CKTI-VIBROSEISM

structural-mechanical consulting engineering firm

DYNAMIC ANALYSIS OF "KUDANKULAM" NPP REACTOR BUILDING

Research Report

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INTRODUCTION

This report contains the methodology of dynamic analysis of reactor building of NPP "Kudankulam" (India).

Besides the Russian Codes and Standards concerning with the design and analysis for Nuclear Power Plants following Codes were used:

- **ASCE STANDARD, ASCE-4-86. Seismic Analysis of Safety Related Nuclear Structures and Commentary on Standard for Seismic Analysis of Safety Related Nuclear Structures.** Approved September 1986.
- **Damping Value for Seismic Design of Nuclear Power Plants.** Regulatory Guide 1.61.
- **Standard Review Plan 3.7.2** Seismic System Analysis, NUREG-0800 Rev. 2, August 1989.
- **Safety Seies No. 50-SG-D15. Seismic Design and Qualification for Nuclear Power Plants.** A Safety Guide, International Atomic Energy Agency, Vienna, 1992.

The dynamic analisys of the reactor building was carried out by finite element method. Finite element software "SOLVIA-99.0" of Swedish Company "SOLVIA Engineering AB" has been used for finite element modeling and analysis. Also the powerful finite element pre- and post-processor software "Femap" of American Company SDRC was involved in the creating and careful checking of the finite element models.

This report contains general description of reactor building model of NPP "Kudankulam" (India), modeling of some equipment units and soil-structure interaction.

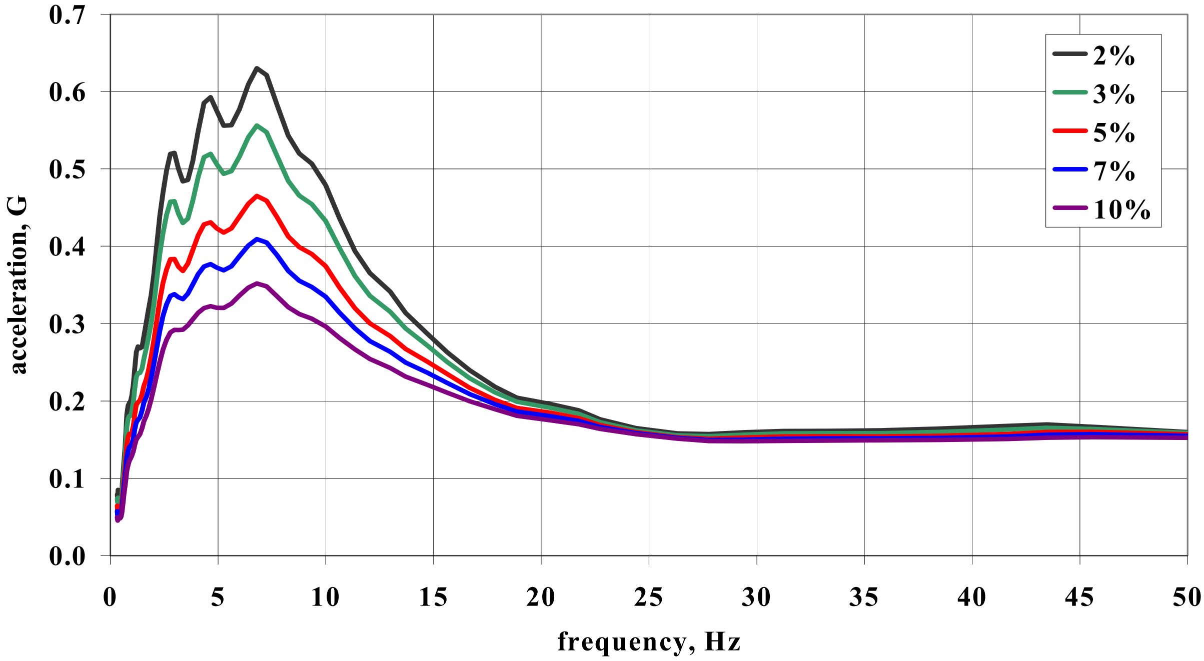
The report contains the general results of dynamic analysis of reactor building such as envelopes of response floor spectra under seismic excitation, airplane crash and air shock wave.

1. INPUT EXCITATION

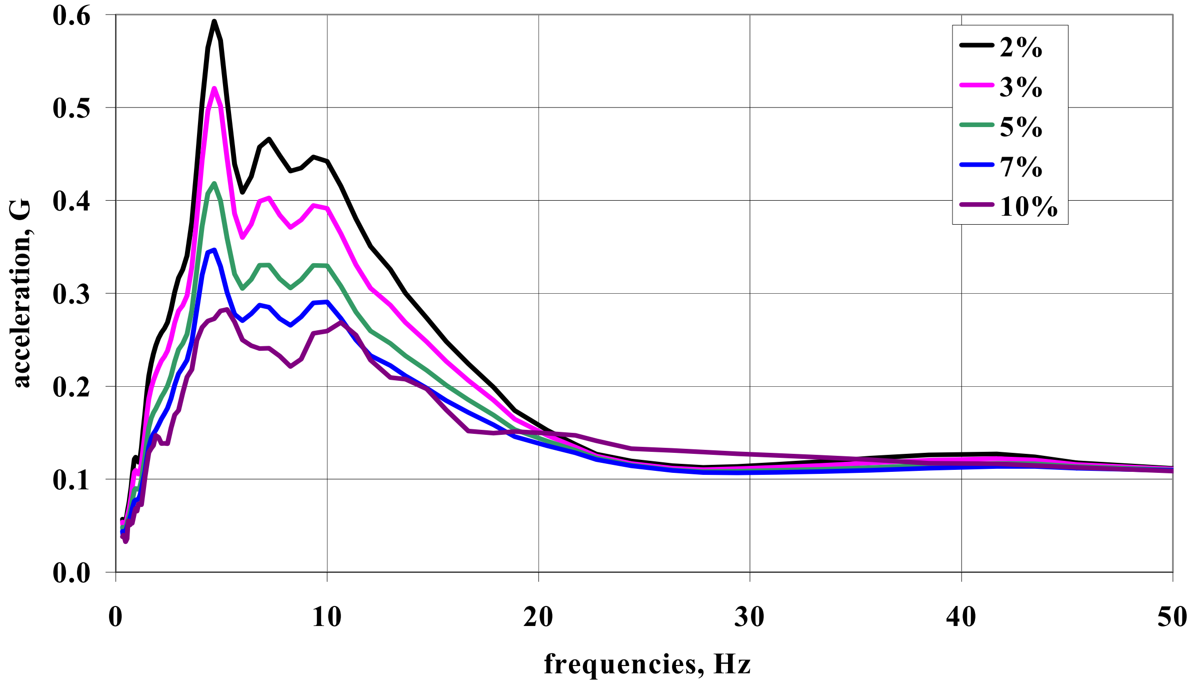
SEISMIC EXCITATION

The ground response spectra and corresponding ground time history accelerations were given as the excitation input of the earthquake.

