Injury biomechanics of a mining machine operator.

Paulina Działak, Mariusz Ptak, Jacek Karliński, Artur Iluk

Abstract This paper presents a new approach to the safety tests for underground mining machine operators. A review of accidents in underground mines indicated some unacceptable assumptions in the current regulations as related to machine operator biomechanics. The authors conducted some numerical tests of the floor uplift, one of the effects occurring in the mine gallery after a rock burst. To verify the injuries sustained by the machine operator, the FAA 50th percentile MADYMO Hybrid III dummy was used. Comparison of the results with and without fastening the seat belt was also conducted. The examinations were preceded with defining the proper boundary conditions for the simulations. The shortcomings of the current regulations are highlighted and some possible improvements are recommended.

Keywords FAA Test Dummy, mining machine operator safety, numerical simulation

I. INTRODUCTION

The current norms and standards which encompass heavy equipment safety are included in the Machinery Directive 2006/42/EC. The document states that every self-propelled mining machine destined to work in an underground mine needs to fulfil requirements of the Roll-Over Protective Structures (ROPS) and Falling-Objects Protective Structures (FOPS) procedures. Protective structures of the machines working underground are subjected to the same examinations of operator safety as civil engineering machinery [1]. However, conditions and accident situations prevailing in the underground mines are significantly different than those in the field of civil engineering or even opencast mining. There are no special requirements for the underground mining machines. However, there are some phenomena that occur only in this specific environment, i.e. inside the rock mass, caused by rock bursts, such as thill uplift, cover caving etc. which may result in severe or even fatal operator injuries. The accident which occurred in the copper mine KGHM Rudna in 2010 clearly supports this statement.

The rock burst with released seismic energy rate equal to 4.1 x 10^7J caused the floor heave and subsequent rock falls and ejections. This resulted in the deaths of two miners and three others seriously injured [2]. One of the fatalities, the circumstances of which are further described in this paper, was the self-propelled underground loader (Fig. 1) operator.

Fig. 1. Self-propelled underground loader with the operator cab in the middle

The machine was thrown upwards due to the thill uplift and, after breaking the connection between the operator cab and machine, the protective structure struck against the roof. The loads acting on the operator caused rapid vertical motion of the operator's body which resulted in his striking the bottom side of the cab roof (Fig. 2). Due to the confidentiality of the post-mortem examination of the operator, the authors, till now, have received the following statement about the cause and manner of death. It is reported that the operator

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suffered lethal cervical spine injury due to ruptured vertebral body, which harmed and transected the spinal cord. Also, his skull bone was depressed and pushed into the brain tissue resulting in severe brain damage despite his wearing the compulsory protective hard hat helmet. What is significant is that, even in the face of the death of the operator, the cab was still considered safe after the accident as measured by the residual deflection sag, according to the present regulations (Fig. 3) [3].

Fig. 2. The operator cab after the accident in KGHM Rudna

Fig. 3. Measurements of the residual deflection sag after the accident of the operator cab according to current regulations

Intensive sub-surface works of greater depths additionally increase the possibility of rock bursts, consequently inducing phenomena such as floor uplift, cover caving or rock ejection. Over the last few decades the risk of rock burst has risen significantly and is still growing, causing serious, even fatal injuries of the machine operators (Fig. 4). Nevertheless, the norms concerning operator safety remain invariable, and take into

