Seismic Non-linear analysis of Polar Crane

Alexander Schukin, Maxim Vayndrakh

CKTI – Vibroseism, Saint Petersburg, Russia

ABSTRACT

One of the requirements for Safe Design of NPP is that structures, systems, and components important to safety shall be appropriately protected against dynamic effects, including the effects of missiles, that may result from equipment failures. Consideration of such hazard is essential especially during seismic event for Polar Crane.

For seismic analysis a comprehensive finite element model of Polar Crane was developed. Model takes into account specific peculiarities of Crane design and dynamic characteristics of supporting structure. The following Crane's main parts were included in the model: Crane itself, special elements for seismic protection (shock absorber devices) and supporting concrete ring.

Seismic excitation in the form of Time History Acceleration was applied in the base of the supporting ring. A special investigation for Crane dynamic response was made with taking into account an angular seismic components. It was shown that crane's response parameters in this case could be amplified by 5 – 15 %.

Analysis of Crane motion has shown that correct accounting of slippage between wheel and rail could reduce seismic loads 4 – 6 times.

An other significant issue of performed analysis was dedicated to the different positions of the Crane during seismic event. On the base of variable calculations the most severe case was identified and analyzed.

POLAR CRANE DESIGN

Polar crane is located on the level of 37.0 m under Reactor Building Containment Dome. Basic design functions of Polar Crane are to perform refueling and all main load-lifting operations with heavy loads during Shutdown period of the Reactor Facility.

Bridge of the polar crane moves along the annular runway of 41 m in diameter and consists of two welded beams made from complex profile with variable cross-section at the edge and constant in the middle of the beam span. Bridge beams are attached to the end girders having a fix point from one side and hinged joint from the other. Crane driver device and retaining rollers are located on the end girder from the side of fix point. Retaining rollers provide fixation of Crane Bridge on the rails. The clearance between roller and rail is 2.5 mm. Wheels of Bridge from the hinged side are not equipped with rollers. Crane Trolley with hoist equipment moves along Bridge Beams.

To prevent Bridge and Hoist Trolley derailing in case of Earthquake Polar Crane is equipped with special Seismic Restraining System (SRS) that includes the following elements:

- Steel Frame for restraining of the Crane Bridge in lateral directions;
- one-way Hydraulic Buffers fixed on the Bridge beams and Steel Frames that transmits horizontal dynamic load from the Crane to the civil structure (Supporting Ring Wall, SRW)

Seismic Restraining System operates in the following way:

- During Normal Operation SRS moves together with Polar Crane (thrust rubber rollers are sliding along Supporting Ring Wall being pressed by internal buffer's spring that is compressed on the half of its travel)
- During Seismic Impact a reaction of Hydraulic Buffer is proportional to the piston's velocity. Due to Buffer's dynamic locking Seismic Loads are transmitted to the Supporting Ring Wall through the rubber rollers. Futher rise of dynamic load leads to closing of 10 mm gap between SRS steel structure and SRW, so the seismic load from the Crane acts directly to the civil structure omitting rubber rollers. Since Buffer works only in compressed state, a contact between Polar Crane and Supporting Wall could be recovered only by internal buffer's spring.

Polar Crane weight is 380 tons including Crane Trolley (132 tons) and hoist equipment (15 tons). Carrying capacity of Polar Crane during Normal Operation is 180 tons.

CRANE MATHEMATICAL MODEL

Fig. 1 shows a coupled FE Model of Polar Crane and Supporting Ring Wall. Inclusion of SRW in the model provided the following benefits for subsequent analyses:

- taking into account flexibility of SRW;
- proper modelling of seismic load path: it was recognized that for seismic response of Polar Crane an angular components of seismic excitation are important. Comparison of Floor Response Spectra generated on the top of SRW (runway) has shown an increasing of response accelerations by 15 – 25 % in the all frequency range of interest (higher than 2 Hz, a first natural frequency of the Crane). Hence, 6 – component Seismic Excitation was applied in the flexural center of the Reactor Building (level 21 m).

Considered FE model was assembled from the set of 3 or 4-nodes shell elements, beam elements, linear springs and lumped masses. Total number of nodes was 14156.