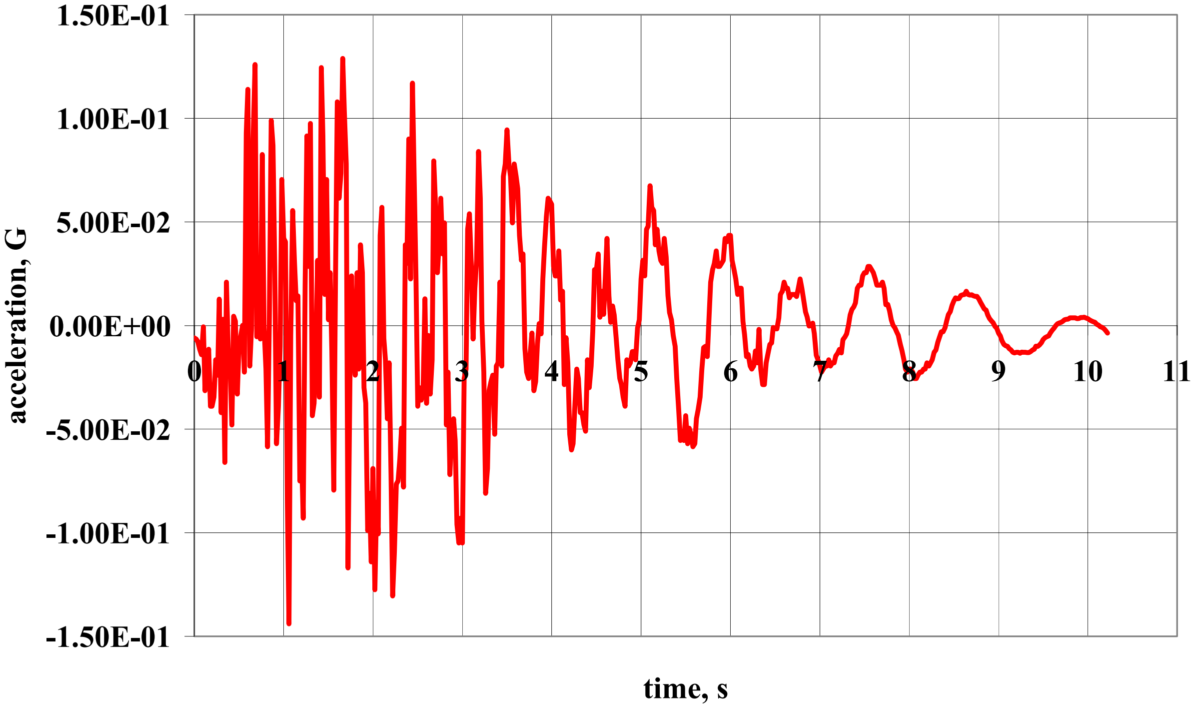
Horizontal ground response spectra



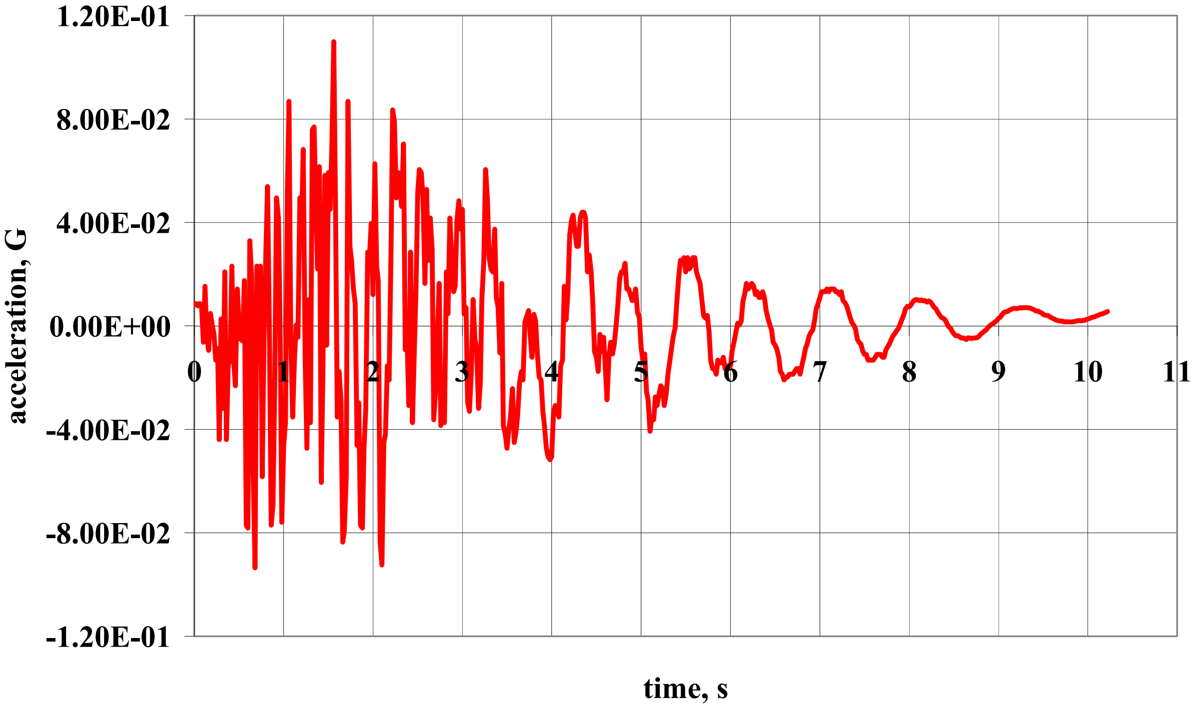
Vertical ground response spectra



Horizontal ground acceleration



Vertical ground acceleration



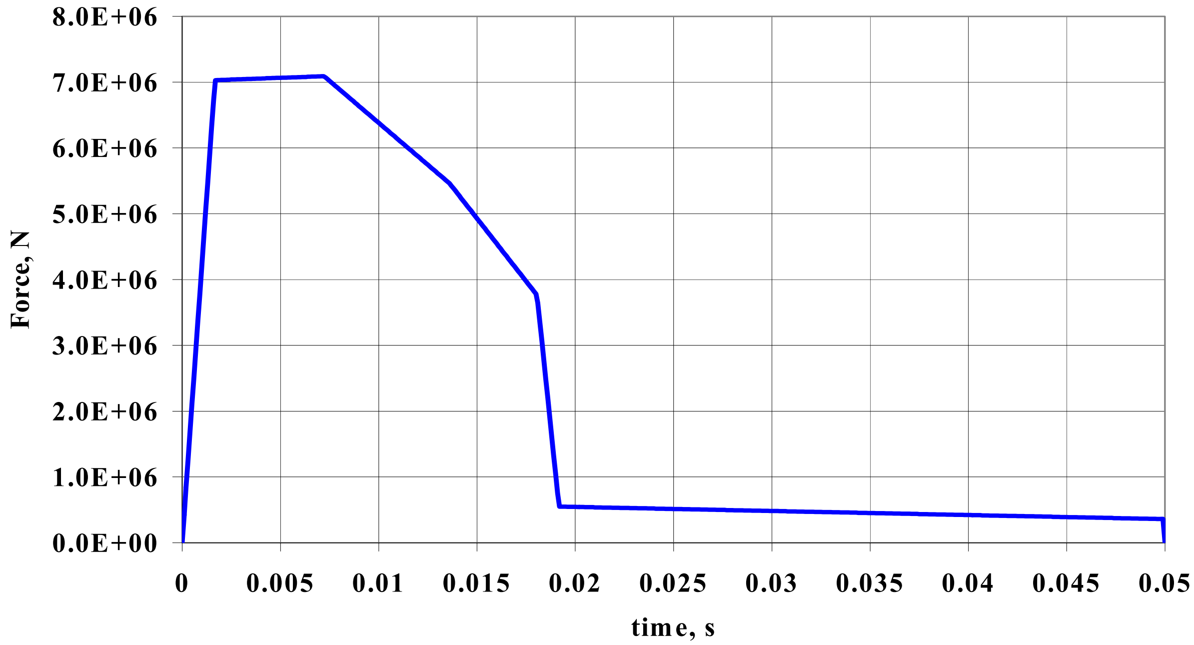
It should be noted that input motion is given by time history acceleration with duration of 10.22 s and time step 0.02 s.
Two time histories shall be considered statistically independent if the absolute value of the correlation coefficient doesn't exceed 0.3[2, item 2.3.1]. The same time history acceleration was given for the both horizontal directions. At the other hand the correlation coefficient for the vertical

