Transactions, SMiRT-23
Manchester, United Kingdom - August 10-14, 2015
Division V, Paper ID 178

NONLINEAR SEISMIC BEHAVIOUR OF A POLAR CRANE: IDENTIFICATION OF SIGNIFICANT MECHANICAL PARAMETERS

Maximilian Billmaier[1], **Tadeusz Szczesiak**[2], **Peter Zwicky**[3]

[1] Dr., Section of Seismic Engineering & Dynamics, Basler & Hofmann AG Consulting Engineers, CH-8032 Zurich, Switzerland (Maximilian.Billmaier@baslerhofmann.ch)
[2] Dr., Section of Structural Engineering, Swiss Federal Nuclear Safety Inspectorate ENSI, Brugg, CH-5200 Brugg, Switzerland, (Tadeusz.Szczesiak@ensi.ch)
[3] Section of Seismic Engineering & Dynamics, Basler & Hofmann AG Consulting Engineers, CH-8032 Zurich, Switzerland, (Peter.Zwicky@baslerhofmann.ch)

ABSTRACT

Large scale polar cranes are usually installed in the upper regions of reactor buildings of nuclear power plants (NPP). The in-structure amplification can lead to significant earthquake induced floor accelerations. In the case of the seismic requalification of existing NPPs calculation models have to consider the interaction between the building structure and the crane because of the significant nonlinear behaviour. Possible impact forces of a crane on the reactor building have to be also taken into account. Therefore, the seismic verification of the polar cranes demands detailed investigations. A proper definition of the dynamic characteristics of the crane and of the crane-structure interface are key issues. This paper describes a study, which has been carried out by the engineering company Basler & Hofmann on behalf of the Swiss Federal Nuclear Safety Inspectorate (ENSI). The impact loads on an existing reactor building, caused by a retrofitted polar crane during the Safe Shutdown Earthquake (SSE), have been examined. Nonlinear time history analyses have been performed using a reduced order nonlinear model of the crane, which takes into account the significant dynamic characteristics. Thanks to the comprehensible model setup, the parameter variations are investigated and interpreted using a MATLAB (2014) framework. The results of the presented calculation were used to verify the nonlinear Finite Element (FE) Method calculation carried out by the designer of the retrofitted crane. The agreement between results obtained by the regulator and those obtained by the designer is satisfactory. It has been confirmed that the reactor building resists the impact loads caused by the polar crane during an SSE and that the collapse of the polar crane can be ruled out.

INTRODUCTION

The BKW Energie AG, the Muehleberg (Switzerland) nuclear power plant (NPP) operator, planned extensive retrofit measures of the polar crane in the reactor building (RB). Different measures have been taken in order to reduce the probability of the fall of a crane part into the fuel pool. Because of the increased crane hoists deadweight and the increased seismic hazard, the crane-structure-interaction during a Safe Shutdown Earthquake (SSE) had to be examined in detail. This required a realistic calculation model of the crane and the crane-structure interface. Two conditions had to be satisfied: possible impact forces must not lead to local damage of the RB and the crane must not fall off its circular runway. The operator carried out the necessary studies and applied for the approval of the Swiss Federal Nuclear Safety Inspectorate (ENSI). Because of the importance of the project, ENSI decided to carry out an independent feasibility study and a comprehensive analysis of the crane safety in collaboration with the engineering company Basler & Hofmann.

In nuclear engineering seismic requalification, problems are challenging from both technical and financial point of view. The required verifications are very complex and time-consuming. Thus, this paper proposes possible modelling approaches to apply model order reduction and to identify significant model parameters in practical applications. It is shown that the chosen approach results in a conclusive and comprehensive model design, which is efficiently used during the early stages of the project as well as for the plausibility study in the final phase.

