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DYNAMICAL STRUCTURAL RELIABILITY BASED ON THE CASE STUDY ANALYSIS

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Abstract. *An important aspect of the support structures' design is their dynamic behavior under extreme conditions. Large-range structures are especially interesting; therefore, the support structure of a mining machine for transportation of tailings (stacker) has been observed dynamically. The dynamic behavior of the entire structure in an incidental situation – the failure of a support tie rod for the pylon-platform connection is observed. The aim of this research is to predict the consequences of breakage on a structure element for the rest of the support structure. This paper shows the theoretical modeling of structures, numerical solution of differential equations, and vibrations after simulated incident. The paper presents a special design – the way of structure testing from the aspect of high structural availability and ability of the structure to compensate overload caused by the incident. To check the model, a real stacker structure was used at the surface mine RBB (The copper mine – Bor, Serbia). The developed numerical model showed the internal stress states of the structure and the law of vibration after the incident. On the basis of several case study analyses, the overall reliability and ability of redundancy of the structure were evaluated.*

Key words: *case study, frame structures, incident behavior, modal analysis, reliability, transient analysis*

1. INTRODUCTION

A good quality of reliable mining machinery is its adjustment to accept all regular and irregular effects that occur during many years of exploitation. On surface mining pits, the significance and price of mining machinery and earth-moving equipment impose tests which are often in the field of rare occurrences. This type of analysis is denoted as the case study analysis on the extreme effects, mainly. Stackers and rotating excavators

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(dredgers) are particularly sensitive, because despite their big masses they have sensitive structural relationship between under-frame structural stand with caterpillars and rotating platform with *Rothe-Erde* bearing [1]. That relationship between two big masses is a delicate part of the structure which allows many vibrations of the upper mass – rotating platform and boom. The aim of good design is the dynamic stability and high stress utilization of the stacker support structure. The case study analysis is used to calculate structure vibration amplitudes under the forced harmonic effect and structural resistance against incidental events such as impact effect, wind gust, seismic wave and other random effects.

Newer studies [2, 3, 4, 5] analyse the case of failure and consequences caused when certain parts of structure break. Rotating excavators and stackers have very sensitive parts which are very high loaded. These are the support tie rods. So, the questions are as follows: Will the failure - local fracture of a support tie rod for the connection of the pylon and rotating platform jeopardize the overall structural stability? Will the redundancy enable the stability preservation of the rest of the structure? The answer to these questions can be obtained by numerical simulation. The transient dynamic analysis of mechanical structure based on energy balance is suitable to be used in the numerical simulation of fracture incident. This paper examined an incidental situation i.e. the interruption of a responsible element of the stacker for the connection between the pylon and a rotating platform (a rear support tie rod). It is not a very frequent failure in practice because the tie rod element has a large cross section (i.e. moment of inertia). However, this failure can occur in exceptional extreme situations such as a collision of two objects or similar.

2. Dynamic Structure Modeling

Dynamic modeling of the stacker was performed by forming the discrete system of mass elements of the support structure and installed machine equipment. The masses are coupled mutually by the elastic connections of structural elements. For practical research, the dynamic modeling can be performed by the FEA modeler. For the modeling in this paper, the real structure of the stacker RBB [3, 5] was used. The analysis was performed using the finite element method [6] and the MSC software [7]. The stacker's elements, as the rotating platform and boom, are the frame structures, so they were modeled by the beam finite elements. The machine equipment, belt, drums and transported material on the conveyor belt were modeled by the dotted finite elements (concentrated masses). The stacker base (pedestal) without caterpillars is placed rigidly on the ground. By this and earlier investigations [2, 3, 5], the discrete model for the FEM analysis and numerical solutions to differential equations has been developed.

The high fidelity model, shown in Fig. 1, represents the stacker of dimensions $L \times H \times W$=55.9×16.88×7.87 m and the total rotational mass of 210,680 kg. The model contains 2134 finite elements (masses) and 1016 nodes in total. This large number of masses makes modeling more realistic and leads to advantages of discrete models.

The aim of structure behavior analysis is to check the existence of incidental situations that can occur due to failures in structure. The support tie rods are expected to be the first elements in failure because of their high level of stress, variable dynamic loads and big lengths. In the moment of a sudden interruption of element function due to the fracture, the potential energy of the interrupted element is diverted to other elements of the frame structure. This impulse increases the static force redistribution dynamically, so that the ability of surrounding elements to take over the impact effect could be questioned. It is a special aim of design which checks the redundancy of structure in the case of failure, in particular dynamically, according to the character and duration of incident.