and horizontal ground accelerations *r=-0.82*. So the given time histories are considered as the statistically dependent.

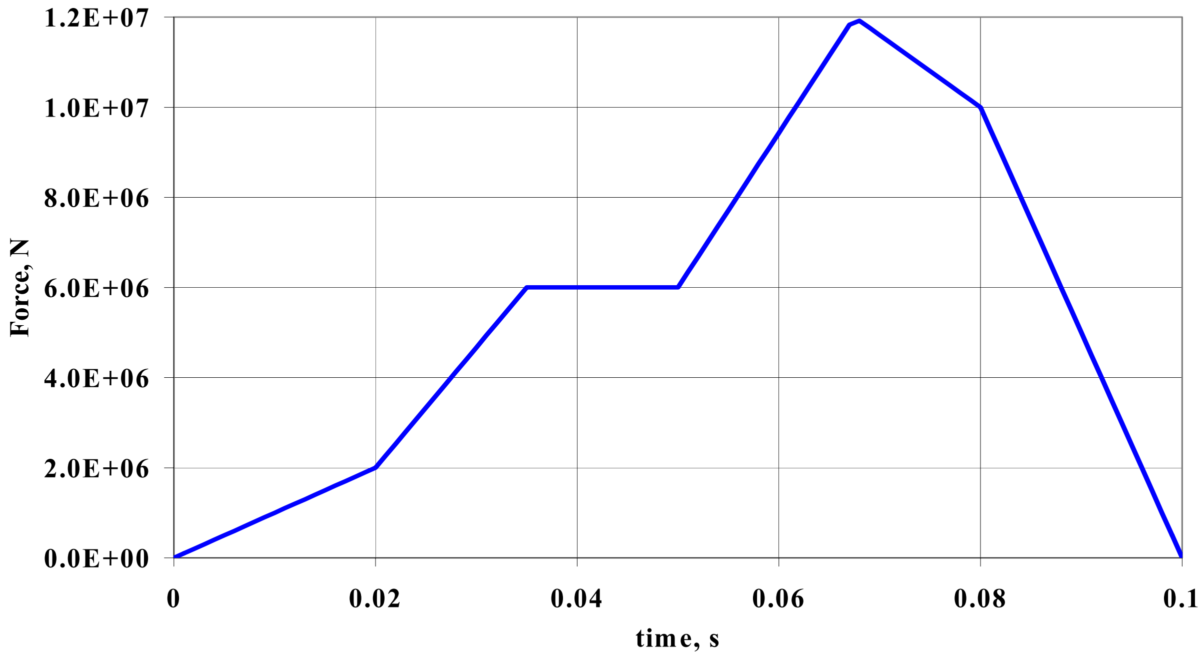
AIRPLANE CRASH

The impact of two general aviation commercial aircraft, a Cessna 210 and Lear Jet 23, is considered. The average impact area given for the calculations was 4 m^2 and 12 m^2, respectively.

Idealized load-time function calculated for a General Aviation Cessna 210 aircraft



Idealized load-time function calculated for a General Aviation Lear Jet 23 aircraft

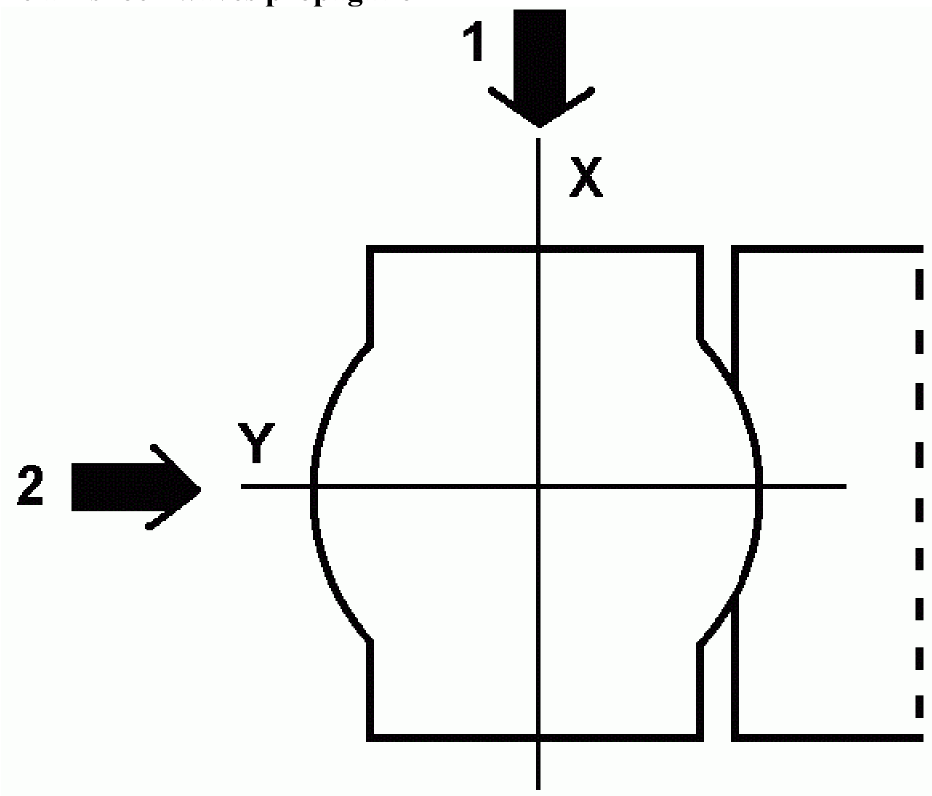


For the each type of the airplane the series of the 9 various load application points was considered. These points were defined by the Customer.

AIR SHOCK WAVE

The two directions of the shock wave propagation are considered. The load-time functions of the pressure wave were given by the Customer in accordance with the Russians Standards.

Scheme of the air shock waves propagation



2. ANALYSIS METHOD

Dynamic analysis of reactor building is conducted by finite element method. The finite element software "SOLVIA-99.0" of Swedish Company "SOLVIA Engineering AB" is used for this purpose.

