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METHOD FOR IDENTIFICATION OF RESULTS OF DYNAMIC OVERLOADS IN ASSESSMENT OF SAFETY USE OF THE MINE AUXILIARY TRANSPORTATION SYSTEM

METODA IDENTYFIKACJI SKUTKÓW PRZECIĄŻEŃ DYNAMICZNYCH W OCENIE BEZPIECZEŃSTWA UŻYTKOWANIA GÓRNICZEGO TRANSPORTU POMOCNICZEGO

Method for identification the effects of dynamic overload affecting the people, which may occur in the emergency state of suspended monorail is presented in the paper. The braking curve using MBS (Multi-Body System) simulation was determined. For this purpose a computational model (MBS) of suspended monorail was developed and two different variants of numerical calculations were carried out. An algorithm of conducting numerical simulations to assess the effects of dynamic overload acting on the suspended monorails' users is also posted in the paper. An example of computational model FEM (Finite Element Method) composed of technical mean and the anthropometrical model ATB (Articulated Total Body) is shown. The simulation results are presented: graph of HIC (Head Injury Criterion) parameter and successive phases of dislocation of ATB model. Generator of computational models for safety criterion, which enables preparation of input data and remote starting the simulation, is proposed.

Keywords: underground mining, anthropotechnical systems, numerical modeling

W artykule przedstawiono metodę identyfikacji skutków przeciążeń dynamicznych oddziałujących na ludzi, mogących wystąpić w stanie awaryjnym górniczej kolejki podwieszonej. Zamieszczono sposób wyznaczania krzywej charakterystyki opóźnienia podczas hamowania za pomocą symulacji z zastosowaniem metody MBS (ang. *Multi-Body System*). W tym celu opracowano model obliczeniowy (metoda MBS) i przeprowadzono dwa warianty obliczeń, różniących się prędkością uzyskaną przez model kolejki podwieszonej. Przedstawiono algorytm prowadzenia analiz numerycznych mających na celu ocenę skutków przeciążenia dynamicznego oddziałującego na człowieka. Zaprezentowano model obliczeniowy (metoda MES), składający się ze środka technicznego oraz modelu cech antropometrycznych ATB (ang. *Articulated Total Body*) oraz wymieniono warunki brzegowe. Zaprezentowano zachowanie się manekina ATB dla dwóch wielkości centylowych: 5 oraz 95 centyli. Omówiono wyniki przeprowadzonych symulacji numerycznych MES dla różnych wielkości modelu cech antropometrycznych ATB, tj. 5, 50 oraz 95 centyli. Wyniki zamieszczono w postaci parametru HIC 36 oraz przedstawienia faz przemieszczeń modelu

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50-cio centylowego. Zaproponowano generator modeli obliczeniowych dla kryterium bezpieczeństwa, umożliwiający przygotowanie danych wejściowych i zdalne uruchomienie symulacji. Wyszczególniono zalety zaproponowanej metody.

Słowa kluczowe: górnictwo podziemne, systemy antropotechniczne, modelowanie numeryczne

1. Introduction

Underground mine auxiliary transportation system in hard coal mining industry is realized on horizontal and inclined routes. It is permanently extended due to necessity of elongation of transportation routes from the shaft to longwall panels as well as due to concentration of mining operations, what requires reliable and safe transportation means.

Transportation means, before setting into operation are tested for their so-called complex safety according to the requirements of Machinery Directive (Rozporządzenie, 2008). According to the assessment criteria, the risk associated with using the machine should be eliminated or minimized already at the stage of designing the transportation means. Assessment criteria are divided into technical and anthropotechnical ones (Winkler, 2001). Technical criteria concern only the assessment of technical objects. They enable assessing such features as: functionality, strength, reliability. Anthropotechnical criteria are associated with presence of people near the machine or equipment. In this group, we can distinguish the following sub-criteria like ergonomic criteria, safety criteria and other.

Statistical data of State Mining Authority (Wyższy Urząd Górniczy, 2013) indicate for about 50% share of accidents on transportation routes.

These accidents are mainly associated with the following situations:

- invading or crushing the workers by a transportation mean,
- collision between transportation means or their derailment.

Collision or derailment as well as emergency braking cause dynamic load to ride-on persons.

Method for identification of consequences of overload that may affect people in emergency states is presented. In the method, the author's generator of models for calculating the operators' cabin in the light of safety criterion was used.

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2. Virtual prototyping of transportation systems in the light of the safety criteria

Technical advance and increasing competition among manufacturers of mining machines make new products more and more safe, more reliable and of longer life. Improved numerical methods enable better and quicker calculations.

