PASSIVE SAFETY OF EARTHMOVING MACHINE OPERATORS

Bezpieczeństwo bierne operatorów maszyn do robót ziemnych

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A b s t r a c t: Falling objects and roll over earthmoving machines are a huge hazard and a major cause of accidents. Safety structures called FOPS (Falling Object Protective Structures) and ROPS (Roll Over Protective Structures) have been used to protect the operators. A FOPS and ROPS cabin should withstand the loads and consume energy during accidents. FOPS and ROPS standards require full scale destructive testing to validate its conformity with the requirements, at present. This is caused due to a lack of fundamental research information on the nonlinear inelastic response of the cabs structures. However, a non-linear, static or dynamic, finite element analysis (FEA) has been used to simulate the FOPS/ROPS testing. The FEA results have been compared with those of experimental testing and the FEA methodology has been improved to get a good correlation. The FEA approach will be used to finalize the FOPS/ROPS design prior to full scale testing to minimize the number of prototype and thereby, to reduce the development cost and time. This paper presents the FEM as sufficiently verified method for both tests, FOPS and ROPS, at the first step of the design process. The accuracy of the mapping of the object with the model adopted for the simulation has a primary impact on the convergence of calculations with test results. This applies both to its geometry, the accepted loads and to the mechanical properties of the materials used.
K e y w o r d s: FEA simulation, operator's safety, FOPS/ROPS testing

S t r e s z c z e n i e: Spadające przedmioty i przewrócenie się są ogromnym zagrożeniem i główną przyczyną wypadków maszyn do robót ziemnych. Do ochrony operatorów wykorzystano konstrukcje zabezpieczające o nazwie FOPS (Falling Object Protective Structures) i ROPS (Roll Over Protective Structures). Kabina FOPS i ROPS powinna wytrzymać obciążenia i pochłaniać energię podczas wypadku. Normy FOPS i ROPS wymagają obecnie przeprowadzenia testów niszczących obiektu rzeczywistego w celu sprawdzenia jego zgodności z wymaganiami. Jest to spowodowane brakiem podstawowych informacji badawczych na temat odkształcania konstrukcji kabin. Jednak do symulacji testów FOPS/ROPS wykorzystano nieliniową, statyczną i dynamiczną metodę elementów skończonych (FEA/FEM). Wyniki symulacji zostały porównane z wynikami badań eksperymentalnych, a metodologia FEA została ulepszona, aby uzyskać dobrą korelację. Podejście to zostanie wykorzystane do sfinalizowania projektu konstrukcji FOPS/ROPS przed pełnym testowaniem obiektu rzeczywistego, aby zminimalizować liczbę prototypów, a tym samym zmniejszyć koszty i czas prac b+r. W niniejszej pracy przedstawiono FEM jako wystarczająco zweryfikowaną metodę zarówno dla testów, FOPS, jak i ROPS, na pierwszym etapie procesu projektowania. Dokładność mapowania obiektu z modelem przyjętym do symulacji ma podstawowy wpływ na zbieżność obliczeń z wynikami badań. Dotyczy to zarówno jego geometrii, przyjętych obciążeń, jak i właściwości mechanicznych użytych materiałów.
S ł o w a k l u c z o w e: analiza MES, bezpieczeństwo operatora, badania FOPS/ROPS

Introduction

Falling objects and roll over earthmoving machines are a huge hazard and a major cause of accidents. Safety structures called FOPS (Falling Object Protective Structures) and ROPS (Roll Over Protective Structures) have been used to protect the operators. A FOPS and ROPS cabin should withstand the loads and consume energy during accidents. FOPS and ROPS standards require full scale destructive testing to validate its conformity with requirements, at present. This is caused due to lack of fundamental research information on the nonlinear inelastic response of the cabs structures. However, a non-linear, static or dynamic, finite element analysis (FEA) has been used to simulate the FOPS/ROPS testing. The FEA results have been compared with that of experimental testing and the FEA methodology has been improved to get a good correlation. The FEA approach will be used to finalize the FOPS/ROPS design prior to full scale testing to minimize the number of prototype and thereby reduces the development cost and time.

Cabs should be designed such that energy absorption occurs without reducing stiffness and strength [1]. When the cab structure element cracks, the energy is not absorbed by the permanent plastic deformation of the FOPS/ROPS components [7]. Absorbing impact or rollover energy structure is usually made as an assembly of bars, tubular frame and sheets. This is the main operator's space protection. Cabs can be equipped with suspension components to reduce vibration hazards. They have got a big influence to course of accident. At the same time, they are the most difficult element for modeling, both in the static and dynamic range.

Improving energy absorption by partially modifying FOPS/ROPS element shapes and mechanical properties is a potential best method. Andrews et al. [2] has reported that cylinder crushes in an axis symmetric mode absorb more energy than in a non-axis symmetric mode. They showed that the crush mode was dependent on the cylinder dimensions (diameter, thickness, length). Partial modeling of cab frame elements geometry was conducted by Elmarakbi et al. [4] using finite element simulations of the thin S-shaped longitudinal members with variable cross-sections made of different materials. They used the optimized members to determine the desired variables for the design of energy absorbing system to enhance vehicle safety. Kotełko [11] described the destruction and energy absorption of the compressed and bent thin plates and thin-walled 13 girders and columns on analytical and FEA way. Full geometry modeling of cab frame leaded by Haruyama [6], obtained that cab structures elements according to their thickness combination were influenced by wrinkle which can reduce energy absorption. Some modification was subjected to increased energy and avoided wrinkle. [12] and [8] modeling cab frame for roll over test according to certain model developed by specific companies and conducted FEA analysis to perform result for later loading condition.