FLOOR RESPONSE SPECTRA COMPUTATION

For dynamic analysis of reactor building under seismic excitation mode superposition integration method was applied. In the case of aircraft crash and shock wave excitations direct integration method was used. In both case the trapezoidal rule (Newmark method with α= 0.25, δ=0.5) is by Solvia software used for the time integration.

The time step is chosen to be sufficiently small to define dynamic forces and to ensure stability and convergence of the solution. For this purpose the time step is taken such that the using of its half does not change the response more than 10% [2, item 3.2.2.2].

As the results of dynamic analysis of the reactor building the floor accelerations are used to compute the floor response spectra.

The floor response spectra are considered for the Customer provided nodes of the reactor building and damping values of 1%, 2%, 5%, 7%, 10%.

The floor response spectra are calculated in accordance with recommendations and requirements of [1, 2, 3, 4].

The floor response spectra are built by following rule. The current frequency value is chosen to be bigger by 2% than the previous frequency value. The lower broad of the frequency is 0.1 Hz. The upper broad of the frequency is 33 Hz in the case of the earthquake excitation. Time step increase of $1/(20{\cdot}f_I)$ is used to calculate response at each frequency value f_i . The 15%-broaden envelope floor spectra are built to take into account the variable soil stiffness [2, 3, 4]. The valleys of the floor response spectra are partially deleted. It is done by the following rules:

- ✓ If the valley width is less than 15%-band for the central valley's frequency, then the spectrum is increased up to the valley edge level.
- ✓ If the above rules are not satisfied then spectrum is not changed near the valley.

The above procedure of spectrum smoothing corresponds to the recommendations of [2].

THE INTERNAL FORCES AND STRESSES COMPUTATION UNDER SEISMIC EXCITATION.

The response spectrum method was used to compute the internal forces and stresses under seismic excitation. In accordance with [2, item 3.2.3] the number of modes included in the analisys shall be sufficient to ensure that inclusion of all remaining modes does not result in more than 10 % increase in total response. For this subject the missing modal mass method is used: the cutoff frequency is determined so that the total modal mass considered is at least 90 % of total system mass. Also all modes having frequencies less than ZPA-frequencies were included into consideration.

The responses from the three earthquake components were calculated separately. For each earthquake component the combination of modal responses was obtained by the SRSS-rule.

$$R_{SUM}^{k} = \left(\sum_{\omega_i \le \omega_u} \left(R_i^k \right)^2 \right)^{1/2}$$

Then the SRSS summation rule was used to combine results:

$$R_{SUM} = \left(\sum_{k} \left(R_{SUM}^{k} \right)^2 \right)^{1/2},$$

here:

R_i^k — modal response of interest in the i^{th}-mode due to the k^{th} component of motion

R_{SUM}^k — the response for the k^{th} component of motion

R_{SUM} — the response of interest

THE INTERNAL FORCES AND STRESSES COMPUTATION UNDER AIRCRAFT CRASH AND SHOCK WAVE IMPACT

For dynamic analysis of reactor building under aircraft crash and shock wave impact direct integration method was used. In both case the trapezoidal rule (Newmark method with α= 0.25, δ=0.5) is used for the time integration.

The time step is chosen to be sufficiently small to define dynamic forces and to ensure stability and convergence of the solution. For this purpose the time step is taken such that the using of its half does not change the response more than 10% [2, item 3.2.2.2].

MATHEMATICAL MODEL

Finite element method is used for dynamic analysis of reactor building. Detailed finite element model of reactor building has been developed to reflect complex spatial structure of the building. Additionally some sufficient equipment units were considered in the comprehensive system model.

Dynamic analyses of the building under seismic excitation, aircraft crash and explosion wave are conducted. Therefore reactor building model should reproduce high frequency oscillation that can be caused by aircraft crash and explosion wave.

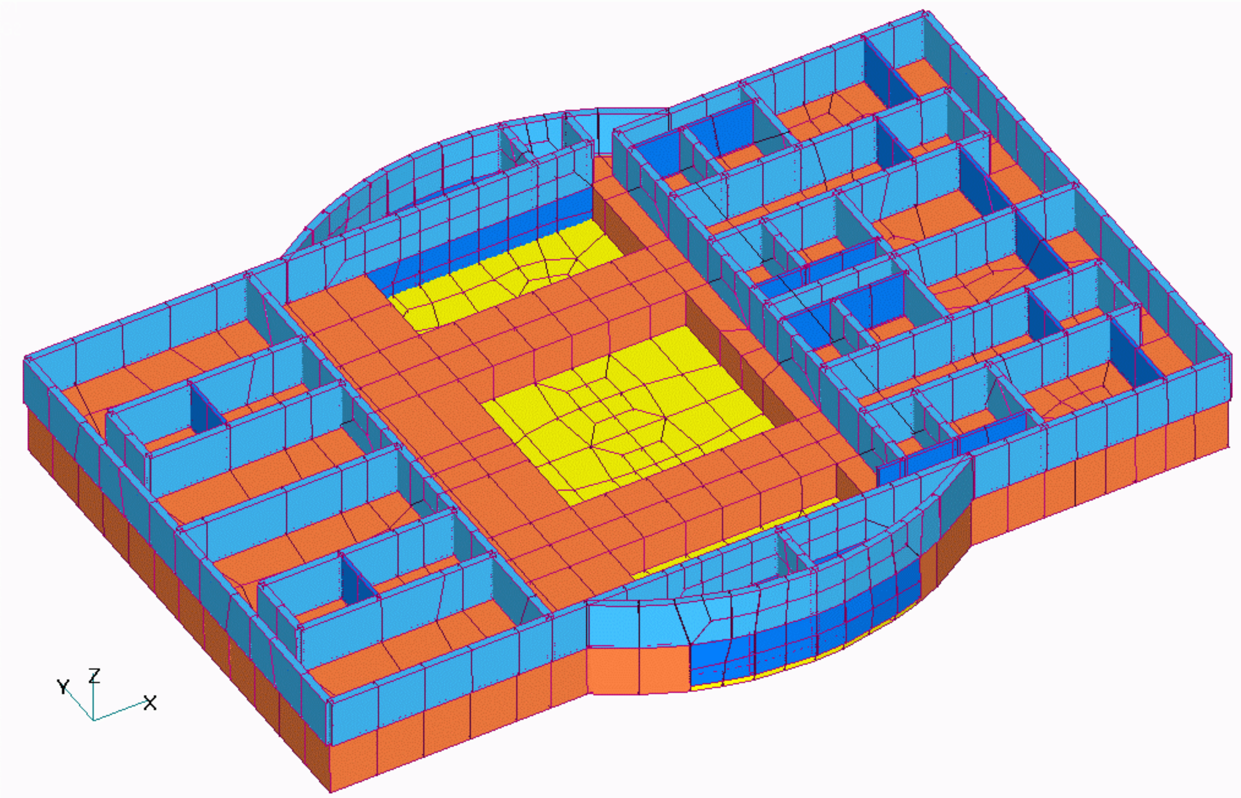
Finite element model of reactor building represents a complex system consisting of finite elements of various types. This model uses the following finite element types:

