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Design Improvement of OPT-H Type Nuclear Fuel Rod Support Grid using Axiomatic design and Optimization

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Summary

The nuclear fuel rod support grid is an important structural part of a nuclear fuel assembly used in the pressurized light water reactor. It provides flexible support for the nuclear fuel rods which experience severe thermal expansion and contraction caused by the harsh operational condition in the core. Diverse design requirements should be set on the performances of multidisciplinary nature such as impact resistance, spring characteristics, possible amount of fretting wear on fuel rods, coolant flow and heat transfer around it, and so on. In this paper, an effort is reported to improve the impact resistance of OPT-H type support grid, a high performance spacer grid developed by Korea Atomic Energy Research Institute. A systematic approach using the axiomatic design and optimization is utilized for this purpose.

Introduction

The nuclear fuel assembly used in the pressurized light water reactor is composed of nuclear fuel rods and the skeletal structure which is also composed of subparts such as top and bottom end pieces, guide thimbles, and the spacer grids, and so on. The spacer grid serves a variety of functions to assure integrity of the fuel assembly under operating conditions of the core. Not only must the grid maintain the precise spacing between fuel rods so that reactor physics and thermal-hydraulic requirements are met, but it must also withstand seismic/loss-of-coolant accident impact forces. Since the fuel rod has slenderness ratio bigger than 400, the structure can be weak against the lateral load and that is why more than six spacer grids are used in a fuel assembly.

Because of the various functional requirements and harsh operation condition in the core, the design of a spacer grid is a challenging task which requires considerations on the multidisciplinary physical aspects. A lot of research has been devoted to experiments, analysis and design of spacer grid[1-3]. Walton[1] studied the design and material for spacer grid, Larson[2] performed a design optimization of outer plate in spacer grid considering the stiffness, impact strength and the flow restriction. Recently, Park[3] adopted the axiomatic design in the conceptual design of spacer grid and performed an optimization considering the impact resistance and support characteristics.

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The OPT-H type spacer grid(Fig. 1) developed by Korea Atomic Energy Research Institute is a high performance spacer grid for pressurized light water reactor. Its outstanding design features include the conformal, contoured contact shape which produces the minimum amount of fretting wear on the fuel rods in the presence of the flow induced vibration, high efficiency flow mixing vane to enhance the heat transfer between hot fuel rods and the coolant. However, the room for the possible design improvement in terms of lateral impact resistance has not been explored enough, and this is what the research presented in this paper tries to make up for.

In next sections, the design of unit OPT-H spacer grid cell is analyzed in the context of axiomatic design[4], and an optimization problem is formulated to find a shape strong against lateral buckling. Also, a possible strengthening with different welding configuration is discussed.

Figure 1: Unit cell of OPT-H type spacer grid

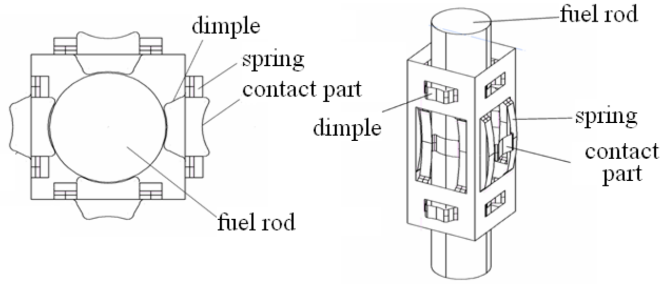


Figure 2: Unit spacer grid structure

Analysis of Unit Grid Structure Design

One unit grid structure is composed of four unit cells as shown in Fig. 2. The spacer grid is made of straps which contains repeated pattern of springs and dimples. The straps are connected orthogonally with each other and form a grid structure with multiple fuel rod slots. The design requirements(FRs) for the unit grid structure can be stated as follows:

FR1: Provide flexible and safe support for the fuel rods

FR2: Provide structural integrity against lateral impact load

FR3: Provide channels for coolant and enhance heat transfer

The design parameters (DPs) associated with the above FRs are as follows:

DP1: Spring-dimple support pattern

DP2: Orthogonally connected base frame that can resist against lateral impact

DP3: Grid made of thin straps with flow mixing vane

Here the base frame means the in-plane part in a strap or in a unit cell with spring and dimple removed(Fig 3). Some of these DPs have their own FRs which can be derived or cascaded from the FRs of above level. They are stated as follows:

