The use of nonlinear dynamic analysis in the calculation of cargo fall onto the hatch of the gondola car

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Abstract. The article studies how things stand in terms of the determination of the stress-strained state of the hatch cover of the gondola car when the cargo falls on the cover. The methods that are currently used were briefly reviewed. The calculation was performed using nonlinear dynamic analysis in CAE (Computer Aided Engineering) NX system.

1 Introduction

In the normative documents [1-2], in accordance with which the freight cars and their assemblies must be designed, there are points according to which it is required to verify the hatch covers of gondola cars in terms of strength under the following conditions:
- when the hatch cover falls on the stops when the gondola car is being unloaded,
- when a lump cargo weighing 2000 kg falls from 3 m height onto the closed cover (when the mass of separate pieces is not exceeding 100 kg),
- when the cargo weighing 150 kg falls from 3 m height onto the center of the closed cover.

Compliance of covers of hatches with these requirements is traditionally checked by experimental methods or a report is drawn in which a picture with stresses' distribution from the static loading is presented, the value of which does not cause stresses exceeding the allowable values, which corresponds to the formal requirements of normative documents [1-2].

Despite the fact that methods of nonlinear dynamic analysis using FEM were developed and implemented in application software program for the computer for quite a while [3-12], this problem was not being solved by design bureaus. The reason for this is the insufficient computational capabilities, the high cost of licenses, as well as the complexity of numerous settings of contact interaction and numerical integration parameters.

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To be fair, it should be noted that in several universities work was carried out in terms of the simulation of the stress-strained state of the hatch cover of gondola car when the cargo falls [13-16]. In these works, the calculation was carried out in a static setting, and the main studies were limited to the determination of the coefficient of dynamism by which the weight of the cargo, having been applied to the surface of the cover, was multiplied. In this approach the inertia forces of the masses distributed along the volume of the cover and cargo, cargo stiffness, the change in the stress-strained state in time and other factors are not taken into account.

The specified drawbacks are not found in the method of the nonlinear dynamic analysis which is used in Scientific-Technical Directorate of LLC “VNICTT” as part of the NX Nastran software package. Into this package there have been integrated ADINA (Automatic Dynamic Incremental Nonlinear Analysis) solvers that implement explicit and implicit methods to tackle the issues of nonlinear dynamic analysis (Sol 601/701) [17].

2 Methods and Results

Next, we consider the regulated [1, 2] case of falling of lump cargo weighing 150 kg from 3 m height onto the closed cover. In the previously mentioned sources [13-16], the loading of the cover (when the cargo falls on it) is estimated using the coefficient of dynamism, which is determined by the formula derived from the equation of the potential energy of the cargo, existing at the height h_0 above a vertically standing weightless rod, and the maximum potential energy of elastic deformations of this rod, which arise when the cargo is falling.

$$K_D = 1 + \sqrt{1 + \frac{2h_0}{\delta_c}} \tag{1}$$

where h_0 – height from which the cargo falls,δ_c – the value of the deflection of the cover in case of the static action of the cargo gravitational force,

Moreover, in the sources [15-16], this formula is interpreted in very different ways. In [15] δ_c value is interpreted as the total deflection of the body on the spring suspension, and in [16] the deflection of the cover itself, to which the corresponding boundary conditions are applied. Hence, the results obtained are significantly different. In [15] they obtained K_D values from 23.1 (for the middle of the center sill) to 91.07 (longitudinal support beam located between the body bolster and the center sill), in [16] the minimum value $K_D = 174$ was obtained. It should be noted that with the coefficient of dynamism $K_D = 174$, the stresses in many areas of the cover will be far beyond the yield point and then the formula (1) loses all meaning. The stress-strained state from the weight of the cargo weighing 150 kg, taking into account the coefficient of dynamism $K_D = 174$, is shown in fig. 1.