- «beam»
- «shell»
- «spring»
- «concentrated mass»

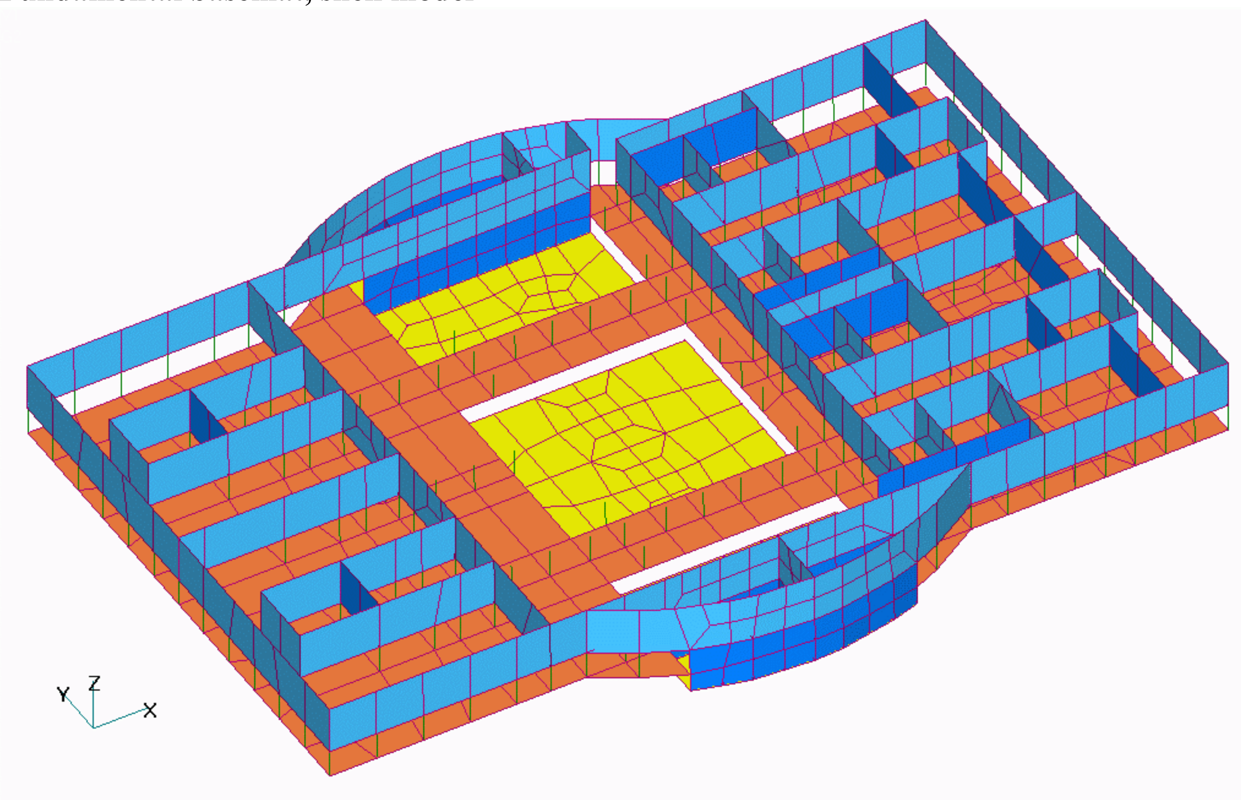
Finite elements of "shell" and "beam" types were generally used for basic building structure development. At this step main construction features of the reactor building were modeled.

At the base of the building a 4.5 m thick slab is placed. This slab is modeled by "shell"-elements. It should be noted that such type of finite elements has no thickness in the sense of the distance from the shell's midsurface to its outer surface (to the walls' bottom on the slab). Thus base plate model consisting only of shell elements may cause excessive flexibility of walls above the slab.
It may have a sufficient effect in the case of great ratios of slab thickness to walls thickness and small height of walls. To avoid errors due to this effect "rigid" finite elements of "beam"-type are used in the reactor building model. "Beam"-elements with a great elastic modulus ($E_{rigid} = 1.E+17$) should be understood under "rigid" "beam" elements. Similar problems in modeling floors of great thickness are also solved by the above method.