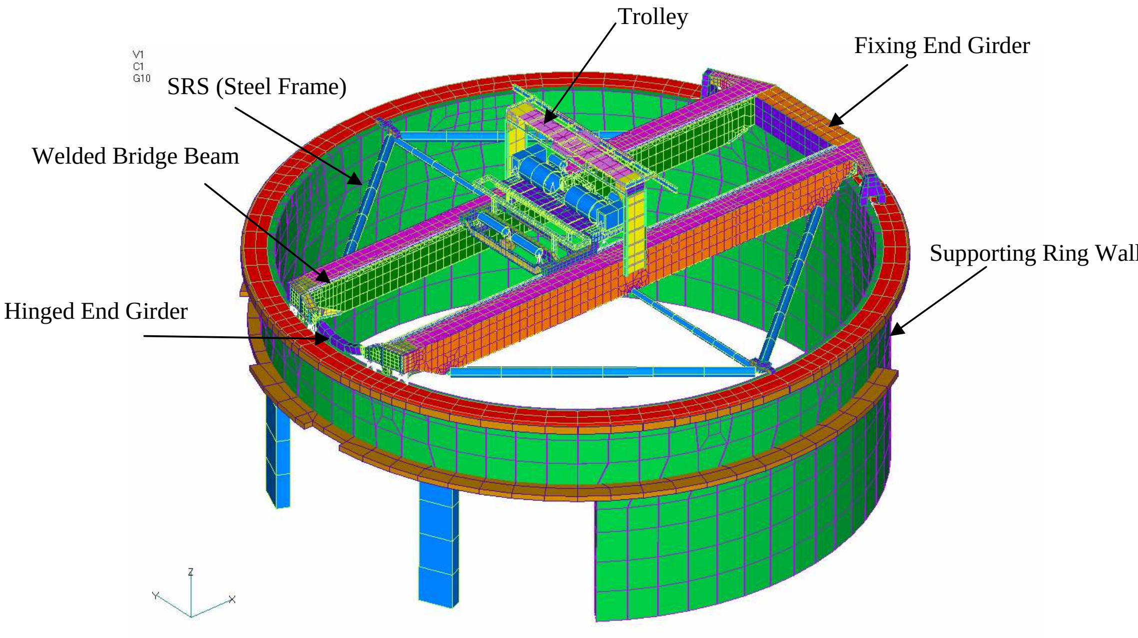

Fig. 1 Coupled FE Model of Polar Crane and Supporting Ring Wall.

Table 1 presents comparison of natural frequencies of the Polar Crane with and without carrying Load. As it could be seen from these results only first 3 frequencies are changed that corresponds to the local movement of hanged Load. Fig. 2 shows a third mode shape (vertical) of Polar Crane carrying Load of 180 tons.

Table 1. Polar Crane Natural Frequencies (Hz)

Mode #	with load	without load
1	0.22*	1.04*
2	0.22*	1.04*
3	2.01	3.24
4	3.24	3.28
5	3.87	3.87
6	4.105	4.105
7	4.61	4.63

* - oscillation of hanged load

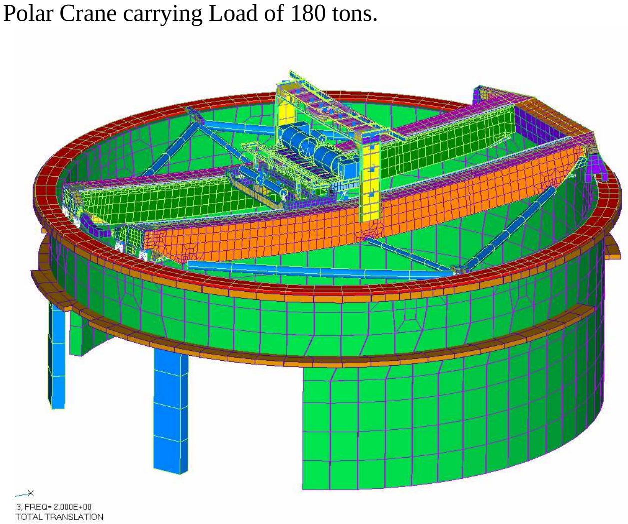

Fig. 2 Third Natural Mode Shape of Polar Crane with 180 tons Load

Fig. 3 shows a dynamic model for Seismic Restraining System of Polar Crane that was composed according to interaction between SRS elements as described above.

