«Substantiation of strength of TVSA-ALPHA fuel assembly under dynamic seismic loads»

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A special place in the substantiation of the safe operation of fuel assemblies is the assessment their operating capability under seismic loads, leading to short-term (several seconds or tens of seconds) the dynamic effects on the reactor core. The level of acceleration of various elements of the reactor installation can be higher than 1,5 g (g - acceleration of gravity) and depends on the height of these elements relatively the ground, which movement causes an earthquake. This dynamic load cause significant deformation of the active zones design element, in particular of the fuel assemblies (FA), which could lead to a contact (or impact) interaction between them. The report presents the results of studies of stress-strain state of FA of TVSA-ALPHA type under the influence of seismic loads of the 8th level on Richter scale using standard approach. According to a normative approach the natural frequencies and modes of FA are calculated in the preliminary stage.

A distinctive feature of FA of TVSA-ALPHA type is the presence of eight high precision hexagonal spacer grids (SG) formed by arch cells with a height of 35 mm and wall thickness of 0.25 mm, uniformly disposed at the FA height on the distance of 510 mm between neighboring SG. SG connected with rigid angle pieces in the corners of the SGs hexahedron creating rigid skeleton which resist against FA curvature during operation. Distance between lover support grid and the first SG is 247 mm, between 7-th and 8-ts SG – 455 mm. Moreover there are 312 fuel rods, 18 GC connected with SG on the friction, central tube, upper spring block.

Large number of structural elements of the FA interacting with each in a complex manner determines the need to build a detailed three-dimensional rod finite element model of FA of TVSA-ALPHA type.

The finite element model of FA of TVSA-ALPHA type with eight SG is presented in figure 2. There are lower support grid and anti-vibrating grid in the FA lower part. The model consists from the rod finite elements which bending and torsion stiffness, geometric parameters of cross sections, and Young modulus were given in correspondence with the design features of FA design elements. Each finite element has the materials number which determines corresponding stiffness and geometric parameters

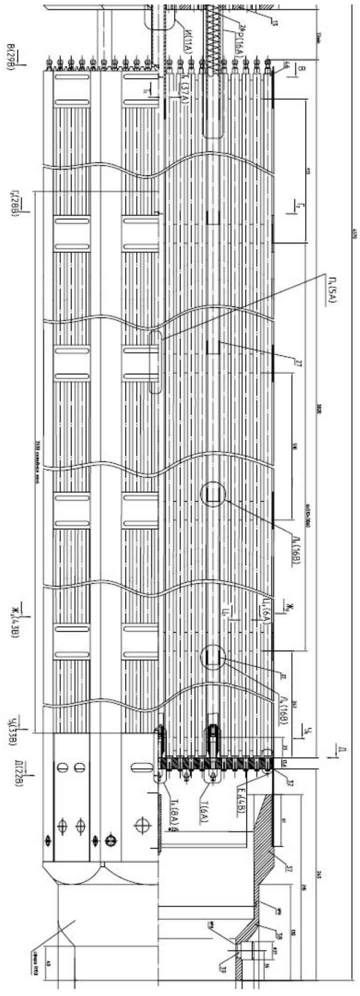


Figure 1. FA TVSA-ALPHA

This approach allows take in to account the main deformation features and also peculiarities of the design elements interaction: of 312 fuel rod shells, of 8 spacer grids, of anti-vibrating grid fixing fuel rods, of 18 guide tubes and angles in the corners of FA hexahedron. According to the design of real FA the distance between spacer grids in the middle part of FA is equal to 510 mm. The length of lower span between lower support grid (LSG) and first SG is 247 mm, the length of upper span is 455 mm. The distance between lower support grid and anti-vibrating grid is 23 mm. Taken in to account that the rod finite element models of SG don't have dimension at height the distance between SG in the model equal to the distance between middle planes of real SG. Thus the distance LSG-SG1 is equal to 265.5 mm, SG1-SG2 is equal to 510 mm, and SG7-SG8 – 472.5 mm. The model of FA of TVSA-ALPHA type consists from 132797 rod finite elements, 211895 nodes, 796782 degrees of freedom.

The model structure and the components are shown in figure. There aren't shown the finite elements of fuel rods and inner finite elements of SG models to "unload" the picture.