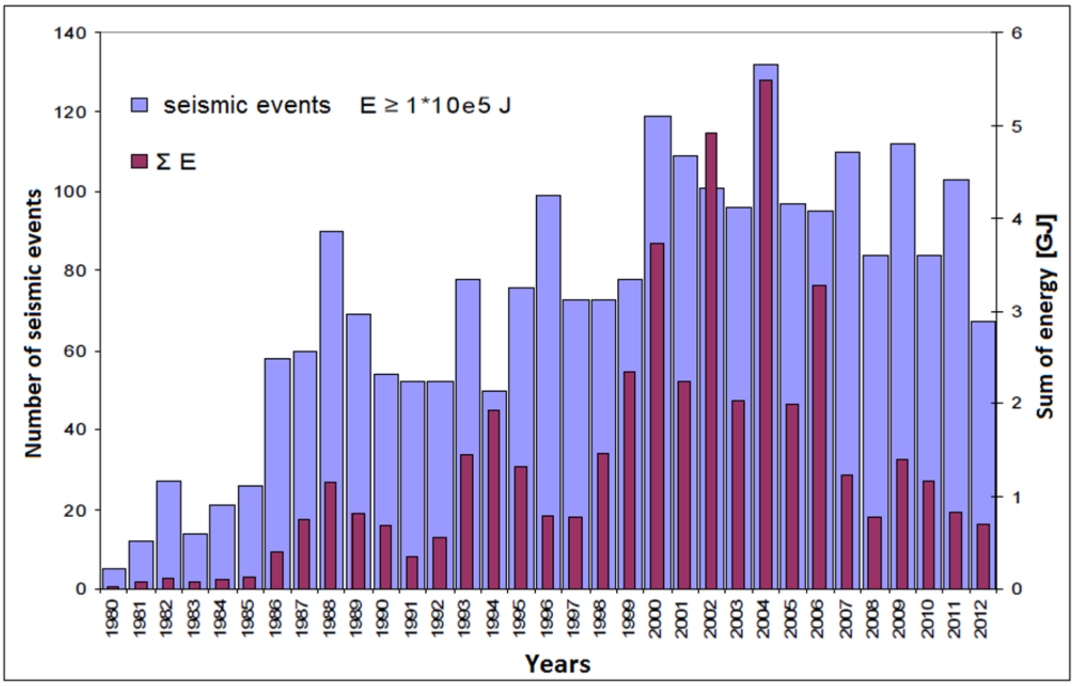


Fig. 4. Number and energy of the seismic events in the copper mines in Poland [2]

account operator protection solely in regard to falling objects and machine rollovers. The other rock burst phenomena are not mentioned in the regulations, although accidents triggered by these effects occur constantly. Therefore, any out of the ordinary situations, like the one described above, should be accurately examined and conclusions should be drawn. Precise analysis of the conditions prevailing in underground mines is necessary [4]. Such analysis of the phenomena occurring inside the rock mass, causing different types of catastrophic events, will contribute to operator safety enhancement. The definition of proper boundary conditions and adequate dynamic tests of various accident situations should be implemented.

Furthermore, instead of using a biofidelic human dummy model, the obligatory examinations utilize the Deflection-Limiting Volume (DLV), which roughly depicts an approximate living space of a large, seated male operator wearing normal clothing and a protective helmet (Fig. 5). The verification tests are considered positive provided DLV remains intact. The norms do not take into consideration either forces acting on the human body during the accident situation or any injury biomechanics.

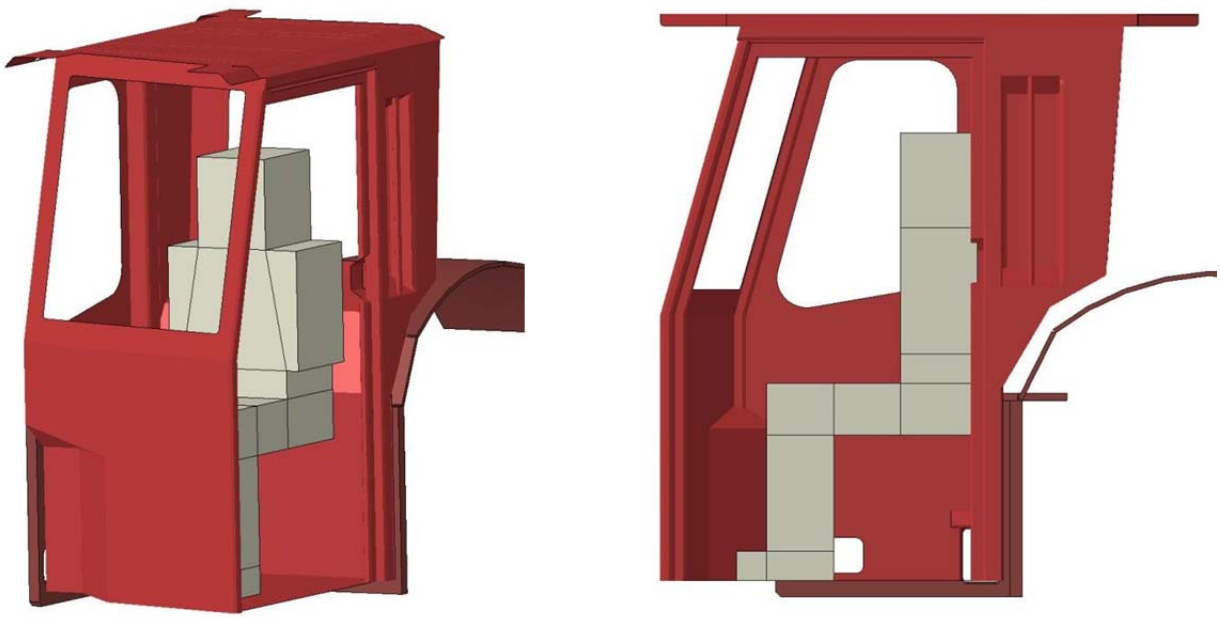


Fig. 5. The deflection-limiting volume fitted into the operator cab

Thus, there is an urgent need to implement a precise human model into the examination of the safety of underground mining machine operators. The application of the mentioned solutions may significantly improve their safety. The test will considerably better cover the actual conditions prevailing in the specific underground mine environment. The examination will also indicate some typical injuries which machine operators sustain during an accident.