Virtual prototype of the machine is assessed during the operations as start-up, normal work etc. Emergency states of the machine, when forces, loads, reactions or material strain are extreme and can lead to machine failure or damage. In such situation, the machine's user can be exposed to injuries. In such cases, the virtual prototype is built on the basis of expanded criterial models containing computational models of technical object completed by models of anthropometric features (Winkler, 2001). Models of anthropometric features enables calculating the biomechanical loads to human musculoskeletal system, range of limbs, field of vision and testing the machine maintenance processes as well as enable identifying the technical and health hazards that can occur during the mechanical systems operation. Numerical analyses, with use of Articulated Total Body models (ATB) (Winkler et al., 2013) of anthropotechnical features are popular in automotive industry, aircraft industry and in the army to assess the results of dynamic overload caused by different phenomena such as crash, fall or explosion (Fasanella & Jackson, 2004; Krzystała et al. 2012). These phenomena are taken into consideration in designing the equipment for disabled people (Dsouza & Bertocci, 2010) as well as in the special vehicles used in sports disciplines (Schau & Masory, 2013).

In designing the underground transportation means, the numerical kinematics and dynamics analysis of Multi-Body System (MBS) as well as Finite Elements Method (FEM) (Chuchnowski et al., 2010; Winkler et al., 2010) were used to identify results of dynamic overloads. MBS method is used in the complex cases, e.g. in the analysis of mechanisms with changeable geometrical features in virtual prototype. Determined forces and reactions are the boundary conditions of computational models used in FEM.

3. Determination of characteristics of braking deceleration of suspended monorail with use of MBS method

Numerical simulations were made with use of MBS method to determine the characteristic of deceleration during emergency braking of suspended monorail. Computational model, which consists of the following components was developed, Fig. 1:

- fixed track of suspended monorail,
- 4 passenger carriages connected with links,
- 2 braking cars,
- 2 driving systems.

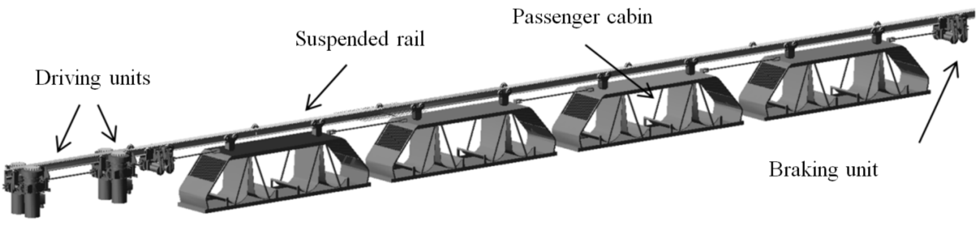

Fig. 1. MBS computational model for determination of deceleration curve during emergency braking of the suspended monorail

The weight of all components was equal to 6332 kg. Two variants of numerical calculations were realized to identify the impact of changes of train speed on deceleration curve during braking. In the first variant the train was speeded up to 2 m/s – the speed resulting from regulations that are in force (Rozporządzenie, 2002), while in the second variant it was speeded up to 4 m/s, Fig. 2.

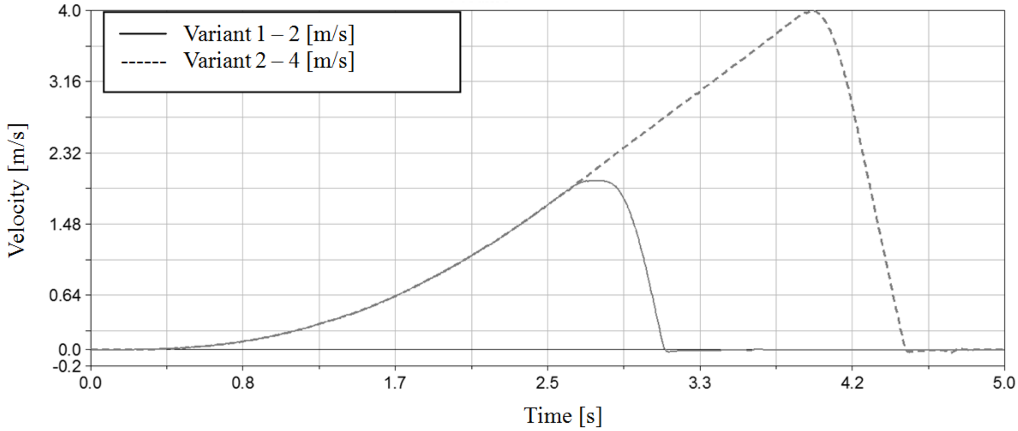

Fig. 2. Diagram presenting the train speed for variants 1 and 2

Then, after reaching the assumed speed, release of brakes in braking systems was simulated. There were four brake blocks, pressed with force of 20 kN, in each system. The increase of force related to the standard time of brakes response in braking cars, Fig. 3.

