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Design Improvement of an OPT-H Type Nuclear Fuel Rod Support Grid by Using an Axiomatic Design and an Optimization

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Abstract

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

Keywords: Spacer grid; Nuclear fuel assembly; Axiomatic design; Buckling strength

1. Introduction

The nuclear fuel assembly used in a pressurized light water reactor is composed of nuclear fuel rods and a skeletal structure which is also composed of subparts such as top and bottom end pieces, guide thimbles, and spacer grids, and so on. The spacer grid serves a variety of functions to assure the integrity of the fuel assembly under the operating conditions of the core of the reactor. Not only must the grid maintain a precise spacing between the fuel rods so that the 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 a slenderness ratio bigger than 400, the structure can be weak against a lateral load, so that is why more than six spacer grids are used in a fuel assembly.

Because of the various functional requirements and harsh operation conditions in the core of the reactor, the design of a spacer grid is a challenging task which requires considerations of the multidisciplinary physical aspects. A lot of research has been devoted to the experiments, analyses and design of a spacer grid (Walton, 1979; Larson, 1982; Park, 2003). Walton (1979) studied the design and material for a spacer grid, Larson (1982) performed a design optimization of the outer plate in a spacer grid by considering the stiffness, impact strength and the flow restriction. Recently, Park (2003) adopted an axiomatic design for the conceptual design of a spacer grid and performed an optimization by considering the impact resistance and support characteristics.

The OPT-H type spacer grid (Fig. 1) developed by the Korea Atomic Energy Research Institute (KAERI) is a high performance spacer grid for a pressurized light water reactor. Its outstanding design features

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Fig. 1. Unit cell of the OPT-H type spacer grid.

include a conformal, contoured contact shape which produces a minimum amount of fretting wear on the fuel rods in the presence of a flow induced vibration, and a high efficiency flow mixing vane to enhance the heat transfer between the hot fuel rods and the coolant. However, the room for a possible design improvement in terms of a lateral impact resistance has not been explored enough, and this is what the research presented in this paper tries to make up for.

In the next sections, the design of the unit OPT-H spacer grid cell is analyzed in the context of an axiomatic design (Suh, 2001) and an optimization problem is formulated to establish a shape that is strong enough against a lateral buckling. Also, a possible strengthening with different welding configurations is discussed.

2. Analysis of the 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 contain a repeated pattern of the 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 a flexible and safe support for the fuel rods

FR2: Provide a structural integrity against lateral impact load

FR3: Provide channels for the coolant and enhance the heat transfer

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

DP1: Spring-dimple support pattern

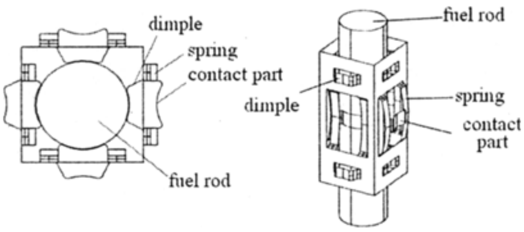


Fig. 2. Unit spacer grid structure.

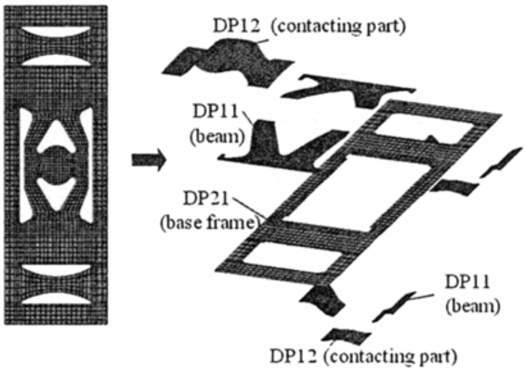


Fig. 3. Design decomposition of the spacer grid unit cell.

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

DP3: Grid made of thin straps with a flow mixing vane

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

FR11: Support fuel rod with an appropriate stiffness and supporting force

FR12: Support fuel rod with a 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 components, or unit cell level FRs are as follows:

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

DP12: Shape of the contacting parts in a spring and dimple

DP21: Method of a strap or cell connection, welding configuration

DP22: Shape of the base frame in a unit cell

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

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{pmatrix} X & O & O \\ X & X & O \\ X & X & X \end{pmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix} \tag{1}$$

$$\begin{Bmatrix} FR_{11} \\ FR_{12} \end{Bmatrix} = \begin{pmatrix} X & O \\ X & X \end{pmatrix} \begin{Bmatrix} DP_{11} \\ DP_{12} \end{Bmatrix} \tag{2}$$

$$\begin{Bmatrix} FR_{21} \\ FR_{22} \end{Bmatrix} = \begin{pmatrix} X & O \\ O & X \end{pmatrix} \begin{Bmatrix} DP_{21} \\ DP_{22} \end{Bmatrix} \tag{3}$$

It can be seen that the current design of the OPT-H spacer grid is a decoupled one. In Eq. (1), the coupling with FR1 and FR2 arises from the fact that the shapes of the cut-outs for the spring and dimples also determine the shape of the base frame (Fig. 4). 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 an improved impact resistance and we should think about the pressure drop across the spring and dimple whenever we change the design. However the design matrix is not invariant and its tolerance is established when determining whether the design is coupled or not.

With the design matrix in Eqs. (1)~(3), we can figure out what can be done to improve its' lateral impact resistance: Firstly, find a shape of the base frame which can maximize the buckling strength, Secondly, find a better way of a strap connection. These should be done in such a way that other FRs, except for 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.