Mk - mass of Crane;
Mp - mass of Buffer Piston;
Mu - mass of thrust traverse;
Kz - stiffness of Buffer internal spring;
B - coefficient of viscous resistance for Hydraulic Buffer;
Kp - stiffness of stopper between Buffer and Thrust Traverse;
Kr - stiffness of rubber rollers;
Ku - stiffness of stopper with 10 mm clearance between Thrust Traverse and Wall

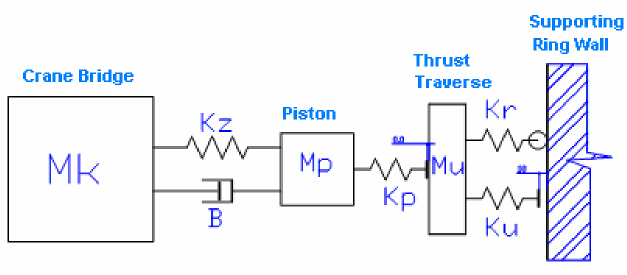

Fig. 3 Dynamic Model of SSR

INFLUENCE OF FRICTION ON THE CRANE SEISMIC RESPONSE

The friction between wheel and rail is one of the main factors influenced on the seismic response of Polar Crane. Table 2 containing data from the parametric study demonstrates influence of the friction on response acceleration.

Fig. 4 shows dependence between friction's coefficient and maximum value of earthquake's acceleration when stresses in Bridge Beams achieve limit (allowable) values.

Table 2. Friction Parametric Study.

Friction Coefficient	Clearance between roller and rail	Response Acceleration, g	
		SRW, Level 37.0 м	Crane Bridge
-	no gap	0.35	1.73
k = 0.2	+/-2.5 mm	0.34	0.31
k = 0.1	+/-2.5 mm	0.34	0.65

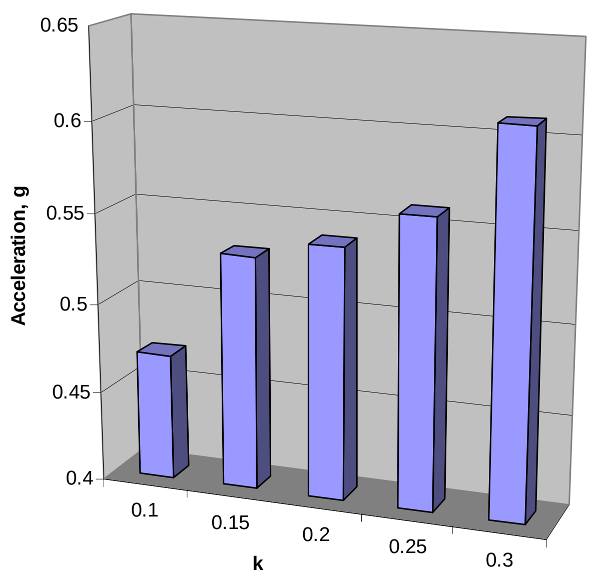

Fig. 4 Influence of friction on ZPGA margin.

SUMMARY OF PERFORMED ANALYSES AND RESULTS

The following three positions of Trolley along Crane Bridge were considered in the frame of performed analyses:

- A – in the middle of Bridge span;

- B – 3 meters from the Fixed End Girder;
- C – 6 m from the Hinged End Girder.

These positions covers practically whole possible range of load distribution for Crane Bridge and SRW. For each Trolley position there were performed 2 variants of calculations: Crane with and without load (180 tons).

Analysis of results presented in Fig. 5 – 6 allows to conclude the following:

- stress distribution in the Bridge Beams depends on Trolley position and carrying Load: stresses are maximum for Trolley middle position;
- for the Fixed End Girder stresses reach maximum value upon approaching the Trolley;
- stresses in the Fixed End Girder are higher for variant without Load.

Fig. 7 shows distribution of stresses in the elements of Fixed End Girder.

