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Protective structures for construction and mining machine operators ☆

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Abstract

The paper presents selected problems concerning the passive safety of the operators of construction and mining machines. Such machines must be equipped with protective structures meeting the requirements of the relevant regulations and standards. Protective structures for engineering machines are described and classified. Requirements and ways of carrying out experimental investigations of protective structures: FOPS, TOPS, ROPS and RSPS are specified. The principles of constructing calculation models for numerical simulations in virtual space by the finite element method are given. A detailed example of FEM tests on a protective structure is provided.

Keywords: FEM; Protective structures; Passive safety; Mining machines

1. Introduction

Construction and mining machines operate in various environmental conditions, both above ground (construction and agricultural machines) and underground (mining machines). Since all kinds of engineering machines are operated by operators, a protective cabin (the operator's workplace) is an inseparable part of almost every such machine. The difficult conditions in which the machines work require that the cabin should ensure safety and be ergonomic.

Currently protective structures for construction and mining machines are required to provide safety in case of a rollover during engineering work (ROPS – Rollover Protective Structure – ISO 3471, EN 13510:2004) and protect construction machines against falling objects (FOPS – Falling Object Protective Structures – ISO 3449, EN 13627:2002). In the case of mining machines safety at much higher impact energies than the ones specified by ISO 3449 must be ensured. This is dictated by the operating conditions and the danger of rock slides. In Poland standard PN-92/G-59001: 'Rock slide protective structures (RSPS). Requirements and tests.' is binding for mining machines.

Protective structures significantly reduce the risk of an accident. In the KGHM Polska MiedŸ Holding Company there have been cases when operators of mining machinery have been saved by such structures in cave-ins, as shown in Fig. 1.

Another example is an excavator rollover (Fig. 2) during demolition of a building, where the protective structure, i.e. the cabin, saved the operator's life.

2. Protective cabins

Today protective cabins are used in all new construction machines and underground mining machines. Their main function is to protect the operator from impact (protection against rockbursts and rock or other object strikes) [5]. In addition, protective structures must provide vibration insulation, sound insulation (noise protection), thermal insulation and protection against harmful environmental chemical agents.

Cabins can be classified according to the site, the aim of the protective measures or the structure. A major criterion for classifying cabins is the consequences against which they must protect the operator and so one can distinguish:

- ROPS — a rollover protective structure (Fig. 3),
- FOPS — a falling object protective structure (Fig. 3),
- TOPS — a tip over protection structure (for compact excavators) (Fig. 4),
- RSPS— a rock slide protective structure (mining machines in Poland) (Fig. 5).

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Fig. 1. Protective structure saved mining machine operator's life in KGHM PM S.A. O/ZG LUBIN — rockburst on 04.08.2003, rockburst energy: $E = 190\,000$ kJ.

One should note that a protective structure can be an integral part of the operator's cabin or it can be an accessory (Fig. 3).

Cabins can be classified according to the site which may be [2]:

- a truck,
- a slow-speed (construction or agricultural) machine working on the ground's surface,
- a slow-speed (mining) machine working underground,
- any other self-propelled machine.

Cabins can be classified according to the aim of protective measures, which may be:

- mechanical impact protection,
- vibration insulation,
- sound insulation,
- thermal insulation,
- protection against harmful chemical environmental agents.

The most important and most clear-cut classification criterion is the kind of cabin structure (including load-bearing structure). And so one can distinguish cabins with:

- a surface load-bearing (shell) structure,
- a load-bearing beam structure,
- a load-bearing beam structure with sheathing.

A typical cabin usually has the form of a frame consisting of posts (made from box profiles) connected by crossbars, covered by a plate roof resting on the posts. The top plate preferably should be a space structure in the form of a frame with sheathing. The frame should be made from steel sections and the sheathing from thick tough plate metal. If the cabin receives a hit from above, the posts locally lose their stability. During the strike the box-profile posts should convert the impact energy into work of deformation [3,4].

Protective cabins have an open (Fig. 6) or closed structure, their height can be adjustable or not and they may differ in their support (the number of supports).

Fig. 2. Overturned excavator on building site.

Fig. 3. Protective structure of ROPS and FOPS type.

The boring machine shown in Fig. 6 has been designed to bore blast-holes in underground minerals mines and tunnels. The open cabin structure ensures good visibility. Movement in low galleries is facilitated thanks to height adjustability. But the cabin's open structure does not protect the operator from the adverse conditions prevailing in the mine. The top plate rests on four posts. The number of supports has a bearing on deformation during impact, absorbed energy and visibility.

Closed cabins can be equipped with air conditioning to enhance work comfort for the operator, as shown in Fig. 7.

3. Passive safety in protective structures

The primary function of protective structures for operators working in difficult and hazardous conditions is to ensure the highest possible level of passive safety. The operators of engineering machines are exposed to several risks. In the case of a rockburst, for example, the protective structure should provide a living space for the operator and protect him/her against falling rock strikes or against side strikes resulting from a scarp slide or a machine tip over.

Fig. 4. TOPS.

Fig. 5. RSPS.

Another important factor taken into consideration when designing such structures is their ergonomics: the operators of the machines should have optimum working conditions.

3.1. Impact-from-above test of protective structure

The requirements which a structure protecting the operator must meet during an impact-from-above test are specified by the following standards currently in force in Poland:

- Standard PN-92/G-59001 'Self-propelled mining machines. Rock slide protective structures (RSPS). Requirements and tests.',
- Standard PN-EN 13627:2002 'Earthmoving machines. Falling object protective structures (FOPS).'

The situation to which the standards apply is shown schematically in Fig. 8.

A protective structure for self-propelled mining and construction machines is a system of structural components arranged on the machine in a way which significantly reduces the risks to the operator. Furthermore, a protective structure can be an integral part of the operator's cabin whereby one gains such benefits as: a cost reduction, an increased operator workspace or a reduced machine height.

The load-bearing structure and all the protective structure components (mounted on the machine) should be ergonomic,

Table 1
Certification test parameters

Standard	Striking energy	Mass of weight	Initial velocity of weight	Impact surface diameter
	E_u [J]	m [kg]	v_o [m/s] (m [kg])	$\varnothing d$ [mm]
PN-EN 13627:2002 FOPS	11 600	230÷330	10.04 (230)	200
PN-92/G-59001 RSPS	60 000	1500÷6000	4.472 (6000)	min 800

Fig. 6. Boring machine with open protective structure.

i.e. so designed, machined and finished that all sharp corners and edges have been eliminated.