II. COMPUTATIONAL MODEL

The numerical model consisted of three main elements: the MADYMO dummy, operator protective structure (the cabin) and seat with a standard lap seat belt (2-point) with its mounting.

Dummy

The MADYMO dummy was used as the human model. Due to the vertical forces acting on the underground mining machine operator's body during the simulation, instead of the standard Crash Test Hybrid III Dummy, the Federal Aviation Administration's Hybrid III Dummy (FAA HIII) was chosen. It is used in testing emergency landing dynamic conditions. The FAA HIII is based on an automotive 50th percentile male Crash Test Dummy, although it is also adapted to measure vertical load occurring in aviation. The FAA dummy is modified to give it an erect seated posture, replacing the driver slouch of the Hybrid III Dummy. It is designed in order to address compression loading from the bottom. The overall noticeable changes, compared to a standard automotive dummy, implemented in FAA HIII to give it better biofidelic and more accurate response under dynamic axial loading are as follows (Fig. 6):

(1) Substitution of the Hybrid III (HIII) lumbar-pelvic adapter block with the Hybrid II (HII) Lumbar Load Cell and its pelvic adapter block to record lumbar responses;

(2) Replacement of the curved HIII lumbar column with the HII straight column;

(3) Substitution of the HIII upper lumbar-thorax adapter with a new adapter made of steel to closely reproduce the mass distribution of the HII upper torso;

(4) Substitution of the HIII abdominal insert for a standard HII abdominal insert;

(5) Replacement of the HIII upper leg body parts for the HII upper leg body parts;

(6) Replacement of the HIII chest flesh jacket with the chest flesh jacket from a HII conveniently adapted to allow the neck to move freely [5].

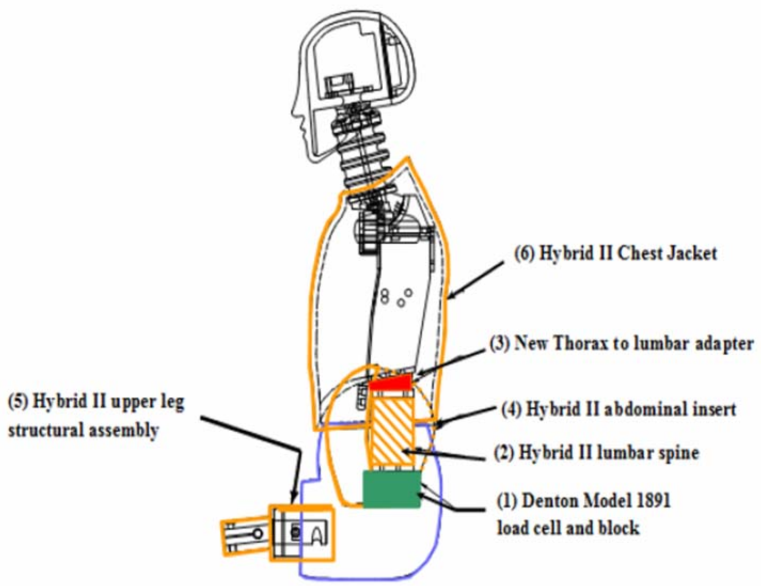


Fig. 6. FAA HIII lumbar-pelvis modifications [5]

The paper focuses mainly on the lumbar-pelvis and head responses of the FAA HIII during the accident situation caused by the rock burst. Since the conducted research of the FAA HIII showed that it achieved a high degree of repeatability and linearity for the lumbar-pelvis results during testing [6], the dummy was chosen for further numerical investigation.

Operator protective structures

The FE model of the two-point lap seat belt was used and positioned to fit the contours of the thighs and hips. The model was modelled with shell (membrane) elements. The seat belt was wrapped around the dummy by using a fitting tool. LS-DYNA seat belt elements were used to represent the cables attached to the ends of the lap belt [7].