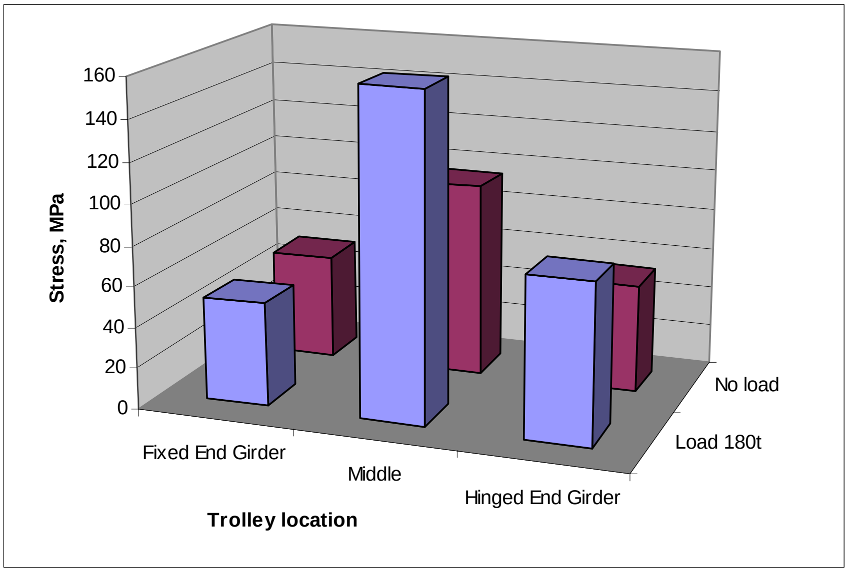

Fig. 5 Stresses in Bridge Beam (Influence of Trolley Position and Carrying Load)

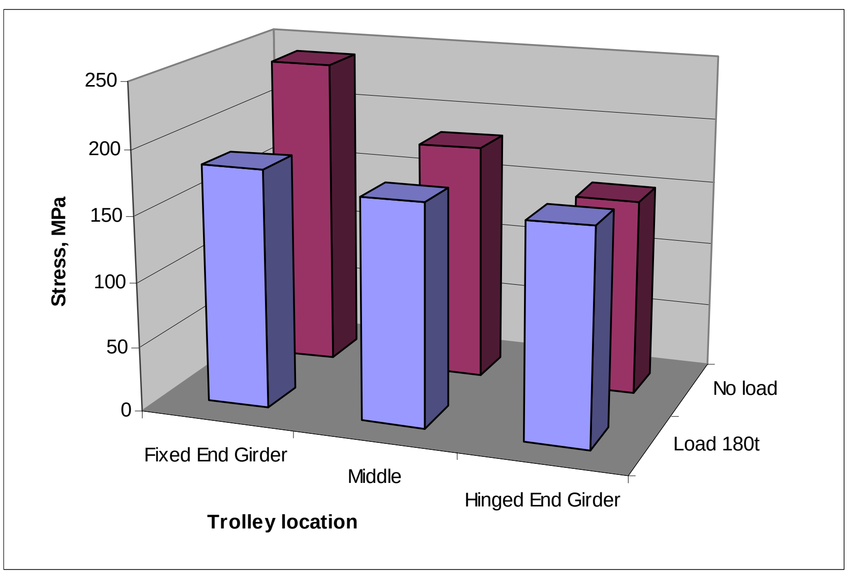

Fig. 6 Stresses in Fixed End Girder (Influence of Trolley Position and Carrying Load)

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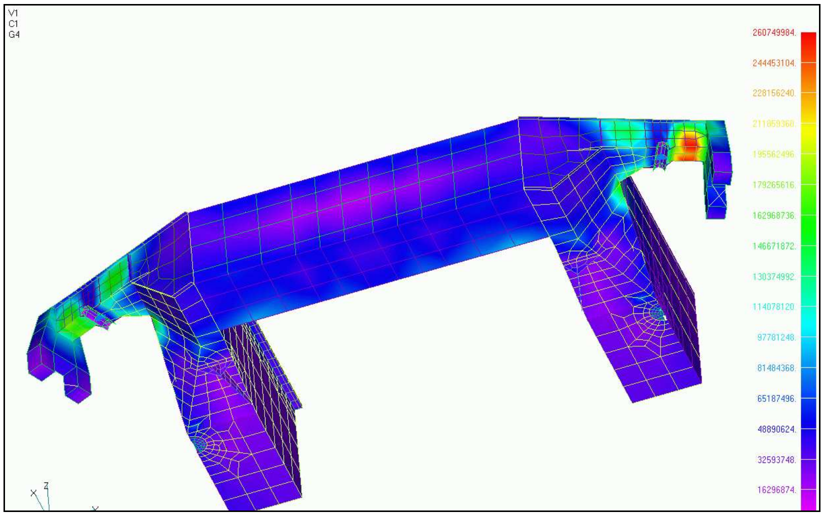

Fig. 7 Stress Distribution in the Fixed End Girder.

