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EVALUATION OF SPACER GRID SPRING CHARACTERISTICS BY MEANS OF PHYSICAL TESTS AND NUMERICAL SIMULATION

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ABSTRACT

Among all fuel assemblies' components, the spacer grids play an important structural role during the energy generation process, mainly due for its primary functional requirement, that is, to provide fuel rod support. The present work aims to evaluate the spring characteristics of a specific spacer grid design used in a PWR fuel assembly type 16x16. These spring characteristics comprises the load versus deflection capability and its spring rate, which are very important, and also mandatory, to be correctly established in order to preclude spacer grid spring and fuel rod cladding fretting during operation, as well as prevent an excessive fuel rod buckling. This study includes physical tests and numerical simulation. The tests were performed on an adapted load cell mechanical device, using as a specimen a single strap of the spacer grid. Three numerical models were prepared using the Finite Element Method, with the support of the commercial code ANSYS. One model was built to validate the simulation according to the performed physical test, the others were built inserting a gradient of temperature (Beginning Of Life hot condition) and to evaluate the spacer grid spring characteristics in End Of Life condition. The obtained results from physical test and numerical model have shown a good agreement between them, therefore validating the simulation. The obtained results from numerical models make available information regarding the spacer grid design purpose, such as the behavior of the fuel rod cladding support during operation. Therewith, these evaluations could be useful to improve the spacer grid design.

1. INTRODUCTION

The fuel assembly for a pressurized water reactor (PWR), as defined by Park et al. [1], is a mechanical structure that has multiple components and it should be designed to resist loads during its normal operation and, as well as external loads, in the case of an accident, such as a seismic shutdown earthquake (SSE) or a Loss-Of-Coolant-Accident (LOCA). The fuel assemblies consist of spacer grids, fuel rods, top nozzle and bottom nozzle, guide tubes, and instrumentation tube, as shown in
Figure 1. Schettino et al [2] state that the correct performance of fuel assemblies depends on a good mechanical and structural design, taking into consideration the core design and thermo-hydraulic limiting conditions. Therewith, the choice of materials to be used, the geometrical characteristics defined and the appropriate fabrication must be of the utmost importance when a finite element model will be constructed.

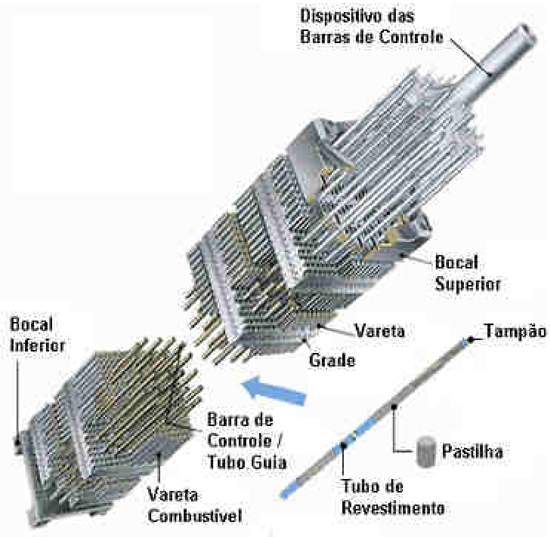


Figure 1: Fuel assembly [3]

Moorthy et al [4] states that the fuel assembly is subjected to two kinds of loads, static and dynamic, during its operation. Because of that, safety of a nuclear reactor is the most important issue in the nuclear energy generation. Therefore it’s essential to ensure, by design, the integrity of the nuclear core components, including the fuel assembly, over the entire life of the reactor. Because of that, physical tests and numerical simulation is a key tool to evaluate such conditions, sometimes mandatory.

Among all fuel assembly components, spacer grid plays a very important role, particularly when a structural characteristic is required. SONG et al [5] define this part is an interconnected array of slotted grid straps, welded at the intersections to form an egg crate structure. The spacer grid assembly supports the fuel rod with springs and dimples stamped into each grid strap within a spacer grid cell, as shown in Figure 2. And also, the spacer grid protects the fuel rods from external impact loads in an abnormal operating environment such as during an earthquake or a Loss-Of-Coolant Accident (LOCA).