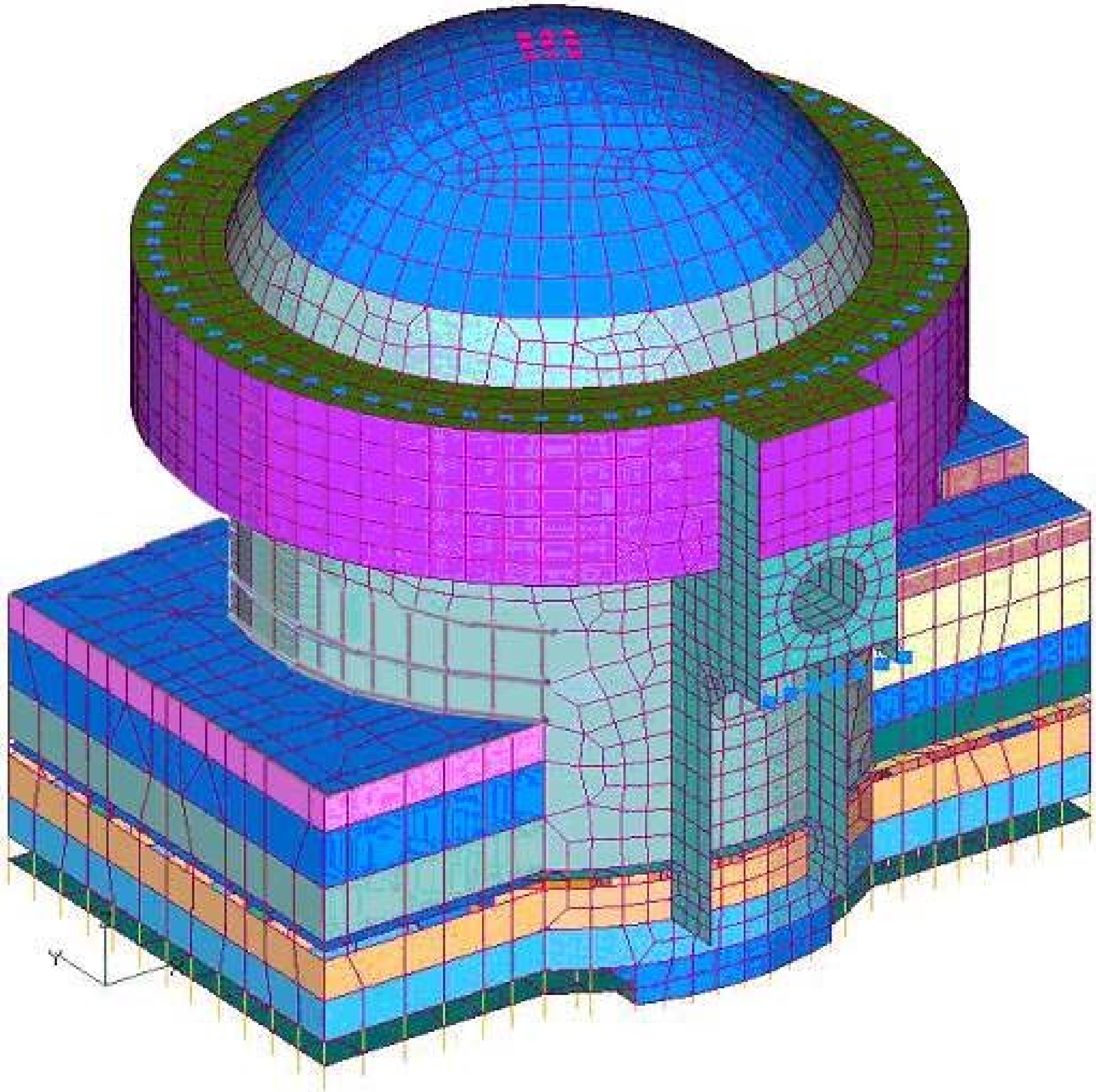
Fundamental basemat, real thickness



Fundamental basemat, shell model



Model of the reactor building



BASINS MODELING

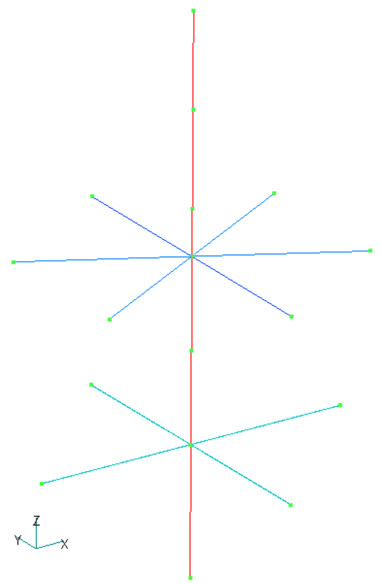
The effects of hydrodynamic mass and damping are considered in the analysis of safety-related nuclear structures [2]. The reactor building has several water basins for nuclear fuel storage. Depth of these water basins is $h = 10.7\ m$. This value does not exceed *15 m*. Thus vertical water mass is lumped at the bottom of basins [2] and finite elements of "directional concentrated mass" type are used.

Modeling of horizontal dynamic water loads on the basin walls uses theory of added water mass [1], [2]. Corresponding to this theory water contained in basins within the reactor building is modeled to represent both impulsive and convective (sloshing) effects. Oscillation of surface layer of water is modeled by convective mass connected elastically to the basins' walls. Basin walls are not considered as a rigid. In accordance with [2] impulsive mass and elastic links between convective mass and basin walls are distributed on certain heights.

MODELING OF EQUIPMENT UNITS

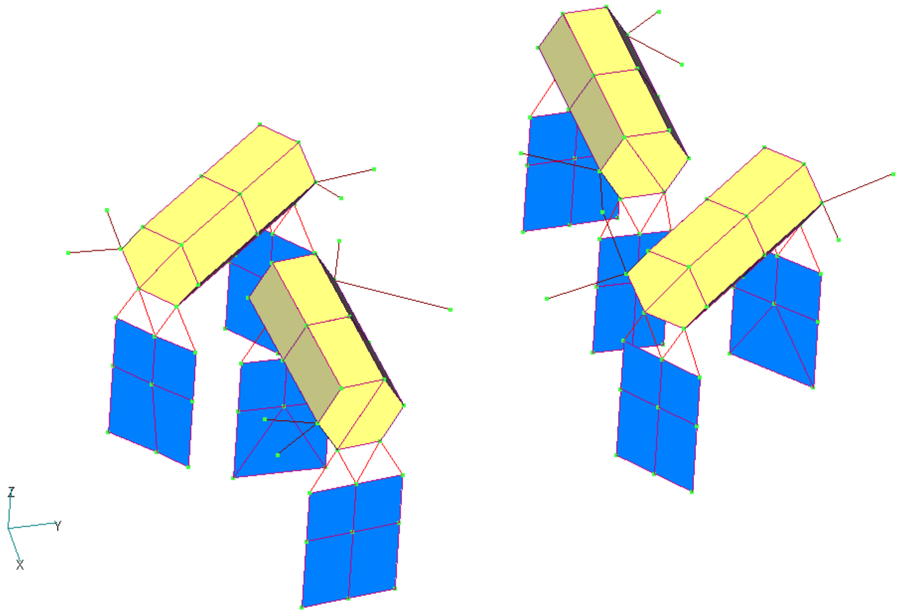
Nuclear reactor is modeled by "beam" finite elements to take into account its inertial characteristics. Reactor supports are modeled by "directional spring" elements.

Model of reactor and its supports.



Steam generators are modeled by "shell" elements. To represent inertial characteristics of the steam generator its mass is distributed on the surface of "shell" elements. Vertical steam generator supports are modeled as vertical springs by the "directional spring" elements. Horizontal steam generator supports are hydraulic snubbers modeled by "axial spring" elements.

Steam generators' model



Soil-structure interaction modeling

According to the data provided by the Customer the reactor building is placed on soils of three types. Based on the wave propagation velocities dynamic characteristics of these soils are obtained [1]:

Modulus of elasticity $E = \rho V_s^2 \dfrac{3\delta^2 - 4}{\delta^2 - 1}$ (1.)

Shear modulus $G = \rho V_s^2$, (2.)

where $\delta = \dfrac{V_p}{V_s}$. Here the above-introduced notations are used.

Following values of the characteristics are taken:

Vp = 2400 м/с *Vs = 960 м/с* *ρ = 2600 кг/м*^{3}*,*

then:

$\delta = 2.5$

From equation (1.):

$E = 6.732 * 10^9$ *newton/m*^{2}

From equation (2.):

$G = 2.396 * 10^9$ *newton/m*^{2}*,*

As the result shear modulus of most soft soil type is G=2.396Н/м^2*.*

Dynamic analysis of reactor building is carried out for three shear modulus' values as is required by the Customer (fax of May 12, 2000.):

- $G_{min} = 0.5G$
- $G_{average} = G$
- $G_{max} = \infty$

The soil below the foundation basemat is considered to be relatively uniform to a depth equal to the largest foundation dimension. The foundation basemat is approximated by equivalent rectangular shape.

The coupled soil-structure system includes the structure and the soil springs and dashpots anchored at the foundation level. Frequency-independent soil spring and dashpot constants are used [2] (Table 2):

Table 2. Lumped Representation of Structure-Foundation Interaction, Rectangle Base [2]

Motion	Equivalent Spring Constant	Equivalent Damping Coefficient
Horizontal	$K_x = 2(1+\nu)G\beta_x\sqrt{BL}$, newton/m	$b_x = 0.576K_x\sqrt{\dfrac{\rho BL}{\pi G}}$, s* newton/m
Vertical	$K_z = \dfrac{G}{1-\nu}\beta_z\sqrt{BL}$, newton/m	$b_z = 0.85K_z\sqrt{\dfrac{\rho BL}{\pi G}}$, s* newton/m
Rocking	$K_\Psi = \dfrac{G}{1-\nu}\beta_\Psi BL^2$, newton*m	$b_\Psi = \dfrac{0.30}{1+\beta_\Psi}K_\Psi\sqrt[4]{\dfrac{BL^3}{3\pi}}\sqrt{\dfrac{\rho}{G}}$,s*newton*m
Torsion	$K_t = \dfrac{16}{3}G\left(\dfrac{BL(B^2+L^2)}{6\pi}\right)^{\frac{3}{4}}$, newton*m	$b_t = \dfrac{1}{1+\beta_t}\sqrt{K_t I_t}$, s* newton*m

where ν and G are as defined previously,
B — width of the basemat perpendicular to the direction of horizontal excitation, m;
L — length of basemat in the direction of horizontal excitation, m;
I_t — polar mass moment of inertia of structure and basemat;
β_X, β_ψ *and* β_Z are the functions of the dimensional ratio, L/B[2](fig. 32):

Soil spring and dashpot constants (Table 2) are the integral characteristics over the foundation basemat. Therefore they are uniformly distributed over the foundation slab of the finite element model. The finite elements of "spring" type are used for this purpose in the reactor building model. The spring stiffnesses are chosen to provide uniform stiffness distribution at foundation slab in both translational and rotational springs.

