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METHOD FOR VIRTUAL PROTOTYPING OF CABINS OF MINING MACHINES OPERATORS

METODA WIRTUALNEGO PROTOTYPOWANIA KABIN OPERATORÓW MASZYN GÓRNICZYCH

Method for virtual prototyping of cabins of mining machines operators is presented in the light of anthropotechnical assessment criteria. Anthropotechnical criteria and design of models of anthropometric features, which are used for assessment of design solutions in the aspect of safety criterion, are divided and discussed. Developed virtual prototyping method for assessment of cabin of underground locomotive operator was used. Initial simulation was made with use of Finite Element Method.

Keywords: mining industry, mining machines, protecting structures, anthropotechnical criteria, anthropometric models, virtual prototyping

W artykule przedstawiono metodę wirtualnego prototypowania kabin operatorów maszyn górniczych w świetle antropotechnicznych kryteriów oceny. Dokonano podziału i omówiono kryteria antropotechniczne. Przedstawiono definicję kryterium urazu głowy HIC (ang. *Head Injury Criterion*) oraz prawdopodobieństwo wystąpienia urazu głowy w funkcji wartości parametru HIC. Zaprezentowano budowę modeli cech antropometrycznych, dedykowanych do oceny rozwiązań konstrukcyjnych w aspekcie kryterium bezpieczeństwa wraz z opisem statycznych i dynamicznych cech antropometrycznych. Omówiono proces tworzenia wirtualnego odpowiednika manekina do testów zderzeniowych, tzw. modelu ATB (ang. *Articulated Total Body*). Podano odniesienia do norm dotyczących konstrukcji chroniących operatorów przed spadającymi przedmiotami. Przedstawiono schemat metody wirtualnego prototypowania kabin operatorów w aspekcie kryterium bezpieczeństwa. Zastosowano opracowaną metodę wirtualnego prototypowania do oceny kabiny operatora lokomotywy dołowej. Omówiono główne elementy składowe modelu obliczeniowego. Zadanie rozwiązano przy użyciu metody elementów skończonych. Przedstawiono wstępne wyniki symulacji, tj. obliczono parametr HIC dla zadanych warunków brzegowych. W podsumowaniu zaprezentowano główne cele wirtualnego prototypowania kabin operatorów dla kryterium bezpieczeństwa. Zwrócono uwagę na uniwersalność zastosowanej metody.

Słowa kluczowe: górnictwo, maszyny górnicze, konstrukcje ochronne, kryteria antropotechniczne, modele antropometryczne, wirtualne prototypowanie

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1. Introduction

Many technical means used in the mining industry require the presence of man (operator). In the case of open pit mining industry, these are the machines such as excavators, loaders, dump trucks and bulldozers. In the case of underground mining industry, these are roadheaders, loaders, self-propelled vehicles, as well as underground railway, suspended monorail and floor-mounted railway. The operators of mining machines are exposed to many hazards. Exceeding permissible values of overloads acting on operator is one of these hazards. This can be the result of such incidents as emergency braking of floor-mounted railway or suspended monorail, collisions with an obstacle or another mean of transportation, derailment, fall of rock parts or other objects causing high impact energy. Some hazards can have no symptoms of emergency conditions, but they are entered in mine operational cycle, e.g. machinery system excavator – dump truck. Impact loads associated with falling of large parts of rocks appear during loading the dump truck with buckets of load-bearing capacity up to 120 [t], at the moment of emptying the bucket (Czaplicki, 2006).

Teams designing the mining machines and equipment are obliged to improve continuously the life and reliability of the machines ensuring minimum level of work safety to people who use them. Use, at the designing stage, the methods and tools enabling assessment of future technical mean, including the method for creation of virtual prototypes, is one of the methods for reaching this objective (Winkler & Tokarczyk, 2007). In the case of mining machines, which are manufactured in short series or as single copies, it is especially important and associated with a diversity of future users' requirements. Virtual prototyping is known and has been used for many years and it has many definitions. A definition formulated by Wang is considered as the most complete one (Wang, 2002). Use of virtual prototyping methods on one hand enables effective reduction of the probability of design errors and on the other hand enables assessment of machines prototypes in the light of anthropotechnical criteria using the hardware and software possibilities. Extended criterial models, including both computational models of technical mean and proper models of anthropometric features, are used for that purpose (Winkler, 2001).

