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Shape Optimization of the H-shape Spacer Grid Spring Structure

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Abstract

In pressurized light water reactor fuel assembly, spacer grids support nuclear fuel rods both laterally and vertically. The fuel rods are supported by spacer grid springs and grid dimples that are located in the grid cell. The support system allows for some thermal expansion and imbalance of the fuel rods. The imbalance is absorbed by elastic energy to prevent coolant flow-induced vibration damage. Design requirements are defined and a design process is established. The design process includes mathematical optimization as well as practical design method. The shape of the grid spring is designed to maintain its function during the lifetime of the fuel assembly. A structural optimization method is employed for the shape design. Since the optimization is carried out in the linear range of finite element analysis, the optimum solution is verified by nonlinear analysis. A good design is found and the final design is compared with the initial conceptual design. Commercial codes are utilized for structural analysis and optimization.

Key Words : shape optimization, design variable, object function, constraint, stress minimization, contact pressure, linear elastic range, optimal solution

1. Introduction

The spacer grid, one of the most important components of a nuclear fuel assembly, is composed of straps, which are crossed to form an egg-crate like structure. It constitutes the skeleton of the fuel assembly together with guide thimbles, top and bottom end pieces. The structural grid assemblies provide both lateral and vertical support for the fuel rods. The pitch of the fuel rods in the core is a carefully selected parameter, which has a major effect on the nuclear and thermal/hydraulic performance of the core. The spacer grid is an interconnected array of slotted grid straps welded at the intersections. The fuel assembly incorporates from seven to eleven spacer grids. The spacer grid outer straps constitute the contact surfaces that can transmit possible seismic loads between the fuel assemblies. The principal design concern with regard to grid strap is that the fuel rods should maintain a coolable geometry and that the control rods should be inserted [1].

These days, the development of the fuel is in progress to high burnup and zero defect fuel. In order to develop the high burnup fuel, it has to need to increase the thermal margin of the fuel. However, these directions for increasing the thermal margin affect the negative function for mechanical integrity of the fuel. Therefore, the necessity of the fuel for increasing the elastic range of the grid spring and high resistant fretting wear is raised. For this goal, the optimized shape of the grid is accomplished and verified with various design requirements.

General roles of the spacer grid assembly are: (1) providing lateral and vertical support for fuel rods (2) maintaining fuel rod space under accidental and operational loading conditions (3) promoting the mixing of the coolant (4) keeping the guide tubes straight so as not to impede the control rod insertion under any normal or accidental conditions.

In this research, new design requirements are proposed for mechanical characteristics such as deflection and force on the spacer grid spring. The force-deflection curve for a spring has to be linear in the range up to 40 N of the external force and 0.4 mm at the initial interference between the spacer grid spring and nuclear fuel rod. Conceptual design of the spring is proposed by engineering sense. Nonlinear finite element analysis is utilized to help the design process. The FE model is created using pre-processor program I-DEAS [2]. The solving is conducted by a software system called ABAQUS/standard 5.8 [3].

After a conceptual design is established, structural optimization is applied to the detailed shape design of the spring. Mathematical optimization has been well developed for linear analysis. However, it is not well established yet for nonlinear analysis [4-7]. Therefore, the optimization is performed in linear range. An optimization problem is formulated for the design of the spring. A commercial code named GENESIS [8] is adopted for the optimization process. The shape optimization module of the software is used. The optimum design is analyzed again in nonlinear range and the result is compared with the initial design and discussed. ABAQUS is utilized for the evaluation. A good design is found and discussed.

2. Spacer Grid Spring

2.1. Design Feature

The structural grids support the fuel rods both laterally and axially with a friction grip. Each cell in the spacer grid employs a fuel rod support system consisting of two orthogonal sets of two dimples and a spring. The support system not only allows the fuel rod to move through the cell axially as