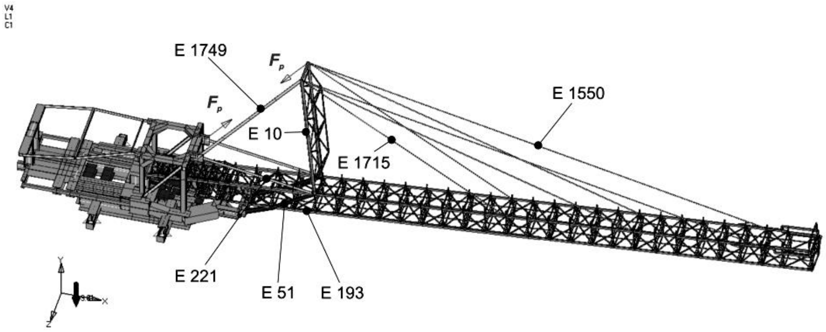

Fig. 1 Geometric model of the support structure of the stacker (E – selected responsible elements, F_p – axial force)

3. Analysis of Free Vibrations

Before transient analysis, the characteristic frequencies of damped vibration are determined. The equations of free un-damped vibrations for a linear mechanical system are expressed in the matrix form, Eq.(1), while the solution of the law of vibration has the harmonic form, Eq.(2) [6, 8]. In the normal modes analysis, for solving the free un-damped vibrations from Eq.(1), the frequency equation, Eq.(3), is used:

$$\mathbf{M}\ddot{\mathbf{q}} + \mathbf{K}\mathbf{q} = \mathbf{0} \tag{1}$$

$$\mathbf{q} = \mathbf{\Phi}_i \cos \omega_i t \tag{2}$$

$$\left|\mathbf{K} - \omega^2 \mathbf{M}\right| \mathbf{\Phi} = \mathbf{0} \tag{3}$$

In previous equations, **M** is the matrix of masses and inertia coefficients, **K** is the stiffness matrix**,** ω_i is i^{th} natural circular frequency (eigenfrequency) in radians per unit time, **q** and $\ddot{\mathbf{q}}$ are generalized vectors of translation and acceleration respectively, while $\mathbf{\Phi}_i$ is the representative vector of mode shape for i^{th} eigenfrequency. Deformation shapes, specific for each eigenfrequency, are called the mode shapes. The analysis of vibration shapes and eigenfrequencies is called the normal modes analysis.

In this research, the modal analysis was performed using the *Lanczos* method and modified *Givens* method [6]. The modified inverse *Sturm* method was also used to extract the lowest eigenfrequency.

Table 1 indicates the values of the computed eigenfrequencies of stacker boom at lateral and vertical vibration. These vibrations arise after fracture of a rear support tie rod (replaced with the axial force F_p in Fig. 1) for the connection between the pylon and rotating platform. The eigenfrequencies from Table 1 are significant for the dynamic load of the support tie rods.

Table 1 Some characteristic eigenfrequencies of the stacker

Mode shape	Mode-12 Lateral	Mode-17 Vertical	Mode-20 Vertical	Mode-31 Lateral, Torsion	Mode-33 Vertical, Torsion	Mode-34 Lateral, Torsion
Eigenfrequency Ω [Hz]	0.467861	0.688175	0.766214	1.954615	2.359128	2.521812
Mode shape	Mode-37 Lateral, Torsion	Mode-38 Vertical	Mode-46 Lateral, Torsion	Mode-50 Vertical, Lateral, Longitudinal	Mode-66 Vertical, Longitudinal	Mode-95 Vertical
Eigenfrequency Ω [Hz]	3.024481	3.181569	4.137398	6.264608	10.79204	12.52006

The first hundred eigenvalues and eigenvectors (modes) were identified by modal analysis of the developed model. The first hundred eigenfrequencies took place between the values Ω=0.0723452 Hz and 12.75624 Hz. Very low eigenfrequencies are consequences of the massive rotating structure reliance on the moving base over a small *Rothe-Erde* bearing. Various models of the rotating platform reliance were tested in order to determine their influences on eigenvalues. In relation to other structure elements, the reliance usually has the greatest influence on eigenvalues.

The first thirty eigenvalues, extracted by modal analysis, are characteristic of support tie rods vibration in the frequency range from 0.0723452 to 1.678639 Hz (Mode-1 to Mode-30). In this range, the lateral - Mode-12 and vertical - Mode-17 and 20 vibration shapes of the boom were exempted. The eigenfrequencies of alternating vertical and lateral bending of the boom, in the presence of a weak torsion, took places in the range from 1.954615 Hz (Mode-31) to 3.196299 Hz (Mode-39). Only the vibrations of the support tie rods occurred again in the frequency range from 3.31963 Hz (Mode-40) to 3.692737 Hz (Mode-45). The expressed torsional vibration of the boom occurred in the interval from 4.137398 Hz (Mode-46) to 6.775579 Hz (Mode-52), with a small exception. The slightly longitudinal undulation of the boom characterizes the range from 7.327017 to 8.48324 Hz (Mode-53 to Mode-59). The eigenvalues of 8.613748 Hz (Mode-60) and 8.707745 Hz (Mode-61) refer to the boom torsion. The vibrations of the conveyor belt and elements of the belt holder were dominant, starting from the vibration shape Mode-62 (8.756838 Hz) to the last extracted shape Mode-100 (12.75624 Hz). In the final frequency range, a certain vibration of the boom structure occurs, for example such as the vibration shape Mode-95 (12.52006 Hz). Figures 2 to 6 illustrate the dominant mode shapes of the developed FEM model of the stacker without a tie rod for the connection between the pylon and rotating platform.