Description Of The Polar Crane Structure

The polar crane consists of two parallel main girders (spacing 6 m, length 36 m and mass 48 t per girder) and a crane hoist (mass 30 t). The two stiff main girders with box sections are connected with relatively flexible transverse beams. The crane is situated on a 360° circumferential runway at the top of the RB walls. When the crane is not in operation, it is placed in the "parking position" and the crane hoist is located close to the left crane support (Figure 1). Furthermore, the main girders and the crane hoists track wheels are blocked in their running directions. In order to avoid uncontrolled longitudinal movement of the crane, additional impact bumper elements are attached to each main girder close to its two supports. These impact bumper elements are designed to limit impact forces acting on the RB during an earthquake. Figure 1 shows the layout of the polar crane and a view of the polar crane support and the impact bumper element.

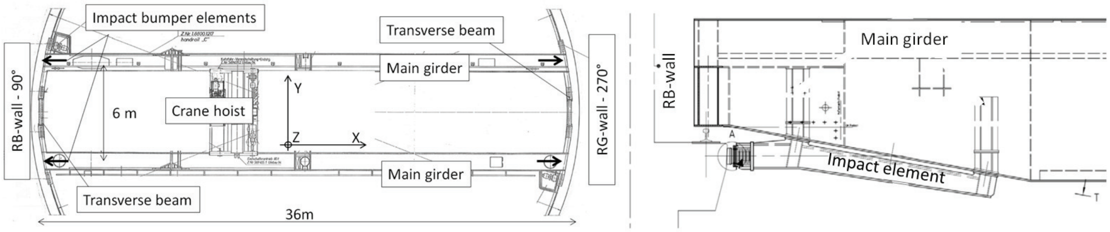

Figure 1. Layout and view of the polar crane support, BKW Energie AG.

Designer Finite Element Model Of The Polar Crane

The design and the related dynamic analysis of the Muehleberg polar crane have been carried out by the company NKM Noell Special Cranes using a 3D nonlinear Finite Element (FE) model in ANSYS, R15 (2013). The model consists of shell elements and nonlinear link elements, among which are suspension elements, contact elements of the crane wheels on rails, friction elements and the impact bumper elements. Damping has been taken into account using the Rayleigh approach with damping proportional to the time dependent tangential stiffness matrix equal to 4 % of the critical damping. The friction coefficients μ are set to 0.2 for all friction elements modelled in the designer model. The seismic design of the requalified crane is in accordance with the guidances KTA 2201.1 (2011), KTA 2201.4 (2012) and KTA 3902 (2012).

REVIEWER MODEL OF THE POLAR CRANE

To insure that the results provided by the operator are enough conservative, the ENSI, which is responsible for the reviewing and approval of the project, decided to carry out an independent verification of the nonlinear behaviour of the polar crane in order to estimate the maximum impact forces on the RB walls induced by an SSE. The possible complex nonlinear system behaviour of the polar crane during an earthquake motivated the reviewer to investigate the influence of variations of the significant model parameters on the impact forces using a reduced order mechanical model. This model has a significantly reduced number of degrees of freedoms compared to the designer FE model. Instead of using the FE method, the equations of motion were formulated directly for the reduced order model and were used to calculate the nonlinear response of the system during an SSE in the time domain in MATLAB.

Earthquake Input

The earthquake time histories were applied using the same 7 sets of displacement time histories (X, Y and Z direction) as the designer model at all four supports of the two main girders. The time histories had been derived considering soil-structure-interaction (SSI) for the whole RB, with the total polar cranes mass, which has been distributed uniformly to the RB walls at the level of the crane. The input of displacement time histories allows taking into account nonsynchronous excitations at the opposite supports of the crane, which can appear because of the global rocking mode of the RB. In the longitudinal (radial) direction, the displacements of the supports of the crane are considered to be identical. The important assumption is that the polar crane is considered not to be coupled with the reinforced concrete structure of the RB. Thus, the interaction forces do not influence the global behaviour of the RB and thus do not influence the seismic input. However, the interaction forces could induce local displacements. This is considered in the reduced order model by using interface springs in the crane longitudinal direction.