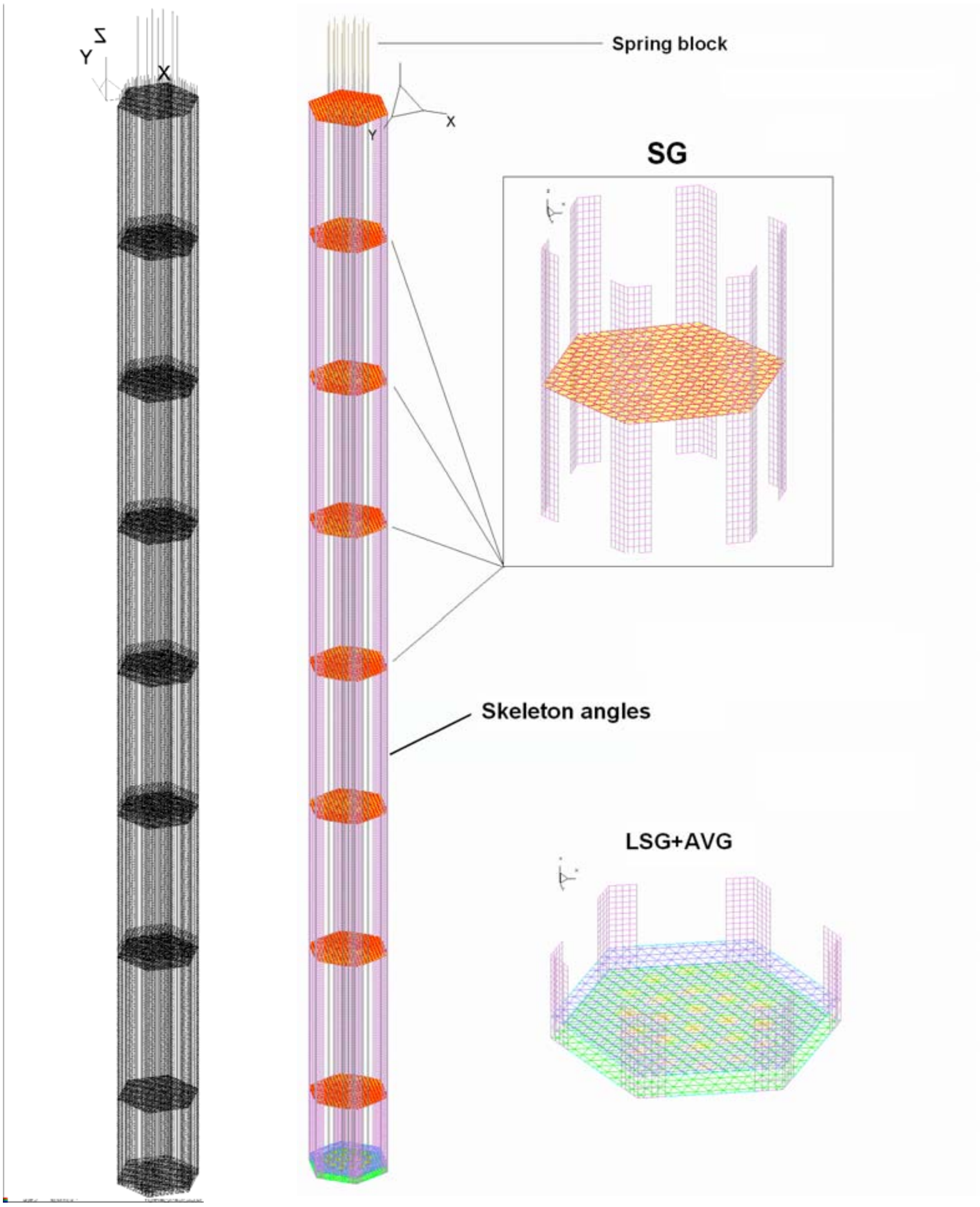


Figure 2 – Finite element model of FA of TVSA-ALPHA type.

To provide the similarity of rigidity characteristics of rod finite element model and real FA it is required to perform calculations of the fragments SG containing fragments of fuel rods and guide channels and also of the fragments of skeleton angles using three dimensional models and equivalent rod models.

The technique of determination of natural frequencies and modes of oscillation realized in the UZOR 1.0 is developed using fnite element approach on the base of the algorithm of the inverse iteration method with using on the stage of system of linear algebraic equation solution of the iterative conjugate gradient approach with preconditioning by the Crout-Cholesky incomplete decomposition method. Detailed description of the methodology, some test examples and verification results are presented in [1]. The results of FA TVSA-ALPHA dynamic parameters calculations are described in details in [2]. The values of obtained natural frequencies are shown in the table 1. Some of natural modes of oscillations are presented in figure 4.

On the basis of data on natural frequencies and modes of oscillations of FA of TVSA-ALPHA type presented in [2], as well as in Table 1 and Figure 4, the forces acting on the FA under the influence of earthquakes are calculated on the methodology described in the «Norms ...» [3] . According to standard methods [3] in the calculations are taken into account “S” lower modes of oscillations, which natural frequencies do not exceed the maximum value on the earthquake generalized response spectra equal to 24 Hz. It means that in calculation are taken in to account the first 13 modes of oscillations (see Table 1).

Further seismic load acting in the direction of ith generalized coordinates and the corresponding to jth modes of oscillations determined by the formula:

$$S_{ij} = m_{ii} \ddot{\varphi}_j \Phi_j x_{ij} \quad ,$$

where

m_{ii} - the element of diagonal mass matrix corresponding to ith component of natural modes of FA oscillations;

$\ddot{\varphi}_j$ - the acceleration determined on response spectra for jth natural frequency;

x_{ij} - ith component of jth modes of oscillation;

Φ_j - the coefficient of jth modes of oscillations calculating by the formula:

$$\Phi_j = \frac{\sum_{i=1}^{N} m_{ii} x_{ij} \cos\alpha_i}{\sum_{i=1}^{N} m_{ii} x_{ij}^2}$$

Hire $\cos\alpha_i$ - is the angle between direction of ith generalized coordinate and of direction of seismic impact.