2. Criteria for assessment of virtual prototype

Assessment criteria are the basis for verification of virtual prototype. They determine both requirements and limitations (Dietrych, 1985). Two main groups of criteria for assessment of virtual prototype can be distinguished, Fig. 1 – technical and anthropotechnical criteria.

Technical criteria refer only to assessment of technical mean. They enable to assess its features such as: functionality, strength, reliability. Anthropotechnical criteria result from the presence of man inside the machine or equipment. In this group, detailed criteria can be distinguished, i.e.:

- ergonomic criteria:
  - ranges of limbs – identification of range zones and comfort zones, including necessity of work in awkward body postures,
  - field of vision,
  - loads in musculo-skeletal system – ability of exerting the forces and torques by the limbs;
- safety criteria – protection against mechanical hazards:
  - collision,
  - stability,
  - Head Injury Criterion (HIC);

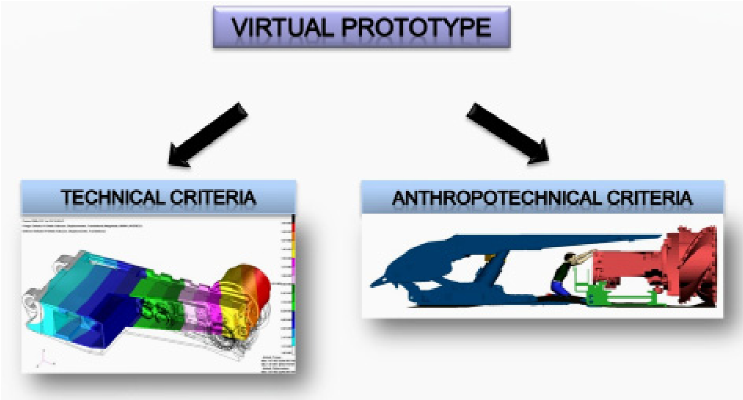


Fig. 1. Main groups of criteria for assessment of virtual prototype of mining machine (Tokarczyk, 2012)

- other criteria (selected):
  - noise,
  - vibration,
  - risk of slippage, stumble, fall,
  - proper lighting – lack of shaded areas, glares and strobe effect.

Moreover, basic rules of so-called complex safety are included in the Machinery Directive (Directive, 2006). They say that elimination and minimization of risk associated with use of machine should be done at the stage of its designing, according to assumed assessment criteria.

HIC enables to asses, in a quantitative way, the risk of head injury knowing time and deceleration at collision of head with an obstacle. It is expressed by the following formula (1) (NHTSA, 1972):

$$HIC = \left[\frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} a(t)\,dt \right]^{2,5} (t_2 - t_1) \tag{1}$$

where:

a — linear acceleration (deceleration) of head centre of gravity [g],

t_1, t_2 — time of starting/ending the contact of head with an obstacle or time interval in which the HIC value is maximum.

Value of HIC parameter above 1000 causes significant increase of probability of head injury, Fig. 2.

Moreover, it is possible to determine the impact of HIC parameter on the heaviness of injuries with use of so-called Abbreviated Injury Scale (AIS) (Prasad & Mertz, 1985). For example, when HIC parameter reaches 1000 it means:

- 18% probability of serious head injury (AIS4),
- 55% probability of moderate head injury (AIS3),
- 90% probability of slight head injury (AIS2).

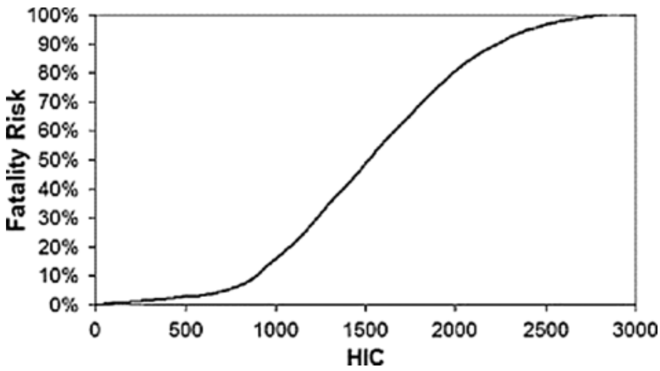


Fig. 2. Probability of head injury in a function of HIC parameter (Yoshida et al., 1999)

The scale refers to adults.