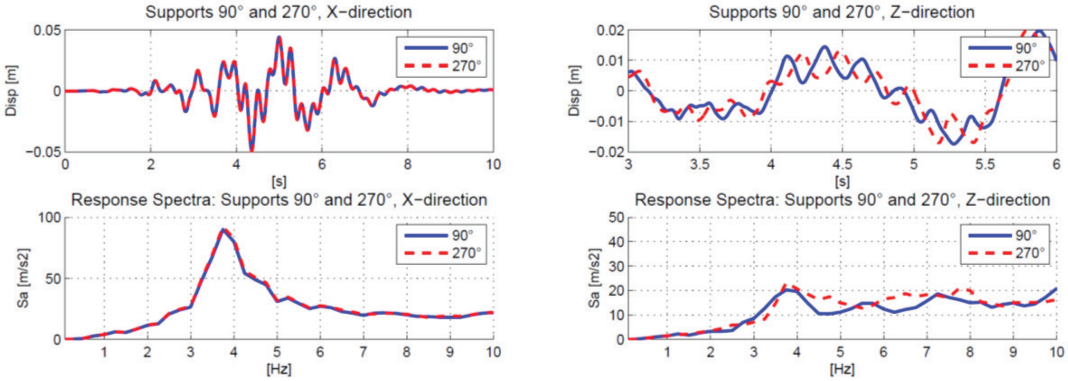

Figure 2. Displacement input time histories and the related acceleration spectra at support points: Horizontal (radial) direction (left) and vertical direction (right)

Reduced Order Model Of The Polar Crane

In the presented study, the goal is to apply model order reduction, based on engineering judgements, to increase the insight in the models characteristics. Only the significant model parameters that really have an influence on the dynamic characteristics are considered. This approach is based on the assumption that for the symmetrical crane structure, only one main girder has to be modelled.

The critical impact forces appear when the impact bumper elements are activated by the girder movements in the longitudinal direction. Further investigations showed that the main structure and the crane hoist cannot lift-off because of the vertical displacements of the supports. Both the vertical forces resulting from bending eigenmodes in the vertical direction and the horizontal forces in the circumferential direction have negligible influence on the impact behaviour. In consequence, the three dimensional mechanical characteristics of the polar crane were reduced to only translational degrees of freedom in the longitudinal direction. The reduced order 1D model with two significant degrees of freedom related to the mass of the girder and the mass of the hoist (a third mass respective the third translational degree of freedom was introduced for numerical stability) was chosen to conduct the dynamic analysis (see Figure 3: x_1, x_2 and x_3). It must be mentioned, that the additional mass m_3 has no influence on the maximum impact forces. In Figure 3, the resulting reduced order model is presented, in which both the mass of the crane hoist and of the main girders are half of their total masses.

Because the horizontal seismic inputs are assumed to be identical at the two opposite RB wall supports, the polar crane is folded with respect to the horizontal axis perpendicular to the main girders, resulting in a further order reduced model. The crane model has only a single support in the crane longitudinal direction. The displacement time histories are applied to this single support only (Figure 3). It is important to notice that this reduced order model is developed for the investigation of the impact forces only.