The resulting values of internal forces, stresses, displacements at the finite element model nodes are calculated for each vector of seismic loads S_{ij} separately and then summed up as:

$$N_k^p = \sqrt{\sum_{j=1}^{S} N_{kj}^2} \, , \qquad (4.3)$$

where k = 8 corresponding to the SG quantity and to the parts on which the model of FA divided.

Table 1

The natural frequencies of FA of TVSA-ALPHA type taking in to account the attached mass of coolant and firmly fixed lower bottom unit, T=320 °C.

Frequency number	Frequency value, [Hz]	Geometry	
1	3,60	Bending	
2	3,60	Bending	
3	7,28	Torsion	
4	7,68	Bending	
5	12,07	Bending	
6	7,68	Bending	
7	12,07	Bending	
8	14,10	Torsion	
9	16,88	Bending	
10	22,17	Bending	
11	16,88	Bending	
12	20,25	Torsion	
13	22,17	Bending	
14	25,91	Torsion	
15	27,92	Bending	
16	27,92	Bending	
17	31,16	Torsion	
18-23	35,75 – 36,1	Fuel rod span oscillations	

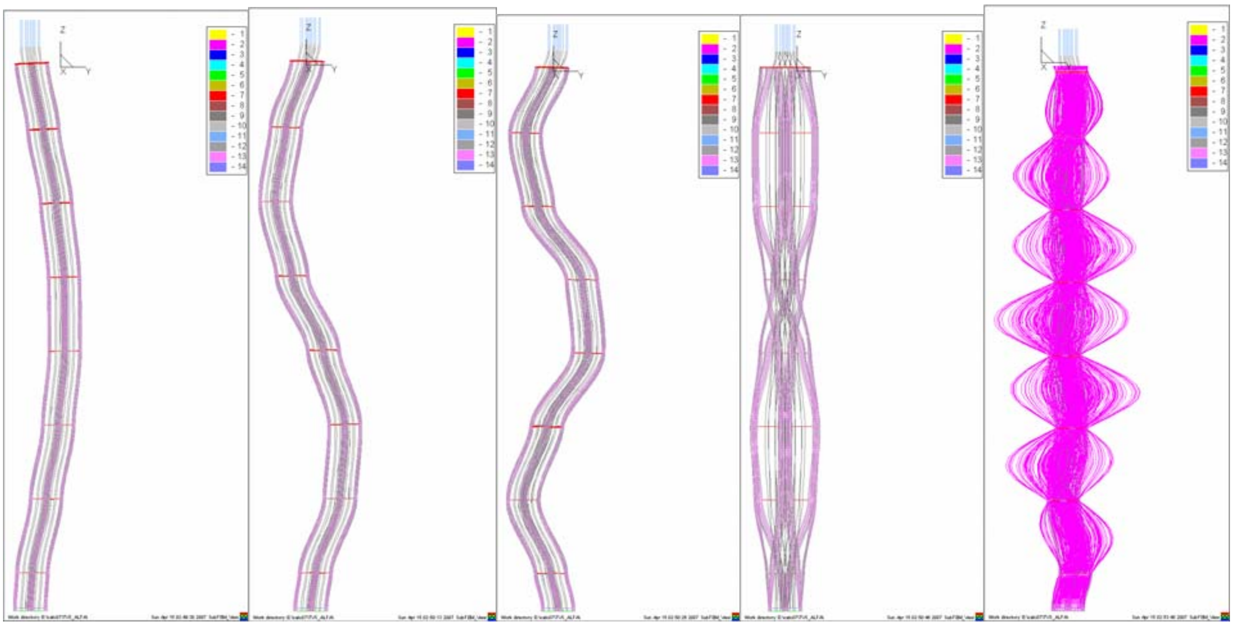


Figure 3 – The natural modes of oscillations of FA of TVSA-ALPHA type, corresponding to the 1st, 4th, 5th, 8ts and 18th natural frequencies.

Since the next stage of calculation is the analysis FA behavior in reactor core using computer code “CORAL” taking in to account of the interaction between FAs, of the gaps values between FAs and of the limitation of movement of the FA placed near the surrounding intra vessel equipment the obtained vector of seismic forces at FE model nodes is reduced to the integral values of force on eight SG. This procedure is the algebraic summation of forces components acting along the OX, OY, OZ axis at the nodes, which are placed in a given part of the FA model bounded by a plane passing perpendicular to the FA axis in the midpoint of fuel rods spans between eight SG.

In assessing the seismic forces influencing on FA can be considered variants of different seismic intensity. In this case the acceleration received for natural frequency of construction using response spectra of 9th earthquake magnitude is multiplied by a factor KS. For 8th earthquake magnitude KS = 0.5, for 7th earthquake magnitude KS = 0.25.

Two variants of choosing of accelerations participating in the analysis modes of oscillations of FA are considered in this example: case 1 - on the generalized response spectra from normative documentation at to zero height level; case 2 (conservative) – assignment for all modes spectrum of the acceleration equal to 1.6 g.

The obtained values of the seismic forces affecting the rim of SG are used in the future investigation as a quasi-static load to analyze of the stress-strain state parameters of SG and to evaluate their strength under seismic loading.