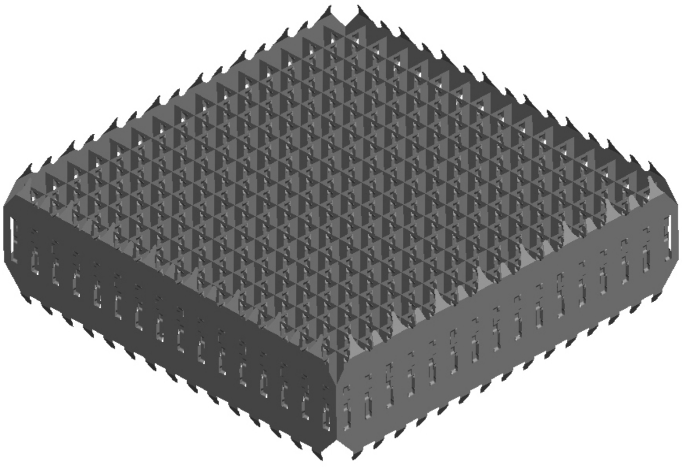


Figure 2: Spacer grid complete

The spacer grids springs must consider a very tight design, when consider its main property, the stiffness. The loads exerted by the spring should be strong enough to keep the fuel rod on its predicted position, but low enough to not hold in excess the growth of the rods, in order to preclude the buckling of the fuel rod tube due to the differences in the support forces.

The spring characteristics, investigated by its stiffness by means of the load versus deflection curve of the specific design of the spring are a function of many parameters. Kim et al [6] mention that the main parameter is related to the spring (or dimple) dimensions, such as the thickness of the strap, the width, the fillet radius, etc. Additionally, it could be mentioned others parameters, such the material (mechanical properties) and the load and/or displacement experienced by the spring.

Throughout the fuel assembly manufacturing , the fuel rod loading process in the fuel skeleton, i.e., insertion of a fuel rod into a cell of the spacer grid, is the condition which the spring force exert its maximum strength. In other words, the spacer grid springs and dimples exert a normal contact force on a fuel rod, from which a friction force is produced at the contact location. The fuel rod can be positioned due to the friction force. Since an excessive friction force can cause fuel rods to bow due to a fuel rod growth under a reactor operation, the design of a spring force is very important [6]. Because of that the mechanical integrity of a fuel rod is a concern even during the manufacturing process, since the maximum force exerted by spacer grid spring occurs when the fuel assembly is mounted.

According to Hooke’s law, the spring force is defined simply as the product of the spring stiffness and the displacement, showed by Equation (1). When a fuel rod is inserted into a spacer grid, the spring and the dimple of a grid are displaced to some extent in the direction of a compression (normal to axial direction of a fuel rod), which Kim et al [6] named as the ‘initial interference’. These authors also identified that dimples are usually much stiffer than a spring, so they are displaced very little as a fuel rod is inserted into a spacer grid.

$$F = k \cdot x \tag{1}$$

An important behavior of the fuel assembly components during operation within reactor core, according to preceding works cited by Kim et al [6], is the spring force reduction as the fuel burnup increases, since the elastic modulus is degraded due to the high temperature and the irradiation effect. The authors also verified that the cladding tubes that were reduced on its diameter, due to creep phenomenon, also contribute to the spring force reduction. These effects should be considered when the initial contacting force between the fuel rod and the spacer grid (termed ‘initial spring force’ in general) is considered on the design stage.

So, to analyze the spacer grid stiffness it was proposed to evaluate its behavior under some operational condition.