The main aim of this work was to evaluate FEA as sufficiently verified method for both tests, FOPS and ROPS, at the first step of the design process in SBŁ-IMBiGS practice. The accuracy of the object mapping with the model adopted for the simulation has a primary impact on the convergence of calculations with the test results. This applies both to its geometry, accepted loads and to the mechanical properties of the materials used.

In the area of earthmoving machinery, the minimum requirements in this regard are laid down in the following standards:

- EN ISO 3449:2009 Earth-moving machinery - Falling-object protective structures - Laboratory tests and performance requirements
- EN ISO 3471:2009 Earth-moving machinery - Roll-over protective structures - Laboratory tests and performance requirements

These standards are harmonized with 2006/42/EC Directive - Machinery.

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RD 165 FHAD (Full Hydraulic Advanced Drive) grader prototype: the first in the graders family was the aim for manufacturer. It was achieved with the cooperation with SBŁ-IMBiGS by carry out grader components such as the main and rear frame, equipment, and integrated control system, hydraulic systems, FHAD and TIER IV Final engine cooling system.

This paper shows simulation and test validation of the graders FOPS/ROPS structure in meeting mentioned above standards requirements.

Fig. 1. RD 165 grader

FOPS test procedure

FOPS test is executed in the dynamic mode. It is made by hitting with a freefalling probe into a protection structure. The probe energy value at the impact moment

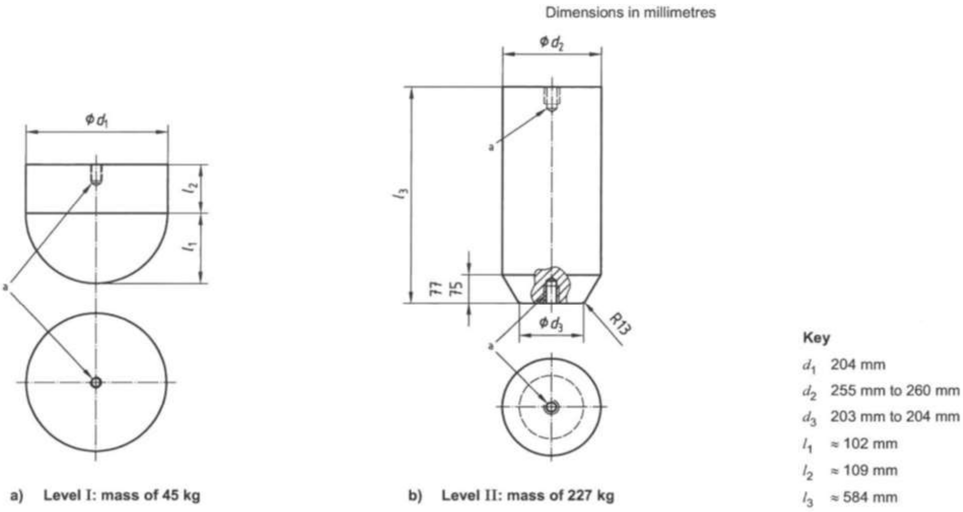


Fig. 2. Shape and dimensions of the test probes. Given values are indicative [13]

must correspond to the selected level of protection. The shape of the probe is also dependent on the energy value. PN EN ISO 3449 defines two levels of protection:

1. protection **Level** I for falling small objects such as bricks, small concrete blocks, hand tools. The energy value in this case is equal to 1 365 J.
2. protection **Level II** occurs in the case of large falling objects' hazards, such as trees, boulders, large stones, etc. The energy value is equal to 11,6 kJ.

The impact point should be closest to the center of the protection area and in the Outline DLV (Deflection Limiting Volume Fig. 4).

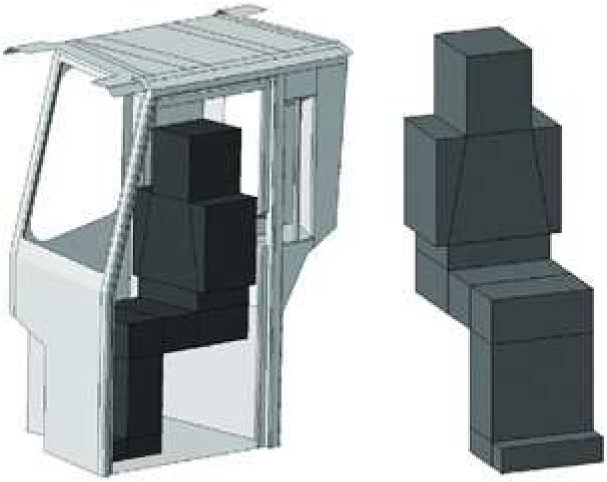


Fig. 3. DLV shape and placement in the cab [5]