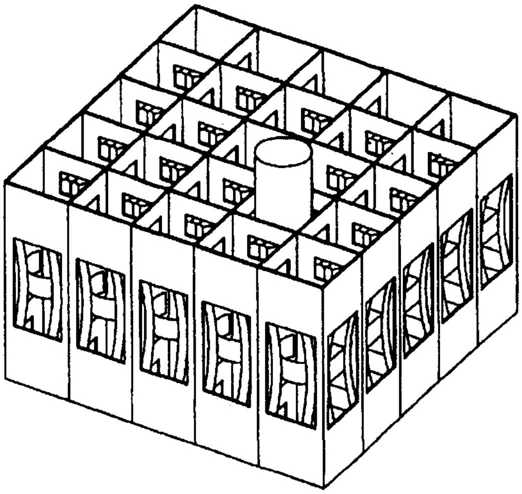


Fig. 1. Schematic Diagram of the Original Spacer Grid

necessary for thermal and rod growth movements, but also follows fuel rod diametral changes in operation while maintaining alignment. A schematic diagram of the initial spacer grid is illustrated in Fig. 1 [9]. A spacer grid for a nuclear fuel assembly has grid springs and opposing dimples, which contact a fuel rod and cushion any vibration impact. The impact is generated between the fuel rods and the grid springs and dimples during reactor operation and during fuel assembly shipping. Also, external forces are imposed on the springs during insertion of the fuel rod into the spacer grid. Because the grid dimples are relatively large in strength compared to the grid spring, their deformation can be negligible.

2.2. Design Requirements

During operation in a nuclear reactor, the grid springs and dimples are exposed to intensive irradiation, which causes the grid springs to lose the initial spring force against the fuel rods. Thus, the grid spring must permit the fuel rods to vibrate and chatter against the dimples. Some conventional spacer grids contribute to an additional problem in that the fuel rod springs and dimples may not accurately position the fuel rod at the center of a fuel rod cell. Deviations from that center position can result in adverse nuclear characteristics in fuel assembly as well as mechanical damage, such as bent dimples and grid springs. A conventional design of the grid spring was conducted in the aspect of the axial and lateral forces so that most of the grid springs were only stiff and large deflection was not considered. However, the grid spring should satisfy not only force but also displacement conditions for the foregoing functional requirements. Hence, the grid design requirements are defined in two categories: displacement and force conditions.

During fabrication, the rod is pulled into each spacer grid cell having a height difference of about 0.3 mm and the grid spring has the same deflection. Manufacturing tolerances causes the height difference of the spring and dimple. After insertion of the rod, the performance of the grid spring can be deteriorated if the grid spring is out of position. The grid spring is designed to have an elastic range of up to 0.4 mm deflection of the spring characteristics curve. This requirement is defined in linear range. However, slight nonlinear deformation is allowed. Later, it will be shown that the requirement cannot be satisfied by the given configuration. Thus, the spring is designed to have maximum flexibility within the given range. Further investigation is required for the definition. Throughout the lifetime of reactor, the grid spring losses 92 % of its strength due to the irradiation-induced relaxation [10]. The irradiation induced property changes are strength and ductility change, stress relaxation, and growth. If they are not considered in the design stages, the integrity of the grid can be jeopardized. During the reactor operation, the required minimum spring force for resisting the flow-induced vibration is more than 2 N [1]. The spring should normally perform up to 25 N. The design of all grid assembly parts should limit flow-induced vibration so it will not lead to vibration-induced fatigue, fretting, and out of position problems. For shipping of the fuel, the grid spring should withstand vertical and lateral accelerations without allowing the fuel rods to shift or the grid spring to deform permanently. Therefore, the requirement of 25 N should be increased to include the unknown disturbances. Putting these various design requirements together, the mechanical characteristic curve for a good spring has to be linear in the range of up to 40 N and 0.4 mm at the initial interference between the spacer grid spring and nuclear fuel rod. And then the stiffness of the grid spring is about 100~150 N/mm.