Obtained forces values influencing on SG and the transversal displacement of SG under seismic load are the initial data for the calculation using computer code “CORAL -LABIRINT”.

The results of the calculation of the displacements of FAs with allowance of their interaction and of the restrictions imposed by surrounding intra vessel designs are shown in Figure 4. The initial field of gaps before the earthquake is conditionally accepted as a random distribution of gaps in the range of 0 - 5 mm and of directions of deflections. This range of deflection is selected according to statistics obtained during monitoring of the FA curvature at the Kalinin NPP. As the measurements have shown the maximum initial deflection FA of TVSA type does not exceed 1.5 mm and the additional deflection during operation is less than 3.5 mm. Thus, the maximum total deflection of FA at the end of exploitation does not exceed 5 mm.

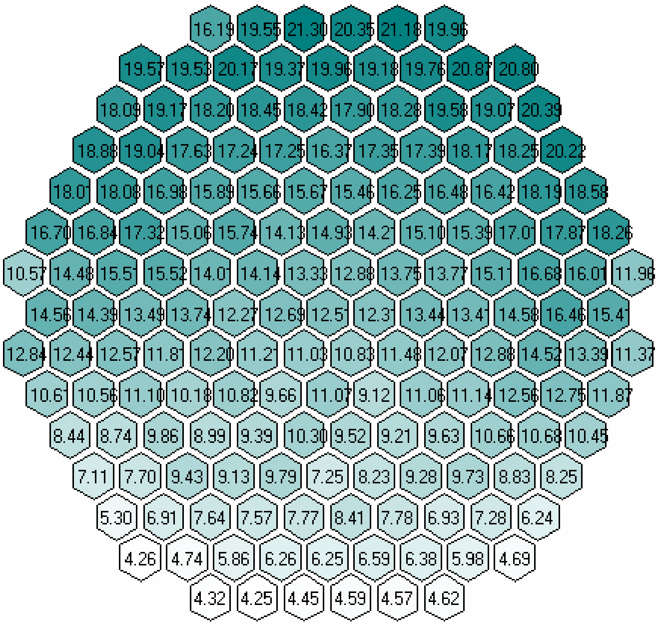


Figure 4 – The charts of TVSA-ALFA deflections modulus in the section of 4th SG in the reactor core of the VVER-1000 under seismic load in the direction of the angle-angle (conservative variant).

Table 2 presents values of the transverse compressive force acting on the rims of SGs of peripheral FA during the earthquake taking into account the interaction of FAs in the reactor core and the existence of gaps between them. The calculations assumed that the peripheral movement of the tape is limited, due to the interaction with surrounding intra vessel designs. The maximum forces influencing on separate SG in that case is much higher than that calculated for a single FA, due to the interaction of FAs in the core, taking up the clearance during application of the earthquake forces.

Table 2

Values of the transversal compressive forces on the SG rims for the most loaded TVSA-ALPHA under seismic impact.

	Force, [N] (Case 1)	Force, [N] (Case 2)
LSG	0	0
SG1	0	0
SG2	0	0
SG3	3214	3256
SG4	14122	21489
SG5	7877	19341
SG6	4847	5928
SG7	0	0
SG8	0	0

The presented results show that the maximum load is applied on the 4th SG and equal to - 14122 N in the first variant (the load was calculated by the response spectrum for zero height and the contribution of natural modes of oscillations depends on the value of corresponding natural frequencies), while for the second variant (conservative with the uniform value of acceleration 1.6 g for the whole natural frequencies spectrum), the maximum force equal to - 21489 N.

Another approach is the direct modeling of seismic influence on the reactor core using explicit methods of integration of differential equations of finite models motion:

$$M\ddot{q} + C\dot{q} + Kq = Q, \text{ where} \qquad (1)$$

q - the vector of finite element model nodes displacement,
$\dot{q}$ - the vector of finite element model nodes velocity,
$\ddot{q}$ - the vector of finite element model nodes acceleration,
M - the mass matrix of the finite element model,
C - the damping matrix of the finite element model,
K - the stiffness matrix of the finite element model,
Q - the vector of nodes forces depending on time.

Among the methods of integrating a set of differential equations of motion we may distinguish unconditionally stable or implicit methods which allow obtaining a reasonably accurate solution even at relative large values of the integration step. These methods call for solution at each time step of an equation set which order equals the number of degrees of freedom of the finite element model. Considering that the size of equation sets may be as large as hundreds thousands, we have implemented the method of explicit integration of an equation set – the central difference method that does not require establishing the matrix inversion procedure. This method allows calculating displacements, velocities and accelerations of the finite element model nodes $q_{i+1}, \dot{q}_{i+1}, \ddot{q}_{i+1}$ at instant $t_{i+1} = t_i + dt$ through their values at instant t_i, where dt is the integration step.