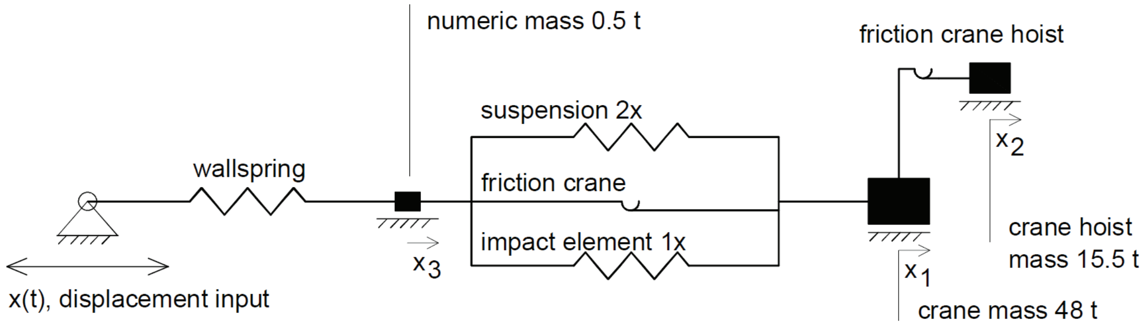

Figure 3. Reviewer model

Nonlinear Spring Elements

In Figure 3, the reduced order model consisting of three masses, three nonlinear spring elements and two friction elements, is presented. The mechanical characteristics of the springs and the friction elements are adapted from the nonlinear FE model. The crane is placed in its parking position. The crane hoists wheels are blocked in the parking position. The mechanical behaviour of the sliding crane changes if the friction force between wheels and the tracks is exceeded. As a result, the main girder slides until it hits the RB wall.

RB Wallspring: In order to calculate the impact forces on the RB walls, the stiffness of the reinforced concrete walls is modelled using a spring element. It has a linear stiffness determined from the linear FE model of the RB developed by the designer using a static analysis. The reference value of the linear local RB wall stiffness was estimated to be 200 kN/mm taking into account 25 % reduction in the initial stiffness of the RB wall due to moderate cracking of the concrete. In the time history analysis, the effective linear stiffness of the walls depends on the models current state: If the impact bumper elements are not activated, both opposite RB wall springs are considered. If an impact bumper element on one side is activated, it is expected that the corresponding RB wall stiffness will be further reduced (due to local effects). To take this into account in the reduced order model, only one half of the RB wall spring stiffness is considered during impact.

Considering the fact that the estimated stiffness of 200 kN/mm of the RB wall is twice as high as the stiffness of an impact bumper element, the reviewer decided to investigate the influence of the local RB wall stiffness changes on the impact forces (see Section “Parameter study” for details). This is done to investigate the influence of the local interaction effects between the crane and the RB wall on the resulting impact forces.

Support spring element: Both main girders are indirectly supported by two transversal beams modelled by support spring elements. In the presented reduced order model, the support elements are considered in an equivalent way to the designer model. The force in the support springs is limited to the maximum friction force of the crane wheels on the circular track. The nonlinear support stiffness has a maximum of 15 kN/mm.

Impact bumper element: The mechanical characteristics of the impact bumper elements have been defined during the cranes requalification project by the designer. The elements are mounted to the main girder as shown in Figure 1. There is a gap of 25 mm between the crane girders and the RB wall. When there is contact with the RB wall, each impact bumper element has a linear elastic spring stiffness of 100 kN/m.

Friction elements: Two friction elements are used in the reviewer model. The first one supports the modelled main girder on the circular track. The second one supports the crane hoist on the main girder. Both friction elements are assumed to have a linear-elastic ideal-plastic element characteristic. The reviewer chose the initial stiffness values in order to guarantee realistic displacement capacities for the connected elements (e.g. the crane wheel supports). The reference value for the friction coefficients is set to $\mu = 0.2$. These nonlinear friction elements are decisive to activate nonlinear sliding behaviour, from which energy dissipation is generated. This modelling approach reduces dependencies on damping models that are physically difficult to interpret.

Damping

Because of nonlinear effects, energy dissipation is critical and has significant influences on the maximum impact forces. Moreover, because of internal friction of the crane and plasticity of the transversal beams, the modelling of the damping has been found to be very challenging in the case of the considered nonlinear system. Typically, the Rayleigh damping model is used in linear dynamic calculations. Considering the fact that the Rayleigh approach has not a physical background, one has to insure that the resulting damping forces are not overestimated. In order to obtain realistic magnitudes of the damping forces, the reviewer assigned only 0.1 % percent of the critical damping as a function of a defined initial stiffness matrix. Using this initially chosen damping matrix, changes in the stiffness terms caused by nonlinear effects do not result in an overestimation of damping forces. The reviewer has calculated the dissipated energy caused by the two modelled friction elements and the viscous damping effects of the reference model. The dissipated energy by the two friction elements is significantly higher. For one of the considered time history sets, set "6B", approximately 60 times more energy is dissipated by nonlinear effects than by the implemented Rayleigh damping model.