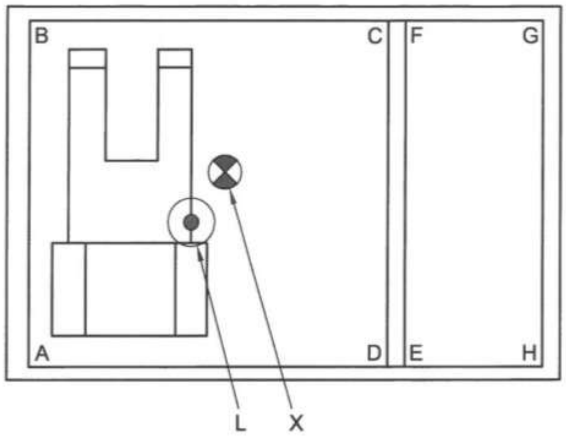


Fig. 4. The impact point placement "L" vs roof center "X" [13]

ROPS test procedure

The ROPS test involves further loading the protection structure from the side, top and along the longitudinal plane of its symmetry. During the lateral load, the deformation energy is calculated. This is the second criterion necessary to be achieved during the test, in addition to the force value.

Load values depend on the type of machine (excavator, loader, dozer, etc.) chassis (wheeled, tracked), frame (rigid, articulated). In addition, PN-EN ISO 3471 makes the value of the structure load forces and its deformation energy to be achieved dependent on the machine total weight.

The force and energy values for a grader with operating mass M [kg] shall be calculated on the basis of the following formulas shown in Tab. 3 [14].

Fig. 5. FOPS test stand example [15]

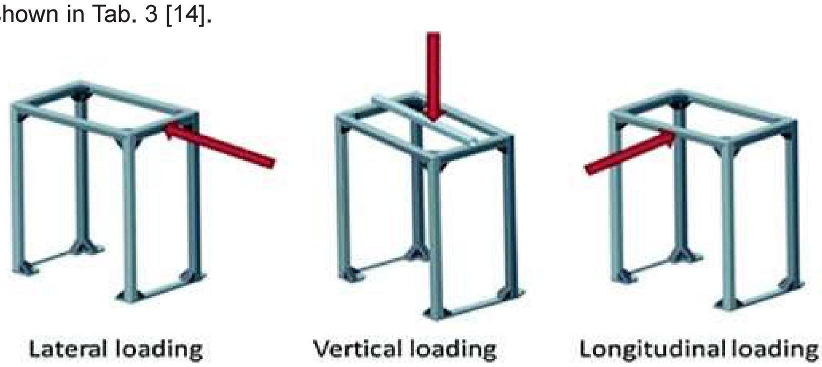


Fig. 6. ROPS tests procedure according to PN-EN ISO 3471:2009 [5]

The RD 165 Grader FOPS/ROPS Structure Testing

Input data

The basic parameters of the protection structure and the position of the seat index point (SIP) are shown in Fig. 7:

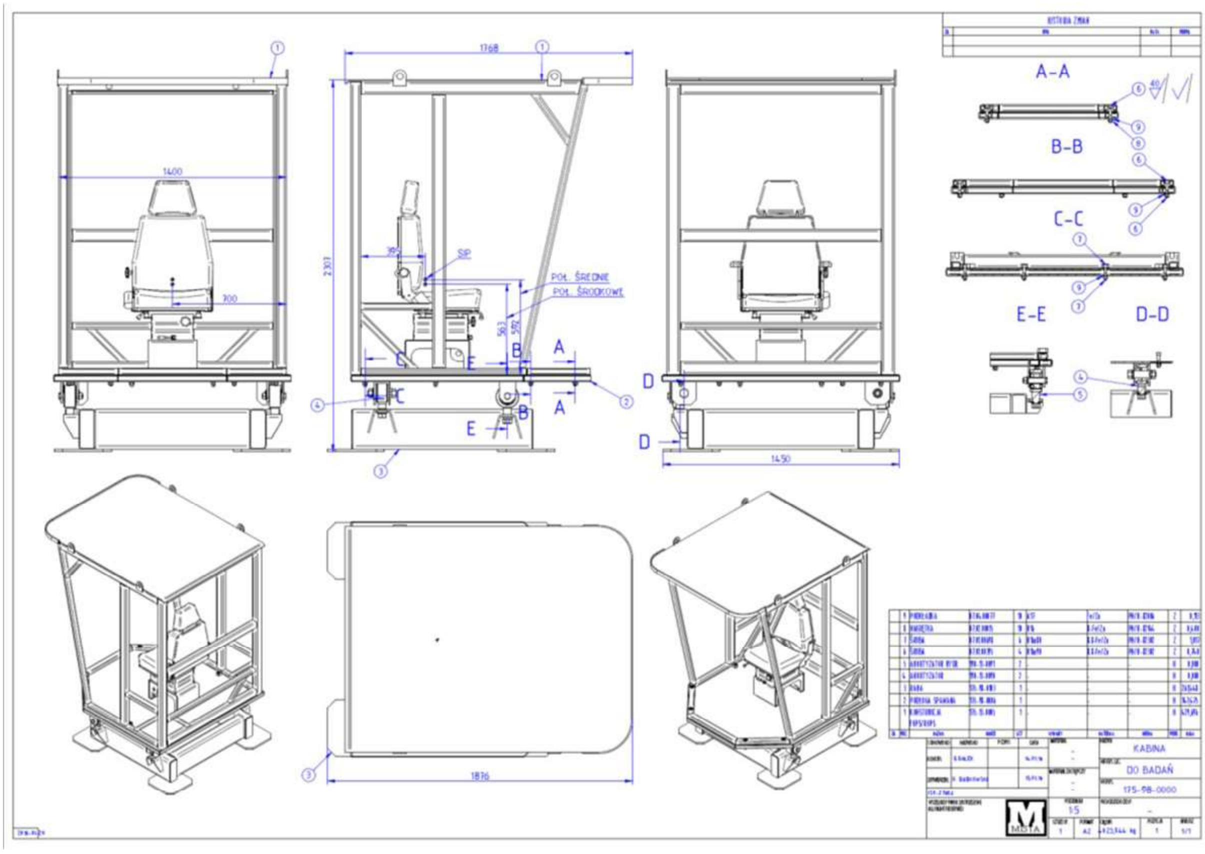


Fig. 7. FOPS/ROPS structure for RD 165 grader

Geometric model

The geometric model of the cabin (Fig. 8) is based on the design documentation (as above) provided by the manufacturer. Solid Works 2020 was used for this purpose.

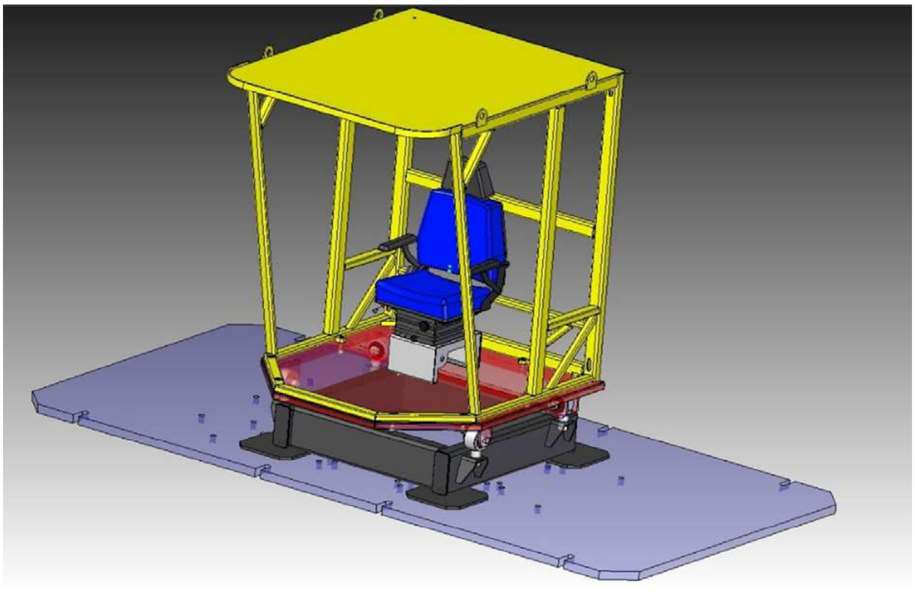


Fig. 8. RD-165 grader's FOPS/ROPS structure geometric model

Material model

The main elements of the protection structure are made of 2 mm thick steel sheet (roof, floor) and rectangular pipes of S355J2+M steel. It is a structural alloy steel, previously known as 18G2A. It is has got high strength and ductility, good workability. The S355J2+M is a steel with guaranteed weldability at an increased yield strength. It is used for the machine structure components manufacturing, mainly load-bearing structures. It is well welded, hot-rolled and cold-formed, with a minimum yield strength ReH = 390 MPa. The mechanical properties of this steel are shown in Tab. 1.

The model shown on Fig. 9 is used for simulation. This is the blinear model. Values from material approvals have been adopted.

Tab. 1. S355J2+M steel mechanical properties

Yield strength () min [MPa]	Tensile strength R_m [MPa]	Percentage elongation after breaking A_{80} Min % Sample thickness t < 3mm	Percentage elongation after break A_5 Min % Sample thicknesst <3mm
390	593	10	12

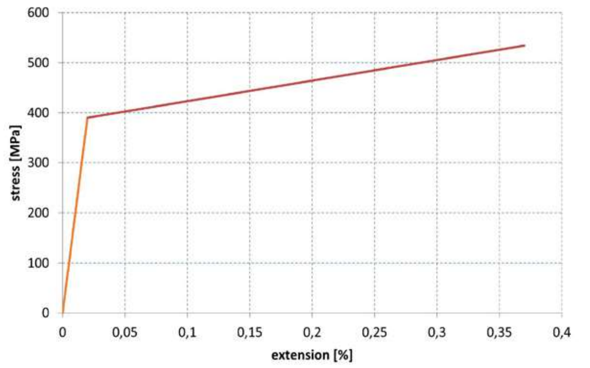
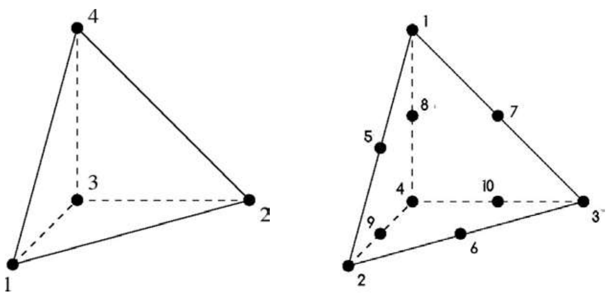


Fig. 9. S355J2+M steel stress-extension curve. Bilinear model adopted to simulation

Fig. 11. Structure mesh

Finite element model

A library tetra4 or tetra10 elements was used to model the finite element mesh. Although some of the structure elements such as roof and floor are made of sheet metal, i.e. one dimension is at least one order smaller than the other two, cab was modeled with a tetra4 elements only. It is a spatial element, a tetrahedral, with 4 or 10 nodes, having 6 degrees of freedom each – displacements and rotations relative to the three axes of the local coordinate system (Fig. 10).



a) „tetra4" element b) „tetra10" element

Fig. 10. Library "tetra" elements

Model mesh has got 175 636 elements with 52 229 nodes.