A standard laboratory test weight (for RSPS) has the form of a cylinder (Fig. 9) and it should weigh 1500–6000 kg at a minimum diameter of 800 mm; dimensions d and l are arbitrary (for the minimum diameter), depending on the weight's mass. At the instant of impact the weight should have kinetic energy $E=60$ kJ (Table 1).

The protected space within the protective structure's outline, called DLV (Deflection Limiting Volume — a space of limit

Fig. 7. Boring machine with open protective structure.

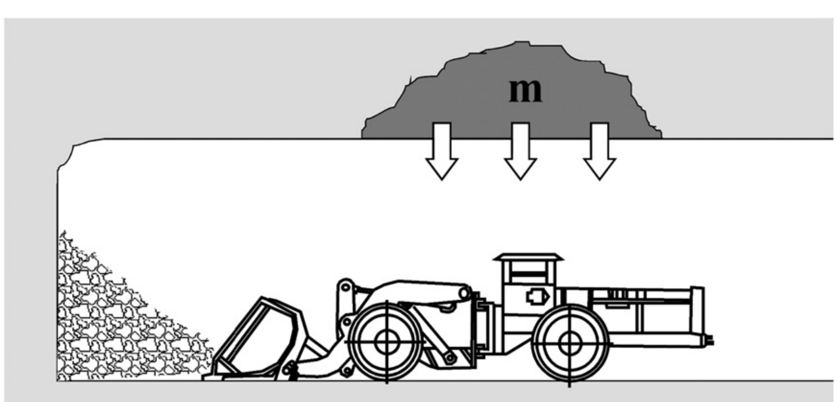

Fig. 8. Working mining machine being buried in excavation.

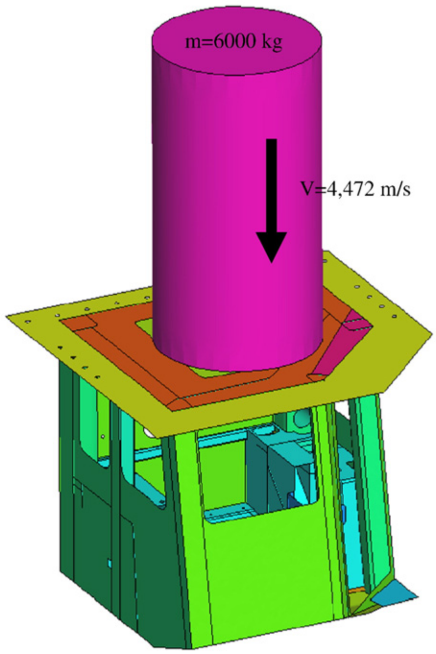

Fig. 9. Schematic of analytical conditions for RSPS test employing standard laboratory test weight with dimensions: diameter $d=800$ mm and height $h=1500$ mm.

deformations, a protected space), i.e. the space into which no part of the cabin or the protective frame should enter, is defined. The shape and the location of the protected space depend on the position which the operator occupies when operating the machine according to its function (Fig. 10).

Self-propelled mining and construction machines have to be equipped with ROPS and FOPS. In Poland mining machines have to be additionally equipped with RSPS.

During the strength test the evaluated structure should be mounted in the same way as during the actual operation of the machine. Such components as: dismountable panels, windows

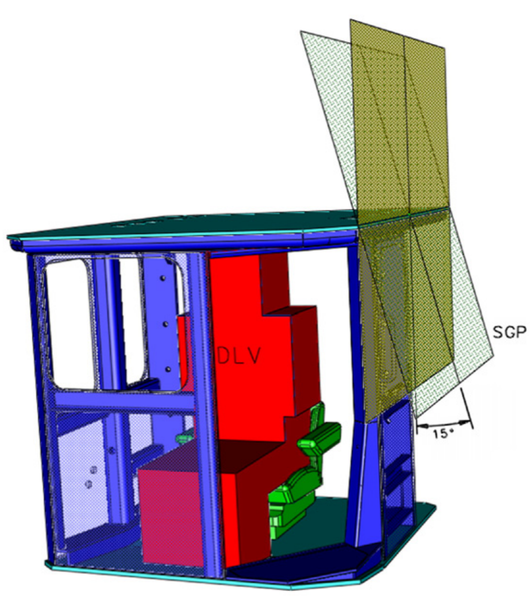

Fig. 10. Simulated ground plane (SGP) — cabin with protected space (DLV).

Table 2
Range of loading force F and absorbed energy U

Types of machines	Loading force F [N]	Absorbed energy U [J]
Wheeled construction loaders, tractors, bulldozers and tool carriers	$F = 60,000\left(\frac{M}{10,000}\right)^{1.20}$	$U = 12,500\left(\frac{M}{10,000}\right)^{1.25}$
Wheeled construction graders	$F = 70,000\left(\frac{M}{10,000}\right)^{1.10}$	$U = 15,000\left(\frac{M}{10,000}\right)^{1.25}$
Construction scrapers and off-road dumper trucks	$F = 95,000\left(\frac{M}{10,000}\right)^{1.20}$	$U = 20,000\left(\frac{M}{10,000}\right)^{1.25}$
Crawler construction tractors, loaders, dozers and tool carriers	$F = 70,000\left(\frac{M}{10,000}\right)^{1.20}$	$U = 13,000\left(\frac{M}{10,000}\right)^{1.25}$

or accessories which are not part of the structure (and so have no effect on its strength) should be removed. Maximum rigidity of the base to which the structure is attached should be ensured. However, no complete machine is required.

3.2. Crushing test of rops

The requirements which operator protecting structures have to meet during a crushing-from-the-side test are specified by the current standard:

- PN-EN 13510:2004 'Earthmoving machines. Rollover protective structures (ROPS). Requirements and laboratory tests.'

The above standard regulates the issues of safety assurance during the rollover of a machine. But it can also be applied to side strikes into a protective structure (e.g. rock strikes), which are more likely in the case of mining machines.

ROPS has to meet two conditions:

- carry the required force,
- absorb the specified energy,with no component breaching the protected space.

The test is destructive and it consists in subjecting a protective structure to a static load from the side. The load is generated by a horizontal force applied via a load distributing plate. The crushing-from-the-side test should be conducted continuously until the requirements as to loading force F and absorbed energy U are satisfied (Table 2). The protective function is considered to be fulfilled when DLV is intact.