Assume that:
S — the area of the fundamental slab
S_i — the area of the fundamental slab that coresponds to the i[th] node.
Then the stiffness acting in the i[th] node for the X-direction is defined as

$$k_X^i = \frac{S_i}{S} \cdot K_X .$$

Similarly the separate stiffnesses for the Y and Z-directions are determined. K_X, K_Y, K_Z — total stiffnesses for the X, Y, Z-directions.

The separate translational stiffnesses generated the following rotational stiffnesses:

$K_{\Psi X}^{трансл} = \sum_i (y_i - y_C)^2 \cdot k_X^i$ — rotational stiffness about X-axis,

$K_{\Psi Y}^{трансл} = \sum_i (x_i - x_C)^2 \cdot k_Y^i$ — rotational stiffness about Y-axis,

$K_t^{трансл} = \sum_i ((x_i - x_C)^2 + (y_i - y_C)^2) \cdot k_Z^i$ — rotational stiffness about Z-axis,

where x_c, y_c — coordinate of the gravity center of fundamental slab,
x_i, y_i —coordinate of the i[th] node.

The separate stiffnesses for the each base node were determined by the relations:

$k_{\Psi X}^i = \frac{S_i}{S} \cdot \left[K_{\Psi X} - K_{\Psi X}^{трансл}\right]$ — about X-axis,

$k_{\Psi Y}^i = \frac{S_i}{S} \cdot \left[K_{\Psi Y} - K_{\Psi Y}^{трансл}\right]$ — about Y-axis,

$k_t^i = \frac{S_i}{S} \cdot \left[K_t - K_t^{трансл}\right]$ — about Z-axis,

where $K_{\psi X}$, $K_{\psi Y}$, K_t — stiffnesses from the table 2.

The separate damping for the each base node were computed by the relations:

$$b_{\Psi X}^{коррект} = b_{\Psi X} - b_{\Psi X}^{трансл} = b_{\Psi X} - \sum_i (y_i - y_C)^2 \cdot \frac{S_i}{S} \cdot b_X ,$$

$$b_{\Psi Y}^{коррект} = b_{\Psi Y} - b_{\Psi Y}^{трансл} = b_{\Psi Y} - \sum_i (x_i - x_C)^2 \cdot \frac{S_i}{S} \cdot b_Y ,$$

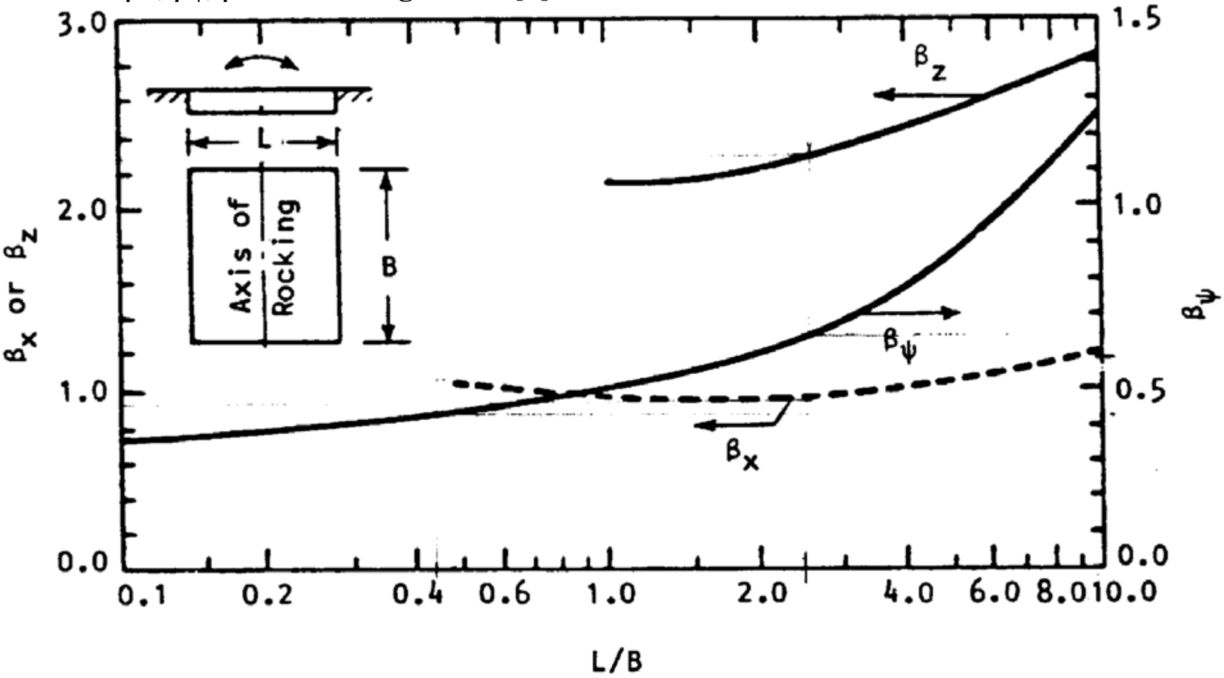
$$b_t^{коррект} = b_t - b_t^{трансл} = b_t - \sum_i((x_i - x_C)^2 + (y_i - y_C)^2) \cdot \frac{S_i}{S} \cdot b_Z \ ,$$

where b_X, b_Y, b_Z — damping along X, Y, Z
$b_{\psi X}$, $b_{\psi Y}$, b_t — rotational damping
$b_X^{крит}$, $b_Y^{крит}$, $b_Z^{крит}$, $b_{\psi X}^{крит}$, $b_{\psi Y}^{крит}$, $b_t^{крит}$ — critical damping

After the relative rotational damping was calculated and set in the each node damping.

In accordance with [4] the damping doesn't exceed 15 %.

Constants β_X, β_ψ, β_Z for rectangle base [2].



Software and analysis method

Dynamic analysis of reactor building is conducted by finite element method. The finite element software "SOLVIA-99.0" of Swedish Company "SOLVIA Engineering AB" is used for this purpose.

SOLVIA System 99.0 consists of pre-processor SOLVIA-PRE, post-processor SOLVIA–POST and solvers — SOLVIA and SOLVIA–TEMP.