For solving the basic task – transient analysis, the two dominant eigenfrequencies, required for energy description (damping velocity), were selected from the modal analysis. Figures 4 and 5 simply show the mode shapes of these eigenfrequencies. These are the circular frequencies whose eigenvectors indicate a combination of torsion and lateral translation of the structure elements of the stacker (Ω_{34}=2.521812 Hz and Ω_{46}=4.137398 Hz).

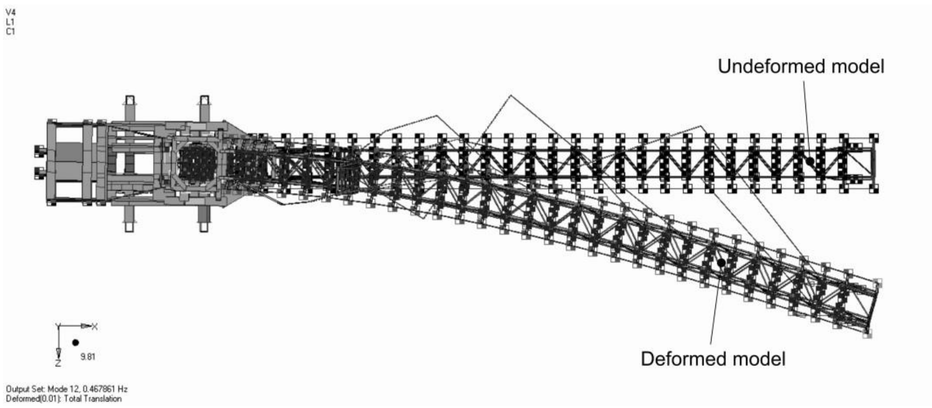

Fig. 2 Lateral vibration (top view), Mode-12, Ω_{12}=0.467861 Hz

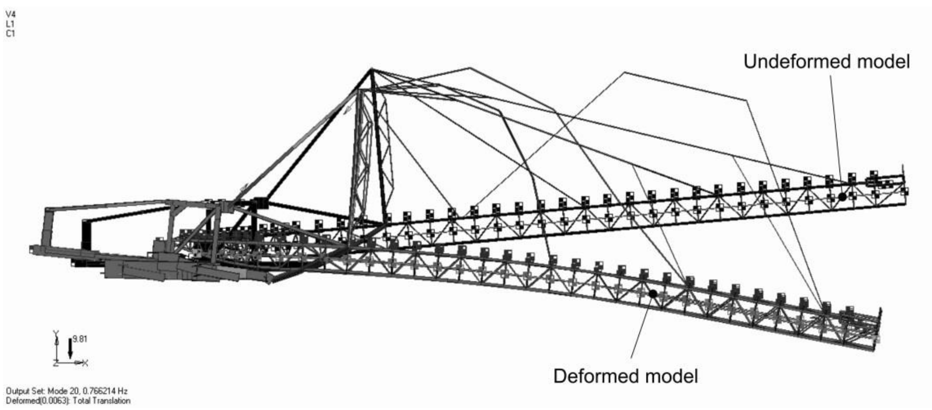

Fig. 3 Vertical vibration (right view), Mode-20, Ω_{20}=0.766214 Hz

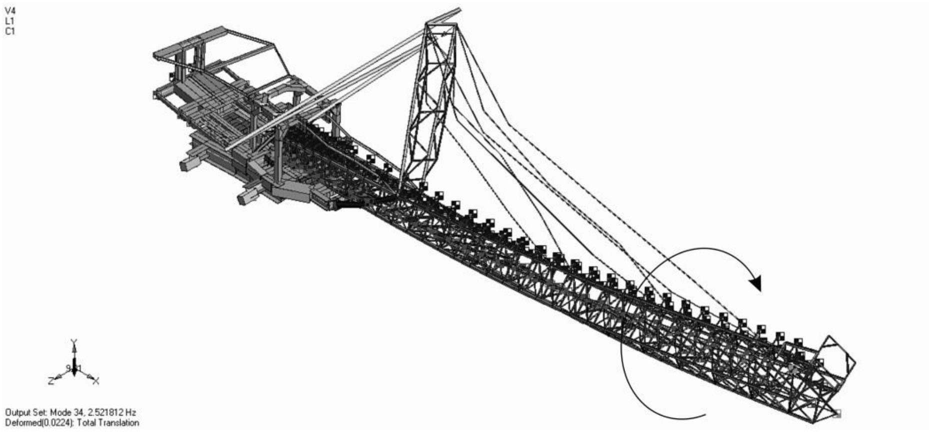

Fig. 4 Lateral vibration + torsion (isometric view), Mode-34, Ω_{34}=2.521812 Hz

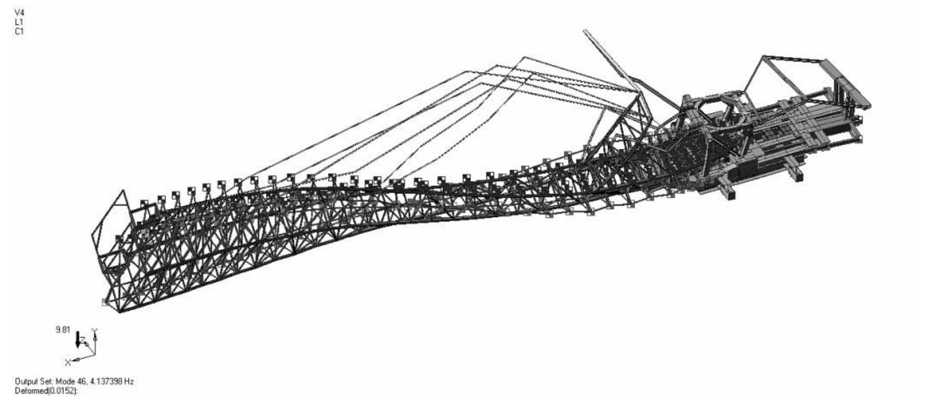

Fig. 5 Lateral vibration + torsion (a spatial view), Mode-46, Ω_{46}=4.137398 Hz

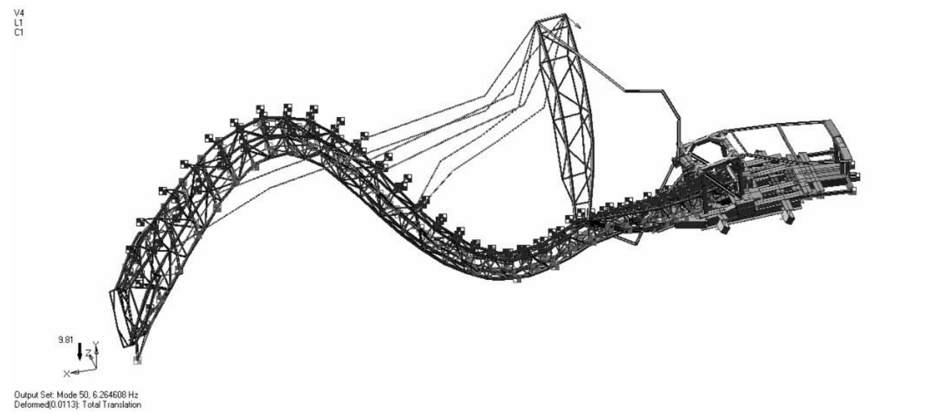

Fig. 6 Vertical + lateral + longitudinal vibration, Mode-50, Ω_{50}=6.264608 Hz

4. INCIDENTAL DYNAMIC ANALYSIS

4.1. Theoretic approach

A linear dynamic model which implies significantly less displacements (vibration amplitudes) in relation to dimensions of the modeled structure is adopted in the research. By this assumption the changes in structural configuration become negligible. Consequently, the stiffness matrix **K** is determined by integrating the original structural configuration, and elastic (internal) structural forces are computed by the direct manner (multiplying the stiffness matrix and displacements). The second assumption of this linear model is the application of a linear-elastic material. It allows the use of a constitutive constant matrix of material. The additional assumption includes the immutability of the boundary conditions during the forced effect.

The paper discusses an incidental case of structural behavior limited by geometric linearity. In the case of significant (large) displacements, geometrically nonlinear transient analysis must be conducted. In the case of linear transient analysis, the differential (dynamic) equation of structure motion has form:

$$\mathbf{M}\ddot{\mathbf{q}} + \mathbf{B}\dot{\mathbf{q}} + \mathbf{K}\mathbf{q} = \mathbf{F}(t) \tag{4}$$

where **M**, **B** and **K** are the mass matrix, damping matrix and stiffness matrix, respectively, **q** is the generalized vector of translation ($\dot{\mathbf{q}}$ – velocity, $\ddot{\mathbf{q}}$ – acceleration), and $\mathbf{F}(t)$ is the external (excitation) generalized force in a vector form.

4.2. Simulation scenario

Shaping of the perturbation force (tie rod axial force) was carried out on the basis of experimental development case study of the real structure under amplified vibrations. An incident – fracture can occur because of the collision of two machines in the immediate proximity or some other random influences.