Pictures presented bellow correspond to the variant B (Trolley is located near by the Fixed End Girder, Crane carries no Load). It was recognized that this variant is most severe for strength of the Fixed End Girder.

Changing of the reaction transmitted through the thrust rollers to the runway is shown in Fig. 8. It should be noted that during seismic impact Crane is turned around a vertical axis. As result, the rollers located from the opposite sides of the Fixed End Girder are working in antiphase. Regions of zero-force shown on this plot correspond to the loss of contact between roller and rail due to technological clearance of ±2.5 mm.

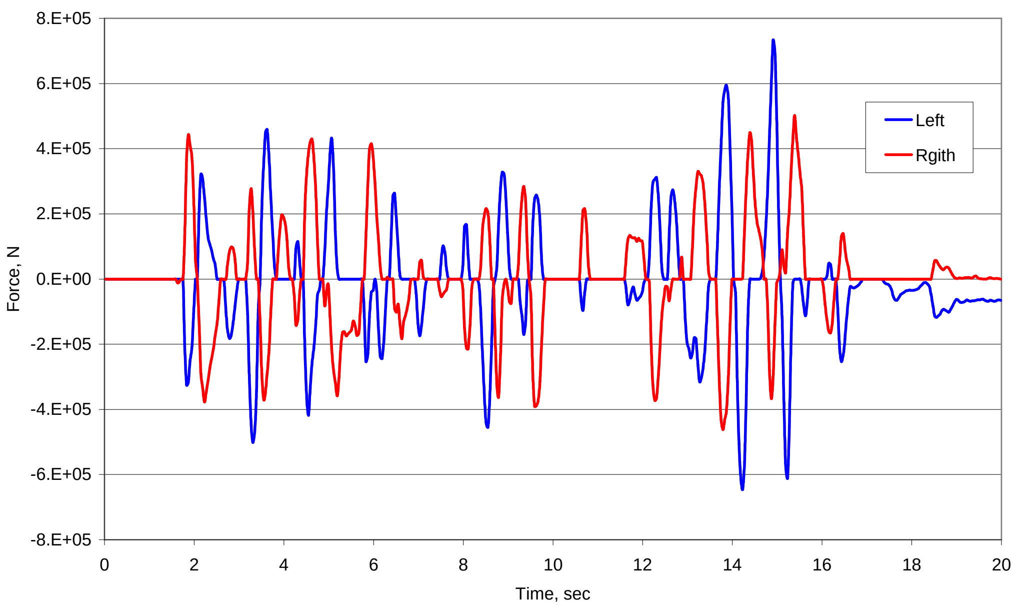

Fig. 8 Thrust rollers reaction

Fig. 9 illustrates work of Seismic Restraining System during Safe Shutdown Earthquake. Reactions of hydraulic buffers installed on the lateral Steel Frames are shown. As it follows from analysis clearance between SRS elements and SRW is increasing with compression of hydraulic buffer under seismic inertial load. Efficiency of Seismic Protection in this case is dropped, since recovering of Hydraulic Buffers is slow (as it could be seen from the plot there were only 5 – 6 work cycles of Hydraulic Buffers during 20 sec seismic impact).