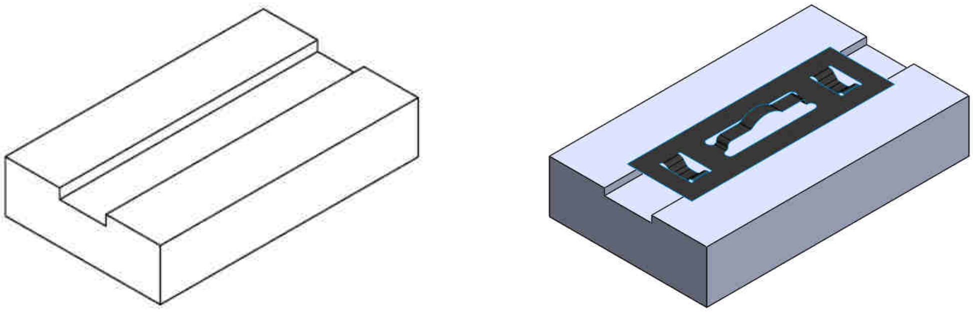
Based on the aforementioned spacer grid spring characteristics, this paper proposes to evaluate, physically and numerically, by mechanical test and by the finite element method, respectively, the stiffness of a spacer grid spring, and then propose a numerical model as tool to analyze this characteristic.

2. SPRING CHARACTERIZATION TEST

Physical tests of nuclear parts from a fuel assembly play an important role during development of new or modified components, working as a proof its reliability and functionality.

To evaluate a spring from a spacer grid assembly, it was cut from an inner strap a single part that composes a wall of a spacer grid cell, as illustrated in Figure 3. It also noted that the specimen has a spring and two opposite dimples to be tested. The specimen was mounted to a hollow-backed testing block. The mounting process consisted of spot welding the spring strap section along the length of the test block to simulate the proper grid cell boundary condition, to prevent a strap from slipping during applying the force as shown in Figure 4. Then this specimen was placed on the testing machine.

Figure 3: Specimen – part from an inner strap of spacer grid



(a) **(b)**

Figure 4: Devise to hold the specimen: (a) support for the strap - spring; (b) support with the strap - spring.

The setup test was carried out using a universal tensile testing machine (UTM), as shown in Figure 5. A loading bar was used to simulate the loading by a fuel rod. The grid spring load deflection test was initially performed lowered this loading bar until it just touch the spring, then a controlled lowering was made step by step until the spring reached 1 mm of compression. The load versus deflection curve for the spring specimen was generating by initiating the crosshead of the testing machine travel, then stopping and reversing the travel when the desired deflection was obtained. After the programmed 1 mm of deflection an unloading process was performed, which was controlled and the unloading curve was obtained as well.

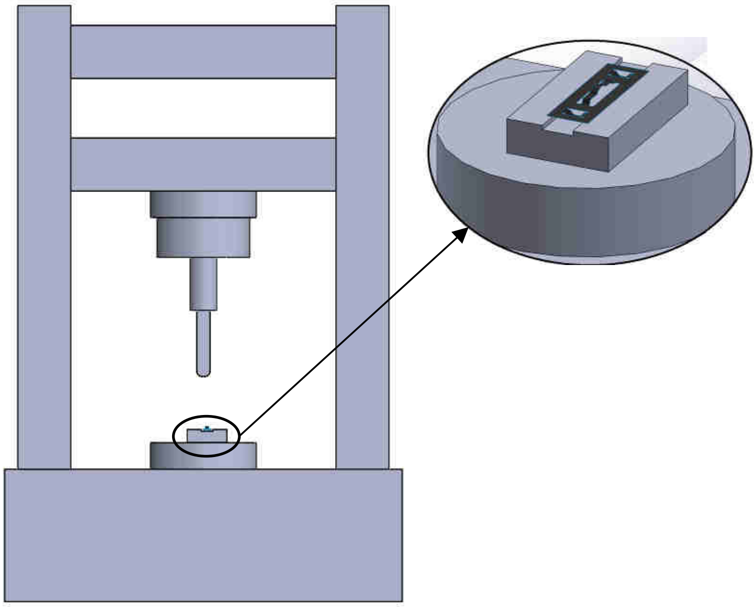


Figure 5: Test machine setup

3. SPACER GRID SPRING FINITE ELEMENT MODELS

Kim et al [7] state that the finite element analysis (FEA) is used for the design since it should be the most efficient tool for such a kind of work, reflecting the easiest manner of modifying the shape, dimension and obtaining the corresponding results immediately.