FOPS simulation

Loads

The initial speed of the test probe is due to the impact energy necessary to reach the expected protection level (Fig. 12). Thus, for level II, it is – 10 m/s. The solution time was assumed to be t=0,015 s and its value was based on data in the literature of the subject [9]. Simulation conditions should be so close to real test conditions as possible.

Fig. 12. FOPS simulation loads

Simulation results

The simulation results are presented on Fig. 13 and Fig. 14 in the graphic mode.

The calculations shown above indicate that the cab roof meets the requirements of PN EN ISO 3449:2009 in terms of II level. The DLV was not broken in any simulation time step. The appearance of an element with a stress value that is many times greater than a tensile strength value may be due to mesh imperfection (shape and size of the element). That appears only in the areas where there are mesh elements with small angles of convergence. In other areas, the stress value does not exceed R_m. However, according to this standard, the final confirmation is a positive result of the position test of the real object.

Maximum stress **3 003E6 MPa**

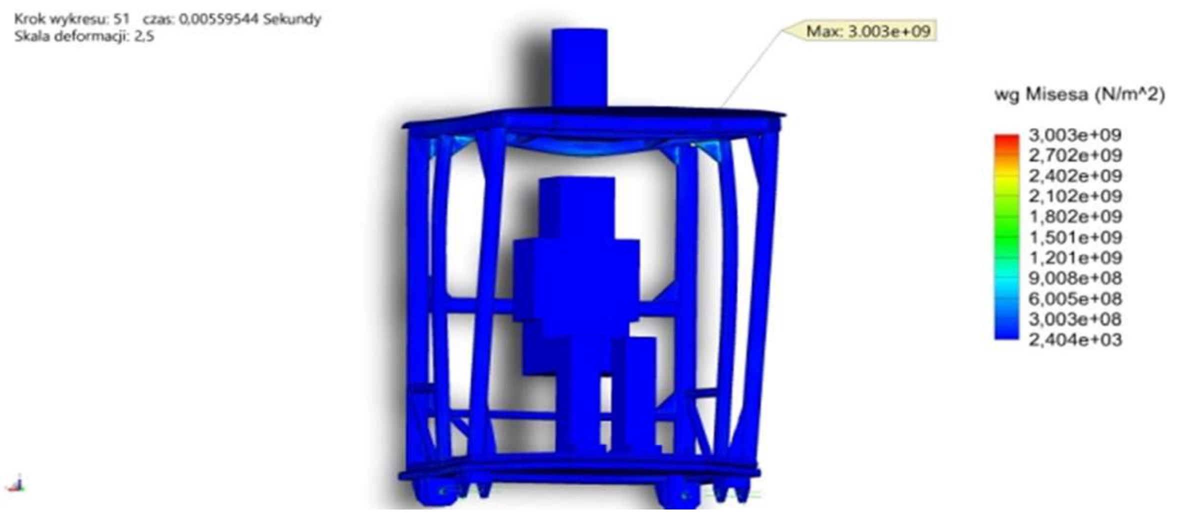


Fig. 13. von Mises stress distribution under the impact load

Maximum translation **49,61 mm**

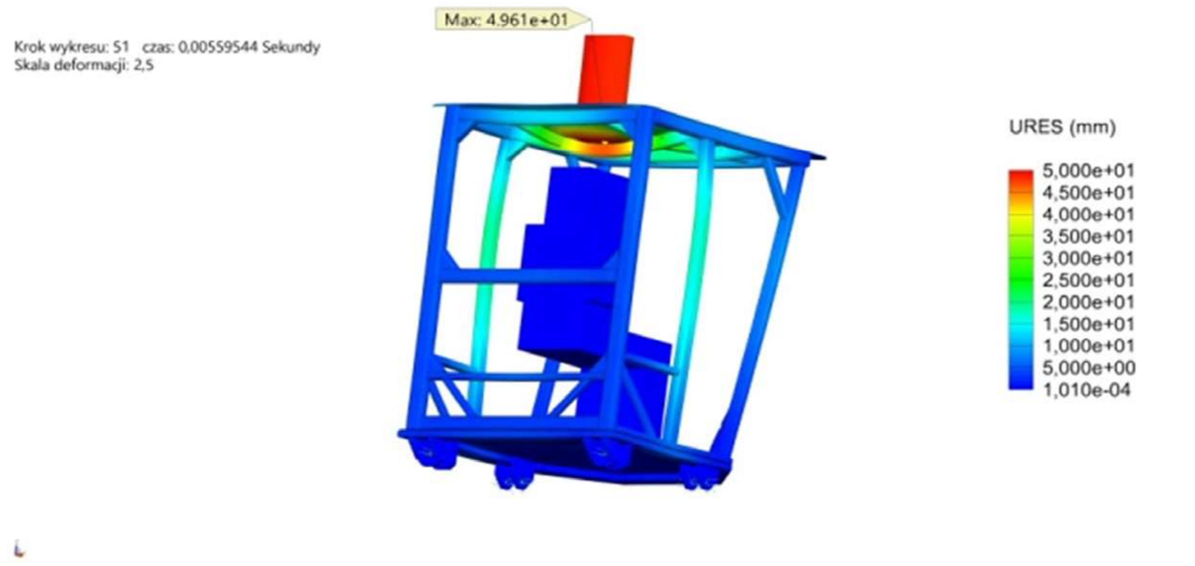


Fig. 14. Translation distribution under the impact load (scale = 2.5:1)

a)

b)

