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Analyses of spacer grids compression strength and fuel assemblies structural behavior

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HIGHLIGHTS

- Modeling of a 16 × 16 spacer grid to reproduce compression tests.
- Evaluation of spacer grids mechanical behavior.
- Modeling of fuel assembly with beam-type finite elements.
- Calculation of fuel assembly natural frequencies by considering fuel rods sliding.
- A new procedure to correct fuel assembly natural frequencies with weighting factor β.

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ABSTRACT

In this work, finite-element models were proposed to evaluate the spacer grids compression strength and structural behavior of fuel assemblies, mainly in terms of their natural frequencies. Firstly, a three-dimensional model was developed to provide consistent predictions of 16 × 16-type spacer grids compression strength. Regarding their original geometry and some possible design variations, the models were submitted to compression conditions to calculate the maximum compression force and they were validated for comparison with experimental predictions. Secondly, fuel assembly models were proposed with the aim at to correct its natural frequencies. For that, two distinct three-dimensional finite element approaches for the spacer grids, called total mesh and inner mesh, were adopted, respectively. For each model, the maximum and minimum fuel assembly lateral stiffness was determined. Also, by adopting the correction factor β, the natural frequencies were corrected by a $\sqrt{\beta}$ value that was characteristic of each model and compared to experimental results. The procedure used in the present work permitted a good agreement between numerical and experimental natural frequencies results with the total mesh model.

1. Introduction

Fuel assemblies are defined by Gouvêa et al. (2000) like arrangements of fuel rods containing uranium, mounted like a spaced and reticulate bundle. The fuel assembly and its components studied in this work can be observed in details in Fig. 1. Their most important structural components are the spacer grids due its great strength against static and dynamic loads, during manufacturing and operation inside nuclear reactors. Thus, in order to prevent breakdown of spacer grid failure, it is important to know the structural behavior of the fuel assemblies and to estimate their lateral strength, as well as their lateral stiffness and natural frequencies, as observed in the pioneer work developed by Lee et al. (1890) by as pointed out by Medeiros (2005). Likewise in a most recent research, Yoon et al. (2001) proposed a numerical method for predicting the buckling strength of the spacer grids by adopting a nonlinear dynamic finite element model. In the same way, Yoon et al. (2001) have performed a physical test and a numerical simulation to predict the buckling behavior on the spacer grid structure. Following these thoughts, Kang et al. (2001) also studied the strength of spacer grids by evaluating their interaction with fuel rods.

The work proposed by Jhung et al. (1992) revealed experimental and numerical results of spacer grids structural behavior by reproducing the actual nuclear reactor operational conditions. In the same context, Park et al. (2003) evaluated an axiomatic design method to achieve a new shape for the spacer grid. However, in these studies the effect promoted by the loads during manufacturing of this component was neglected.

It is well known that the control of the spacer grid straightness and the fuel assembly vibrations during the nuclear energy generation process plays an important role on its structural integrity.

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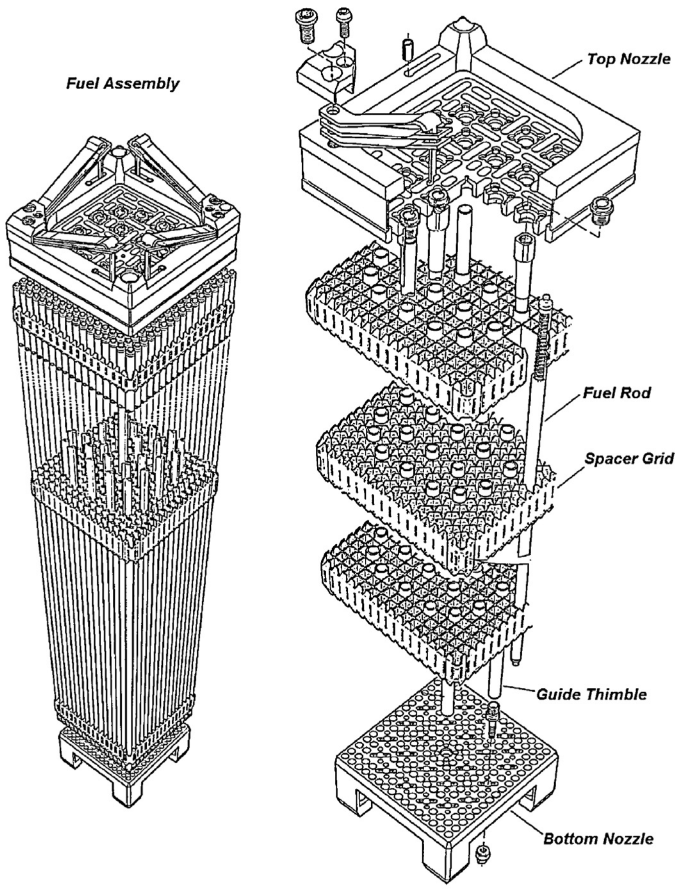
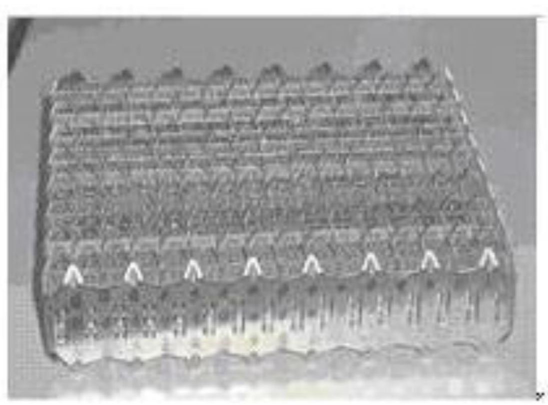