Three numerical models were prepared using the Finite Element Method, with the support of the commercial code ANSYS, in order to simulate the behavior of the spacer grid spring during its compression by the fuel rod. The first numerical model was constructed to validate the simulation according to the performed physical test. The second numerical model was built inserting a gradient of temperature, with the intention to simulate a BOL (Beginning Of Life) hot condition, where the fuel assembly is inserted in the nuclear reactor core but the temperature is still low and the neutron fluence affecting the spring and tube materials could be neglected. The third model was modeling with the objective to evaluate the spacer grid spring characteristics in EOL (End Of Life) condition, where the fuel assembly is experience the full power within the nuclear reactor, in other words, the temperature is high and the neutron fluence is affecting the spring and tube materials.

The geometrical model was generated using the CAD software SOLIDWORKS, then it was imported to the CAE software ANSYS, where the numerical model was constructed and solved, and then the results were extracted for each case, i.e., post processed. For all the models it was used two kinds of finite elements: SHELL281, for the spacer grid strap body, and the SOLID186 for the fuel rod cladding tube. The shell finite element used has eight nodes with six degree of freedom at each one: translational in x, y and z axes, and rotations about the x, y and z axes. This element is well-suited for linear and large strain nonlinear applications.

The material properties of the Inconel 718 and Zircaloy-4, the material used by the spacer grid and fuel rod tube cladding section, respectively, for the first model, are placed in the Table 1, where the Young modulus, Poisson coefficient and the temperature are shown. It is important to quote that the nonlinearity of the spring material was used, in other words, a stress versus strain curve data was inserted in the model.

Table 1: Material properties of the Inconel 718 and Zircaloy-4

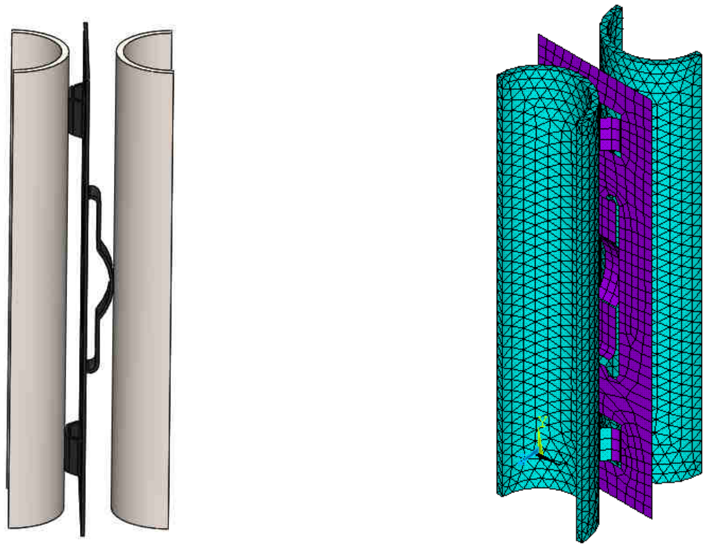
Material	*Temp. [°C]*	*Young Modulus [GPa]*	*Poisson Coefficient*
Inconel 718	20	200 x10³	0,294
Zircalloy-4	20	98,3 x10³	0,296

For the others two models the temperature is modified. The second case, BOL model, the temperature raised up to 50 °C, and for the third case, EOL model, the temperature raised more and reached 310 °C. Because of that, the materials properties change, then the stress versus strain curve was fitted to supply the new values according to the temperature for each case. The new data points are presented on Table 2.