Figure 7 shows the critical assumption form of the normalized perturbation force $\Delta F/F$ (for the axial force F_p). In this figure, Δt_{bf} is the time before fracture, Δt_f is the fracture time and Δt_{pf} is the post-fracture time. After t=60 s, large deformations of the rear pair of tie rods (for connection between the pylon and rotating platform) and the first sign of fracture occur due to the straining. The total interruption (failure) of a support tie rod occurs in the moment of simulation t=60.5 s. The structure is maximally loaded by the load on the conveyor belt for the whole duration of simulation $T_s = \Delta t_{bf} + \Delta t_f + \Delta t_{pf}$ =120 s.

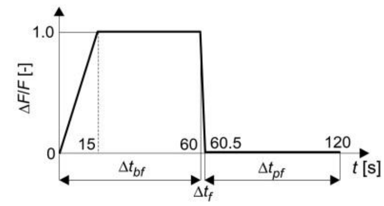

Fig. 7 Normalized disruptive force

The overall structural damping coefficient G=0.03 was used in the analysis. Damping is proportional to the velocity of vibration at selected and close frequencies [9] which were determined in previous modal analysis. The integration step was proportionally smaller of highest significant frequency obtained by modal analysis, i.e. 0.01 s. The number of steps amounted to 12,000.

4.3. Transient response analysis

The obtained results of the conducted transient analyses are the subject of next analysis evaluation of the structure. The evaluation of system reliability can be performed on the basis of the following five technical categories of dynamic structure behavior: *a*) the stress level of structural elements in relation to the permissible stress, *b*) the dynamic coefficient of structural elements as the ratio of forces or stresses, *c*) preserved or lost structure stability (the presence of other structural parts fracture), *d*) class – size of some interesting elements displacements (small or large displacements) and *e*) the possibility assessment of event (failure) repetition and calculation of reliability value (stress reserve).

For analysis of transient structural response, the seven responsible elements of the FE assembly were selected. These are: E-1749 - the remaining rear support tie rod for connection between the pylon and rotating platform (Fig. 1), E-10 - the main vertical holder of the pylon, E-1550 - the first pair of boom support tie rods – longest boom tie rod, E-1715 - the third pair of tie rods – shortest boom tie rod, E-221 - the slanting rod for fixing the pylon at the root, E-51 - the slanting support carrier and E-193 – the element of the main bottom belt of the boom below the pylon. In these elements, increment of stress and axial force were monitored at the moment of the incident occurrence – fracture of the tie rod element (t=60s).

All obtained static stresses (before fracture) are located in the permissible stress area which corresponds to structural steels of Group I (Yield point of $290\cdot10^6$ Nm^{-2}, EuroCode3), for the third load case and the safety coefficient of 1.2 ($\sigma_p=290\cdot10^6/1.2\approx242\cdot10^6$ Nm^{-2}). After the fracture of the tie rod, balancing of internal forces with the help of reserve structural resistance happened again. The structure has suffered the fracture in terms of the first criterion (*a* – above mentioned the stress level). Table 2 provides a preview of initial static stresses before the fracture and maximal dynamic stresses caused by the incident.

Table 2 Stresses in the selected elements [Nm^{-2}]

	The first pair of the boom tie rods; Element E-1729	The second pair of the boom tie rods; Element E-1719	The third pair of the boom tie rods; Element E-1550	The boom belt below the pylon; Element E-193
Max/min static complex stress*	0.708E+8	0.942E+8	0.890E+8	-0.965E+8
Max/min dynamic complex stress	0.515E+9	0.765E+9	1.745E+9	-1.559E+8

*Static stresses were obtained in the previous static FEM analysis of the structure [3]

Expressed stress changes occur at the tension of the third pair of boom support tie rods (the longest tie rod E-1550) in a longer simulation time (Fig. 8). Tensile stresses have been changed from minimal to extremely high values, above the recommended, in the stepwise time intervals. Thereby, the stress did not exceed the critical value – Yield point. The stresses of pressure were most expressed in the boom belt element (E-193). However, these stresses were significantly lower than the highest stresses of tension, in their absolute values. It is preferred that the stresses, obtained on this way from the dynamic response on incident, are an additional criterion of structural design because such criterion indicates when structure succeeds to compensate the damage caused by a local incident. The properties of redundancy, obtained in this manner, are special properties which lead to high reliability and low operating costs in exploitation.

