bar. The loading bar has a cylindrical shape the same as an actual fuel rod. And the left and right sides of the loading bar are cut straight to pass through a test cell without any interference from the other springs and dimples located on the left and right sides of a cell. Figs. 2 and 3 show a schematic drawing and a real picture after the device is set for the spring characterization test.
2.3 Test condition

The characterization test is conducted at a room temperature condition. The upper cross head speed is set at 0.5 mm/min for the in-grid boundary test and the sampling rate is five points per second (3). The condition of a deformation is a 1.2mm upwards loading (i.e. 1.2 mm compression of spring) and a cyclic unloading to -0.05mm. Nine cells in four zones for one 16by16 SG for the assembly-based test are tested repeatedly for the displacement condition value.

2.4 Test results

Typical results of the characterization tests for the spring are shown in Fig. 4. For a spring performance satisfying the foregoing proposed design requirements, the spring stiffness is selected as a performance evaluation parameter. The stiffness is computed by the ratio of displacement to reaction force in the linear range of a characteristic graph. Although the ratio during an unloading process is usually used to evaluate spring performance, the ratio for a loading process in a linear range is applied for spring stiffness in this project. The linear range for the loading process is selected by the linear fitting method in Origin 6.1 (3). The linear range is chosen when a correlation coefficient is bigger than 0.9997 (99.97%).

Table 1 presents the spring stiffness of each spring located in the nine test cells. The average stiffness of the optimized H type spring is 116.66 N/mm, and the average of a 95% confidence interval using the student’s t-distributed interval estimation method is 108.45 N/m.
Fig. 4 Characteristic curves of the nine H type springs

Table 1 Test results of the H type spring for a 1.2mm loading

<table>
<thead>
<tr>
<th>No</th>
<th>Stiffness (N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>131.03</td>
</tr>
<tr>
<td>2</td>
<td>135.32</td>
</tr>
<tr>
<td>3</td>
<td>124.83</td>
</tr>
<tr>
<td>4</td>
<td>124.16</td>
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<tr>
<td>5</td>
<td>104.26</td>
</tr>
<tr>
<td>6</td>
<td>102.55</td>
</tr>
<tr>
<td>7</td>
<td>115.16</td>
</tr>
<tr>
<td>8</td>
<td>106.81</td>
</tr>
<tr>
<td>9</td>
<td>105.84</td>
</tr>
<tr>
<td></td>
<td><strong>Average 116.66</strong></td>
</tr>
<tr>
<td></td>
<td><strong>P_{95%} 108.45</strong></td>
</tr>
</tbody>
</table>

The used student’s t-distributed estimation equation is Eq. 1.

\[ P_{95\%} = P_{\text{avg}} - t_{0.05} \sqrt{\frac{\sigma}{n-1}} \]

where \( P_{95\%} \): Average of 95% confidence interval

\( P_{\text{avg}} \): Average

\( t_{0.05} \): Student’s t-distribution of 95% interval

\( \sigma \): Variance of the observations

\( n \): Total number of results.

3. In-grid spring characteristic analysis

3.1 Geometric data and material properties

The outline geometric data of the model is 64.25×64.25×40mm and the thickness of the thin plates is 0.46mm. The commercial preprocessor code I-DEAS (6) is used to create
the geometry of a 5by5 spacer grid. Because each test zone is 6by6 as a maximum, a spring analysis using a 5by5 partial SG could predict a spring characterization without tests. Also, an assumption is used that the position of an analytic cell in a model has no effect on the analysis because the inner straps are welded at cross points.

![True stress and strain curve of Zircaloy-4](image)

Fig. 5 True stress and strain curve of Zircaloy-4

The material of the strap is Zircaloy-4, with an elastic modulus of 113.67GPa, an yield strength of 379.47MPa, density of 6550kg/m³, and Poisson’s ratio of 0.34. The characteristic behavior of the grid spring is considered to be plastic deformation phenomena, and the mechanical properties of the straps have to be considered in a piecewise elastic-plastic characteristic curve. To obtain the mechanical properties of Zircaloy-4 at room temperature, a unidirectional tensile test of the Zircaloy-4 was conducted with ASTM. The elastic-plastic material properties of the Zircaloy-4 were achieved, that is, the true stress and strain data are converted from the engineering stress and strain data, as shown in Fig. 5.

### 3.2 Finite element model and constraints

3 node, triangular and 4 node, quadrilateral, shell elements (S3, S4) are used for the horizontal and vertical straps. The FE model consists of about 142,000 nodes and 123,000 elements. As shown in Fig. 6, the horizontal and vertical straps have slits for a fabrication process. The welding bead is modeled by rigid beam elements as shown in Fig. 7. The rigid beams connect the upper node on the vertical strap with the center node in the horizontal strap and the lower node on the vertical strap with the center node in the horizontal strap. This rigid beam translates and rotates with a rigid body motion.

![The vertical strap](image)

Fig. 6 The vertical strap
Four analytical surfaces are inserted into the fuel rod cell to simulate the fuel rods, as shown in Fig. 8 because the stiffness of a fuel rod is much higher than its supports, such as the springs and dimples. Reference nodes located in the middle of each surface are assigned to each analytical surface. Also, the compressive load on a spring is simulated by displacing a rigid rod, initially contacting the top of the spring, up to a specified distance. This loading rod is defined as a curved rigid surface. A reference node is assigned to this surface and a specified deformation is applied to a spring and the resultant reaction force is obtained at this reference node.

When loading a spring, the contact definition between the upper/lower nodes on a slit of the horizontal/vertical strap with the surface of the vertical/horizontal strap is specified to prevent the horizontal/vertical straps from penetrating into the vertical/horizontal straps. To reflect the initial interference between the rods and springs, circular analytical surfaces for the fuel rods are made with a bigger diameter than a real fuel rod, 9.5mm. And then, the rigid analytical surface pushes the springs and dimples at the first step to apply the initial interference phenomenon. A commercial code ABQUS Standard ver. 6.6-3 (7) is used for the FE analysis of the optimized H type spring characterization results.

4. Comparison of the test and analysis results

In the analysis case, the spring stiffness is obtained by the same method as a test, that is, the ratio of displacement to force during a loading process is used. The spring stiffness obtained by the analysis is 100.54 N/mm and the test result is 108.45 N/mm in a linear
range of a characteristic curve. The FE analysis results yields a good agreement with only a 7% discrepancy.

![Optimized H type spring assembly-based test](image)

Fig. 9 Spring characteristic curves for the test and analysis

In the characteristic curve of the test and analysis, the discrepancy after a 0.2mm displacement appears to be due to not enough mechanical plastic properties of the Zircaloy-4, non-uniform welding beads, manufacturing errors, and test errors.

5. Conclusions

Spring characteristic analysis method for an in-grid boundary condition has been researched to predict the characteristic curve of a grid spring and its stiffness. FE method for predicting a grid spring performance without characterization tests has been established and verified through a comparison with the test results. The analysis result yields only a 7% difference with the test results and thus this method is useful for predicting the behavior of a grid spring in an in-grid boundary condition. The FE analysis method by using contact definitions could simulate an examination without impractical phenomenon such as penetrations between horizontal and vertical straps, fuel rods and springs (or dimples). This method could be used for estimating a spring’s stiffness and its characteristic curve under an in-grid condition.

Acknowledgement

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