The operator protective structures used in the simulations are the products of Mine Master, a company specializing in underground mining equipment. The cabs were already examined for the operator safety in compliance with the current regulations and met all requirements. The protective structure geometrical Computer-aided Design (CAD) and Finite Element (FE) models were created in accordance with the technical documentation provided by Mine Master (Fig. 6). Despite the significant disparity of the cab and dummy stiffness the authors decided not to model the cab as a rigid body mainly due to former cab validation against the real object [8]. Therefore, the material model of the cab is based on bilinear elastic-plastic with kinematic hardening parameters described in [3].

a)

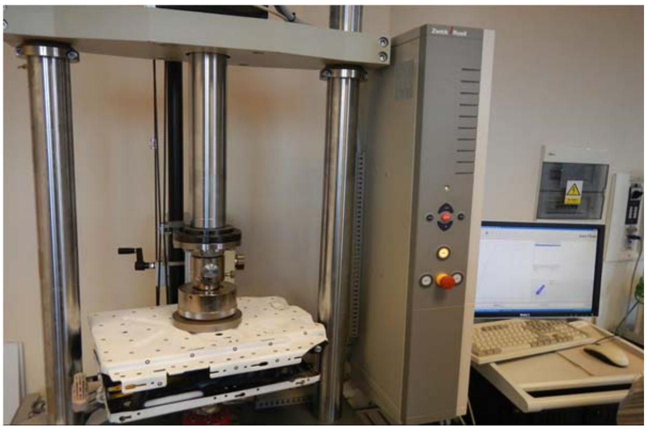
b)

Fig. 7. Two different constructions of the analysed operator protective structures:
a) underground drill rig FM 2.3 cab, b) underground loader SLP 8 cab

Seat

The geometrical model of the cab seat was created through 3D scanning by the use of a photogrammetry system and the ATOS Compact Scan device. Once the recreation of the geometry was completed from the obtained cloud of points, a FE model was generated. It is based on the Maximo series seat manufactured by Grammer. The stiffness and strength of the seat mounting were examined experimentally on the universal testing machine Zwick Z030. The measurements enabled the authors to design the simplified model of the mounting. The material data for the cushion seat foam were also obtained empirically from the testing machine (Fig. 8).

a)



b)

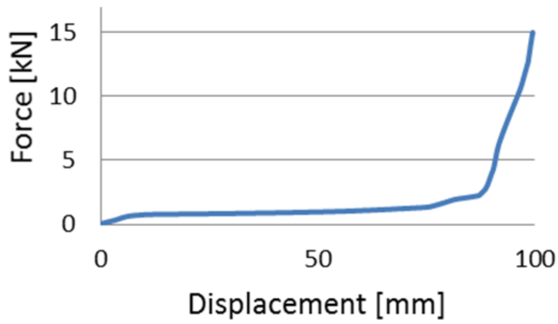


Fig. 8. Measurements of the seat mounting:
a) examination on the universal testing machine, b) stiffness of the mounting spring

Seat absorber – future direction

Currently, as it was reflected in the FE seat model, the operator seats of mining machines are not mounted directly to the load-bearing structure of the cabs. There is an element between the machine frame (floor) and seat, enabling the operator to set up the seat in an ergonomically desirable position.

The preliminary research proved that this element, after some modifications, may also serve as an energy absorber. The authors have already started the research in this field. However, for the time being, these are conceptual designs under development (Fig. 9). They still require further analysis and for the sake of consistency the concept was not implemented in the following numerical simulations described in this paper.