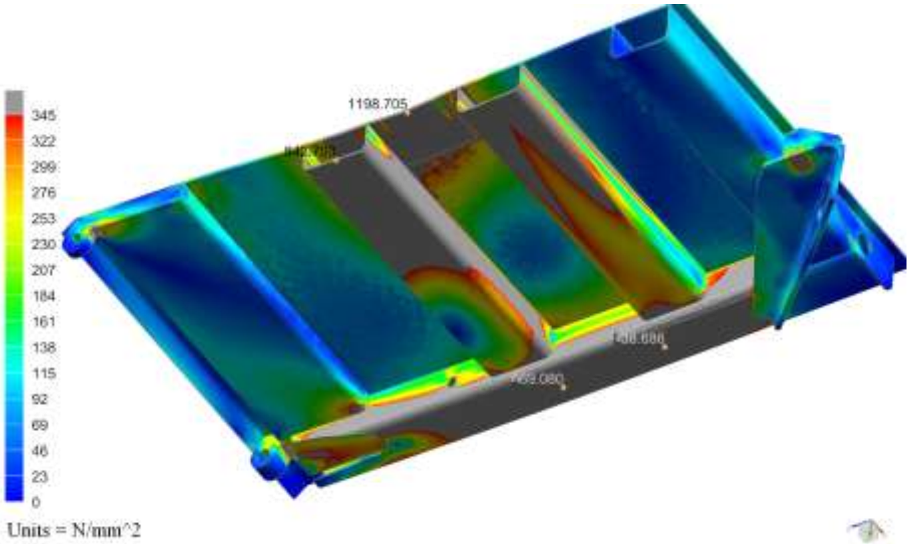

Fig. 1. Stress-strained state of the cover caused by the weight of the cargo, weighing 150 kg, taking into account the coefficient of dynamism $K_D = 174$.

As was previously noted, the determination of the loading on the cover when the cargo falls onto it via the coefficient of dynamism according to the formula (1) has a significant drawback, which lies in the fact that this formula is derived for the case of a fall of a completely rigid cargo onto a vertically mounted weightless rod, the material of which works only within the elastic deformations; accordingly, the inertia forces are not taken into account, as a result, stresses at the same moment of time at all points of the rod are equal.

This drawback does certainly not exist in the methods of nonlinear dynamic analysis, which takes into account the stiffness of all interacting bodies, inertia forces and friction forces occurring during the interaction, the work of the material in the area of plastic deformations.

Finite-element model with boundary conditions used to perform the nonlinear dynamic analysis is presented in fig. 2. In order to reduce the dimension of the task the symmetry condition was used.

In order not to waste computational resources for the timeframe till the cargo gets into contact with the cover, in its initial position, the cargo is at a distance of 5 mm from the cover. In this case, the initial cargo speed corresponds to the height $h_0 = 2995$ mm and amounts to $V_0 = \sqrt{2gh_0} = 7665.6$ mm/s.