$$q_{i+1} = q_i + dt\dot{q}_i + \frac{dt}{2}\ddot{q}_i,$$

$$\dot{q}_{i+1} = \frac{1}{2dt}(q_{i+1} - q_{i-1}),$$

$$\ddot{q}_{i+1} = \frac{1}{dt^2}(q_{i+1} - 2q_i + q_{i-1}).$$

Let us write equation (1) for instant t_i :

$$M\ddot{q}_i + C\dot{q}_i + Kq_i = Q_i \, .$$

Substituting approximate dependencies for the vector of displacements, velocities and accelerations (1.8) into the obtained equation, we arrive at:

$$(M + \frac{dt}{2}C)q_{i+1} = R_i \, , \text{ where}$$

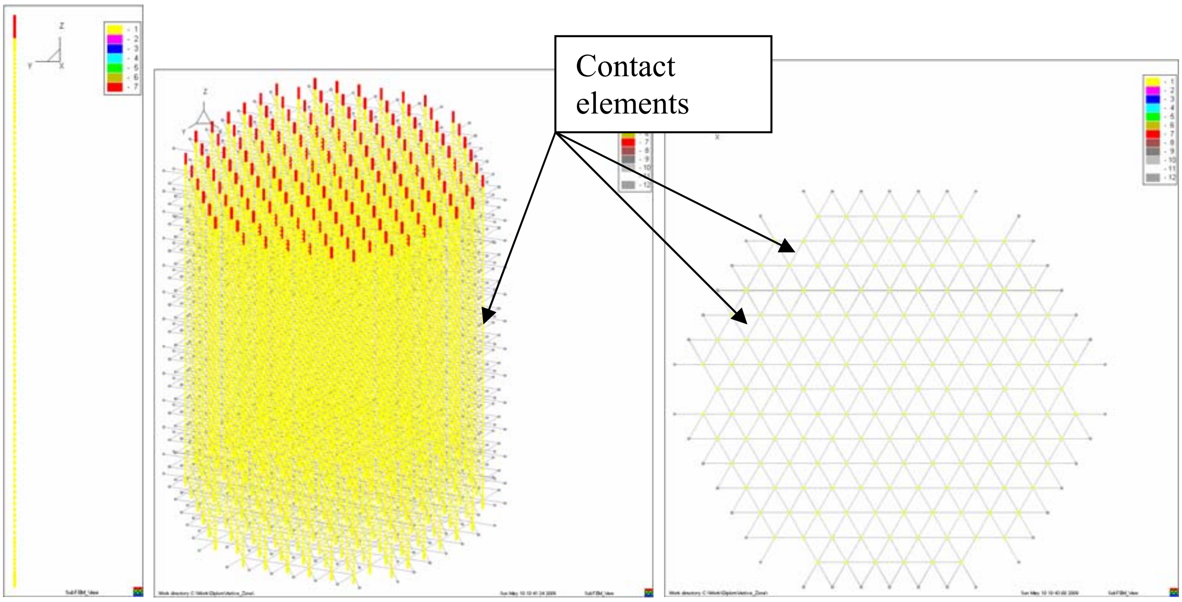
$$R_i = dt^2(Q_i - Kq_i) + M(2q_i - q_{i-1}) + \frac{dt}{2}Cq_{i-1} \, .$$

The above relations in combination with the initial conditions comprise the procedure of stepwise integration of the set of equations of motion of the finite element model.

Implementation of this algorithm is simplified if the mass matrix has a diagonal or block-diagonal structure, and there is no damping, or when the damping matrix is proportional to the mass matrix.

As it was mentioned above the acceleration values of the design elements of a reactor unit under seismic load can reach the level of 1,5 g and higher (g – gravity acceleration) and depend on the height of their position relatively of ground level, which movement happens during earthquake. Dynamic load of such level cause significant deformation of design elements of reactor core, particularly FAs, which can lead to the contact interaction between them.

The methodology of the FA group behavior simulation under seismic load is considered on an example of VVER-1000 reactor core consisting from 163 fuel assemblies of TVS-2M type, presented in the model as the rod finite element models – figure 5.



(a) (b) (c)

Figure 5 – Rod finite element model of FA of TVS-2M type (a), the model of reactor core VVER-1000 included 163 FAs (b,c).

When solving some problems, for example, in case of contact interaction between objects of the system under study when values of stiffness parameters may vary by several orders of magnitude, a significant reduction in the integration time step is required. To solve this problem an algorithm of integration of equations of motion with variable time step was developed.

The rigidity characteristics of the equivalent rod finite element of TVS-2M are alculated using experimental investigation of full scale model of FA.

Taken in to account that the transversal deflection of FA can reach tens of millimeters under seismic load VVER-1000 reactor core there appears the necessity of simulation of contact interaction between pairs of neighboring FAs and of peripheral FAs with surrounding designs. For this purpose in the model of rector core the special contact element connecting FA model nodes at the levels of SG position are included. The length of the contact elements (Lc = 235 mm) is equal to the distance between the vertical axes of FA (233 mm) plus the gap between FA(2 mm). The length of peripheral contact element was equal Lc = 237 mm because the gap between FA and surrounding designs is 4 mm.

The horizontal seismic load is applied to all nodes of finite element model in the direction of the axis OX as a time varying vector of inertia load calculated as the product of finite element mass and acceleration at the current time instant. The dependencies of horizontal displacements of the upper, lower core plates and ground on time are shown in figure 6. It is assumed that the acceleration values are changed linearly along the FA height.