FR11: Support fuel rod with appropriate stiffness and supporting force

FR12: Support fuel rod with minimum contact stress or fretting wear

FR21: Connect straps with enough strength

FR22: Bear enough in-plane buckling strength

The DPs for these second level, or unit cell level FRs are as follows:

DP11: Shape or topology of supporting beams in spring and dimple

DP12: Shape of contacting parts in spring and dimple

DP21: Method of strap or cell connection, welding configuration

DP22: Shape of base frame in unit cell

With these FRs and DPs, the design matrix for current OPT-H spacer grid can be constructed as follows:

$$\left\{ \begin{array}{c} FR_1 \\ FR_2 \\ FR_3 \end{array} \right\} = \left(\begin{array}{ccc} X & O & O \\ X & X & O \\ X & X & X \end{array} \right) \left\{ \begin{array}{c} DP_1 \\ DP_2 \\ DP_3 \end{array} \right\} \tag{1}$$

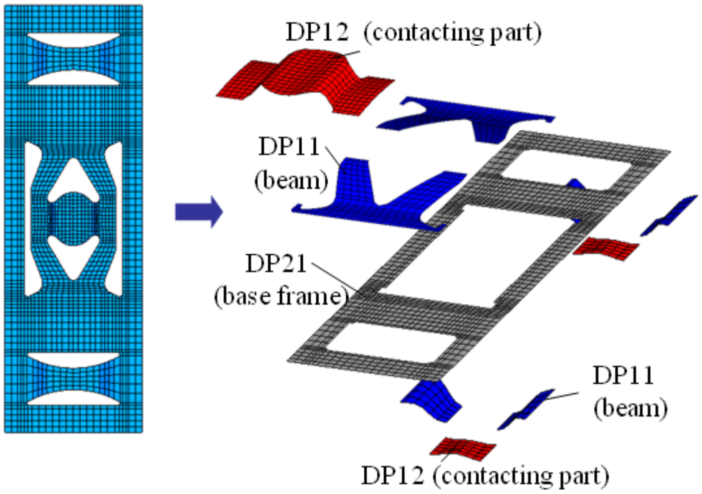


Figure 3: Design decomposition of spacer grid unit cell

$$\begin{Bmatrix} \mathrm{FR}_{11} \\ \mathrm{FR}_{12} \end{Bmatrix} = \begin{pmatrix} \mathrm{X} & \mathrm{O} \\ \mathrm{X} & \mathrm{X} \end{pmatrix} \begin{Bmatrix} \mathrm{DP}_{11} \\ \mathrm{DP}_{12} \end{Bmatrix} \tag{2}$$

$$\begin{Bmatrix} \mathrm{FR}_{21} \\ \mathrm{FR}_{22} \end{Bmatrix} = \begin{pmatrix} \mathrm{X} & \mathrm{O} \\ \mathrm{O} & \mathrm{X} \end{pmatrix} \begin{Bmatrix} \mathrm{DP}_{21} \\ \mathrm{DP}_{22} \end{Bmatrix} \tag{3}$$

It can be seen that the current design of OPT-H spacer grid is a decoupled one. In Eq. (1), the couple with FR1 and FR2 arises from the fact that the shapes of cut-outs for spring and dimples determine also the shape of base frame(Fig. 3). It is also noticeable that the hydraulic performance(FR3) is influenced by DP1 and DP2 as well as DP3. That's why we cannot weld straps with big beads even if it assures improved impact resistance and we should think about the pressure drop across spring and dimples whenever we change the design. However the design matrix is not invariant and appropriate tolerance is taken when determining whether the design is coupled or not.

With the design matrix (1)∼(3), we can figure out what can be done to improve the lateral impact resistance: Firstly, find a shape of base frame which can maximize the buckling strength, secondly, find a better way of strap connection. These should be done in such a way that other FRs than FR2 are not affected by the change of DP2 and further the design should not become coupled as a result. The following two sections are devoted to these efforts.

Design Optimization Considering Buckling Load

To improve the buckling strength of base frame and maintain good features of current OPT-H spacer grid design, an optimization problem is formulated as follows:

$$\begin{aligned} & Find\ \ d_1, d_2\ such\, that \\ & Maximize\ F_{CR}^1 \\ & Subject\, to\ \ \left|D_{\text{spring}} - D_{\text{spring}}^0\right| \leq D_{\text{spring}}^0 \times \varepsilon \\ & \qquad \left|D_{\text{dimple}} - D_{\text{dimple}}^0\right| \leq D_{\text{dimple}}^0 \times \varepsilon \\ & \qquad \sigma_{\max} \leq \sigma_{\max}^0 \end{aligned} \tag{4}$$