Calibration Of The Reviewer Model

The calibration of the reduced order model has been a major issue for the reviewer and thus it is derived with extensive parameter variations. Fortunately, because of the clear setup of the reduced order model and the short required calculation time for each time history analysis, the calibration has been carried out with convincing results. The influences of parameter variations (stiffness assumptions, changes of mass and damping forces) were also carefully investigated to ensure a realistic behaviour in the final model. Figure 4 allows to draw conclusions about nonlinear stiffness effects. The subfigures in the first row show the associated spring characteristics for the wall spring element, an impact bumper element and a support spring. The second row gives insight to the friction behaviour of the main girder sliding on a RB wall support and of the crane hoist sliding on the modelled main girder. These plots are used to estimate the energy dissipation and to adjust the hysteresis parameters. In the bottom right subfigure, the relative displacements of the crane to the crane supports are plotted over time. These displacements are relevant for the evaluation of the impact forces.

Time History Calculations

The time history calculations have been carried out using the simple explicit Euler method. Because of the reduced model order, this direct integration method with even a small constant time step, results in a calculation time of some seconds for a 15 s input displacement time history on a standard desktop computer (4 cores @3.1 GHz, 8 GB RAM). This reduction of analysis time gives the engineer the possibility to investigate the influence of the variation of model parameters easily, and reduce the dependence on costly commercial software packages.

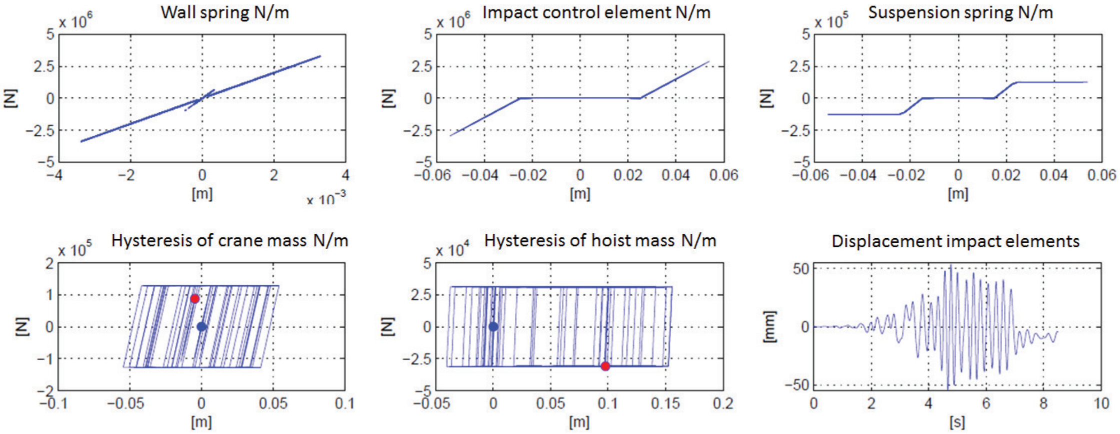

Figure 4. Model calibration: nonlinear stiffness elements properties, time dependent behaviour.

RESULTS OF THE STUDY

Impact Forces

In Figure 5, the impact forces of a single crane girder acting on one side of the RB (kN) are plotted over time (s) for the time history run "6B" in the longitudinal direction of the crane. These two time histories have been calculated both with the designer and the reviewer model. The reader should turn his attention to the shape of the time histories. It is concluded that the reduced order model, with two dominating masses connected to each other with nonlinear spring elements, shows equivalent dynamic behaviour as the sophisticated higher order nonlinear designer model. The reviewer considers the comparison in Figure 5 and the estimated impact forces amplitudes as conclusive and satisfactory and, therefore, accepts the results of the designer.