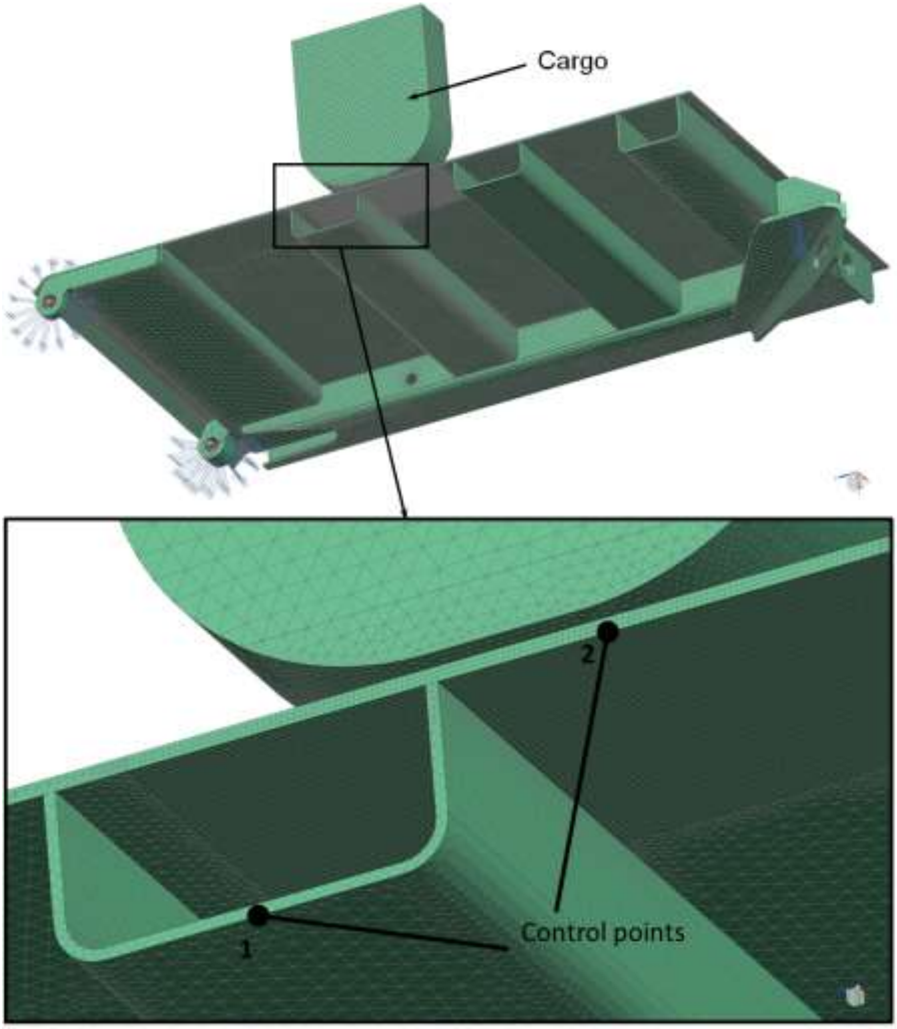

Fig. 2. Finite-element model with boundary conditions.

The material of the cover elements – steel 09Г2С with yield limit $\sigma_y = 345$ MPa. The nonlinearity of the material was set by the tabular dependence of the stresses on strains (see fig. 3).

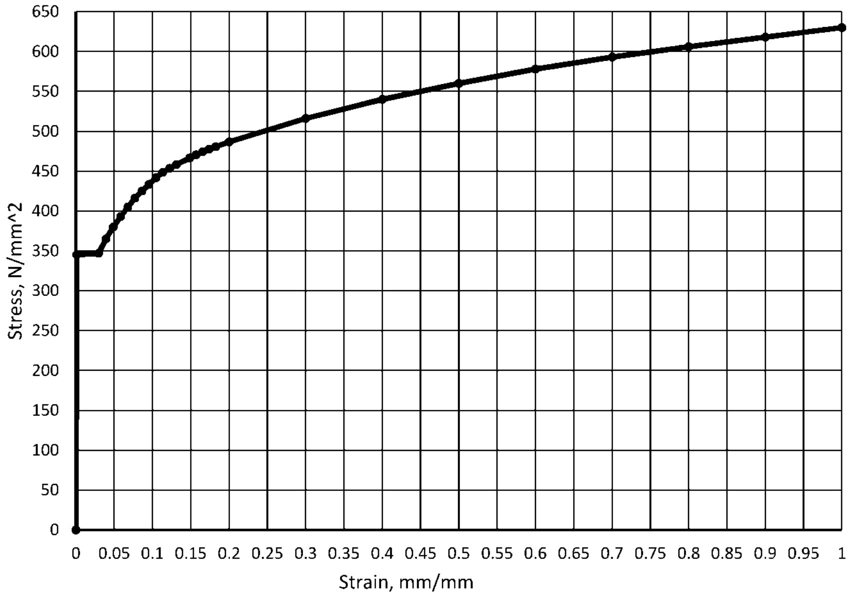

Fig. 3. Nonlinear dependence of stresses on strains of the cover material.