ROPS is a system of structural elements arranged in a way which significantly reduces the degree of risk to the operator if the machine rolls over or is hit from the side. Similarly as FOPS or RSPS, ROPS can also be an integral part of the operator's cabin. Machine mass M (which determines required loading force F and absorbed energy U) includes the work attachments, the protective structure (ROPS or ROPS-RSPS), all the tanks

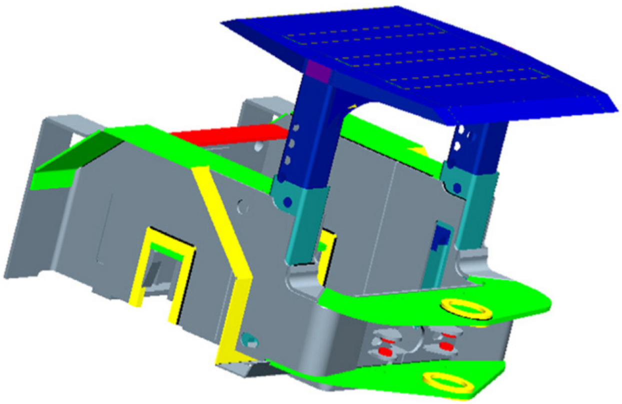

Fig. 11. Protective cabin with platform.

filled to maximum capacity, the tools (belonging to the machine's fittings) necessary for servicing or maintenance, but no operator, cargo or hauled attachments and no elements connecting the attachments to the machine.

A simulated ground plane (SGP) is a conventional plane corresponding to the actual surface of the ground during the test. It is schematically shown in Fig. 10.

4. Principles of constructing discrete models of protective structures

Because of the responsible functions they perform, protective structures are subject to destructive certification tests. In the ROPS test (PN-EN 13510:2004) the minimum side force and the minimum energy of protective structure deformation are specified. Both depend on the type of vehicle and its mass. Also in this case if the protected space is breached, the tested structure is disqualified (Table 2).

Using advanced computer techniques one can simulate the above tests already at the design stage whereby the adopted design solutions can be verified [5]. Numerical simulation of a crash is a difficult dynamic analysis since large configuration changes (deflections, local stability loss, etc.) are involved and the material's behaviour is nonlinear (plasticization, strain hardening effects, dependence of material characteristics on the rate of deformation) [6]. Also contact phenomena between the weight and the protective structure and between the protective structure's elements should be taken into account [4]. When a vehicle-mounted protective structure is tested, some of the impact energy is dissipated. So far numerical simulations have not taken into account this fact. Furthermore, the impact time is very short (from a few to a few tens of milliseconds) and wave effects appear (especially in the first stage of impact).

Therefore it becomes necessary to search for new comprehensive solutions already at the stage of designing a protective structure (cabin) for a construction machine, a mining vehicle and so on.

Before a physical prototype of a protective structure is made, one should carry out tests (through numerical simulations) on its virtual prototype [7]. For this purpose mathematical (discrete) models of the cabin's load-bearing structure in 3-D, describing its geometry and the physical loading condition resulting from the tip over of the machine on a slope or from a rockburst (cave-in) in an excavation, are developed. An example of a rockburst in a mine excavation is shown in Fig. 1.

In order to assess the effort of the structure and the latter's way of deforming under a dynamic impact load the designer must precisely specify the analytical conditions [8]. This applies to model geometry mapping accuracy, fixing model boundary conditions (i.e. the character of the external loads and the way of restraining) and to model material parameters. Increasingly more often the designer must take into account momentary loads characterized by a very high amplitude and intensity in order to determine the consequences of dynamic loads. This applies to many objects whose intended use often decides about a person's life and safety, e.g. the protective structures used in construction and mining machines and vehicles as well as some components of the vehicle load-bearing structure. So far the so-called dynamic excess coefficient has often been calculated and used as a scale factor and the results of a structural analysis have been used to calculate the structure's effort. In this way a time-consuming dynamic analysis has been avoided. But the quantity

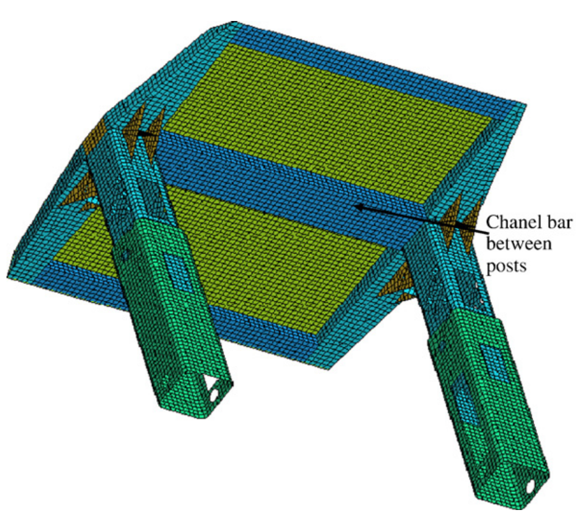

Fig. 12. Discrete model of protective structure.

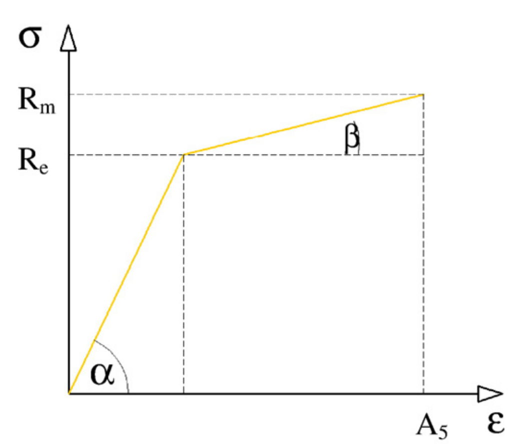

Fig. 13. Bilinear elastic-plastic material model.