where F_{CR}^1, D_{spring}, D_{dimple}, and $\sigma_{\max}$ mean the buckling load of first mode(Fig. 4), displacement at the center point of spring and dimple contacting part, and the maximum von Mises stress in the whole model, respectively. The superscript 0 indicates the value at the initial design. ε is the allowable ratio of deviation from the initial value and is set to 0.15. The design variables d_1, d_2 are the location and width of dimple cut-out as shown in Fig. 5. With this optimization, we try to find a better shape of base frame with small allowable change in spring-dimple characteristics. The consideration on the hydraulic performance(FR3) is omitted since we know in advance that d_1 and d_2 don't affect the hydraulic performance.

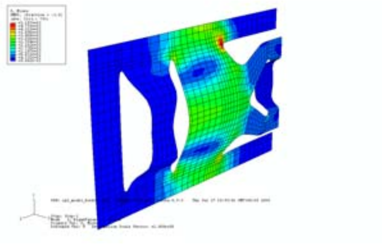


Figure 4: First buckling mode of unit cell

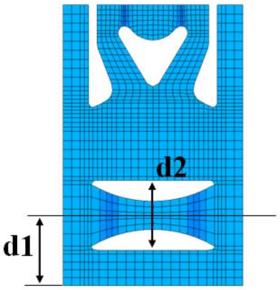


Figure 5: Design variables of optimization

The performance measures are calculated using the finite element analysis with ABAQUS and the boundary condition, loading for buckling analysis and static analysis are set considering the in-grid condition(Fig 2). Detailed descriptions are omitted here due to the lack of space. For optimization, the sequential quadratic programming (SQP) is used and the optimization process is established integrating SQP, ABAQUS and design parameterization code so that the whole process can be run automatically. As a result of optimization, the buckling strength is increased by 18 % and the constraint on the dimple stiffness is activated, that is, the displacement at dimple contact part changed by exactly 15% from the initial value. The optimized shape is shown in Fig. 6.

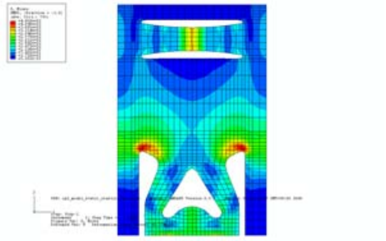


Figure 6: Optimized shape of unit cell

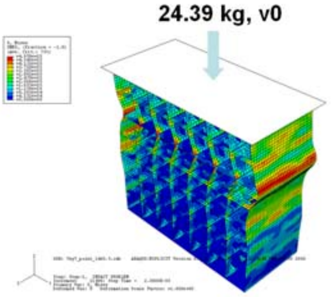
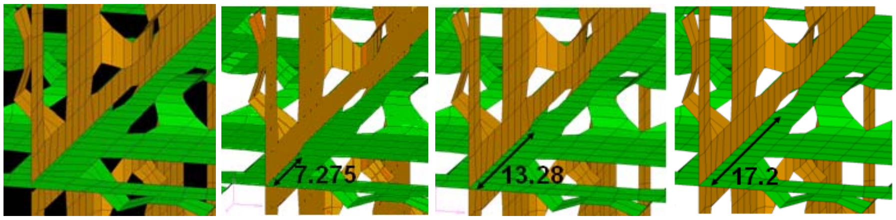


Figure 7: Impact analysis of 7 by 7 grid

Strengthening by through-grid welding

Another way of improving the impact resistance is strengthening the connection between straps. In impact test(Fig. 7) [5], we tried four different models of welding (Fig 8). The point welding adopted in the current design is simulated by the connection of nodes at welded points using rigid beams and the through grid welding is modeled by merging the adjacent nodes.

The dynamic impact loads are calculated by ABAQUS/Explicit with different initial velocities of impacting rigid plate and the maximum values are captured for each case. It is found that the optimal welding depth is about 13 mm and in this case the maximum impact load is increased by 33 % compared to the case of point welding. It is noted that the welding depth doesn't affect the hydraulic performance of the structure.



(a) point welding (b) through grid welding with different depth (in mm)

Figure 8: Different welding setting

Conclusions

A systematic approach for design improvement of current OPT-H type spacer grid is made using axiomatic design and optimization. Two important DPs are figured out to strengthen the structure against the lateral impact, and possible ways of design modifications are presented. With this approach, more than 30 % of improvement is achieved. Future works includes the verification of new design in real size grid structure and the test with experiments.

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