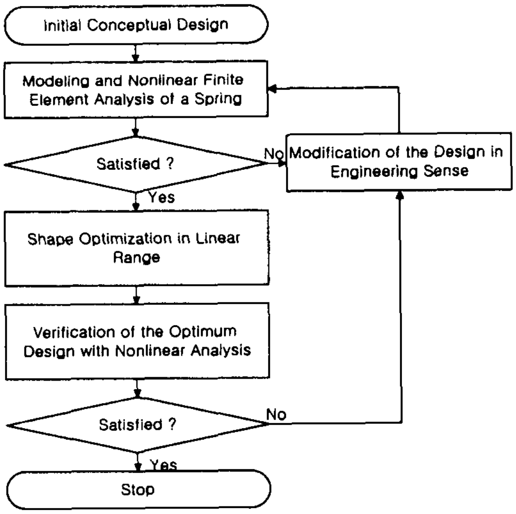


Fig. 2. Flowchart for Shape Optimization of the Spacer Grid Strap

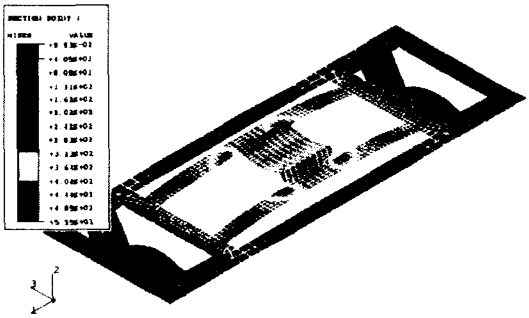


Fig. 3. Von Mises Equivalent Stress Contour of the Original Spacer Grid

3. Application of Shape Optimization

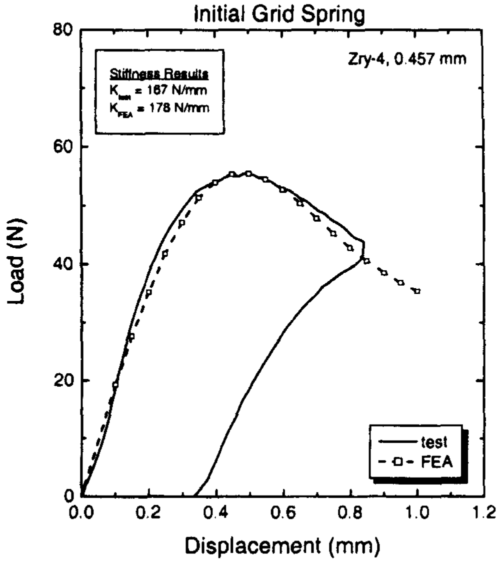


Fig. 4. Characteristic Curve of the Original Spacer Grid Spring by Test and FE Analysis

A spring in a grid set is analyzed and designed. The flow of the shape optimization process is defined and illustrated in Fig. 2. Because various aspects are involved, it is extremely difficult to define each step with an automatic design process. Instead, a practical design using engineering sense is very efficient in some steps. The flow in Fig. 2 includes those characteristics. Each step is explained in the following sections:

3.1. Conceptual Design

At first, the spring is designed by engineering intuition and the previous design. The spring should fit in the structure in Fig. 1. It is difficult to have drastic shape change in optimization. The drastic shape modification can be made in this step. Design requirements in the previous chapter are defined in a linear range. The spring slightly reaches the plastic (nonlinear) range. Therefore, the conceptual design is carried out with nonlinear analysis. The design is directed to have maximum flexibility and lower maximum stress by trial and error. A spacer grid cell with imposed displacement boundary conditions is modeled for analysis of the spacer grid spring characteristics. The finite element model of the unit cell is created using the commercial preprocessor, I-DEAS. Because of the symmetry, only a quarter of the structure treated as thin shell elements is analyzed using ABAQUS 5.8.

For the spring characteristics satisfying the foregoing proposed design requirements, the stiffness of the spring is selected as a performance evaluation. The stiffness is computed by the ratio of the reaction force developed at the final load step and the prescribed displacement. The linear range of the stiffness is also selected as a performance measure. The stiffness is related to the maximum stress in a model with nonlinear material property. The linearity of the stiffness is insured when the maximum stress does not exceed the yield stress of the spring at the load step. The analysis result of the initial design is illustrated in Fig. 3.