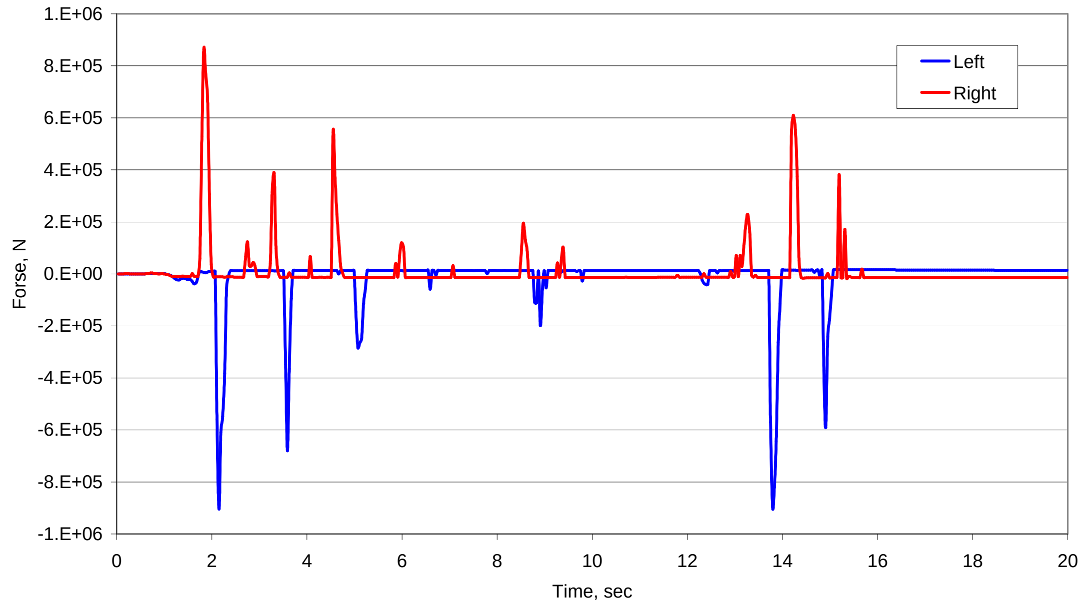

Fig. 9 Lateral Hydraulic Buffers Reaction

Seismic movement of Trolley along Crane Bridge runway is shown in Fig. 10. Two variants were considered: Crane with and without 180 tons Load. Figure demonstrates that during earthquake Trolley is permanently moves along Crane Bridge due to slippage between wheels and rail (friction coefficient 0.15 was assumed in this case). A Maximal displacement of Trolley relatively a runway is 20 mm for case with Load, and 90 mm for no Load case. At the same time a seismic Load that acts along Bridge Crane from the Trolley carrying Load is higher than "no Load" variant on the value of Friction Force (180 tons * 0.15 = 27 tons).

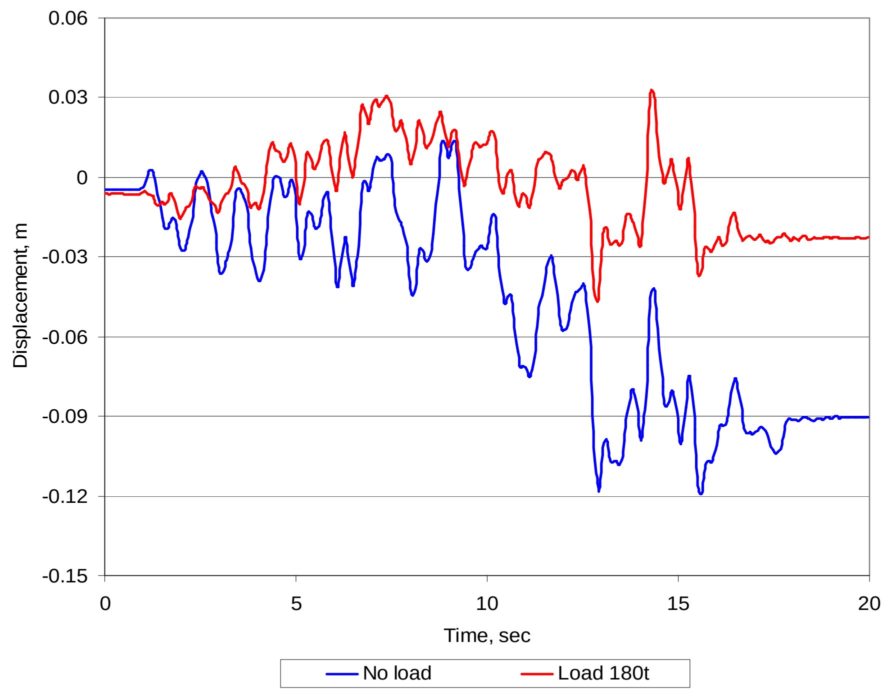

Fig. 10 Seismic Movement of Trolley along Crane Bridge

Presence of Load influences also on the value of thrust rollers reaction (Fig. 11). Due to difference in friction force level and character of dynamic reaction is different for two considered variants.