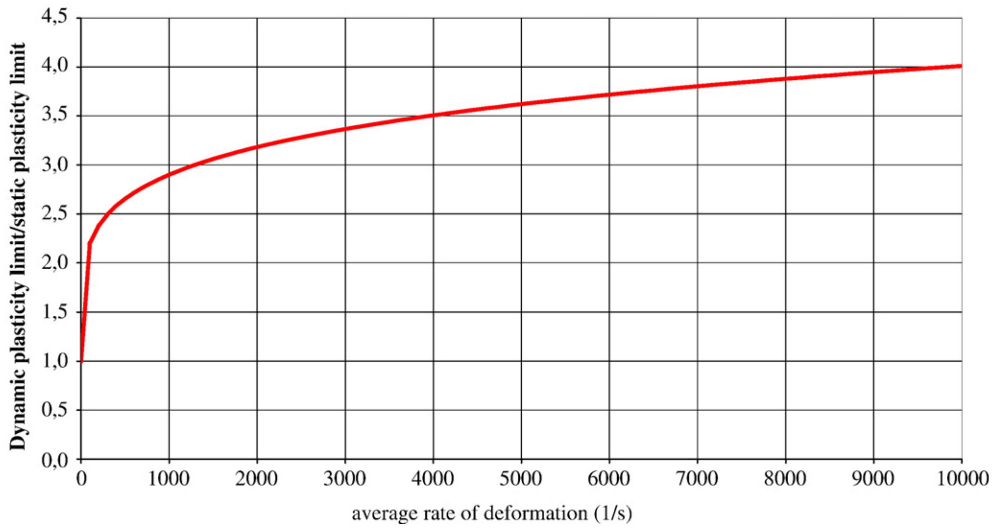

Fig. 14. Influence of deformation rate on dynamic plasticity limit.

and quality of information about the behaviour of a structure under an impact load, available to the designer is dubious. The behaviour of a structure on which very often a person's life depends must be exactly known, which means that this behaviour and the phenomena occurring in the structure under momentary high-amplitude dynamic loads must be thoroughly investigated. One should distinguish here the phenomena whose character is indicative of periodicity from the ones which occur a few times or only once (but impactively) during service life [9].

For numerical simulation, impact loads can be divided into three main groups:

- mass impacts, which greatly depend on the energy of a body with a given mass, moving with a certain velocity; also the velocity with which the body strikes the investigated structure is important;
- kinematic impacts, e.g. excitation by a displacement or imparting an initial velocity, which are important for structures exposed to tectonic movements or for vehicles subject to excitation due to surface bumpiness;
- impulse impacts — associated with the adopted model of external forces acting on a body, e.g. propagation of a shock wave produced by an explosion, often described by a mathematical model (e.g. the Dirac delta function).

The structure's resistance to impact loads can be shaped to a large extent through changes in geometric shape and through material selection. The high requirements which structures designed to carry such loads must satisfy and stimulate a search for new efficient calculation methods which would accurately map the (geometrically and physically) nonlinear phenomena in the highly complicated structure and take into account the effect of the speed of the phenomena on the way the structure deforms and on the material constants [10].

Numerical methods, particularly the finite element method, allow one to achieve the above objectives.

It is important to adopt proper evaluation criteria. In the case of structures working under static and periodically variable loads, the strength criterion is decisive. Whereas for impact loaded structures the structure's rigidity and stability (no changes in the structural configuration) is the principal criterion. Also deflections and the way in which the structure deforms are critical. The strength criterion is complementary to the principal one, but it is indispensable in the investigation of a structure's resistance to impact loads.

Mainly two methods are used to directly integrate equations of motion: an implicit method (e.g. the Wilson, Newmark, Humbold method) and an explicit method (e.g. the central difference method, two-cycle iteration with the trapezoidal rule and the Runge–Kutty method of order 4) [1,11,12]. In recent years the explicit method has been increasingly applied, particularly to nonlinear problems of dynamics, thanks to the ever higher computing power of computers.

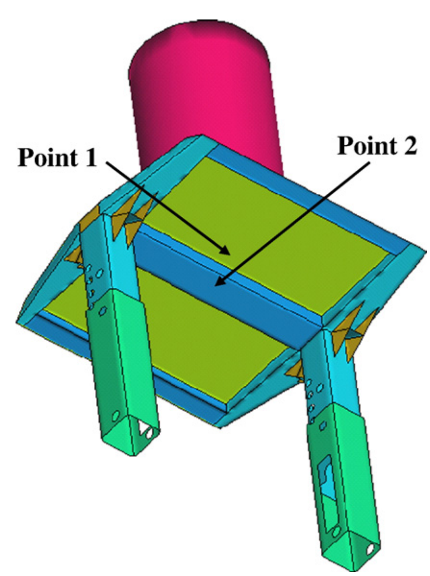

Fig. 15. Selected cabin and weight points.

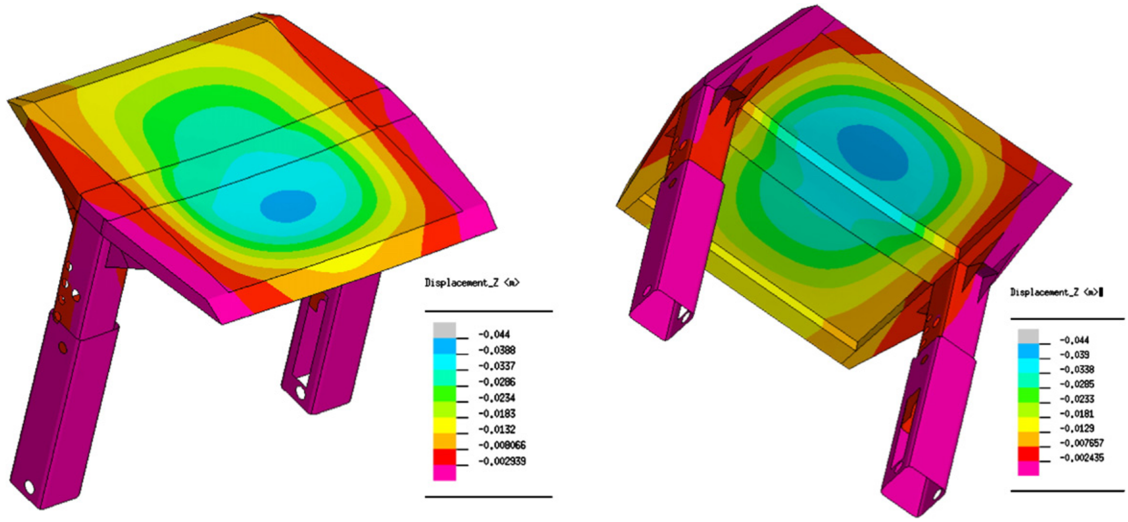

Fig. 16. Vertical displacement contour lines for maximum displacement.