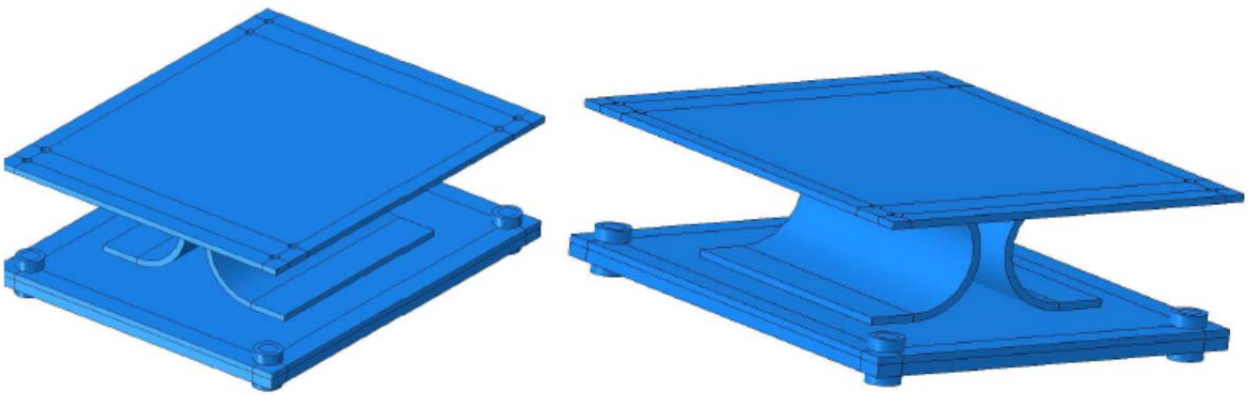


Fig. 9. Conceptual design of the seat absorber

III. NUMERICAL SIMULATION

The performed simulations entailed the combination of two different numerical codes – i.e. Finite Element Analysis and Multibody. Thus, to conduct the simulations LS-DYNA–MADYMO coupling was applied. This method enabled combining the capabilities of the Multibody (MB) with Finite Element (FE) code, by using them in a parallel simulation. It is considered a valuable tool during safety examination. On the one hand MADYMO contains advanced, well-developed and validated dummies; on the other hand LS-DYNA provides accurate contact definitions and state-of-the-art materials models. An additional advantage of the coupling process in the computational testing is time efficiency [9]. The use of the MADYMO dummy instead of the FE model enabled reducing the duration of the numerical calculations significantly. Therefore, embedding the MADYMO FAA HIII dummy into LS-DYNA FE environment was considered a suitable solution.

The definition of the boundary conditions for the simulations was one of the major issues. The physical data concerning phenomena occurring inside the rock mass in the underground mines are relatively difficult to obtain. However, after accident analyses the authors managed to estimate the approximate velocity curve of the operator cab after the thill heave (Tab. I). To determine the curve run, the average acceleration of the cab after the thill uplift and average distance between the top surface of the cab and the bottom surface of the gallery roof were taken into consideration. This facilitated the further numerical calculations.

TABLE I
VELOCITY CURVE

ms	m/s
0	0
30	10
50	10
55	0

The simulations of the floor uplift in the underground mine after the rock burst were conducted for two different operator protective structures: FM 2.3 and SLP 8 with the lower roof height. The seismic energy released from the rock mass resulted in a rapid upwards machine ejection. Afterwards, the cab with operator struck the roof of the mine gallery. Despite the compulsory installation and wearing of seat belts in all protective structures, the operators tend not to fasten them due to both poor safety awareness and comfort issues. Numerous descriptions of the accidents indicate this issue [2]. Hence, simulations with and without seat belt were conducted (Figs. 10 and 11).

a) b)