Fig. 15. FOPS structure under test procedure (a) and roof deformation after impact load (b)

Cabs testing

Simulation is verified on the base of real object test results.

A FOP testing of the protection structure for RD 165 grader was conducted in Machine and Construction Laboratory of Lukasiewicz - Institute of Mechanized Construction & Rock Mining. They were made under the conditions specified in EN ISO 3449:2009.

The maximum deformation value is amount 38 mm without braking DLV space.

FOPS conclusions

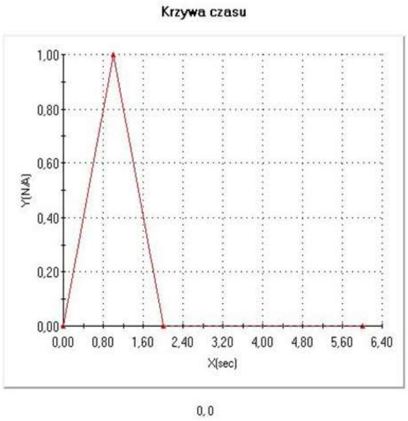
The simulation displacement values exceed test values on 11 mm i.e. 29%. It is a satisfactory factor for the initial step of the design process. Thus, the key to obtaining acceptable accuracy of the simulation is:

1. Correctly determining of the material mechanical properties, including elasticity and damping coefficients;
2. Impact time value;
3. Probe impact point on the roof structure should be so close to test condition as possible;
4. Mesh density;
5. Correctly defined structure components' contacts.

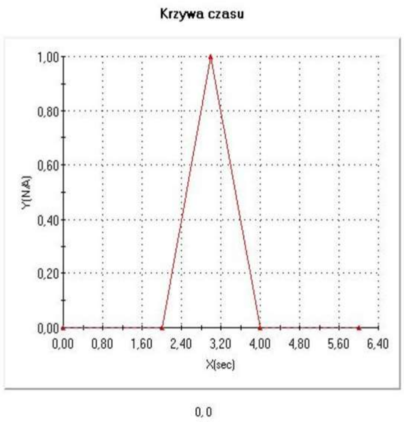
ROPS Studies

Simulation
Load model

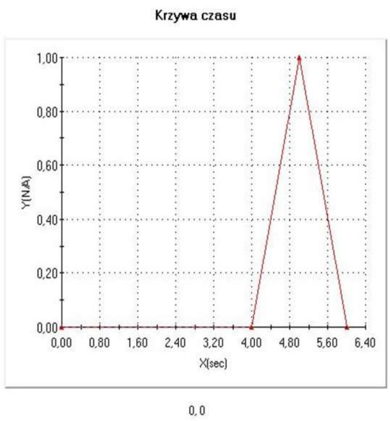
The load model of the protection structure, both in the terms of operating directions and force values, was in accordance with the methodology described in EN ISO PN 3471:2009. This is illustrated in Fig. 16. Loads, structure fixing and material properties were mapped to real conditions as close as possible.



Lateral force 134 000 N



Vertical force 353 000 N



Longitudinal force 107 000 N

Fig. 16. ROPS load force coefficients vs time and force values

Tab. 2. Test properties

Analysis	Nonlinear static analysis
Large displacement expression	On
Solver type	Large Problem Direct Sparse
Solver control	Force
Iteration method	NR (Newtona-Raphson's method)
Integration method	Newmark

Simulation results

Simulation results at after the longitudinal load were shown below in the graphic mode on Fig. 17 and Fig. 18.

Maximum stress value **461,3 MPa**

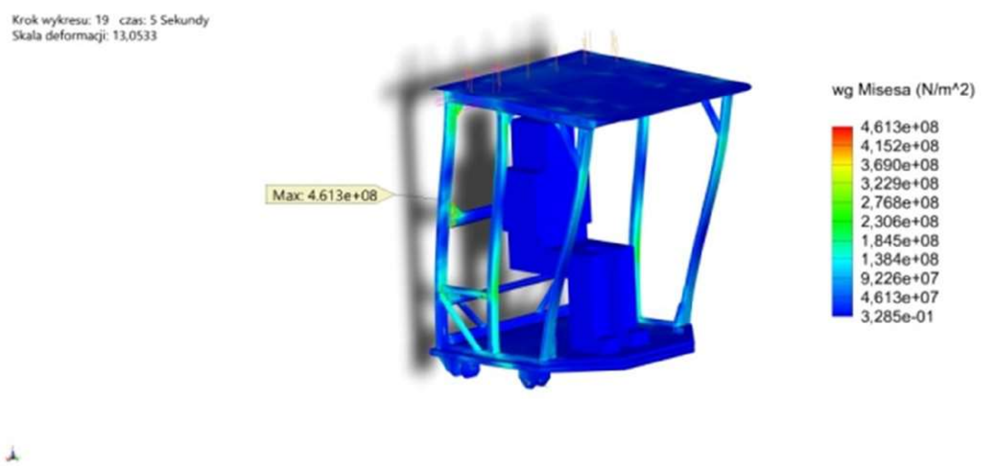


Fig. 17. Stress distribution (von Mises)