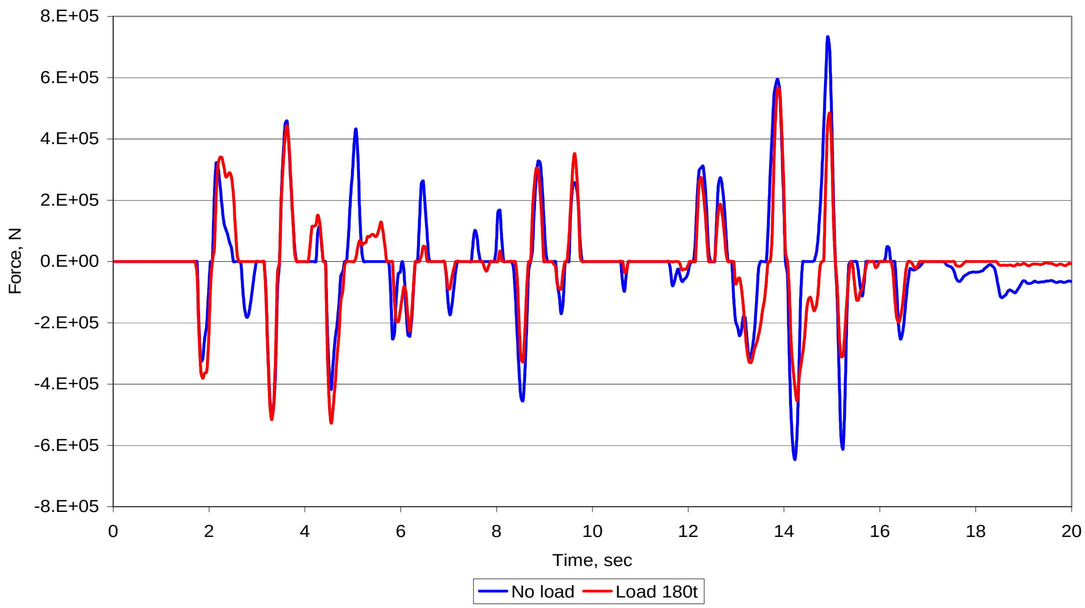

Fig. 11 Change of thrust rollers reaction

SEISMIC FRAGILITY ANALYSIS

The fragility analysis has been performed for the Crane using simulation method: a series of dynamic computations of the reduced model were done. For this simplified model a number of DOFs was reduced 3.5 times in comparison with "deterministic" one. At the same time all nonlinear elements representing SRS modelling were kept (friction, gaps, Hydraulic Buffers).

Two categories of parameters having influence on seismic response scattering were chosen according to procedure of fragility analysis: an earthquake input motion as a source of randomness and friction's coefficient between wheels and rail as uncertainty parameter. Variations of input motion was defined through a family of accelerograms corresponding to three different sources of potential earthquake which vary in its turn by different types of soil characteristics: «soft», «mean» and «hard» (total number is nine).

Among uncertainty parameters that should be considered in the frame of fragility analysis there are the Trolley position and the Bridge orientation. However previous analyses have shown that it is possible to consider the only one configuration of the Crane: unloaded Trolley is set close to a Fixed End Girder and orientation of Bridge corresponds to a Crane parking position. This assumption is quite acceptable since Crane is set in this position most of its operating time and probability of this realization is several orders greater than any other.

Allowable stress limits and failure criteria have been chosen the same as in deterministic analysis. Since a relation between seismic response and level of seismic demand is nonlinear, limiting state was determined after a several trials sequentially approached to the installed failure criteria (5% neighborhood around allowable stresses).

Thus, it has been done more than a hundred of dynamic calculations to obtain median values of ZPGA, logarithmic standard deviations and corresponding fragility curves (Fig. 12).

The entire family of curves may be approximated by:

$$A = A_m \varepsilon_R \varepsilon_U,$$

where: $A_m = 0.91g$, $\beta_R = 0.28$, $\beta_U = 0.015$.