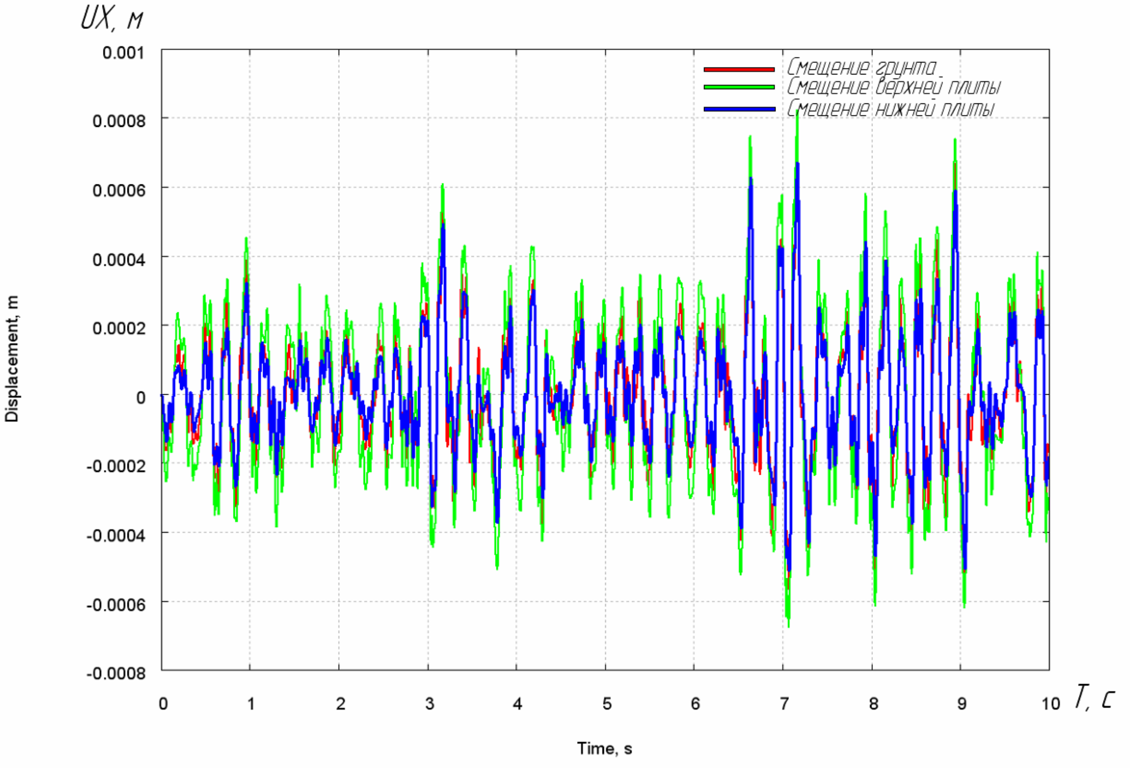


Figure 6 – Dependencies of horizontal displacements in the OX direction of the ground, upper and lower core plate on time.

The task is carried out in increments of the nodes displacement vector. The criterion of contact between the FA rims constituting the group is the reducing of the contact element length (rod elements with material number 12) to a specified value. Initial size of the contact rod is Lc = 235 mm in the task of group TVS-2M behavior investigation. The length of contact element equal to the distance between the vertical FA axes plus the gap length equal to 2 mm. Contact occurs when the length of the contact element reduced to a critical size Lcs = 233 mm, that means disappearance of the gap between neighboring FAs. It is clear that in the process of simulation at the beginning of a step-time Lc is larger than critical value, but at the end of that step it is being lower than this value. In order to exactly determine the instant of contact occurrence there is used an algorithm of time step dividing in half. At the considered transitional time interval an infinite iteration loop is organized. The value of time step is calculated by dividing of current value on 2 at each iteration of this loop. This increment is subtracted from the current step of time or added to it, according to a fact more or less the current value Lc of critical value Lcc. These iterations are performed until the absolute difference (Lcc - Lc) will not be less than the specified ε value, which is equal to 10^{-6} in this example.

After the contact element switches to a contact state the contact force is calculated as the product of its longitudinal deformation calculated according to the displacements of element nodes and of the rigidity EF, where E is Young modulus and F is the cross section area of a rod finite element.

When the contact appears the stiffness matrix of finite element model is modified on the subsequent solution steps in accordance with the changed stiffness of contact element.

The finite element model of VVER-1000 reactor core consists from equivalent rod finite element of FA of TVS-2M type having 13 spacer grids. It consists from 11924 quadratic rod finite elements, 6708 from which are the contact elements, and 18239 nodes. The maximal value of integration step is $\Delta t_{\max} = 1.0 \cdot 10^{-5}$ second if the contacts absence, $\Delta t_{ini} = 1.0 \cdot 10^{-9}$ second when contact appears, $\Delta t_{\max}^{cont} = 0.3 \cdot 10^{-6}$ second when the contact interactions presence. The first 5 steps after stiffness matrix changing due to contact appearance are performed with the constant value of time step and then doubled the next step to achieve maximum value for the current state of the model.