For the evaluation of structure reliability on incidental dynamics, the dynamic coefficient K_d is adopted. It is the ratio of the min(pressure)/max(tension) post fracture dynamic force F_{pf} after an incident and the equilibrium force F_{eq} in the same element, Eq.(5), Fig. 9.

$$K_d = \frac{F_{pf}}{F_{eq}}, \quad (K_d > 1) \tag{5}$$

The dynamic response gives the insight into another dynamic parameter. It is about the coefficient of overall force growth K_F. Actually, this coefficient is the ratio of the min/max post fracture dynamic force F_{pf} and the mean value of the load force before fracture F_{bf} in a selected element, Eq.(6), Fig. 9. The coefficients K_d and K_F indicate the new equilibrium situation of a structure and local reallocation of forces after an incident (redundancy).

$$K_F = \frac{F_{pf}}{F_{bf}}, \quad (K_F > 1) \tag{6}$$

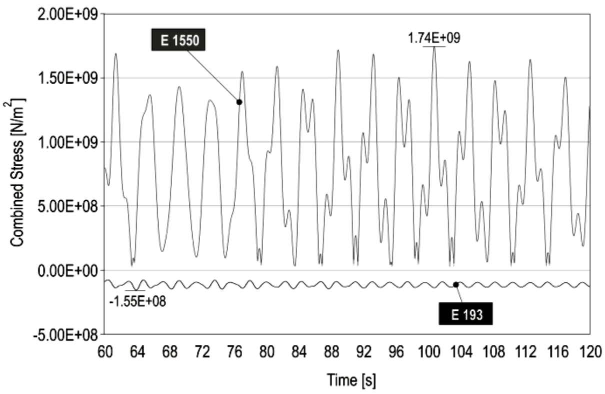

Fig. 8 Combined stress: maximal E-1550, minimal E-193

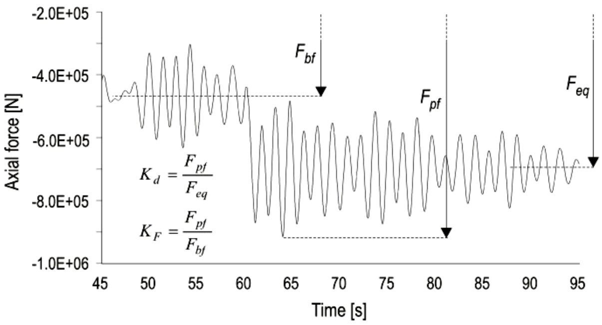

Fig. 9 An explanation for the dynamic coefficients

Table 3 shows the values of axial – internal force of the selected responsible elements of the stacker structure as well as the coefficients K_d and K_F for the same elements. Figure 10 shows the diagrams of the axial forces. It is about structural elements with a sufficient dynamic reserve since the dynamic coefficients from Table 3 did not exceed the recommended value i.e. K_d<K_p=1.5 in the case of fracture of a tie rod.

Table 3 Dynamic coefficients of the selected structure elements

Structural element	Before fracture axial force F_{bf} [N]	Post fracture equilibrium force F_{eq} [N]	Min/max post fracture force F_{pf} [N]	Action time* t (s)	Dynamic coefficient K_d [-]	Total force growth coefficient K_F [-]
(1)	(2)	(3)	(4)	(5)	(4)/(3)	(4)/(2)
E-10	-301907	-516267	-673604	62.45	1.30	2.23
E-51	-471173	-697070	-915653	63.95	1.31	1.94
E-221	478677	557306	742057	62.50	1.33	1.55
E-1715	58744	87726	106771	61.00	1.22	1.82
E-1749	279849	489873	642288	62.45	1.31	2.29

*The time in which the max/min force occurs in an element, measured from the beginning of simulation and after a fracture of the tie rod.

The structural elements from Table 3 were selected due to the expected increase in their internal forces. Thus, the biggest value of the axial force of pressure (minimum of force) occurs in the slanting support carrier (E-51) after the incident (fracture) and it is easy to see on the diagram in Fig. 10. On the other hand, the biggest nominal value of the tensile force occurs in the slanting rod for fixing the pylon at the root (E-221) after the interruption of a connection between the pylon and rotating platform, Fig. 10 (maximum of force). The biggest relative jump of force from an equilibrium state was recorded in the remaining rear tie rod (E-1749) which can be seen in Fig. 10 as well as on the basis of the total force growth coefficient K_F=2.29 in Table 3.