The analysis is carried out in 11 load steps and the maximum displacement prescribed at the final step is 1.0 mm. Fig. 3 shows the fringe plot of the

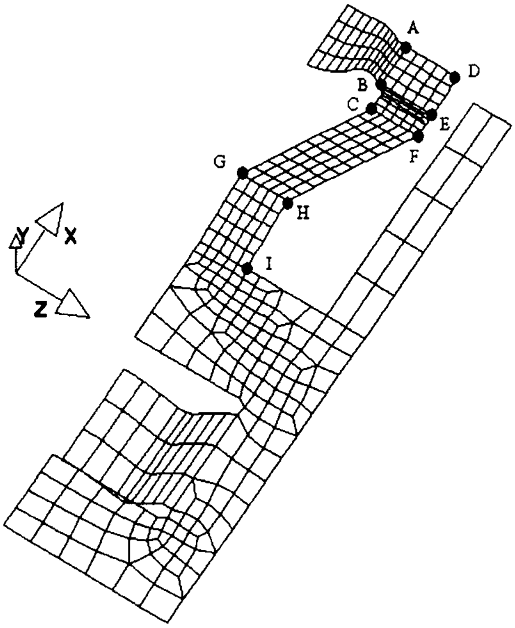


Fig. 5. A Quarter FE Model and Design Variables

Table 1. Result of Shape Optimization

	Design Variables	Initial Values	Optimum Values
DV1	Scale factor of perturbation vector of y-coordinate of node A, B, C in Fig. 5	0.0	0.01
DV2	Scale factor of perturbation vector of y-coordinate of node D, E, F in Fig.5	0.0	0.14
DV3	Scale factor of perturbation vector of y-coordinate of node G in Fig.5	0.0	-0.11
DV4	Scale factor of perturbation vector of y-coordinate of node H in Fig.5	0.0	-0.11
DV5	Scale factor of perturbation vector of z-coordinate of node I in Fig.5	0.0	0.54
DV6	Scale factor of perturbation vector of x-coordinate of node G in Fig.5	0.0	1.61
DV7	Scale factor of perturbation vector of x-coordinate of node H in Fig.5	0.0	0.94
DV8	Scale factor of perturbation vector of z-coordinate of node H in Fig.5	0.0	-2.0
β	Bound on stress	2.0	0.371
Obj.		0.371	

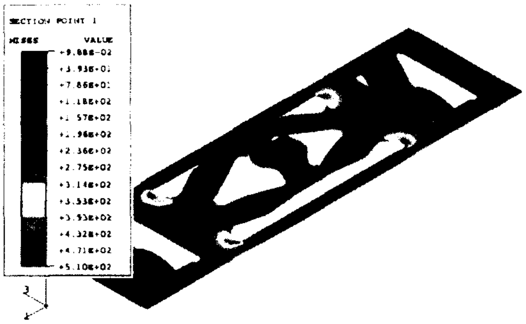


Fig. 6. von Mises Equivalent Stress Contour of the Optimized Spacer Grid

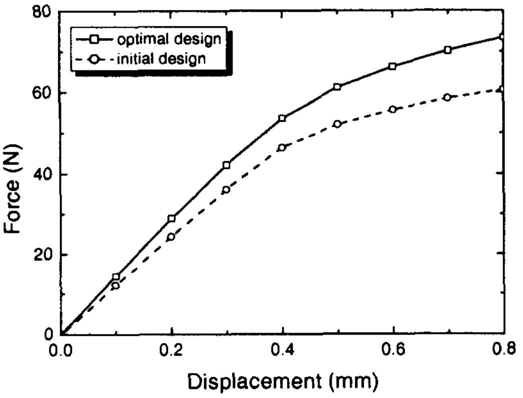


Fig. 7. Comparison of the Spring Characteristic Curve of the Optimized Spring with Initial Spring

von Mises stresses on the performed structure at 0.3 mm displacement step. The force-deflection response of the grid spring at the initial design is shown in Fig. 4.

3.2. Formulation

The overall shape is determined in the conceptual design process. The detailed design is carried out by shape optimization. A slight modification of the shape is made. As mentioned earlier, the optimization is performed in a linear range. Generally, the objective function in structural optimization is defined by the weight of the structure. However, it has been proved that the structure does not have a feasible solution for allowable stress with the given configuration in Fig. 1. Therefore, the problem is formulated with the maximum stress as the objective function. The optimization problem is defined as follows:

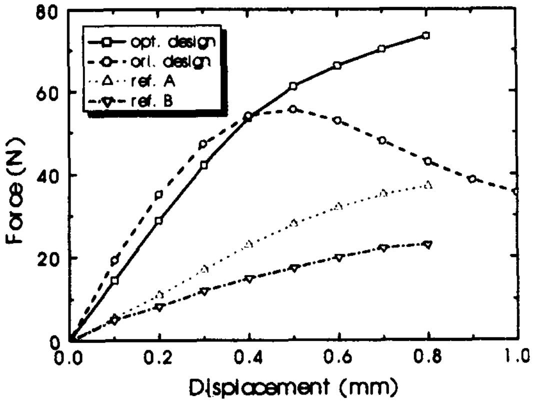


Fig. 8. Final Result of the Spacer Grid Spring After Shape Optimization

Find	design variables	
Minimize	maximum σ	(1)
Subject to	$\delta - 0.4 = 0$	(2)
	$F_{spring} - 40 = 0$	(3)

Where σ is stress, δ is the deflection at the center of the spring and F_{spring} is an external force on the spring. The displacement condition in Eq. (2) is from the first requirement and the force condition in Eq. (3) is from the second requirement. The optimization problem in Eq. (1) is converted to make a smooth problem as follows [4-5, 11]:

Find	design variables
Minimize	β

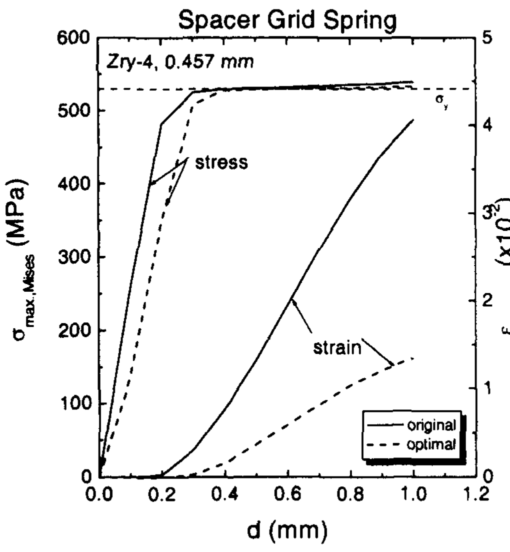


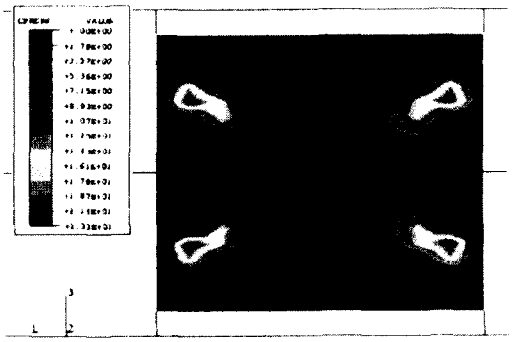
Fig. 9. von Mises Equivalent Stress and Plastic Strain of the Initial and Optimized Grid Spring

Subject to $\sigma - \beta$

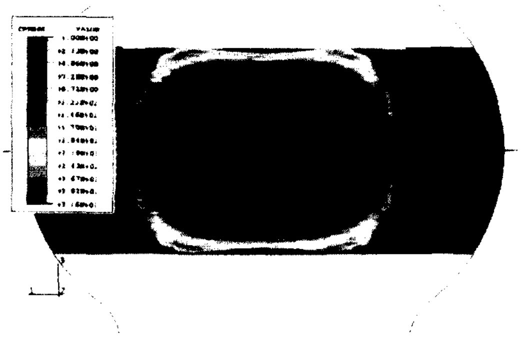
0 (4)

$\delta - 0.4 = 0$

F_{spring} - 40 =0



(a) Original Shape



(b) Optimized Shape

Fig. 10. Contact Pressure Configuration of the Grid Spring at 0.4 mm Displacement

4. Optimization Result

4.1. Shape Optimization

A quarter of the finite element model is illustrated in Fig 5. Eight design variables are selected. The design variables are indicated in Fig. 5 and Table 1. The optimization procedure is carried out using the commercial code, GENESIS 6.0. The initial design for the optimization established from the result of the conceptual design. The results of the optimization are shown in Fig. 6 and Table 1. The first, the maximum stress exceeds the yield stress of 0.536 GPa. Because a little plastic deformation is allowed, the design is considered acceptable. A nonlinear analysis is performed with the optimum design. The result from this analysis is illustrated in Fig. 7. It is noted that the optimum design is more flexible than the initial design. The optimum design is compared to the initial conceptual designs by nonlinear analysis. The comparison is illustrated in Fig. 8.