Table 2: Material properties of the Inconel 718 and Zircaloy-4 at Operational Temperatures

Material	*Temp. [°C]*	*Young Modulus [GPa]*	*Poisson Coefficient*
Inconel 718	50	197 x10³	0,290
	320	184 x10³	0,272
Zircalloy-4	50	95 x10³	0,293
	320	75 x10³	0,258

The finite element models were built considering just a part of one strap of the whole spacer grid and a half of a fuel rod tube section, see Figure 6. The boundary condition present on all three models are presented in Figure 7. A restriction on all the degree of freedom can be seen at the edge of the strap, simulating the weld connection. Additionally, a restriction on the fuel rod tube section was carried out in order to provide a guided connection to the spacer grid strap/spring and tube interface, which can be seen by the degrees of freedom introduced, i.e., translation movement in the “z” direction, toward to compress the spring. It was necessary to generate a contact element due to this tube/spring interface.



(a) **(b)**

Figure 6: Finite Element Model built: (a) geometric model; (b) finite element mesh

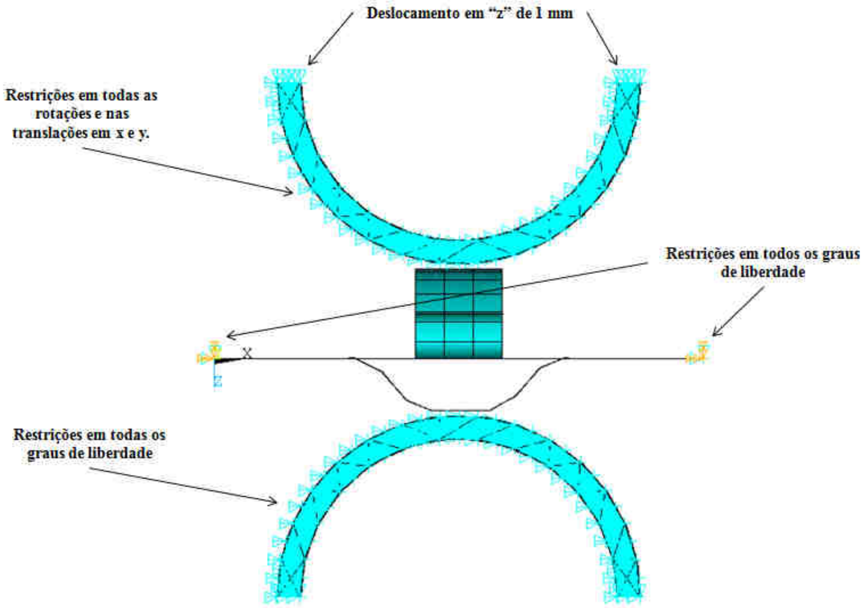


Figure 7: Numerical model boundary conditions

The loading conditions implemented to the models are indicated in Figure 7 also. It can be noted that a displacement of 1 mm was applied on the fuel rod tube section in order to push the spring. The analysis type performed in the present work, for both models, was the static nonlinear.

It is important to note that the numerical model built does not consider a complete spacer grid and fuel rod arrangement, once this structure, as an assemblage, does not significantly influence on this simulation. This is the major assumption for all finite element models.

4. RESULTS AND DISCUSSION

The result obtained in the physical test can be shown by a graphic that relates the force of the spring according to its displacement, present in Figure 8. The slope of the acquired curve is the stiffness of the spring.