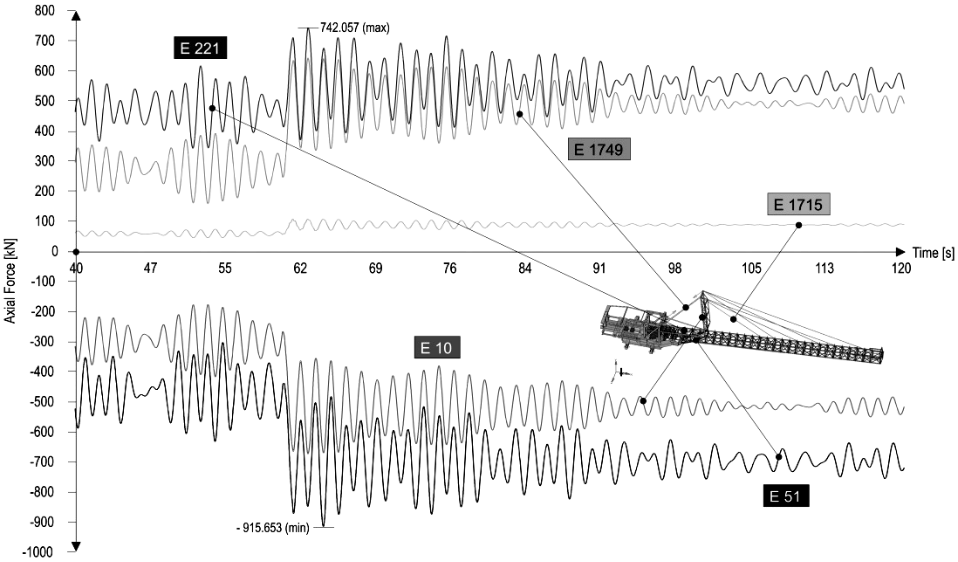

Fig. 10 Axial forces in the selected responsible elements of the stacker

From the transient response, one can conclude that the rear tie rod interruption did not jeopardize the total structure stability (criterion *c*) and the local elements damage did not occur (criterion *a*). However, the tie rod fracture caused the vibration shapes with the dominant lateral translation of the pylon (Δz_{max} in Fig. 11) and the vertical translation of the top of the boom (Δy_{max} in Fig. 12), according to criterion *d*.

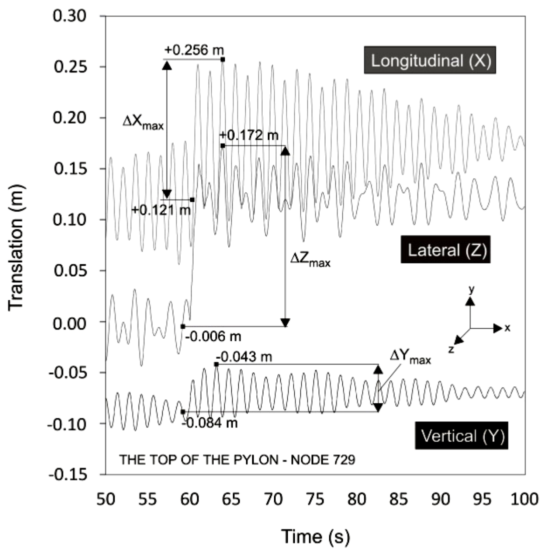

Fig. 11 Translation of the top of the pylon (Node N-729)

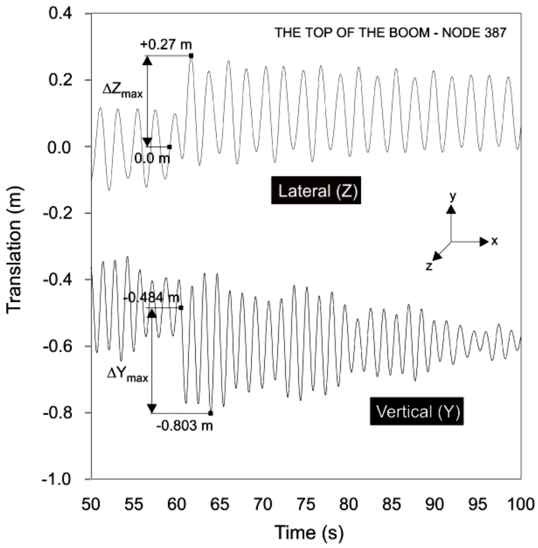

Fig. 12 Translation of the top of the boom (Node N-387) in two directions (translation in *x*-direction is negligible)

Beside the biggest translation in lateral direction Δz_{max}=0.172-(-0.006)=0.178 m, caused by an incidental dynamics, the top of the pylon, introduced by the node N-729, has also longitudinal (Δx_{max}=0.256-0.121=0.135 m) and vertical translation (Δy_{max}=-0.043-(-0.084)=0.041 m), Fig. 11. On the other hand, the top of the boom, introduced by the node N-387, translates in vertical direction most significantly (Δy_{max}=**-0.484**-(-0.803)=0.319 m) and then in lateral direction (Δz_{max}=0.27 m), Fig. 12. The longitudinal translations of the top of the boom (along *x*-axis) can be regarded as negligible.

Reliability of such frame system is probability that the support structure will perform successfully the function of criteria set, such as the criterion of stability preservation primarily, upon entry into the area of permitted deviations. Stress reserves must be sufficient for preservation of the working functionality of machine in the projected life cycle and conditions of incidental states such as fracture of responsible elements.