The information about nodes displacements output at certain intervals is accumulated during the problem solving which gives an indication of the geometry changing of the core during the dynamic loading. In addition there are calculated the contact efforts in each contact element, which are the consequences of the deformation and of the fuel assemblies impacts in the reactor core.

As the result of computer code application we can analyze the deformation processes of FA in time and also the impact forces influence at the whole FA or at separate spacer grid.

The deformed state of the VVER-1000 reactor core corresponding to the time instant 0.826 sec. and the position of the contact element being under interaction are shown in figure 7. The displacement magnitude is 40.

The dependence on time of contact forces on the rim of SG7 for most loaded during seismic impact FA are presented in figure 8.

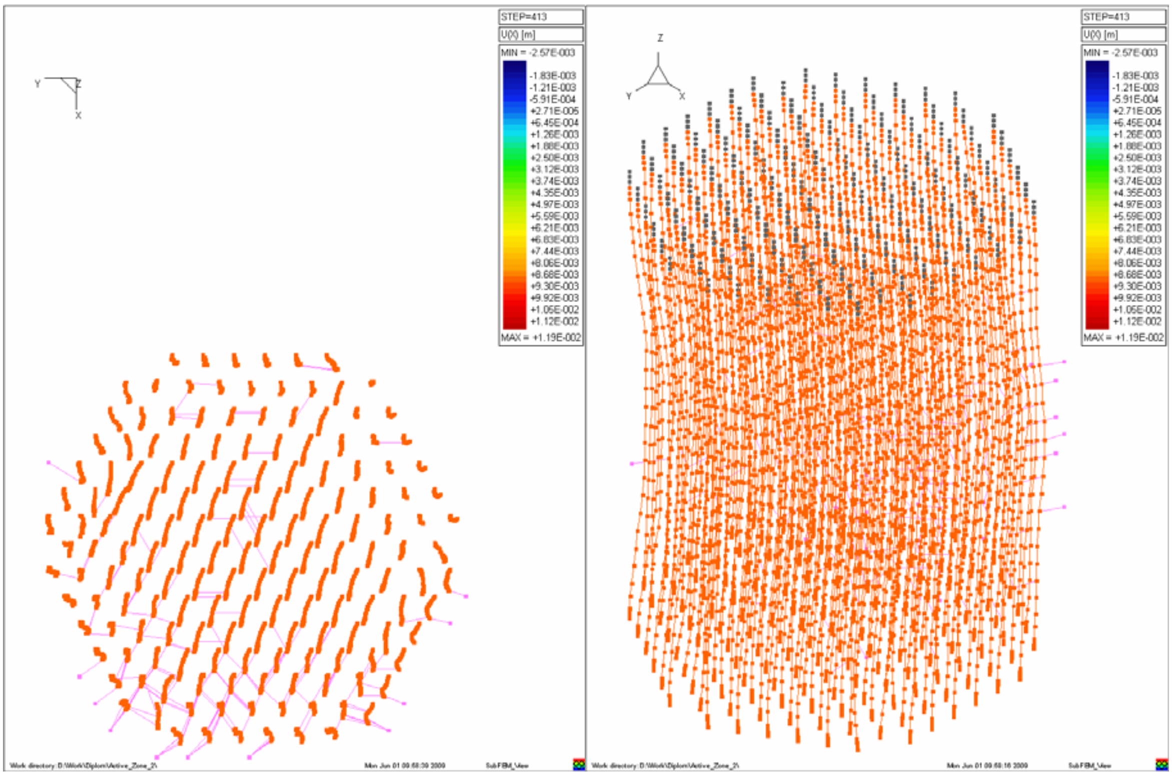


Figure 7 – Deformed state of VVER-1000 reactor core under seismic load at time 0.826 sec.

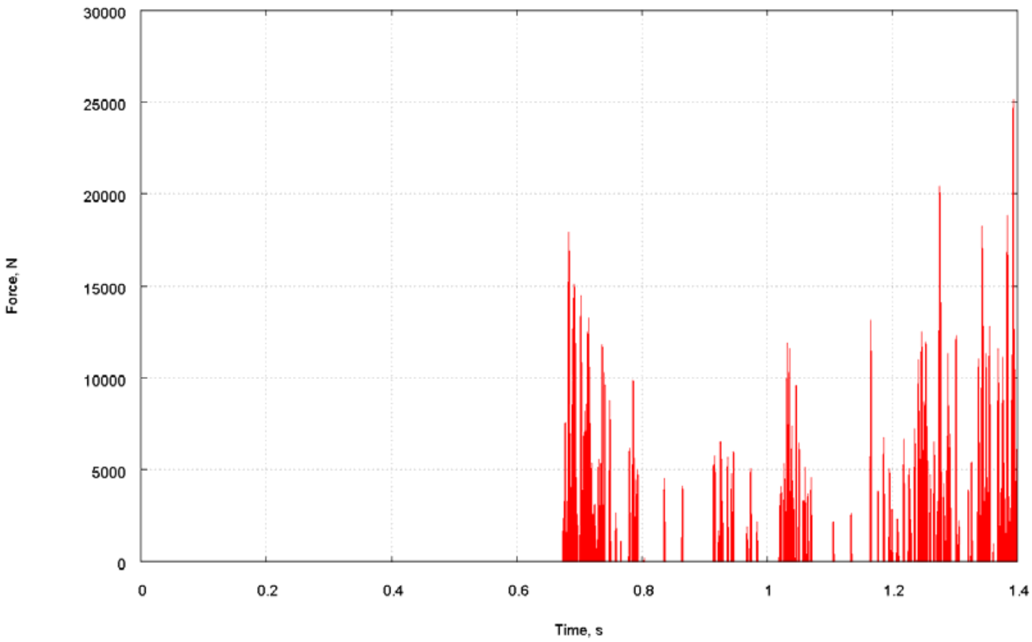


Figure 8 – Dependence of the contact forces influencing on the rim of SG7 on time.