The results are calculated using the reduced order model with the reference parameter values. In order to compare the results of the MATLAB model of the reviewer and the designer model, the influences of possible relative displacements of the two main girders have to be considered. In the reduced order model, only one single main girder is modelled. However, considering the design of the crane (the two main girders are connected with two flexible cross beams), relative displacements of the two girders reduce impact forces compared to the reduced order model, in which the girders are assumed to be connected rigidly. Thus, two of seven calculated impact time histories have not been compared because of partially torsional behaviour, which is not considered in the reduced order model. Comparisons show that the maximum values of forces acting on the RB walls for five displacement time history inputs in the cranes longitudinal direction are 20-45 % higher than the forces calculated with the designer model. The reviewer is aware of the differences and identifies the following reasons for these deviations. To ensure conservative results, only a very low level of Rayleigh damping of 0.1 % of the critical damping has been used. Thus, the majority of energy dissipation effect results from the nonlinear model dynamics (60 times more as introduced in Section Damping). Moreover, the rigid connections of the two main girders in the reduced order model results in an increase in the impact force. The RB walls (reinforced concrete) are verified with the forces estimated by the designer of the crane.

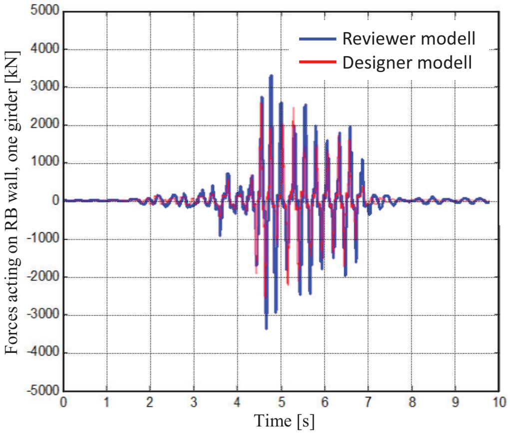

Figure 5. Comparison of calculated impact time histories
Blue line: reviewer reduced order model, red line: ANSYS 3D FE model of the designer

Sensitivity Analysis

The reviewer model, which has been defined to represent the mechanical behaviour of the polar crane, is used to perform the sensitivity analysis of the impact forces on the RB walls. The reference model has been designed to represent the designer model in the best possible way and in such a way that it is in agreement with the reviewers' engineering judgements. Table 1 shows the varied parameters. In order to ensure the comparability of the computed results, four groups of parameters were investigated independently. In the first group, only the variation of the cranes mass and the crane hoists mass were considered. In the second group, only the stiffness of the support elements and of the impact element is changed. The third group consist of one parameter only, which is the RB wall stiffness. In the fourth group, the key parameters are the friction coefficients of the longitudinal girder and of the crane hoist.

Table 1: Applied model parameter variations in the reduced order model, evaluated using three of the seven sets of time histories

Varied model parameter	Parameter variation	Max. reduction in the impact forces [%]	Max. increase in impact forces [%]
Crane mass	±5 %	-6	5
Crane hoist mass	±5 %	-2	1
Support element stiffness	±40 %	-5	6
Impact bumper element stiffness	±40 %	-6	11
Wall stiffness	-99 % / +200 %	-99	1
Friction coefficient crane girder	μ = 0.3 / 0.1 [-] (±50%)	-24	27
Friction coefficient crane hoist	μ = 0.3 / 0.1 [-] (±50%)	-12	8

The relative changes of the impact forces for three of the seven given displacement time histories, from which the highest impact forces are estimated, are compared. For every parameter, the minimum (column 3) and the maximum (column 4) relative changes in the impact forces, resulting from the parameter variations (column 2), are shown in this table.