Fig. 4 shows the variation of stresses in the course of time in control points 1 and 2 of the cover, obtained by explicit and implicit solvers.

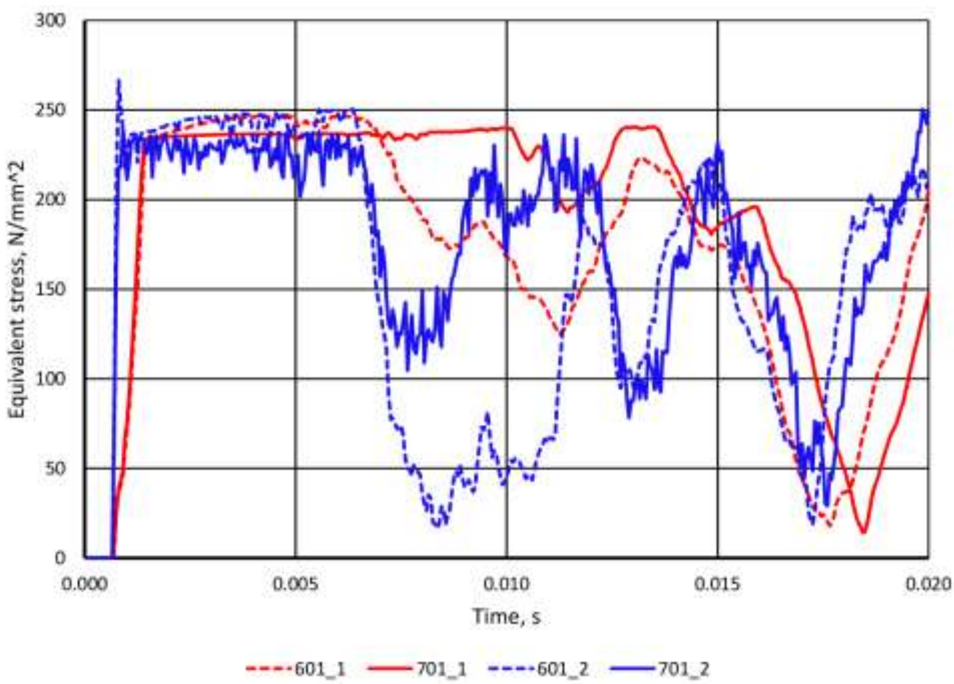

Fig. 4. Change, in the course of time, of stresses in control points 1 and 2.

From the graphs, presented in fig. 4, it is seen that even after the cargo has jumped away from the cover, oscillatory processes will continue to exist in the cover.

Fig. 5 shows the stress-strained state at the moment of time when maximum stresses occur in the control point 1. Dynamic stresses in points 1 and 2 are $\sigma_{1dyn} = 245$ MPa, $\sigma_{2dyn} = 250$ MPa.