The detailed finite element model of SG with fragments of fuel rods, GC, skeleton angles, adequate simulating real cells geometry collected using spot welding was developed to perform the analysis of stress-strain state under transverse compressive load calculated above. The model contains from 587222 nodes and 279390 linear eight-node finite elements - Figure 9.

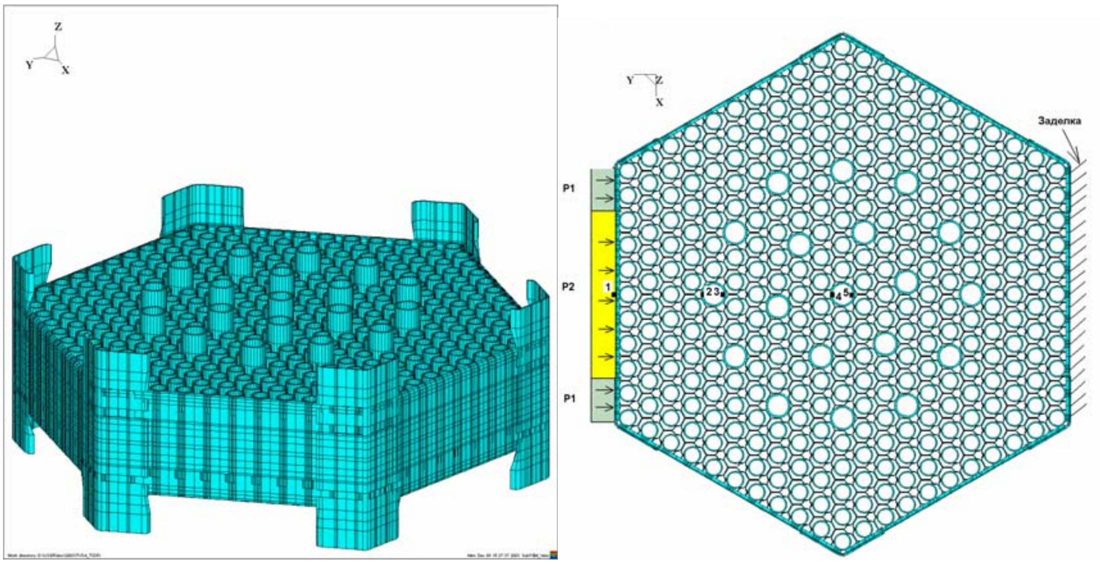


Figure 9 – Finite element model of SG of TVSA-ALPHA filled by fuel rod fragments, GC, and skeleton angles.

The calculations of stress-strain state of SG were conducted in elastic-plastic formulation. As the calculations have shown there are elastic deformation of the part of SG rim on which the load influences up to 4 load steps (load 800 kg). The plastic deformations occur in relatively small local areas near bugling in cells. Cells of SG located at some distance from the zone of force application are less loaded. Zones of stresses concentration exist in the cells adjacent to the rim at the corners of SG hexagon. If the level of the load are increased the plots of displacements becomes nonlinear due to the developed plastic deformation in local areas near bugling. In the calculations were accepted an ideally elastic-plastic material's model without hardening with a yield limit 14.5 kg/mm^2 corresponding to the yield limit of zirconium at a temperature of 300 ^{o}C [3]. Graphs of displacement for the diametrically opposing points on the GC surface show that even at the load level 2000 kg the essential deformation of GC didn't happen. There is taken place a decrease of a GC diameter in the direction of the OY axis on 0.046 mm, i.e. SG deformation occurs mainly due to deformations of fuel rods and SG cells, because they have lower rigidity in comparison to GC.

The obtained results are conservative from the point of view that in the real FA design the most loaded SG in the middle of the fuel assemblies are made in a combined with mixing grid variant, which are joint by a common rim. This increases the overall carrying capacity of SG as compared with the calculation SG model. It is also necessary to bear in mind that the dynamic (impact) loading the basic mechanical properties of the material may have a significant difference from static (standard) values. This refers in particular to the yield limit, the value of which can be several times higher than specified in the calculation.

1. Fulfillment of works on UZOR-1 calculating code verification for using in analysis of thermal-mechanical behavior of FA "KVADRAT". Report of RRC "Kurchaton institute", 180.1 / 051 – 08, Moscow, 2008.
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3. Standards of strength calculations of equipment and pipelines of nuclear power plants. PNAE G-7-002-86, Gosatomnadzor USSR, Moscow, Energoatomizdat, 1989.