Reliability **R**(t) can be introduced to the cumulative function without cancellation work in the case of continual state changes [10].

$$\mathbf{R}(t) = 1 - \mathbf{F}(t) = 1 - \int_0^{t_1} \mathbf{f}(t)dt \tag{7}$$

i.e., in the case of discrete state changes of system

$$\mathbf{R}(t) = \frac{n - N}{n} = \frac{T_{ur} - N \cdot t_{ur}}{T_{ur}} \tag{8}$$

In Eq.(7) and (8), **F**(t) is the cumulative function without cancellation work, **f**(t) is the density function of time probability to the failure of frame structure or structural elements, n is the total number of system states, N is the total number of the system states in failure at the moment of observation, (n-N) is the total number of the system states in operation at the moment of observation, T_{ur} is the total time of system work and t_{ur} is the mean time at work (between discrete failures).

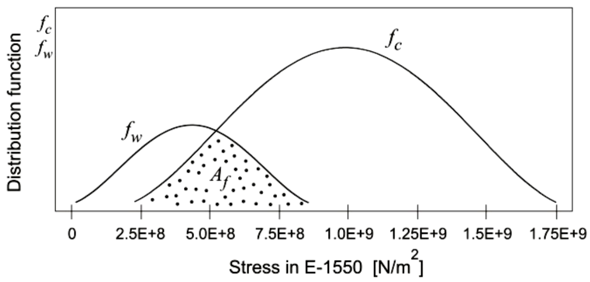

Fig. 13 Stress distribution functions in the element E-1550:
f_w – working stress, f_c – critical stress

The area A_f in Fig. 13 represents a probability that the working stresses in structure will be bigger than the critical. According to this value – probability, the degree of safeness ν from Eq.(9) can be defined and then perform the dimensioning of responsible elements of the stacker structure.

$$\mathbf{f}(\nu) = \frac{\mathbf{f}_c}{\mathbf{f}_w} \tag{9}$$

Since stresses are variable at simulation time, the stress distribution function can be used, i.e. $\mathbf{f}_w$ in the case of working stresses and $\mathbf{f}_c$ in the case of critical stresses. Thus, the degree of safety is not constant but instead changes according to the appropriate distribution $\mathbf{f}(\nu)$ [10].

5. CONCLUSION

On the basis of the conducted dynamic analyses, and taking into account the exploitation conditions and dynamic properties of the stacker, one can conclude the following:

- The quality of proposed FEM model of the stacker lies in a high fidelity of the structure (with very small approximations) introduced for all carrying and constructive elements of the real machine.
- The proposed FEM model has universal usage, making its additional quality. Namely, the model can be easily adjusted in order to check other incidental situations with support tie rods, wind and other additional effects.
- Introduction of the influence of ground is very desirable in dynamic analysis. The ground, on which these machines are placed, usually is unconsolidated because of their origin from the layers of material rejected in mining process (incompact ground).

- The modal analysis and experimental investigation correspond well with each other according to the frequency range in relation to the number of identified frequencies. The investigations indicated a large frequency range of the structure. The amortized vibration frequencies of structural parts were easily extracted in modal analysis according to the direction of eigenvectors propagation.
- The vibratory analyses indicate a stable dynamic behavior of this frame structure. The local fracture (incident) of a responsible structural element did not jeopardize the total structure stability because the rest of the structure disposes redundancy.
- The stress reserve of the frame stacker structure is large as well as the dynamic coefficient values which indicate a high reliability of the machine even in conditions of repetition events with similar incidental character.
- The model allows the identification of locations to install the sensors for monitoring dynamic properties of the structure in various exploitation situations. It can be a sensor for measurement of acceleration, stress and deformation (translation), so that the transportation capacity of material is always held to a maximum.

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DINAMIČKA POUZDANOST STRUKTURE ZASNOVANA NA ANALIZI STUDIJE SLUČAJA

Bitan aspekt dizajna nosećih struktura je dinamičko ponašanje u ekstremnim uslovima. Posebno su interesantne strukture velikih razmera, pa je dinamički posmatrana noseća struktura rudarske transportne mašine - odlagača. Posmatrano je dinamičko ponašanje celine pri incidentu - lomu jedne odgovorne zatege za vezu pilona i obrtne platforme. Cilj ovog istraživanja je da se predvide posledice loma na ostatak noseće strukture. Ovaj rad pokazuje teorijsko modeliranje strukture, numeričko rešenje diferencijalnih jednačina kretanja i nastale oscilacije posle simuliranog incidenta. Rad pokazuje specijalan dizajn strukture – način testiranja sa aspekta sposobnosti i raspoloživosti strukture da kompenzuje preopterećenje izazvano incidentom. U analizi je korišćena realna noseća struktura odlagača na površinskom kopu Rudnika bakra u Boru. Razvijeni numerički model je pokazao unutrašnja naponska stanja i zakone oscilovanja strukture posle incidenta. Na bazi više Case Study analiza sposobnosti rezerviranja moguće je oceniti ukupnu pouzdanost strukture.

Ključne reči: *studija slučaja, okvirne strukture, ponašanje izazvano incidentom, modalna analiza, pouzdanost, tranzijenta analiza.*