A best estimate fragility curve may be defined using a composite of the randomness and uncertainty variabilities. The composite variability β_c is defined as: $\beta_c = \sqrt{\beta_R^{\,2} + \beta_U^{\,2}} = 0.28$

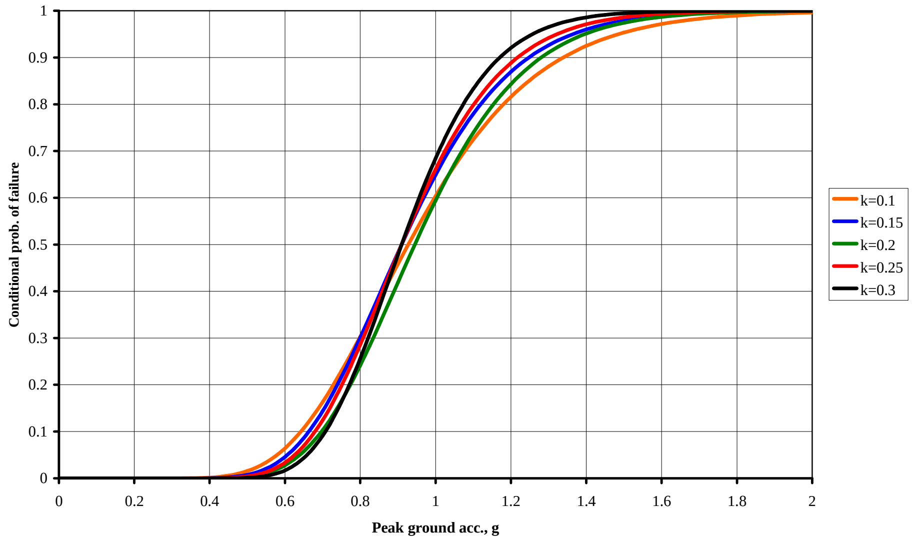

Fig.12 Conditional probability of Crane's failure (fragility curves) for different coefficients of friction

CONCLUSIONS

1. Comprehensive Finite Element model of the Polar Crane coupled with civil structure (Supporting Ring Wall) is developed for dynamic (seismic) analysis.
2. Peculiarities of dynamic behaviour of the whole system are taken into account by introducing in analysis a nonlinear elements for Polar Crane Seismic Restraining System (springs with gaps, one-way hydraulic buffers, friction elements). It was recognized from the variant calculations that friction between wheels and rail has a most significant influence on the Crane Seismic Response.
3. Detailed Evaluation of Seismic Restraining System's specific features has shown that proper accounting of Friction between wheels and rails permits to reduce Crane Seismic Response for 4-6 times. It leads to conclusion that accounting of Friction phenomenon in Crane Components is methodologically significant and should be considered.
4. At the same time, increasing of friction coefficient for 3 times (from 0.1 to 0.3) leads only to 30 % increasing of ZPA margin values (from 0.47 g up to 0.61g).
5. It was recognized that operation of one-way hydraulic Buffers during seismic impact could induce an increasing of gaps between Crane Elements and Supporting Ring Wall, that in its turn inducing an essential raise of stresses in Crane structures.
6. Variant calculations have demonstrated that maximal stresses in the Fixed End Girder (element that fixes Crane on the runway) are dependent on the Trolley position and presence of Load. The most dangerous variant was determined and analyzed: location of Trolley near by Fixed End Girder with no carrying Load. It should be noted that this position and state of Trolley corresponds to the Crane Parking between Shutdown periods.
7. Seismic Fragility Analysis performed in the frame of this study has demonstrated a sensitivity of seismic response to chosen types of uncertainties which have an influence on seismic resistance of the Polar Crane. A scattering of ZPGA margins caused by uncertainty of the friction's coefficient appeared to be a small in comparison with scattering caused by different possible realizations of seismic input motion. At the same time sensitivity of response to the friction's coefficient under the specific demand may be greater. Finally, the obtained fragility parameters may be used for subsequent steps of PSA procedure.

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3. NP 031-01, "Standard for Seismic Design of Nuclear Power Plants", GOSATOMNADZOR, Russia, 2001