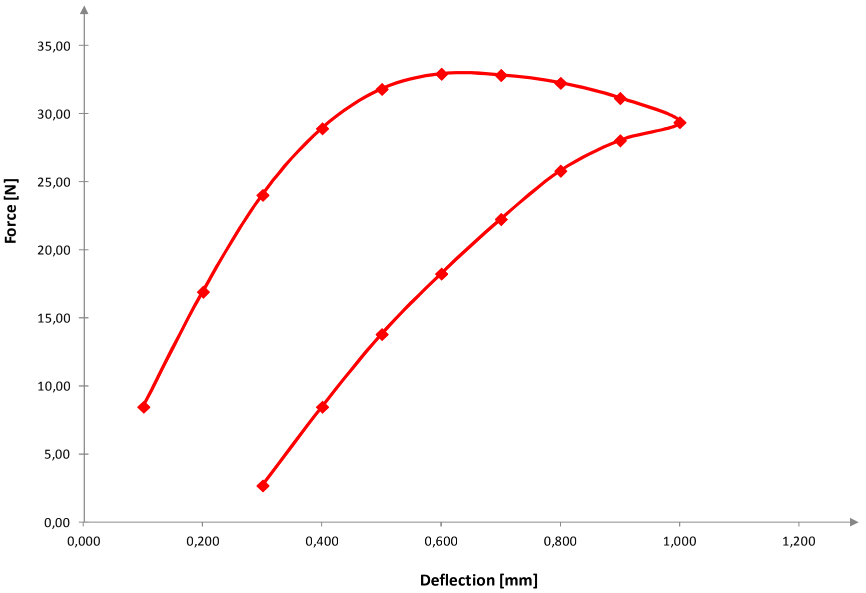


Figure 8: Force versus deflection curve from characterization test

The plots obtained for each case during the post-processing phase of the numerical model show the deformed spring due the compression, leaded by the fuel rod tube displacement, as can be seen in Figure 9.

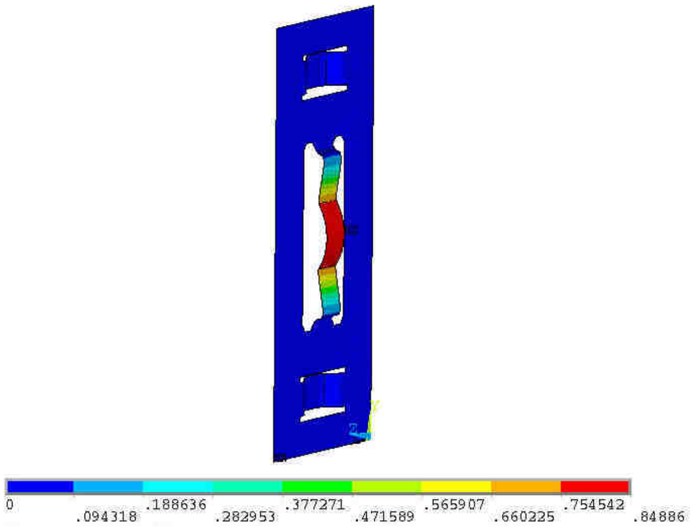


Figure 9: Numerical model deflected due to spring compression by the cladding tube

The results extracted in the finite element model were the displacement and the reaction force acting on the spring, due to the displacement applied in the fuel rod. The first case, spring compression at room temperature (20 °C), the numerical analysis provide a result that can be plotted in a graphic and compare the curve with the tested one (see Figure 10).