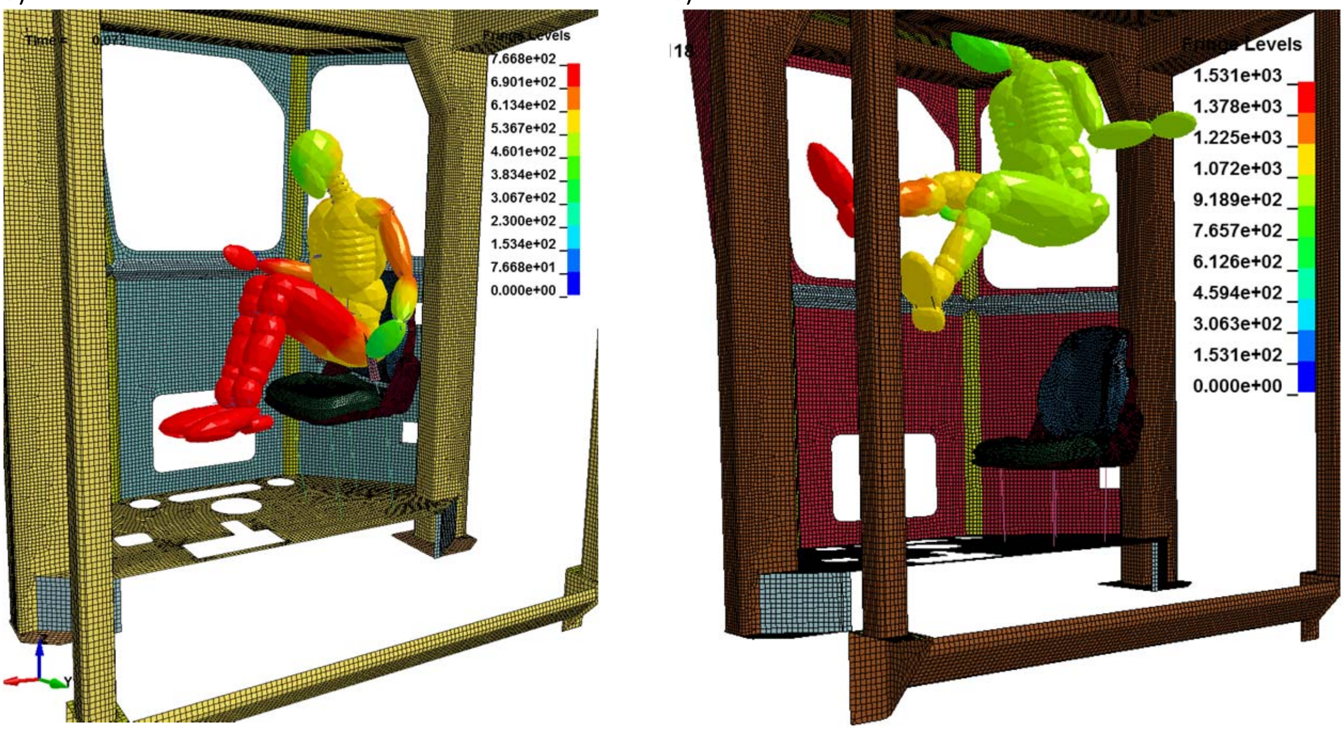


Fig. 10. Simulations of the floor uplift for the FM 2.3 protective structure (Z-displacement magnitude [mm] of the dummy): a) with seat belt, b) without seat belt

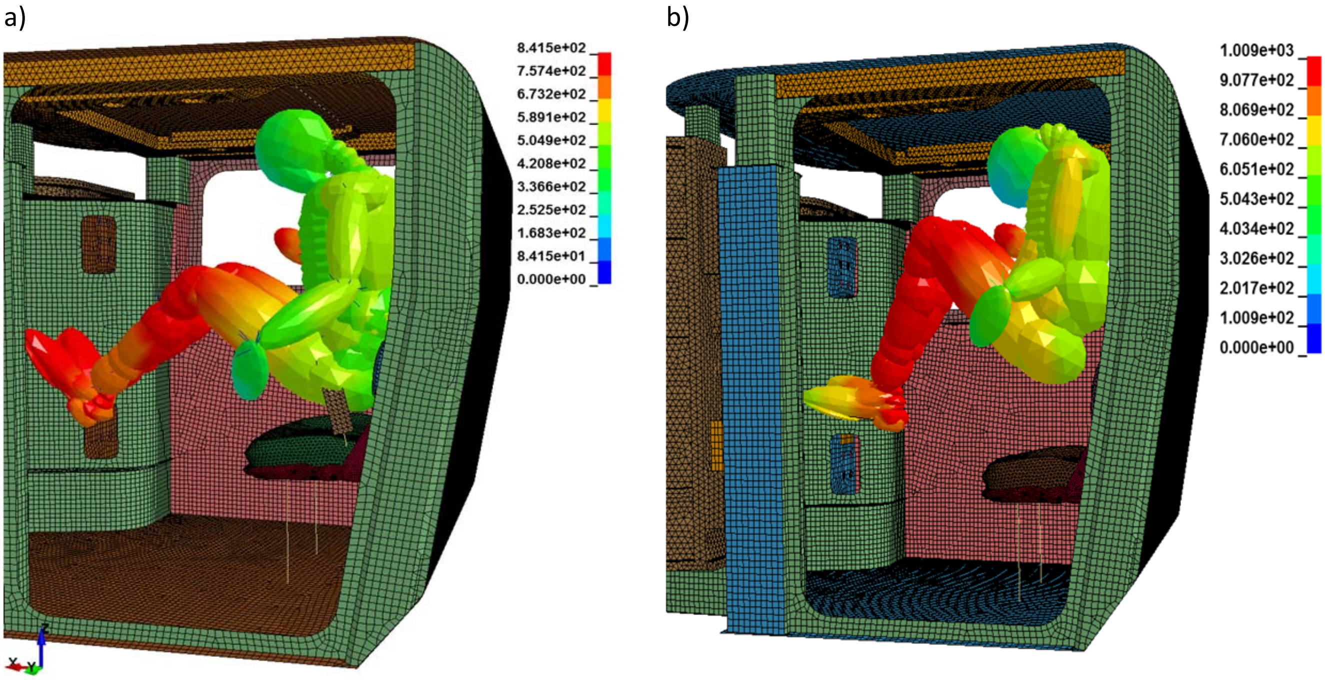


Fig. 11. Simulations of the floor uplift for the SLP 8 protective structure (Z-displacement magnitude [mm] of the dummy): a) with seat belt, b) without seat belt

Using the precise MADYMO dummy allowed the authors to determine whether the loads such as acceleration acting on the human body during the accident situation may be life-threatening or even fatal. The injury criteria taken into consideration during analysis are presented in Table II.