(a)



(b)

Fig. 1. Fuel assembly structure: (a) the fuel assembly and its components and (b) geometry of the spacer grid.

Therefore, the determination of strength limits for spacer grids deformation, before and after the process conditions, and the fuel assembly natural frequencies are necessary. In this sense, finite element-based simulations represent a reasonable alternative for that when compared to the high costs associated to experimental tests. In this context, distinct three-dimensional finite element models have been developed in the present work. Initially, it is proposed a model able to evaluate spacer grids behavior during fuel assembly manufacturing. This assessment is done by calculating the maximum compression force which it structural component undergoes. After that, a second model is idealized to analyze the fuel assembly structural behavior and extract its natural frequencies.

Table 1
Mechanical properties of Inconel 718 and Zircaloy at 25 °C.

	Inconel 718	Zircaloy
Properties		
Young's modulus (Pa)	2E11	1E11
Density (kg/m^3)	8300	9309
Friction coefficient	–	0.35
Poisson ratio	0.3	0.35

2. Finite-element modeling

2.1. Spacer grid static compression analysis

2.1.1. Experimental compression tests

Nuclear industry and nuclear research centers perform a spacer grid physical test commonly called static compression test or static crush test. This test is required to obtain the strength limits of the spacer grids. It is used to verify the loads from the assembly's bench clamping devices that holds the spacer grids during fuel rod insertion into the skeleton of the fuel assembly. Each spacer grid is seated on respectively clamping device with the guide tubes already inserted in their respective positions. Therefore, this device applies a very high compressive load, so that the skeleton of the fuel assembly is fixed in the assembly bench, and then the fuel rods can be inserted in their respective positions. This compressive load must have a maximum limit, thus the spacer grid does not exhibit any kind of deformation due this compression load.

The physical test exactly reproduces the conditions described above, and then the limits for compressive loading are determined. It is performed using a universal tensile machine, which in turn applies a compressive load. The data acquisition is done by a computer system that records the forces and the displacements at every specified increment. Furthermore, the maximum compression force achieved is recorded. A scheme of the test device is shown in Fig. 2.

2.1.2. Modeling of compression test

A three-dimensional 16×16 spacer grid was constructed by using shell finite elements in order to reproduce the designed component. This kind of modeling demands a lot of computational resources, since the number of elements, and consequently the number of nodes, is very high. To correctly design spacer grid shape it was used the geometrical nominal values. After that, the Inconel 718 material properties listed in Table 1 were attributed to the model. It was used the quadrilateral four nodes shell element SHELL63 to mesh the full model. It is important to notice that the external straps are thicker than the inner one, so in order to represent this difference, the finite element type used request a thickness on each node of the element. Additionally, two bars were modeled to represent the compression device; each of them was located in the bottom and top outer strap of the spacer grid modeled. These bars were modeled according with the actually test device by considering the elastic properties of a stainless steel with $E = 200$ GPa and $\upsilon = 0.3$. The meshing was done using the brick-eight nodes finite element SOLID45 type. Fig. 3 presents the whole model discretized with the bars for compression. Contact elements between the bars and spacer grid top and bottom outer strap was used to produce the correct behavior of bars acting in the compression directions, and the static friction coefficient, μ, equal to 0.25 was applied between the parts. For the boundary conditions were applied nodal displacements on specifics locations, as can be seen in the scheme presented in Fig. 4. The lower bar was restrained on all degree of freedom and it was applied a displacement about 0.65 mm in the upper bar in the compression direction.