In the process of virtual prototyping, the hazards and criteria for their assessment are recreated during creation of computational models in a form of initial and boundary conditions, models of materials and the results obtained from simulation. The following numerical methods (detailed methods) are used in that case:

- Computer Aided Design (CAD),
- Multi-Body System (MBS) – analysis of kinematics and dynamics of multi-body systems,
- Finite Element Method (FEM),
- Human Body Modelling (HBM).

3. Models of anthropometric features in the light of safety criterion

Anthropometric features enable to describe human silhouette in both standing position and a position depending on current activity (Wykowska, 1994). These features are of static and dynamic character. To determine static anthropometric features it is required to take measurements for non-moving, standing or sitting silhouette of among others:

- heights for determination of distance between anthropometric points and a reference plane,
- length (of each body segment),
- width and depth,
- perimeter, of e.g. head,
- diameters of handles grip.

To determine dynamic features the following angles are measured:

- deflection of upper and lower limbs (whole limbs and their parts): downwards, upwards, to the left and to the right,
- deflection and turn of head,
- turn of limbs and their parts,
- deflection of hand clenched on cylindrical handle.

Values of anthropometric features are within a certain range for a given population, being the subject of normal Gaussian distribution, from which percentile values equal to 5, 50 and 95 percentile are isolated. Models of anthropometric features are created for these values. For ergonomic analyses the models of anthropometric features have a layer structure with the following information:

– external anthropometric features as well as clothes and equipment,
– skeletal system,
– kinematic chains.

They enable to determine the employee field of vision at the workplace and comfort and range areas (zones). Comfort zone is calculated on the basis of so-called normal range determined during rotation of forearm around the elbow joint, when limiting by horizontal planes are at the height of elbows and shoulders. Range zone is calculated on the basis of the zone determined by the centre of the palm of straight upper limb and the centre of rotation in the shoulder joint (Gedliczka, 2001).

Creation of models of anthropometric features is associated with assessment of safety in man – machine – environment relationships. There are the following two main types of models of human silhouettes for the purposes of safety assessment (Winkler et al., 2013):

– crash test dummies (Anthropomorphic Test Devices ATD) – real dummies made in 1:1 scale, developed to determine probability of injuries and behaviour of human body during dynamic forcing. They are used in automotive industry for assessment of the safety of driver, passengers and pedestrians, as well as in aeronautics and arms industry. Assessment of safety is made on the basis of values of longitudinal overloads, deflections and forces determined by the sensors installed in the model of head and in other body segments. This model is used for assessment of results of frontal, side and rear impacts. Dummy of Hybrid III type is presented in Fig. 3.
– virtual representatives of dummies for Articulated Total Body (ATB) crash tests – in their version V they correspond to real ATD dummies of Hybrid III type. These models, depending on version and purpose of their use, are designed basing on Multi-Body System (MBS) numerical methods and Finite Element Method (FEM), which enable defining the boundary conditions and "printout" of results enabling estimation of risk of body injury.

4. ATB models

ATB model representing ATD dummy of Hybrid III type consists of 17 segments combined with each other by 16 articulated joints of different degrees of freedom, representing each joint – Fig. 4. Segments and joints create kinematic chains.

Each segment is formed by an ellipsoid and determined by such parameters as weight, coordinates of the centre of gravity (it often is not on the axes of symmetry of the ellipsoid) and mass moments of inertia. The ellipsoids define contact planes for ATB model.

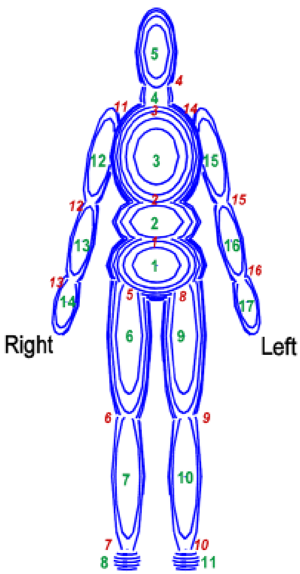
Creation of ATB model consists of the following stages:

– GEBOD software programme (Cheng et al., 1998) – creation of mathematical model on the basis of physical properties of segments and constrains for persons of different weight, height and age,
– entering input data describing the movement of vehicle during hit, turning, etc. – so-called crash pulse,

a)

b)

Fig. 3. Hybrid III dummy used for assessment of results of dynamic overloads: general view (a), parts of head model (b) (Humanetics, 2013)



I	SEGMENT NAME	SYMBOL		J	JOINT NAME	SYMBOL	JNT(J)	CONNECTS SEGMENTS
1	Lower Torso	LT		1	Pelvis	P	1	1 - 2
2	Center Torso	CT		2	Waist	W	2	2 - 3
3	Upper Torso	UT		3	Neck Pivot	NP	3	3 - 4
4	Neck	N		4	Head Pivot	HP	4	4 - 5
5	Head	H		5	Right Hip	RH	1	1 - 6
6	Right Upper Leg	RUL		6	Right Knee	RK	6	6 - 7
7	Right Lower Leg	RLL		7	Right Ankle	RA	7	7 - 8
8	Right Foot	RF		8	Left Hip	LH	1	1 - 9
9	Left Upper Leg	LUL		9	Left Knee	LK	9	9 - 10
10	Left Lower Leg	LLL		10	Left Ankle	LA	10	10 - 11
11	Left Foot	LF		11	Right Shoulder	RS	3	3 - 12
12	Right Upper Arm	RUA		12	Right Elbow	RE	12	12 - 13
13	Right Lower Arm	RLA		13	Right Wrist	RW	13	13 - 14
14	Right Hand	RH		14	Left Shoulder	LS	3	3 - 15
15	Left Upper Arm	LUA		15	Left Elbow	LE	15	15 - 16
16	Left Lower Arm	LLA		16	Left Wrist	LW	16	16 - 17
17	Left Hand	LH						

Fig. 4. Structure of ATB model in version V (Cheng et al., 1998)

– defining the models of contacts associated with potential collision (e.g. interior of operator's cabin), seat belts and airbags,
– FEM pre-processor (Patran, 2012) – is used to create a mesh of finite elements corresponding to a given anthropometric model with a possibility of putting the segments against each other, Fig. 5. It is possible to hide the ellipsoids: only flat finite elements, which are assigned and moving with motion of a given ellipsoid, are visible. Contact is detected between ellipsoid and obstacle.

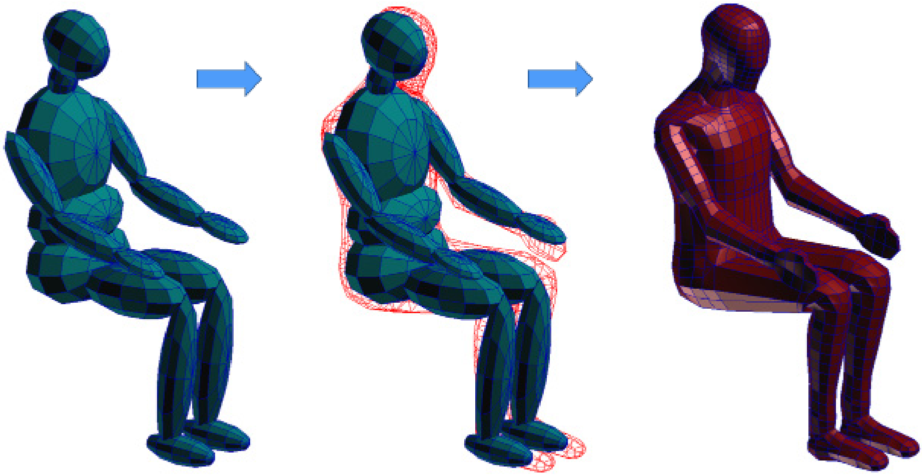


Fig. 5. Types of views computational model of Hybrid III dummy (Patran, 2012)

ATB models are used in simulations of dynamic character, due to what obtained results change in time and include, among others: linear and angular position of each segment, velocities, accelerations, forces and torques in joints acting on anthropometric model (e.g. forces resulting from the contact between a given segment and an obstacle).

Results, which enable assessment of results of dynamic overloads affecting human, are obtained basing on simulation with use of ATB models. Injuries of head, cervical spine, chest or other injuries that have no direct impact on loss of life, e.g. potential damages of joints or breaks of lower limbs, are such results (Cichos et al., 2005).