Maximum displacement **15,5 mm**

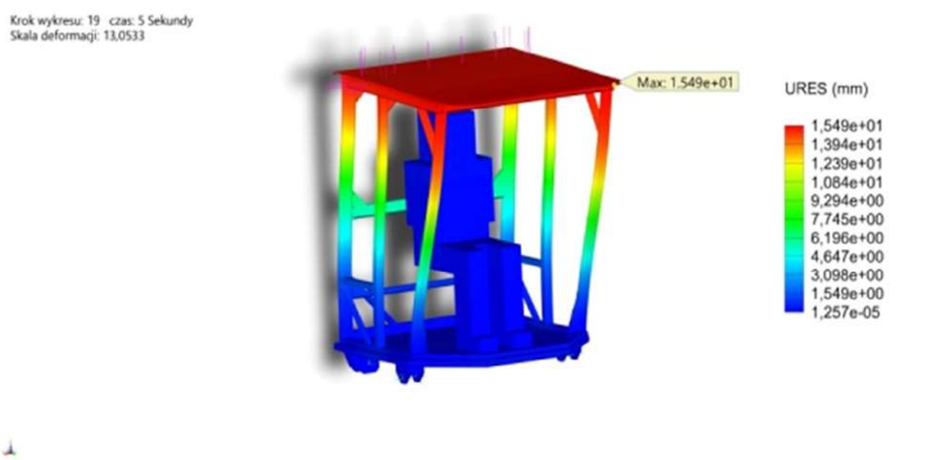


Fig. 18. Displacement distribution

Real object studies

The ROPS was tested in accordance with the procedure described in PN-EN ISO 3471:2009 p. 5 and was mapped in simulation studies.

The studies included the following tests:

- Lateran load;
- Vertical load;
- Longitudinal.

The minimum values requirements for each test are shown in Tab. 3.

Tab. 3. ROPS structure minimum values of test loads

Parameter		Formula	Value
Machine mass	M [kg]		**18 000**
Energy with lateral load	E_p [J]	$15\,000 \cdot \left(\frac{M}{10\,000}\right)^{1,25}$	**31 274**
Lateral force	F_p [N]	$70\,000 \left(\frac{M}{10\,000}\right)^{1,1}$	**140 175**
Vertical force	F_v [N]	$19.61 \cdot M$	**352 980**
Longitudinal force	F_w [N]	$56\,000 \left(\frac{M}{10\,000}\right)^{1,1}$	**106 902**

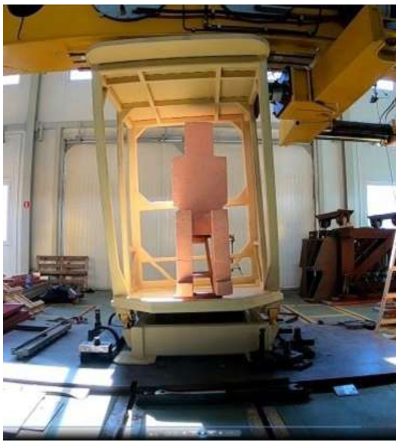


Fig. 19. ROPS structure under the lateral load

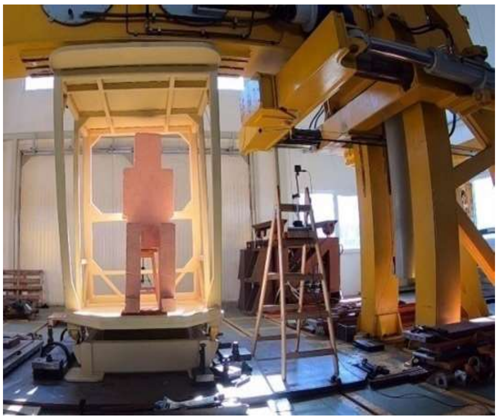


Fig. 20. ROPS structure under the vertical load

Comparison of the simulation and test results

A comparison of the results of FEA and real object studies indicates that the key to acceptable accuracy of simulation are:

1. correct determination of the values of the material mechanical properties;
2. the mapping accuracy of the load model in simulation and studies;
3. Mesh density and type of split mesh and elements contact conditions.

The discrepancy in the resulting displacement values is mainly due to differences into model and real object cab's mounting to the frame. It is actually only possible to obtain the displacement-load characteristics of susceptible components for cab cushioning on the basis of repeated destructive tests. For obvious reasons, this could not have been the case here. The purpose of the simulation was therefore to check whether the protective structure itself would fulfil its role in worse load conditions from the point of view of strength. Since, as the position studies have shown, the largest share of the resulting displacement values is deformation of shock absorbers, the simulation results should be considered valid.

Conclusions

The research of cab structure was described above to provide comprehensive explanation about phenomenon at FOPS/ROPS. Finite element analysis simulation and real object test results pointed the main conclusion of this research as:

1. The design solution adopted for the cab roof covering meets the level II requirements of EN ISO 3449:2009, in this particular case.