The parameter study shows that an increase in the crane mass by 5 % results in an increase in the impact forces by only 5 %. The mass of the crane hoist has less influence on the impact forces. An increase in the stiffness of the impact bumper elements by 40 % results in an increase in the impact forces by 11%. Because of the impact bumper element design, the increase is within a realistic range. An increase in the stiffness of the support elements results in an increase of the impact forces of 6 %. The spring element to model the RB wall is designed relatively stiff (upper force limit) and no increased impact force has to be considered in the prequalified crane, even though the wall stiffness, particularly the local wall stiffness, is a relatively uncertain parameter. The estimated stiffness of 200 kN/mm is thus a justifiable value. Finally, the variations of the friction parameters show that they are critical parameters. The friction coefficient for the hoist supported on the main girders has a smaller effect on the impact forces than the friction coefficient of the main girders on the RB wall support. Thus, it can be confirmed that the magnitude of the impact forces of the reference model is realistic.

CONCLUSIONS

The presented study shows the development and the application of a reduced order model of a polar crane in a nuclear power plant (NPP). This reduced order model has been used by the Swiss Federal Nuclear Safety Inspectorate (ENSI) and the engineering company Basler & Hofmann (B&H) during the review procedure of the retrofitting measures taken by the operator of the NPP in Muehleberg in Switzerland. Besides the verification of the magnitudes of the impact forces on the reactor building (RB), which occur during a Safe Shutdown Earthquake (SSE), the main purpose of the independent calculation carried out by the reviewer was to identify the most important mechanical model parameters and to conduct a sensitivity analysis.

The derivation of the reduced order model is based on the identification of the significant model parameters and on the subdividing of the nonlinear system into single parts with known well-defined nonlinear properties. The presented reduced order model shows similar nonlinear behaviour as the designer high order FE model of the polar crane under longitudinal seismic excitation. Thus the reduced order model can be used to realistically estimate of the impact forces on the RB walls and can also to conduct proof checking by the reviewer.

The following decisive model parameters are identified: the mass of the crane and of the hoist; the linear stiffness of the RB wall; the nonlinear stiffness of the seismic bumper and the support of the crane; friction between the crane and the hoist; and the friction between the crane and the railway. The stiffness of the impact bumper element and the friction coefficient of the crane are found to be the most important parameter, because the impact forces could be increased by approximately 30 %. Using these parameter studies, the local RB-crane interaction has been reviewed.

The reviewer concludes that the parameter estimations are derived realistically. This can be concluded from the parameter studies and also engineering judgements during the development of the reduced order model. Parameters are chosen in a conservative manner in order to estimate upper force limits.

The reduced order model gives the engineer the possibility to perform complex nonlinear time history calculations using standard engineering software (MATLAB, Octave, ...). The calculations can be conducted with great engineering flexibility. The reduced order model offers great transparency and allows efficient parameter studies.

Furthermore, the reviewer used the reduced order model to calculate the amount of energy dissipated using nonlinear model behaviour. Thus, it is shown that the Rayleigh damping applied by the designer is used conservatively enough to estimate realistic forces.

The calculations by the performed reviewer confirms the results obtained by the designer using the challenging and time consuming nonlinear FE analysis. It is shown that the capacity of RB walls is sufficient to resist the maximum impact forces during an SSE design earthquake. The approval of the retrofit measures was, therefore, granted by the ENSI to the operator.

REFERENCES

Nuclear Safety Standards Commission KTA (2011); “Design of Nuclear Power Plants against Seismic Events; Part 1: Principles“, *Safety Standard*, KTA 2201.1, 2011-11.
Nuclear Safety Standards Commission KTA (2012); “Design of Nuclear Power Plants against Seismic Events; Part 4: Components“, *Safety Standard,* KTA 2201.4, 2012-11.
Nuclear Safety Standards Commission KTA; (2012), Design of Lifting Equipment in Nuclear Power Plants", *Safety Standard*, KTA 3902, 2012-11.
ANSYS, R15 (2013), *Finite Elemente software*, www.ansys.com.
MATLAB R2014b (2014), *numerical computing environment*, http://ch.mathworks.com.