5. Assessment of design solutions of operators′ cabins in the light of safety criterion

Operators' cabins are one of applications of ATB models for assessment of safety of mining machines. These cabins should ensure enough safety of the persons, which are in the cabins. In the case of self-propelled machines it results from the fact that these vehicles can be in areas, where there are for example falling rocks. Analysis of design solutions of cabins of operators of different means of mine transportation, e.g. railway or floor-mounted railway, shows that many of them also meet the requirements for impact energy equal to 11.6 [kJ]. It means that deformation of cabin during impact load cannot cause injury to the operator and the cabin does not collapse. Operators' cabins are also assessed in the light of ergonomic criteria (Michalak, 2013).

The cabins, which ensure protection of the operator, are divided into the following groups:

– Falling Object Protective Structures (FOPSs):
  - level I – structure protects against falls of impact energy not exceeding 1365 [J], what corresponds to impacts of bricks, small parts of rocks or hand tools,
  - level II – structure ensures protection against impacts of energy of up to 11600 [J], protects against collapsing trees or medium-size parts of rocks,

– Rock Slide Protective Structures (RSPSs) – protect against impacts of energy of at least 60 [kJ]. This value corresponds to fall of large parts of rocks,
– Roll Over Protective Structures (ROPSs) – protect especially during machine rollover,
– Tip Over Protective Structures (TOPSs) – are of structure equivalent to ROPS and dedicated to smaller, so-called compact excavators.

In the case of FOPS detailed requirements are included in the following standards:
– PN-EN ISO 3449:2009 Standard (PN-EN ISO 3449:2009, 2009) – presents correlation of height of weight suspension in function of its mass, shapes of the weights for impact energy of I and II level as well as it describes the method of destruction test, i.e. selection of hitting point, structure attachment and the criteria of assessment of the material used to manufacture FOPS,
– PN-EN ISO 3164 Standard (PN-EN ISO 3164:2009, 2009) – describes geometric features of deflection limiting volume (DLV), i.e. rectangular approximation of 95-centile operator wearing protective clothes and helmet together with coordinates of Seat Index Point (SIP),
– PN-EN ISO 3411:2007 Standard (PN-EN ISO 3411:2007, 2007) – includes anthropometric dimensions of the operators in three groups: small, medium, tall. Dimensions are given for sitting and standing positions. Dimensions of minimal space around the operator are also given in the standard. Those dimensions were given in relation to SIP,
– PE-EN ISO 5353:2011 Standard (PN-EN ISO 5353:2011, 2011) – presents the method for determination of coordinates of SIP, which is in the seat symmetry plane.

On the basis of literature survey of methods for destructive tests of FOPS on testing facilities (Kalita, 2013) as well as on the basis of results from simulation of FOPS by finite elements method (Kaneda & Tamagawa, 2003; Karliński et al., 2007; Karliński et. al., 2008) it has been found that impact of rigidity of vehicle suspension can be neglected in assessment of results of impact load. In the standard (PN-EN ISO 3449:2009, 2009) it is recommended that the vehicle protective structure is installed on the vehicle frame, however, from the protective structure assessment point of view it is only improvement of protective condition in the result of yielding the structure support. However, to carry out comprehensive assessment of the results of impact load, it is required to extend the calculation model of FOPS design by values of rigidity and amortization of vehicle suspension and seat suspension as well as to use the models of anthropometric features of ATB type. In Fig. 6 the author's method of virtual prototyping of operators cabins in the aspect of safety is presented. So-called generator of calculation models of operators' cabins for safety criterion is its integral part. Automation of building the calculation model of operators' cabins for safety criterion i.e. preparation of input files for the calculation model is the main task of generator.

6. Example of using the method of virtual prototyping of operator′s cabins in the aspect of safety criterion

On the basis of geometric model of the operator's cabin of underground locomotive, a finite elements meshing was developed. The meshing contains elements of the cabin interior, including the operator's seat, Fig. 7.