3. Design optimization considering the buckling load

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

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

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

The performance measures are calculated by using the finite element analysis with ABAQUS and a boundary condition, and the loadings for the buckling analysis and static analysis are set by considering the in-grid condition (Fig 2). Detailed descriptions are omitted here due to a lack of space. For an optimization, the sequential quadratic programming (SQP) is used and the optimization process is established

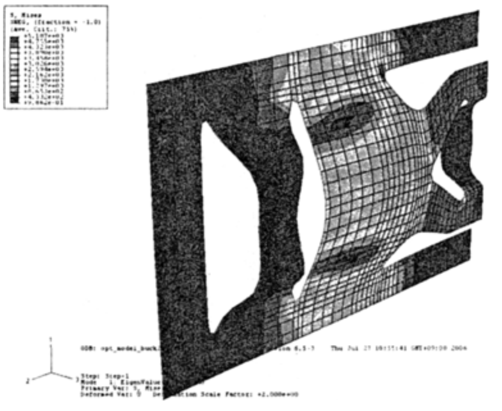


Fig. 4. First buckling mode of unit cell.

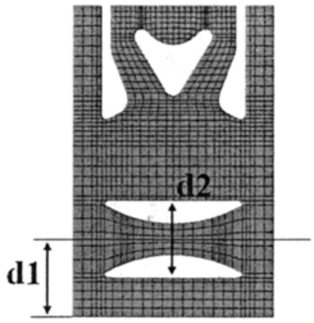


Fig. 5. Design variables of optimization.

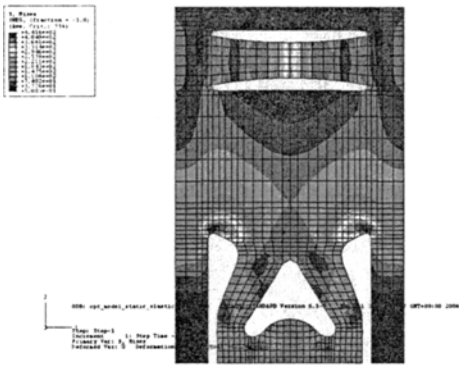


Fig. 6. Optimized shape of unit cell.

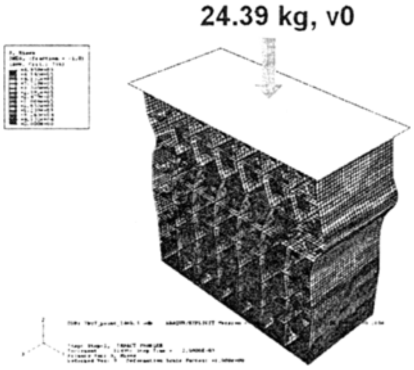


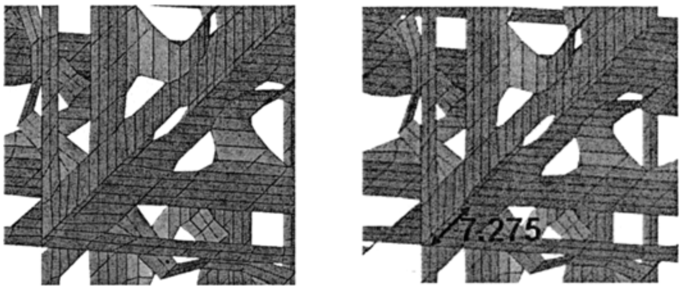
Fig. 7. Impact analysis of 7 by 7 grid.

by integrating the SQP, ABAQUS and design parameterization code so that the whole process can be run automatically. As a result of an optimization, the buckling strength is increased by 18 % and a constraint on the dimple stiffness is activated, that is, the displacement at the dimple contact part is changed by exactly 15% from the initial value. The optimized shape is shown in Fig. 6.

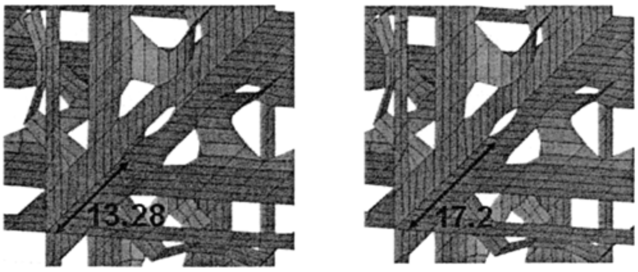
4. Strengthening by a through-grid welding

Another way of improving the impact resistance is a strengthening of the connection between the straps. In the impact test (Fig. 7) (Yoon et al., 2004), we tried four different configurations of a welding (Fig. 8). The point welding adopted in the current design is simulated by the connection of nodes at welding points by 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 impact velocities 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 % when compared to the case of a point welding. It is noted that the welding depth doesn't affect the hydraulic performance of the structure.



(a) Point weld (b) Through grid weld (7.275 mm)



(c) Through grid weld (13.28 mm) (d) Through grid weld (17.20 mm)

Fig. 8. Different welding settings.

5. Conclusions

A systematic approach for a design improvement of the current OPT-H type spacer grid is made by using an axiomatic design and an optimization. Two important DPs are established to strengthen the structure against a lateral impact, and the possible ways for design modifications are presented. With this approach, up to 30% of an improvement is achieved. Future works will include a verification of the design in a real size grid structure and a test with experiments.

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