The spinal column acceleration is the maximum acceleration between lumbar and pelvis elements of the FAA HIII. The limit values of these criteria correspond to a 20% possibility of moderate to severe injury at the level of AIS2+ [10]. The acceleration required for the criterion was measured in a lumbar-pelvis part of the spine. Head Injury Criterion (HIC) is a measure of the head injury possibility during the accident situation. The limit HIC value is equivalent to an 18% probability of a severe (AIS 4) head injury, a 55% probability of a serious (AIS 3) injury and a 90% probability of a moderate (AIS 2) head injury to an average adult [11]. The acceleration for HIC was measured in the centre of gravity of the FAA HIII head model. The limit values of the criteria used are based on the military air transport requirements [12] and presented in Table II.

TABLE II
INJURY CRITERIA

Criterion	Units	Limits
Spine column acceleration	g	14.5
HIC	-	1000

IV. RESULTS

The results of the simulation are presented on the charts in Figs. 12 and 13.

a) b)

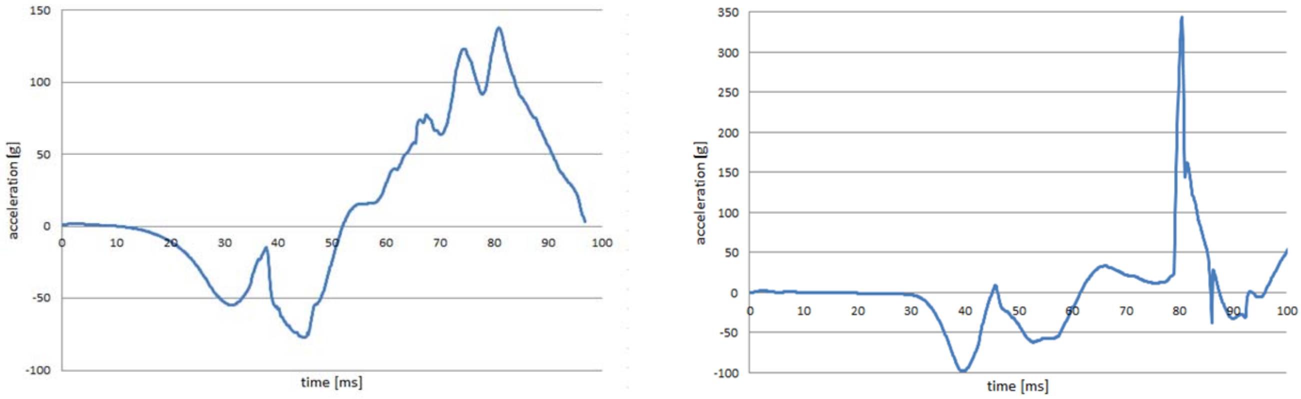


Fig. 12. Head acceleration of the FAA HIII dummy fastened with seat belt:
a) FM 2.3 b) SLP 8.

a) b)

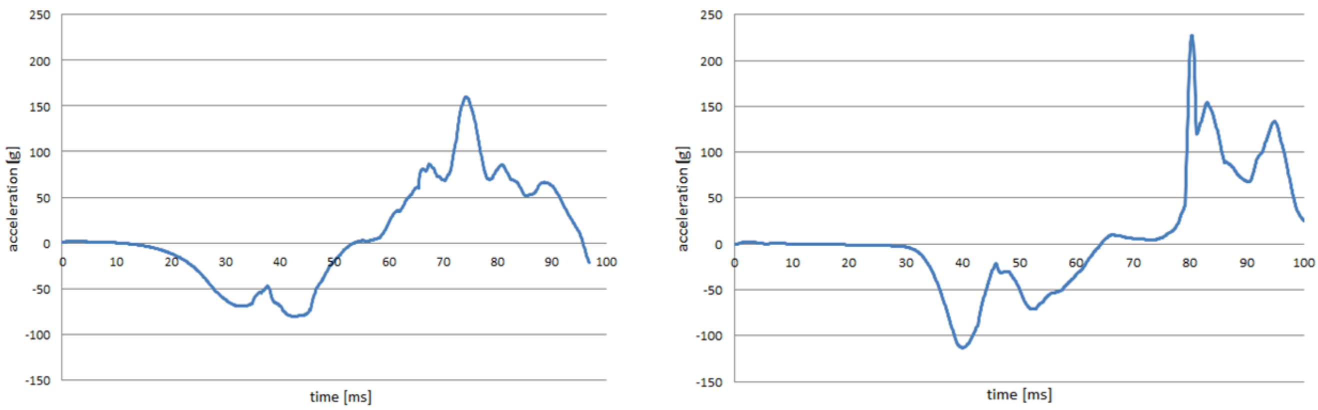


Fig. 13. Spinal column acceleration of the FAA HIII dummy fastened with seat belt:
a) FM 2.3, b) SLP 8