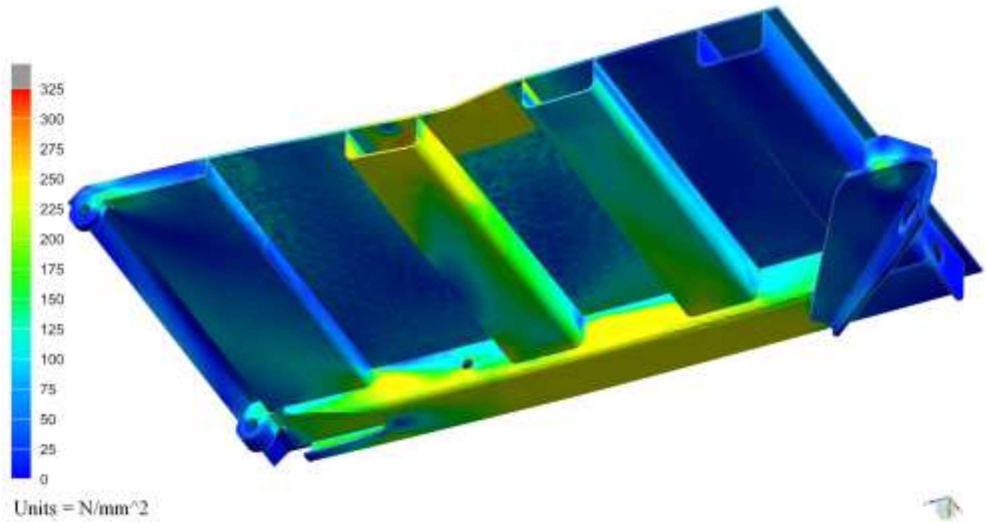

Fig. 5. The stress-strained state of the cover at the moment of time of 5.850 ms, when maximum stresses occur in the control point 1.

Fig. 6 shows the stress-strained state of the cover in case of static loading by the cargo force of gravity. Stresses in points 1 and 2 were $\sigma_{1st} = 6.37$ MPa, $\sigma_{2st} = 19.27$ MPa. Thus, real coefficient of dynamism for these points:

- point 1 — $K_{D1} = \sigma_{1dyn}/\sigma_{1st} = 245/6.37 = 38.46$;
- point 2 — $K_{D2} = \sigma_{2dyn}/\sigma_{2st} = 250/19.27 = 12.97$.

In the nonlinear dynamic analysis, which was performed, as well as in the similar case, in which $K_D = 174$ was obtained, the compliance of the railcar body and its spring suspension was not taken into account. The obtained results are very different, which indicates that it is not acceptable to use the formula (1) to determine the coefficient of dynamism.