The initial spring shape is shown in Fig. 5. The design variables are the width of each position. The final optimized H-shape spring is shown in Fig. 6. In Fig. 8, the reference A and B springs used the commercial fuel assembly for pressurized water reactor. These reference springs had good elastic behavior, but these range spring forces had

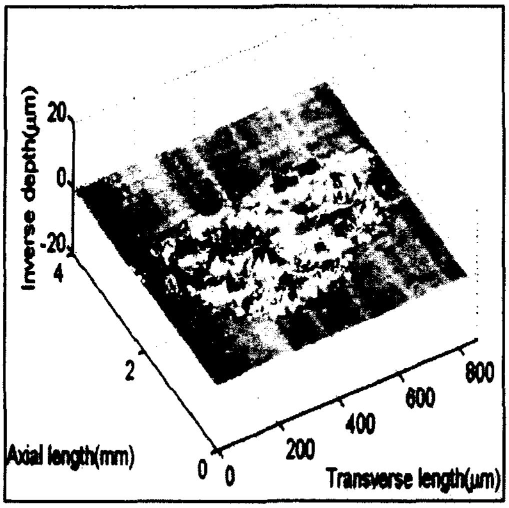


Fig. 11. Fretting Wear Configuration of the Original Shape Grid Spring by Axial Fretting Wear Test

insufficient spring force to support the fuel rod. Therefore, this optimal H-shape spring have designed two points of view. One is that to satisfy the minimum required spring forces, another is that to extend the elastic range of the grid spring. The optimal H-shape grid spring showed the good performance as above two design points.

The performance of the spring seems to be quite improved. In previous paragraph, the characteristic curve of the grid spring is specified as 0.4 mm displacement vs. 40 N spring force. This means that the stiffness of the grid spring is 100 N/mm. Therefore, the design guideline for the grid spring is determined that the stiffness of the grid spring is within 100 to 150 N/mm based on the displacement of the spring during the manufacturing of the fuel.

The second, the equivalent plastic strain minimized even though the maximum displacement of the grid spring. The comparison is illustrated in Fig. 9. Of course, the position occurred the maximum plastic strain is different each other. The maximum plastic strain of the initial shape grid spring is approximately 4(10-2, but that value of the optimum shape grid spring is 1.4(10-2. It is about three times than that of the optimum shape grid spring. The smaller strain of the grid spring at the same displacement, the better performance it will be during the life cycle of the fuel. In view of the integrity of the grid spring, it is the better design, which have the smaller strain in the spring.

The third, the contact pressure between spring and fuel rod has to minimize within the working displacement of the spring. And it is needed that the uniform contact pressure between contact surfaces. Because of the smaller contact pressure and uniform contact contour, the better performance it has in view of the fretting wear. In Fig. 10, the contact pressure configuration of the initial shape spring showed the non-uniform contact configuration. However, that of the optimum shape spring showed the uniform configuration.

In order to verify the effect of the uniform contact pressure, the axial fretting wear test is established. The wear volume of the fuel rod by fretting test is showed in Fig. 11. To evaluate the wear volume is often necessary to analyze the wear phenomenon, especially for wear modeling. The wear volume is evaluated by using a specially developed program. The algorithm of it is based on a signal processing technique such as Fast Fourier Transform and Windowing [12]. Ra value of the tube specimen (= 0.76 (m) is used for the baseline of the volume integration. The program is very much useful when the wear is locally distributed on the contact surface and its shape is arbitrary, as are found in the present experiment. Therefore, the wear volume of the spring is related to the contact configuration of the contact surfaces.

4.2. Conclusion and Future Research

The present paper deals with the shape optimization procedure of the grid spring. The optimization procedure is established in view of the three design object functions. They are as follows that the spring shape having the more expansion elastic working displacement of the grid spring, the minimized plastic strain and the uniform contact configuration. Although, the available displacement of the spring or dimple is constrained with the various geometric dimensions, the final spring shape after optimization procedure satisfied the design requirements. Of cause, this final grid shape will be verified by the fretting wear test.

Acknowledgement

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