Table III presents maximal values obtained during the simulations. The results obtained for the unbelted operator were not even taken into consideration, because received values of the injuries considerably exceeded any sort of reasonable limits for all the criteria.

TABLE III
MEASURED PARAMETERS

Name	Units	Max measured value (FM 2.3/SLP 8)
Spinal Column Acceleration	g	160/230
HIC	-	2050/2000

Spinal Column Acceleration and Head Injury Criterion significantly exceeded the limit of the criteria. Spinal criterion however is not related to duration of the acting load. For the operator in cab FM 2.3 simulations the maximal range of the acceleration between 130-160 g remains for 3 ms. In the case of SLP 8 maximal Spinal Column Acceleration is higher and it remains at the level 200-230 g for 1 ms, when contact of the operator with the bottom surface of the roof occurs. Around 1.5 ms during the simulation, Spinal Column Acceleration was greater than 150 g. Results obtained from the simulation are in the area of severe, possibly even fatal spine injuries. Figure 12 presents Eiband tolerance curve, where Spinal Column Acceleration is referenced to the duration time.

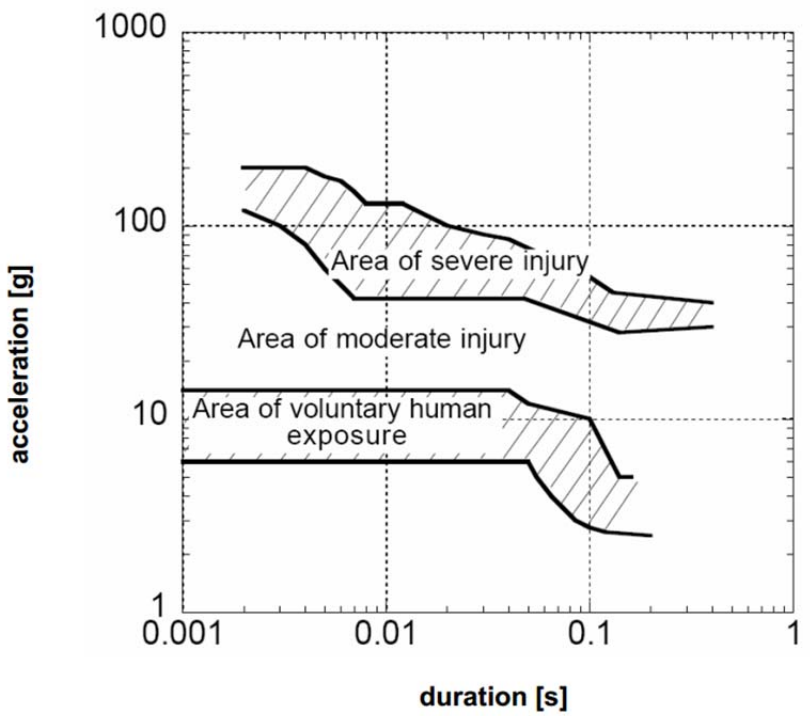


Fig. 14. Eiband tolerance curve [13]

V. CONCLUSIONS

This paper describes some important issues regarding the biomechanics of the mining machine operator. Based on actual accidents, the authors analysed the current requirements for protective structures in regard to operator safety aspects. Current type-approval tests do not examine any phenomena related to typical accidents in underground mines, such as rock bursts resulting in thill uplift, lateral rock tosses, or cover caving. In many cases they may result in severe or fatal injuries of the mining machine operators. Through numerical tests using coupled FE and MB codes, various underground mining accident scenarios were analysed which showed some thought-provoking circumstances when the protective structures are still considered as safe for the machine operator, although the operators sustained fatal injuries. Therefore, there is a need to incorporate a precise human model into operator safety tests and reconsider the current standards since the regulations do not consider the dynamic phenomena occurring in the specific underground environment. Furthermore, current intensive deep underground mining increases the risk of these devastating effects in the forthcoming years.

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