Which method is selected to a large extent depends on the character of the investigated phenomenon. Depending on their rate, phenomena occurring over time can be put into three groups:

- quasi-static — processes in which forces of inertia do not play a significant role in comparison with the other internal and external forces, e.g. deep sheet metal stamping [11];
- inertial — phenomena in which the dynamic response of the structure as a whole is important and the inertial forces are significant in comparison with the other forces, but the time over which the load changes is long relative to the time of propagation of the deformation wave in the whole object;
- wave — phenomena which occur over a time comparable with the time in which the wave passes through the whole object; then one must consider the way in which propagation proceeds in the structure's material, taking into account such phenomena as wave reflection and interference.

The primary tool used nowadays for such analyses is the finite element method [12,13] which allows one to run numerical simulations of the behaviour of structures subjected to dynamic loads. A computing algorithm suitable for the kind of analysed phenomenon can be selected.

Within the finite element method one can distinguish two different types of algorithms for numerically solving equations of the dynamics of mechanical structures in the nonlinear range, i.e. implicit algorithms and explicit algorithms [14].

5. Numerical example

FEM strength calculations for a protective structure for a mining machine are presented below. A discrete model of the protective structure was built on the basis of a geometric shell model (Fig. 11). SHELL4T and SHELL3T elements from the I-DEAS library were used to construct the FEM model. These are

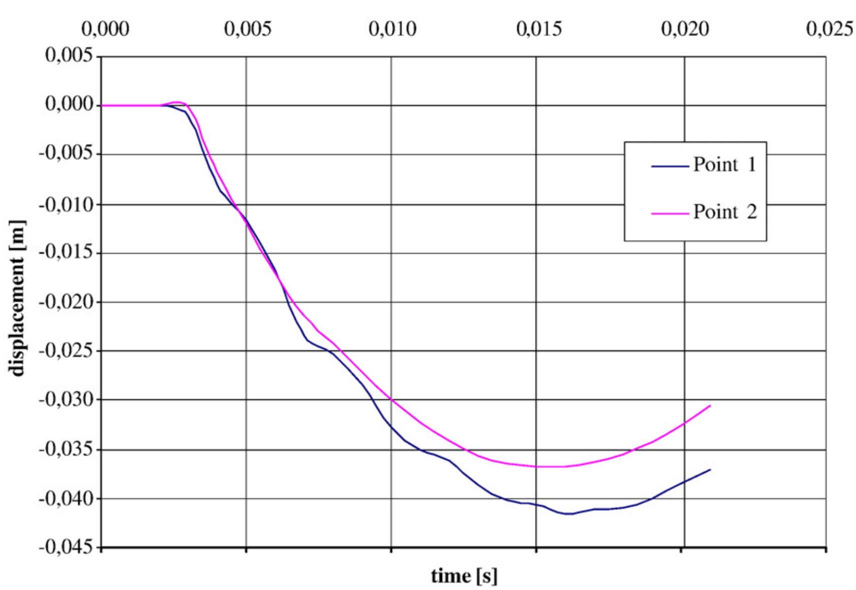

Fig. 17. Vertical displacements of points 1 and 2 over time.

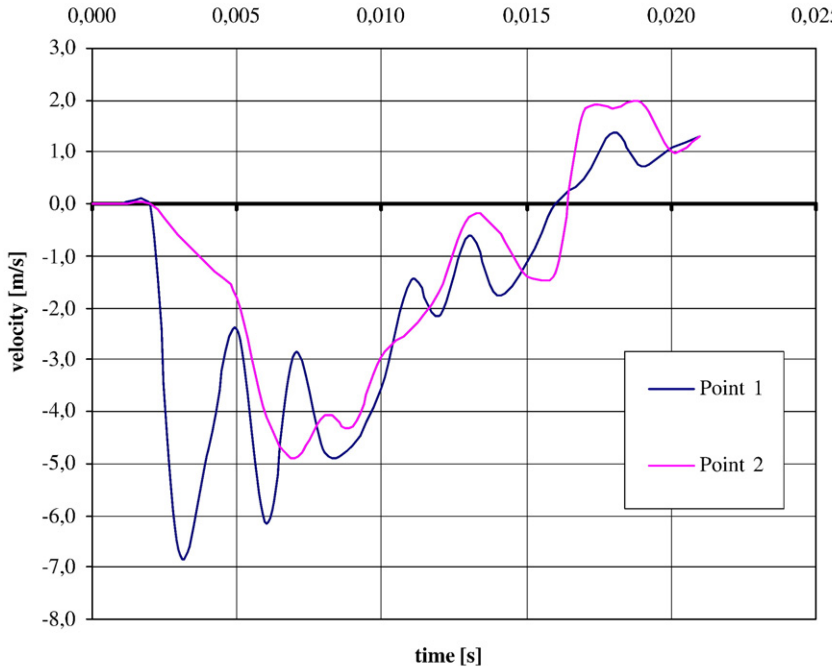

Fig. 18. Vertical velocities of points 1 and 2 over time.

quadrangular and triangular elements with respectively 4 and 3 nodes. The nodes have 6 degrees of freedom. The average size of the element side is 25 mm. The finite elements take into account thick shell theory and are suitable for computations with both geometric and material nonlinearity. An exemplary discrete model of the protective structure is shown in Fig. 12.

Both static and dynamic characteristic were used to describe the material model. Static characteristics describe the qualitative changes taking place in the material while dynamic characteristics take into account the viscosity effect which occurs in low-alloy steels under dynamic loads [6]. A general material model covering diverse phenomena would be very complicated and would require complex methods of solution. The most commonly used material models are:

- an elastic model,
- an elastic-plastic (bilinear, multilinear) model [15],
- an elastic-ideally plastic model,
- a rigid-plastic model,
- a rigid-ideally plastic model,
- material characteristics $\sigma(\varepsilon)$,
- a model based on the power law (for the plastic part) [10].

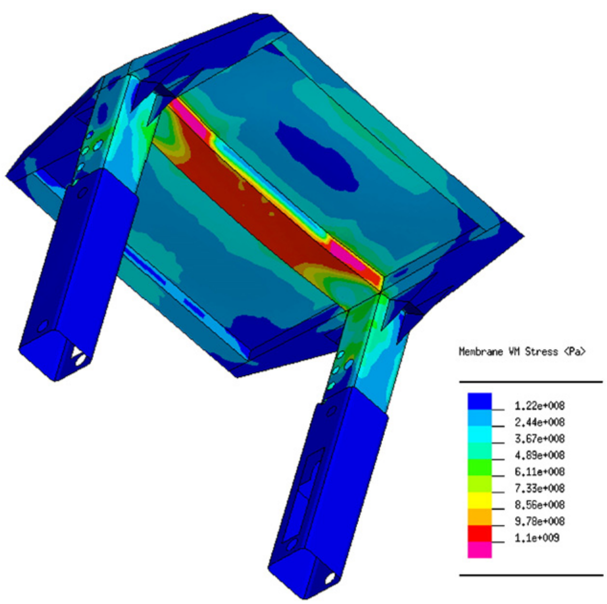

Fig. 19. Reduced stress intensity acc. to Huber–Mises theory for maximum deflection in protective structure.