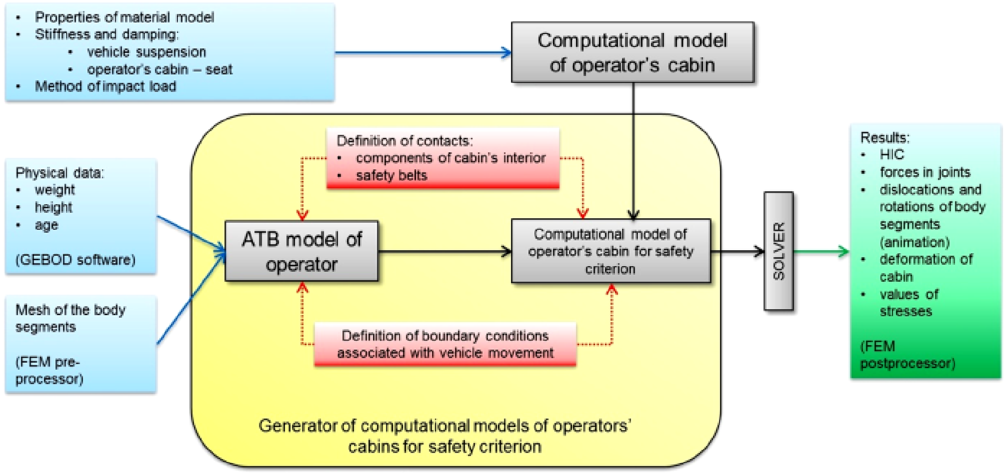


Fig. 6. Method of virtual prototyping of operators cabins in the aspect of safety criterion

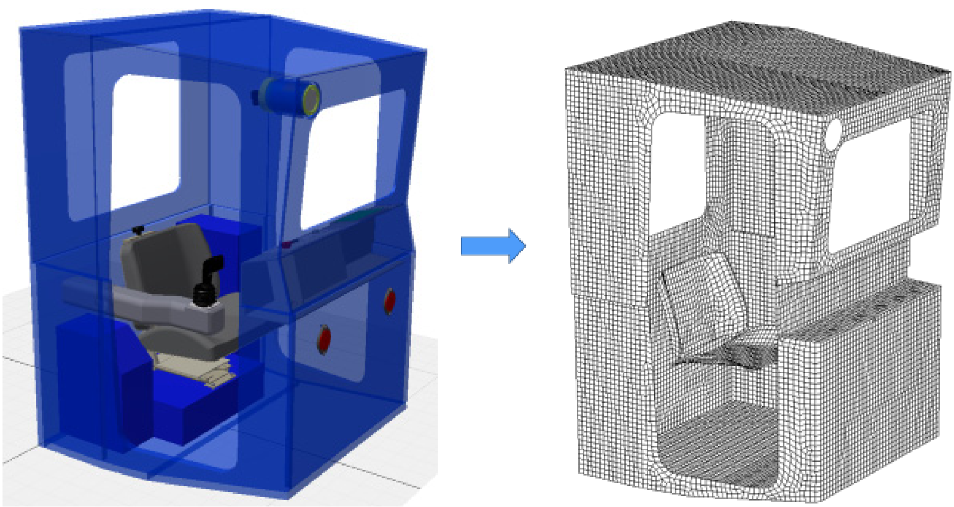


Fig. 7. 2D mesh of the calculation model of operator's cabin based on CAD model

The following information was additionally defined in the calculation model:
- elastic-and-plastic model of the material without strengthening,
- sheets thickness,
- rigid connection of the seat with cabin,
- stiffness and damping referring the locomotive suspension,
- impact load of energy 11.6 [kJ]: non-deformable weight of mass 520 [kg] impacts the upper sheathing of the cabin (above the operator's head) with initial velocity 6.67 [m/s],
- action of gravitation force.

The cabin calculation model was extended by virtual model ATB of Hybrid III type dummy in a sitting position, Fig. 8. Contact models between ATB model and cabin interior and the seat was defined.