2. The key factor is the material properties used during the simulation process. In the studies presented above, this was a relatively simple bilinear model. It already gives an acceptable, especially at an initial stage, accuracy of calculations. For dynamic simulation, it is difficult to determine stiffness and damping coefficients for structure elements. The lack of an access to these data is an additional difficulty.
3. The third factor is the adopted suspension model. Of course, this problem does not occur in the case of a structure rigid fixing to the machine frame, as is the case, for example, in dozers and other crawler machines. It is therefore necessary to obtain strength characteristics for the elements of the sleeper pads, dumpers, etc. Manufacturers of these elements shall provide, rarely, data on dynamic load conditions. As the results of the studies have shown, they do not have a significant impact on the results of FOPS simulation studies (dynamic). Sufficient accuracy, especially at the initial design stage, due to the direction and the duration of the load, is obtained for the elastic-plastic model of the suspension element material. Probably due to longer time response than load time.
4. In assessing the advisability of computer simulations, the so-called economics of calculations are an important aspect. Increasing accuracy, especially by using a fine mesh with more elements, is associated with an increase in calculation time. This is not always advised, especially at the initial stage of designing the structure.

For these reasons, both standards do not allow FEA as a procedure for assessing the conformity of a structure with the requirements. Thus, it is always necessary to conduct the studies of the real object. From the information held by the authors, in technical committee No. 127 ISO, discussions related to the recognition of the Finite Element Method as a conformity assessment procedure have been ongoing for many years. For now, no effects have been obtained.

Simulation results tend to be approximated as compared with the lab test results. Caution will be needed when they are used in designs that pursue optimization of cost reduction and strength assurance to the required limit.

The lead time of the simulation process is proportional to the expected accuracy. 3D shell models developed data for analytic purposes creates a bottleneck. Otherwise, 2D models make worse accuracy.

Future Development

This research studies show that the FEA simulation could be acceptable method for the first step to FOPS/ROPS design. To increase the accuracy of calculations, the following work should be carried out in the future.

The different models of cabs' suspension system should be developed for dynamic mode simulation.

Static simulation (ROPS) needs more fitted stress-extension curves for more steel grades as a library data.

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References

[1] Adachi T., Tomiyama A., Araki W., Yamaji A. 2008. „Energy absorption of a thinwalled cylinder with ribs subjected to axial impact". International Journal of Impact Engineering 35(2): 65-79.
[2] Andrews K.R.F., England G.L., Ghani E. 1983. "Classification of the axial collapse of cylindrical tubes under quasi--static loading". International Journal of Mechanical Sciences 25(9-10): 687-696.
[3] Chen C., Wang Q., Zhang Y., Zhang Yan, Si J. 2012. „Effect of lateral stiffness coefficient of loader ROPS on human injury in a lateral rollover incident". Biosystems Engineering 113: 207-219.
[4] Elmarakbi A., Long Y. X., MacIntyre J. 2013. "Crash analysis and energy absorption characteristics of S-shaped longitudinal members". Thin-Walled Structures 68: 65-74.
[5] Gomathinayagam A., Antony Stephen P., Prabhakaran K., Suresh R. 2017. Simulation of Roll Over Protective Structure Testing of Earth Moving Equipment Cabin, 317-326. Conference proceedings ICoRD 2017.
[6] Haruyama S., Oktavianty O., Darmawan Z., Kyoutani T., Kaminishi K. 2016. "Study on Energy Absorption Characteristic of Cab Frame with FEM". International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering 10(3): 570-576.
[7] Jixin W., Mingyao Y., Yonghai Y. 2011. "Global Optimization of Lateral Performance for Two-Post ROPS Based on the Kriging Model and Genetic Algorithm". Journal of Mechanical Engineering 57: 760-767.
[8] Karlinski J., Ptak M., Działak P. 2013. „Simulation Test of Roll-Over Protection Structure". Civil and Mechanical Engineering 13(1): 57-63.
[9] Karliński J., Ptak M., Działak P., Rusiński E. 2016. The approach to mining safety improvement: Accident analysis of an underground machine operator, 503-512. ACME, 31.03.2016. https://www.researchgate.net/publication/301695108 [access: 24.10.2020].
[10] Karliński J., Rusiński E., Smolnicki T. 2008. "Protective structures for construction and mining machine operators". Automation in Construction 17(3): 232-244.
[11] Kotełko M. 2011. Nośność i mechanizmy zniszczenia konstrukcji cienkościennych. Warszawa: Wydawnictwa Naukowo-Techniczne.
[12] Pardeshi V. 2015. "Design of ROPS (Roll over Protective Structure) For Operator Cabin". International Journal on Future Revolution in Computer Science & Communication Engineering 1(2): 06-09.
[13] PN EN ISO 3449:2009 Maszyny do robót ziemnych - Konstrukcje chroniące przed spadającymi przedmiotami - Wymagania i badania laboratoryjne.
[14] PN EN ISO 3471:2009 Maszyny do robót ziemnych - Konstrukcje chroniące przy przewróceniu się maszyny Badania laboratoryjne i wymagania techniczne.
[15] https://www.youtube.com/watch?v=Syb_cl6fzfY (frame from the movie) [access: 24.10.2020].

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