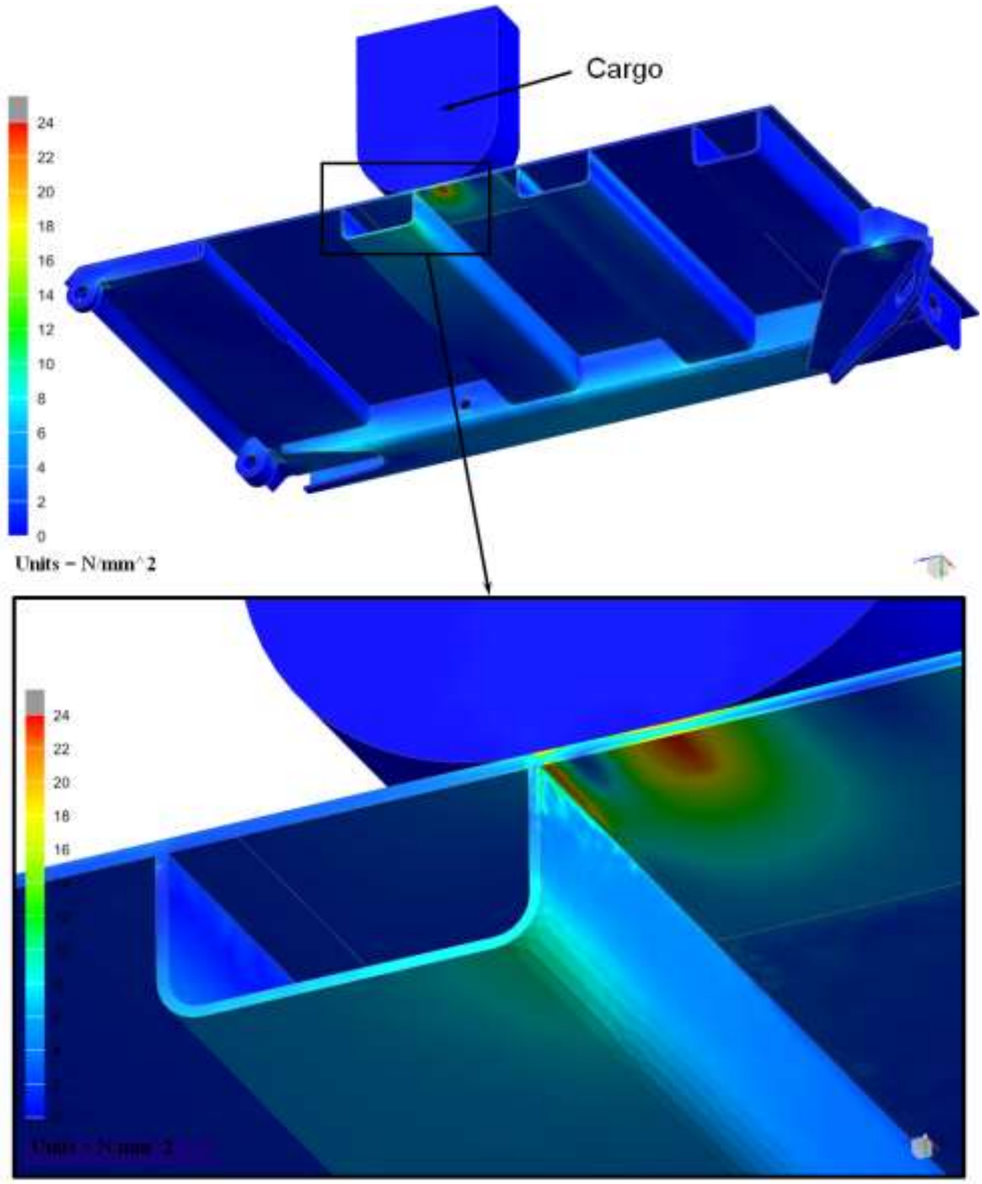

Fig. 6. Stress-strained state of the cover under static loading by the cargo force of gravity.

3 Conclusion

The analysis of literature sources, devoted to the study of the loading of the hatch cover of the gondola car when the pieces of cargo are falling onto the cover. The drawbacks of the methods presented in the sources are identified.

Finite-element model (in which nonlinear properties of the material are taken into account) of the cover of the hatch of the gondola car was made. Nonlinear dynamic analysis with the application of explicit and implicit methods for the calculation mode of 150 kg lump cargo's falling from 3 m height onto the cover center was performed. According to the results of the calculations, the value of the coefficient of dynamism in the existing methods is significantly overestimated. It should be noted that during the tests the falling of cargo on the cover happens at the moment when the cover is a part of the railcar, which elements also perceive kinetic energy of the falling cargo; in addition, to avoid local surface deformations of the cover, a layer of sand is poured onto the cover, the sand also absorbs a part of energy and redistributes the force of interaction between the cargo and the cover on the larger area. In order for the research-engineers to unambiguously interpret the conditions for which the calculation of the impact interaction is performed, the normative documents [1] and [2] must be supplemented. Otherwise, research-engineers will obtain the results that differ enormously.

Further on we will give key parameters which have to be specified:

- cargo shape and sizes,
- cargo mechanical properties,
- cover boundary conditions,
- falling height or speed of the cargo at the moment when the cargo comes in contact with the cover,
- for the most widespread materials from which covers of hatches are manufactured, there should be presented the dependence of deformations on stresses (tabular or in the form of graphs).

It is also necessary to conduct full-scale tests and compare the tests' results with the results of calculations; then, on the basis of the results obtained, to derive the dependence of the coefficient of dynamism, suitable for practical use by research-engineers when solving this problem in a linear static setting.

Methods of nonlinear dynamic analysis can be widely used in the field of calculation and design of railcars and their assemblies, in particular, during the calculation of the body for the longitudinal impact, simulation of elastic-friction draft gears and in other fields. Moreover, broad prospects for the use of nonlinear dynamic analysis appear for the design of the technological tooling; this tooling is performing the operations in which assemblies and parts of railcars are subjected to plastic deformations (stamping, bending of flat rolled steel and shaped rolled steel, etc.).

The reported study was funded by RFBR according to the research project №19-08-01241a. The authors declare that there is no conflict of interest regarding the publication of this paper.

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