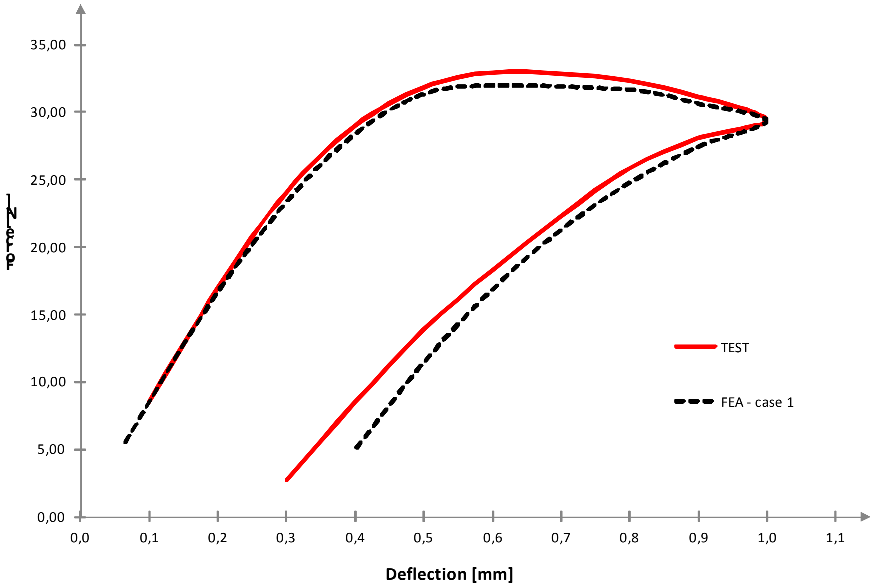


Figure 10: Force versus deflection curve of the numerical model for case 1, and its validation with the characterization test curve

The curve obtained for the first numerical model (case 1) well fit the characterization test curve, which proves that the built models are validated regards those physical tests, as the results are very close.

For the analysis performed by the finite element method, for the other two cases (model 2 and 3), the achieved results are summarized in Figure 11, which shows the force versus displacement of the spring for both cases. However the curve plotted for the case 3 in this graphic is taking in account only the thermal contribution (320 °C). This figure also compares case 1 with the other two.

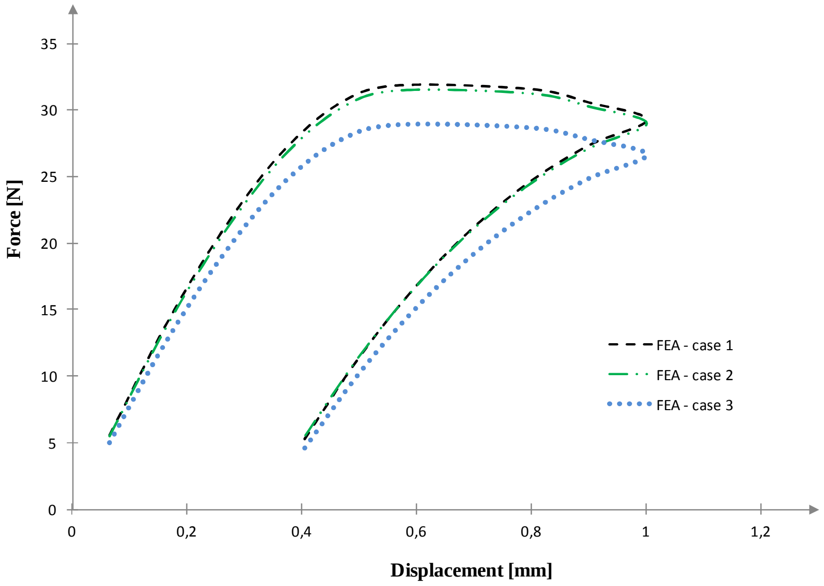


Figure 11: Force versus deflection curve of the numerical models - case 1 (20 °C), case 2 (50 °C) for BOL and case 3 (320 °C) for BOL

It is noted in previous graphic that, as expected, when the temperature raises less force can be supplied by the spring. However, the spring still keep the same profile.

The grid spring strength under irradiation is analyzed on the model built for case 3, where a neutron fluence and fuel rod creep-down are take in account. Lee et al [8] cited that beyond temperature, the neutron fluence due to irradiation contributes to the spring relaxation, in other words, the spring loses its deflection capacity, without lose its stiffness. It's well known that the spring relaxation and the fuel rod cladding tube creep-down is caused due to the neutron fluence, and this phenomenon is a function of the burnup, as Billerey [9] has studied. In his work, it is presented an equation - see Equation (1) - linking the spring force with the neutron fluence and the creep-down, where F is the spring force, k is the stiffness, x_{creep} represents the loses of deflection due to creep, Øt is the neutron fluence (>1 MeV), Q is the activation energy, T is the temperature and the others variables (A, B and w) are constants.

$$F = \frac{k \cdot x_{creep}}{\left[\mathrm{A} \cdot \ln(1 + \mathrm{w} \cdot \phi\mathrm{t}) + \mathrm{B} \cdot \phi\mathrm{t}\right] \cdot \exp\left(- {}^{\mathrm{Q}}\!/\!{}_{\mathrm{T}} \right)} \tag{2}$$

From this equation it is notice that the spring force exposed to a flux of neutrons loses its strength.