Model damping

In the case of the modal supperposition integration the stiffness-weighted modal damping was used[2, item 3.1.5.1]. The modal damping ratios are specified for each elastic material and weighted for mode *i* as

$$\zeta_i = \frac{\varphi_i^T \overline{K} \varphi_i}{\omega_i^2},$$

where ζ_i — coefficient of relative damping on the i[th] mode,

φ_i — column vector of i[th] mode shape,

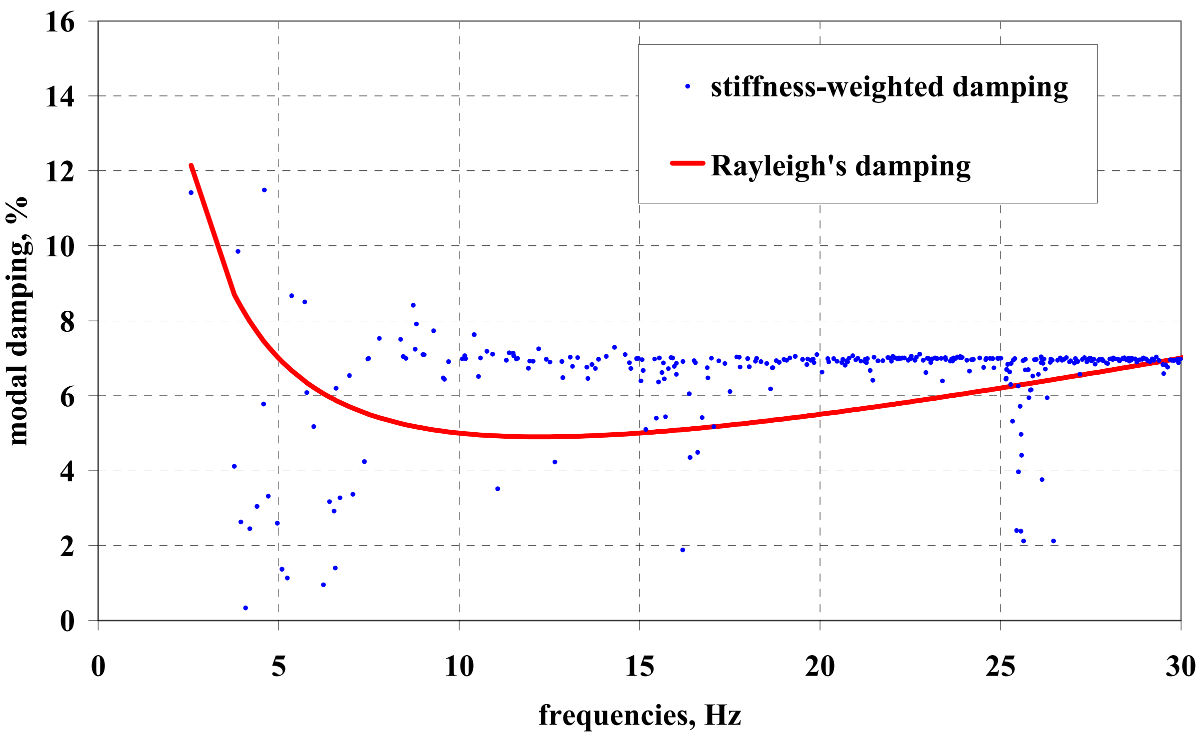
ω_I — circular frequency for the i[th] mode,

$\overline{K}$ — modified global stiffness matrix constructed by assembling the element matrices formed by the product of applicable material modal damping ratio and the linear stiffness matrix.

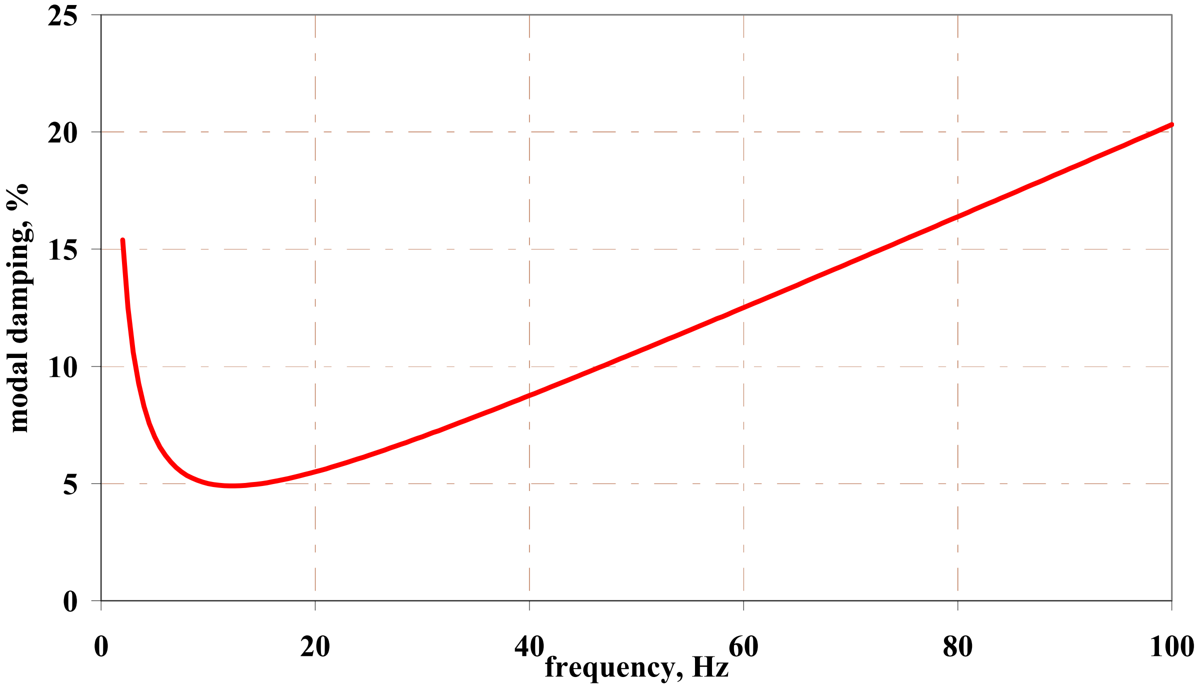
In accordance with [2,3] modal damping values are taken as 7% for concrete structures and as 2 % for steel structures under seismic excitation of SSE-level.

In the case of the direct integration the proportional Raylegh's damping was used. The parameters for this damping were such chosen that the resulting damping values were less or equal to the modal damping values 7% for concrete structures and as 2 % for steel structures under seismic excitation [2, item 3.1.5.1.1].

Comparison of the proportional Rayleigh's and stiffness-weighted damping



Proportional Rayleigh's damping



References

1. **Birbraer A.N. Seismic analysis of structures.** S.-Petersburg, Nauka, 1998.

2**. ASCE STANDARD, ASCE-4-86. Seismic Analysis of Safety Related Nuclear Structures and Commentary on Standard for Seismic Analysis of Safety Related Nuclear Structures.** Approved September 1986.

3. **Damping Value for Seismic Design of Nuclear Power Plants.** Regulatory Guide 1.61.

4. **Standard Review Plan 3.7.2** Seismic System Analysis, NUREG-0800 Rev. 2, August 1989.