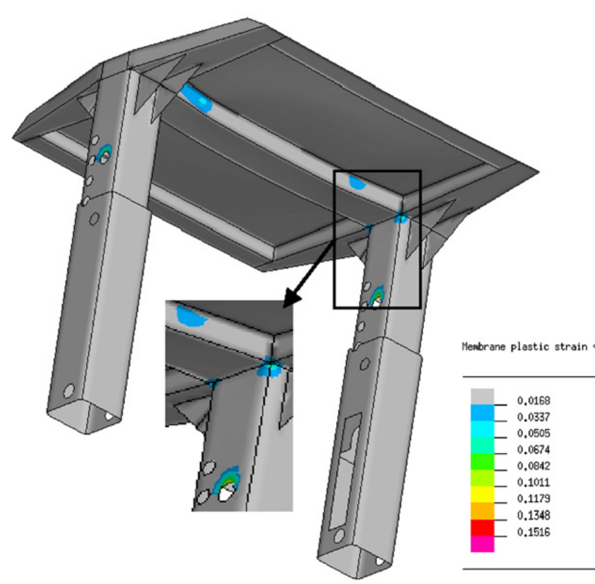

Fig. 20. Plastic strain in protective structure.

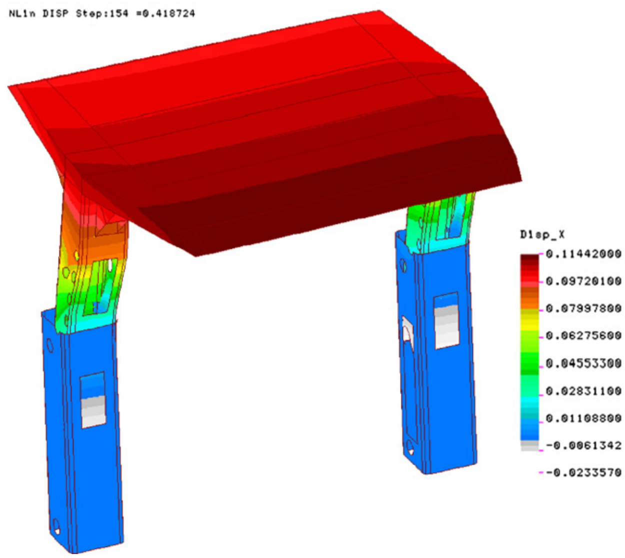

Fig. 21. Contours of horizontal displacements (conforming with loading force direction) at instant of failure (deformation scale 1:1).

A static material model characteristic based on the steel's properties was plotted. Fig. 13 shows a bilinear elastic-plastic model of the material [16].

$E = tg\alpha$ Young's modulus
$E_{TAN} = tg\beta$ A tangent modulus
$E_{TAN} = (\mathrm{Rm} - \mathrm{Re})/(A_5 - (\mathrm{Re}/A_5))$

Taking into account the quantitative changes taking place in the material, i.e. strain hardenings at the rate of deformation, models based on the assumption of material viscoplastic properties are obtained [10]. A comprehensive review of such models can be found in P. Perzyna's papers [6]. Strain hardening rate $\dot{\varepsilon}$ breaks down into elastic strain hardening rate $\dot{\varepsilon}_{el}$ and viscoelastic strain hardening rate $\dot{\varepsilon}_{vp}$

$$\dot{\varepsilon} = \dot{\varepsilon}_{el} + \dot{\varepsilon}_{vp},$$

while the stress amounts to:

$$\sigma = \frac{E}{\dot{\varepsilon} - \dot{\varepsilon}_{vp}}.$$

The finite element method employs models of strain hardening at the rate of deformation, based on the above model, such as:the Cowper–Symonds model

$$\sigma = \overline{\sigma}_0\left[1 + \left(\frac{\dot{\varepsilon}}{D}\right)^{\frac{1}{p}}\right],$$

the Johnson–Cook model

$$\sigma = \overline{\sigma}_0\left[1 + \left(\frac{1}{p}\right)\ln\left(\max\left(\frac{\dot{\varepsilon}}{D}, 1\right)\right)\right],$$

where

$\overline{\sigma}_0$ A static plastic limit,
p, D Material constants.

The Cowper–Symonds model was used for the calculations. Fig. 14 shows the influence of strain hardening on the dynamic plasticity limit.

5.1. Impact-from-above test of RSPS

The crash test was simulated using the PAM-CRASH finite element software [17]. The characteristic points for which displacement and velocity versus time were determined are shown in Fig. 15.

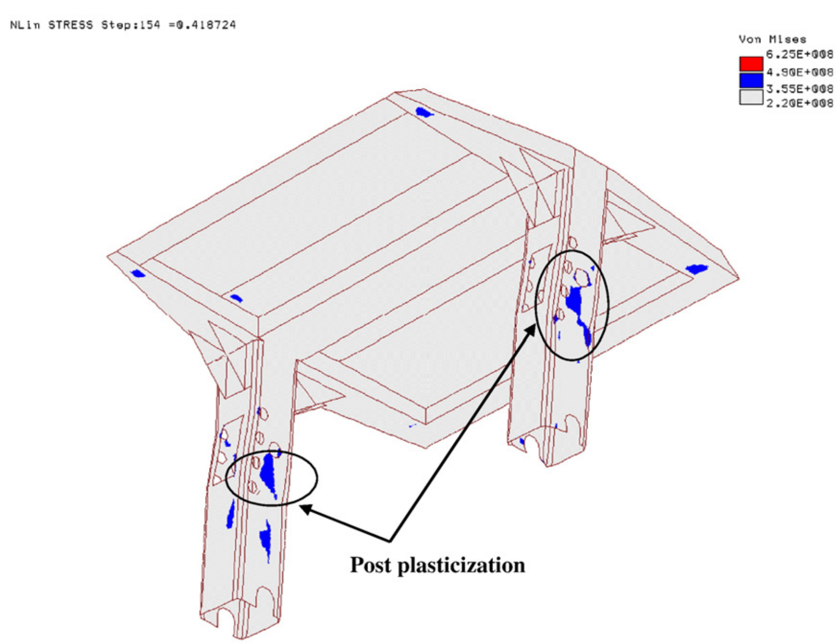

Fig. 22. Distribution of plastic zone at instant of failure (side view).