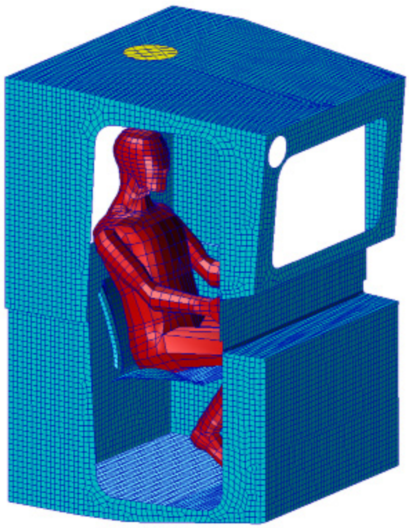


Fig. 8. Example of the calculation model of operator's cabins in the aspect of safety criterion

The simulation results indicate for decrease in plastic deformation of the operator's cabin in relation to the variant, where the cabin is rigidly supported. In the case of yielding suspension, there is an instantaneous deformation of the cabin in according to a direction of weight impact (downwards). As the process is dynamic (duration of simulation from the moment of impact, stop of cabin and its return to an initial position is below 0,2 [s]), there is a momentary "levitation" of ATB model, which does not deform with the speed equal to a speed of the cabin. After absorption of the impact energy, i.e. after stopping the cabin, it starts to move with the opposite sense. In the case, where the seat has not suspension in relation to the cabin (rigid connection is often used in mine vehicles), the seat hits the operator. Calculation results, i.e. (a) dislocation of ATB model (initial position – blue colour, end position – black colour, hidden lines are not visible) and (b) HIC parameter, are given in Fig. 9.

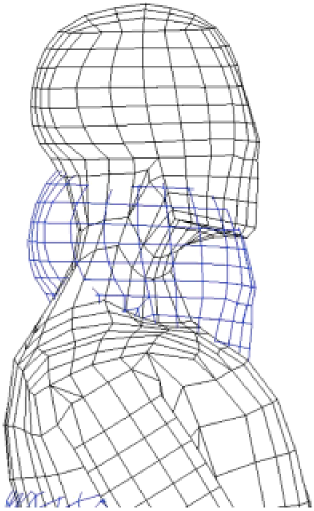
The results show that in the discussed example, the risk of heavy head injury is small, but "medium" and "light" head injuries can appear.

7. Conclusions

There are the following objectives of virtual prototyping as regards safety criterion:

– improvement of safety of machines users i.e. operators and transported people,
– identification and elimination of those components of the cabin equipment that increase a risk of injury,
– development of assumptions and guidelines for minimization of risk of head injury.

a)



b)

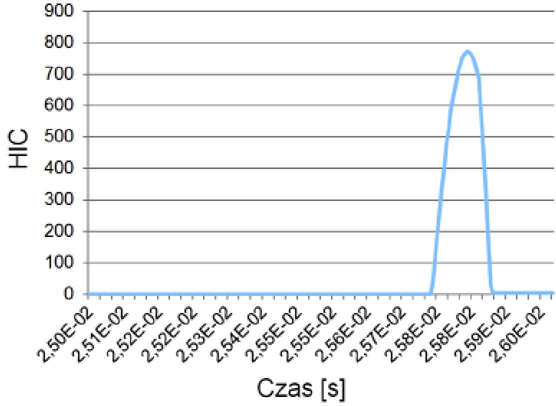


Fig. 9. Calculation results: (a) displacement of ATB model (b) HIC parameter

Assessment of particular design of operator's cabin of underground mine locomotive is the simulation objective. The cabins are not covered by the requirements of cited standards concerning the protective structures. The given example indicates that analysis of simulation results of impact load with use ATB models should include not only potential violation of DLV, but also an assessment of parameters concerning probability of operator injury.

Rigid support of operator's cabin causes that the structure absorbs all impact energy and it is not possible to assess all effects of impact energy such as hit to any interior element in a result of non-stable displacement of ATB model or overload caused by vibration of the cabin and seat.

The suggested method of virtual prototyping of the operators' cabins considering the safety criterion enables automating the process of creation of calculation models of operators' cabins. Scope of the method covers a process of designing the cabins for operators, which are at the same time the protective structures as well as the cabins, which are not assessed for such requirements. The method enables calculating the probability of injuries being the result of dynamic loads caused both by underground mine transportation means such as suspended monorails, floor-mounted railway, regular mine railway as well as by vertical transport. Besides, because of the method versatility, it is possible to assess passenger space of any transportation mean. Impact loads can be a result of falling objects, crashes, collisions and other accidents.

Possibility of comparative assessment of the cabins of similar design as regards safety criterion is an important aspect of the developed method enabling the selection the optimal design.

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