The curves present in the graphic of Figure 12 are related to the model built for the case 3, but one of the curves is for the numerical model built (also presented in Figure 11), where the thermal contribution is the only consideration, on the other hand the other curve presented is obtained by fitting the previous curve considering the neutron fluence and the creep-down, as a function of the burnup. The spring relaxation considered in this analysis was 30%.

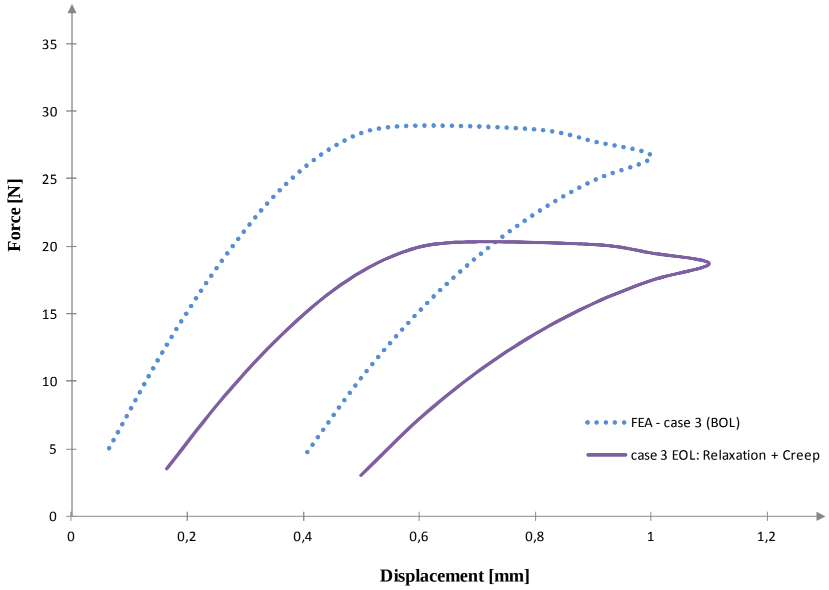


Figure 12: Force versus deflection curve comparison case 3 (320 °C) – BOL and EOL

From the curve plotted above, it can be recognized that the profile for the relaxed curve (“case 3 EOL: Relaxation + Creep”) is very similar to the thermal curve (“FEA – case 3 BOL”), and the spring stiffness remain the same. Nevertheless, the force and the available room for displacement decrease a lot. Billerey [9] studied that the relaxation varies from 50% to 90%, depends on the spacer grid level, as the neutron fluence rises when the fuel assembly middle span get closer.

5. CONCLUSIONS

To perform a design change on fuel assemblies it is very important to make a lot of analysis and tests before to insert it within nuclear reactor core, in order to prove its reliability. The evaluation present in this work reveals the finite element method contribution on analyze changes in the fuel assembly structure.

The proposed numerical models could evaluate the behavior spring force according to the thermal contribution, and provide valuable results. Notably, the model for EOL condition (case 3), the obtained results for the thermal performance plus the spring relaxation and the tube creep down provide results that give knowledge to understand the irradiation induced on the spacer grid support, i.e., contact between spring and tube.

The results show that the amount of burnup (and, consequently, neutron fluence) decreases a lot the spring force and the available room for displacement. This behavior of the spring should be taking into account when a new spacer grid design will be created, in order to preclude a fretting failure on the fuel rod.

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