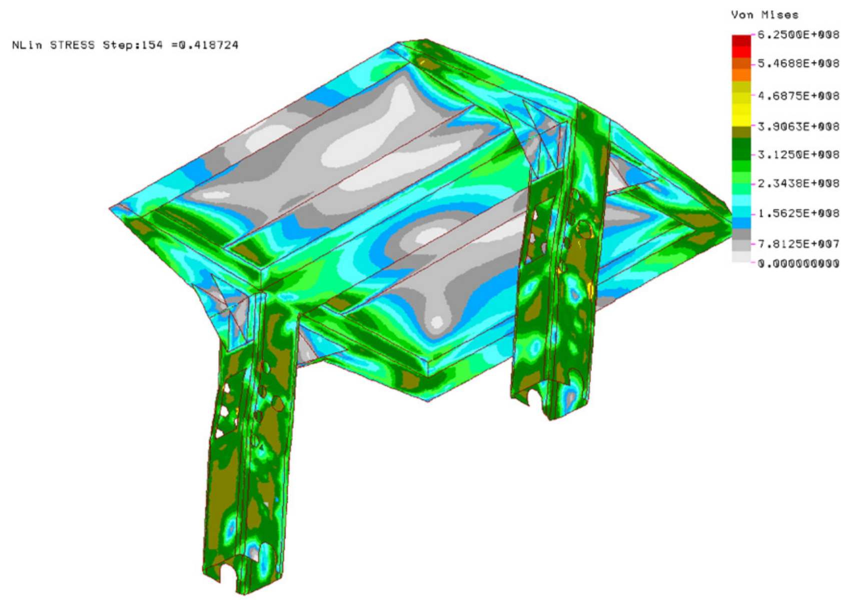

Fig. 23. Contours of reduced stress at instant of failure (bottom view).

The maximum deflection for the protective cabin occurred in the bottom part of the top plate (Fig. 16) and it amounted to: $f = 0.0483$ m.

The transfer of the weight's kinetic energy on contact with the cabin's surface (a series of events, equalization of cabin and weight velocities, conversion of the system's kinetic energy into the cabin's deformation energy) is shown in Figs. 17 and 18.

Fig. 19 shows stress intensity distribution contours for the stress reduced by the protective structure while the plastic strain areas are shown in Fig. 20.

5.2. Crushing-from-the-side test of ROPS

A crushing-from-the-side test of ROPS was carried out in accordance with the current standard PN-EN 13510:2004 'Earthmoving machines. Rollover protective structures. Requirements and laboratory tests'.

Strength computations for the protective structure were performed using the finite element based COSMOS/M software [18]. Simulations were run until the failure of the structure, taking into account the latter's geometric and material nonlinearity. A modified iterative Newton–Rapson method was used for the computations [14]. The following were calculated:

- the force–displacement relation,
- the reduced stresses for the elements in the elastic state and the stress intensities for the plasticized elements in the particular time steps,
- the cabin failure energy,
- the failure form.

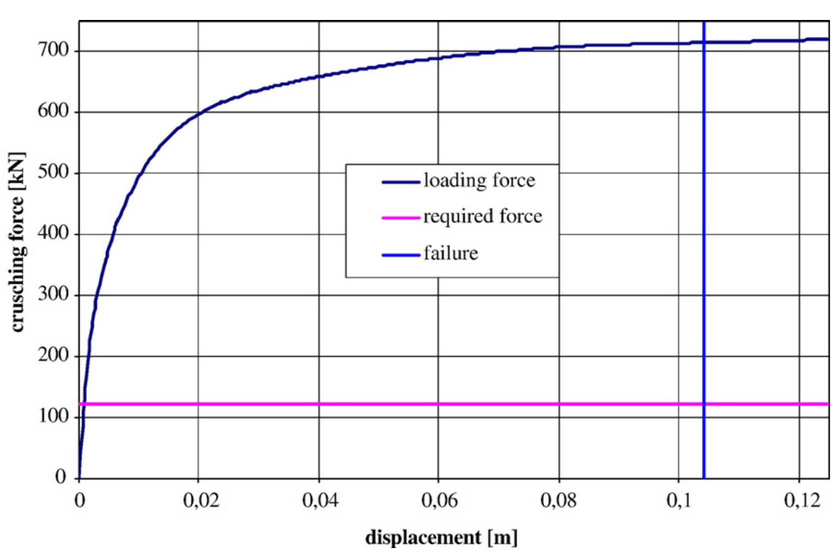

Fig 24. Transmitted crushing force versus displacement.

In the simulation the horizontal displacement process was controlled at the force application point. The protective structure was loaded from the side uninterruptedly (continuously until the requirements as to the magnitude of loading force F and energy U absorbed by the structure were satisfied). In conformance with the standard, the force was applied via a load distributing plate.

According to PN-EN 13510:2004, the required loading force and absorbed energy values are related to the machine mass:

$m = 18,000$ kg.

The minimum magnitude of loading force F is:

$F_{\min} = 60,000*(m/10,000)^{1.2} = 121.5$ kN.

The minimum absorbed energy is:

$U_{\min} = 12,500*(m/10,000)^{1.25} = 26.1$ kJ.

The deformation form and the displacements, the plastic strains and the contours of reduced stress at the instant of failure of the structure are shown in respectively Figs. 21, 22 and 23.

The transmitted crushing force versus displacement for the side loading until the failure of the protective structure is shown in Fig. 24.

6. Conclusions

Nowadays thanks to modern numerical methods it has become possible to reduce the costs of experimental research involved in the development of a structure satisfying standard requirements. Tests are only used to verify the satisfaction of the standard requirements. In this way structures which do not meet the requirements are eliminated already at the design stage.

In virtual models of protective structures simplification is limited to models of the material and its behaviour under impact loads and to the quality of the manufacturing technology.

The results of FEM calculations are always on the safe side, providing a sufficiently accurate answer to the set loading states and boundary conditions.

Conformance to standard requirements is tested already at the design stage using 3D models in virtual space and the finite element method. Such protective structure strength calculations were the basis for the design of the Boart Longyear Face Master 2.0 boring machine shown in Fig. 25. The machine's protective structure satisfies the standard requirements as to protective space preservation. It should be stressed that strength calculations by the finite element method greatly speed up the design process and reduce project costs owing to the fact that the protective structure is investigated and tested on virtual models in virtual space.

If the influence of material and geometric nonlinearities is neglected in the calculations, this may lead to erroneous conclusions concerning the load-bearing capacity of the designed structure [8,19]. Calculation methods which take into account the physical phenomena that occur during an accident yield results closer to the actual behaviour of the structure. This approach allows one to optimise the structure by reducing its mass while increasing its strength.

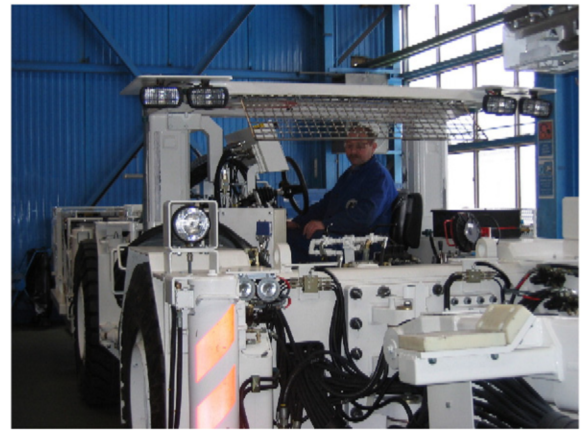

Fig 25. Boart Longyear Face Master 2.0 boring machine.

It seems that the key to the problem lies in understanding the nature of the phenomena that occur during an impact, particularly the way in which the structure deforms under the dynamic excitation. The principal factors here are excitation time and contact and wave phenomena (associated mainly with the time over which a phenomenon occurs). The standard requirements can be met through numerical simulation which allows one to verify the design assumptions during the design process and to continuously optimise the structure. Consequently, it becomes possible to design an optimum (for the given operating conditions) protective structure.

When performing a numerical analysis one should not only accurately map the protective structure's geometry, but also select a proper material model and most accurately describe its properties. In other words, the following conditions must be fulfilled:

- material properties, particularly the dynamic ones must be precisely determined,
- a proper material model (appropriate to the velocity phenomenon) must be selected,
- an effective method of solving the equations of motion [9] must be used.

All the above conditions can be fulfilled by applying the finite element method.

References

[1] Ryszard Gryboś, Stability of Structures under an Impact Load (in Polish), PWN, Warsaw, 1980.

[2] Eugeniusz Rusiński, Tadeusz Smolnicki, Jacek Karliński, Numerical simulations of nondestructive tests of Toyota car protective structure, Samoch. Spec. 2 (1998) 56–59 9 figs, 2 tabs, 10 refs.

[3] T. Wierzbicki, Calculations of Structures under Dynamic Loads (in Polish), Arkady, Warsaw, 1980.

[4] E. Rusiński, A. Kopczyński, J. Czmochowski, Tests of Thin-Walled Beams Joined by Spot Welding, Journal of Materials Processing Technology, 157–158 (2004), 405–409. Czmochowski J., Moczko P.: Analiza drgań nadwozia koparki kołowejwieloczerpakowej. Górnictwo Odkrywkowe.

[5] Eugeniusz Rusiński, Tadeusz Smolnicki, Jacek Karliński, Selected problems of modelling protective structures for impact loaded machines

(in Polish), 2nd Technical-Scientific Conference on Impact Resistance of Structures, Conf. Proc., Rynia near Warsaw, [9–11] December 1998, Warsaw, WAT, 1998, pp. 291–300, 10 figs, 8 refs, sum.
[6] P. Perzyna, Theory of Viscoplasticity (in Polish), PWN, Warsaw, 1966.
[7] A.K. Pickett, H.G. Hoeck, A. Poth, W. Schrepfer, Crashworthiness Analysis of a Full Automotive Rollover Test Using a Mixed Rigid Body and Explicit Finite Element Approach, VDI Conference, Wurzburg, 1990.
[8] S. Dobrociński, Stability of solutions to problems of the impact strength of structures (in Polish), 2nd Scientific-Technical Conference on Impact Resistance of Structures, Rynia, 1998.
[9] T. Belytschko, Survey of numerical methods and computer programs for dynamic structural analysis, Nucl. Eng. Des. 37 (1976).
[10] P. Kłosowski, Nonlinear numerical analysis and experimental investigations of elastic-viscoplastic plates and shells, Monographs, Gdańsk Polytechnic, vol. 8, 1999.
[11] A.K. Pickett, Quasi-Static Nonlinear Large Deformation Analysis Using Conventional Explicit Finite Element Methods and Dynamic Relaxation Techniques, VDI Conference on Numerical analysis in Automotive Engineering, Würzburg, 1992.
[12] E. Rusiński, J. Czmochowski, T. Smolnicki, Advanced Finite Element Method for Load-Bearing Structures (in Polish), Wrocław University of Technology Press, Wrocław, 2000.
[13] O.C. Zienkiewicz, Fourth Edition, The Finite Element Method, vol. 1, 2, London, McGraw-Hill Book Corp, 1989, 1991.
[14] M. Kleiber, Cz. Woźniak, Nonlinear Mechanics of Structure, PWN, Warsaw, 1991.
[15] Eugeniusz Rusiński, Tadeusz Smolnicki, Numerische Simultation von Schutzkonstruktionen fuer Lader (Numerical Simulation of Protective Structures for Loader), Deutsch. Hebe- u. Fordertech, Jg 39 H. ½, 1993, pp. 63–68, 12 figs, 14 refs.
[16] Eugeniusz Rusiński, Tadeusz Smolnicki, Jacek Karliński, Simulation studies of mining machine protective cabin safety (in Polish), Prz. Mech. 57 (15) (1998) 20–25 12 figs, 8 refs, sum.
[17] PAM-CRASH™ Training Guide for Technical University in Wroclaw, Plzen, (2000).
[18] E. Rusiński, System COSMOS/M Finite Element Method (in Polish), WKŁ, Warsaw, 1994.
[19] P. Diez, M. Arroyo, A. Huerta, Adaptive Analysis of Softening Solids Using a Residual-Type Error Estimator, Computational Mechanics, Barcelona, 1998.