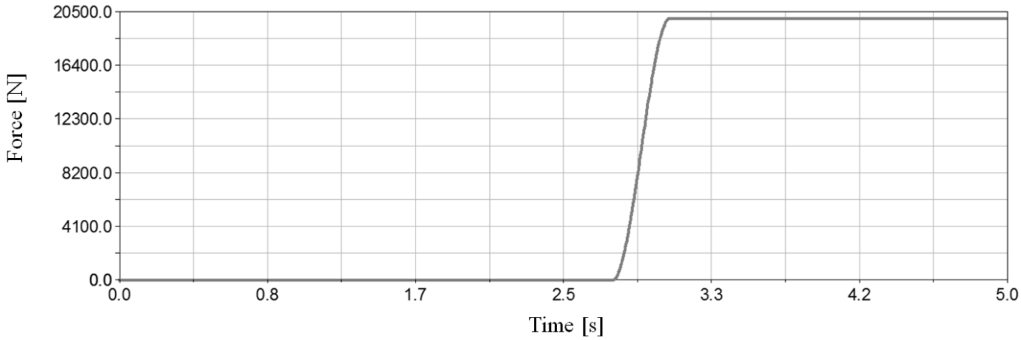

Fig. 3. Increase of force in a model of braking car

Assumed increase of force pressing the brake blocks was the same for both variants. Brake blocks pressed to the web of suspended rail caused friction force equal to 64 kN. Coefficient of kinetic friction between brake block and rail was assumed as 0.4. Pressing force and friction coefficient were selected in such way that deceleration did not exceed 10 m/s^2. The speed of suspended monorail was reduced after release of brakes. Maximum deceleration for both variants was of about 10 m/s^2, Fig. 4.

Differences in maximum decelerations acting on passenger carriages for variants 1 and 2 are the result of numerical errors. The parameters presented in Table 1 were calculated on the basis of simulations.

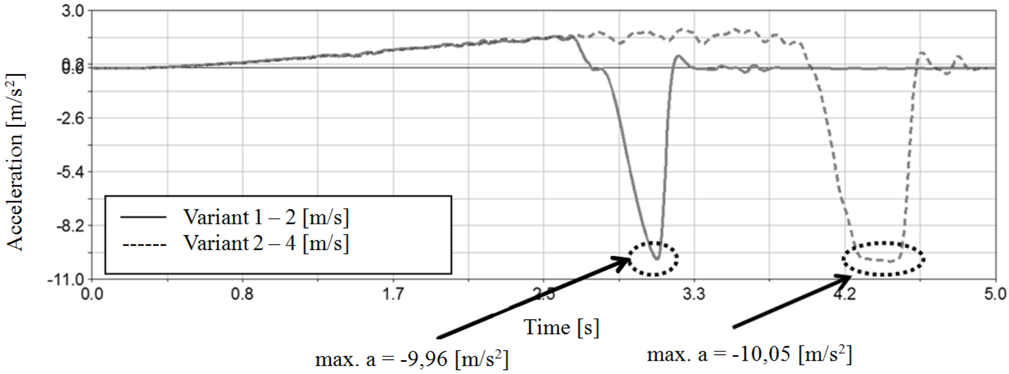

Fig. 4. Deceleration acting on passenger carriages for variants 1 and 2

TABLE 1

Results of simulation of braking of suspended monorail for variants 1 and 2

Variant	Time of deceleration [s]	Max. deceleration of braking [m/s^2]	Braking distance [m]
1 [2 m/s]	0,38	9,96	0,487
2 [4 m/s]	0,56	10,05	1,357

4. Identification of results of dynamic overloads on the example of emergency braking of mine suspended monorail

The results of dynamic overloads, which can occur during transportation of people, were identified according to the algorithm given in Fig. 5.

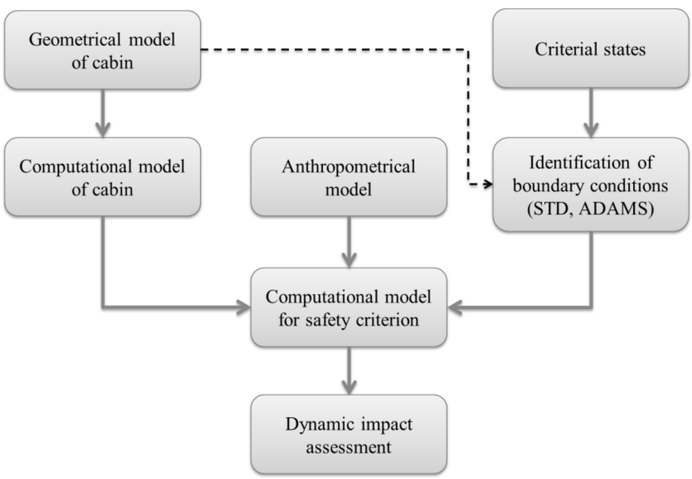

Fig. 5. Algorithm for identification of results of dynamic overloads

According to the presented algorithm, the computational model of carriage was developed on the basis of its geometrical model. The mesh of surface components of 8-person carriage of suspended monorail is presented in Fig. 6.

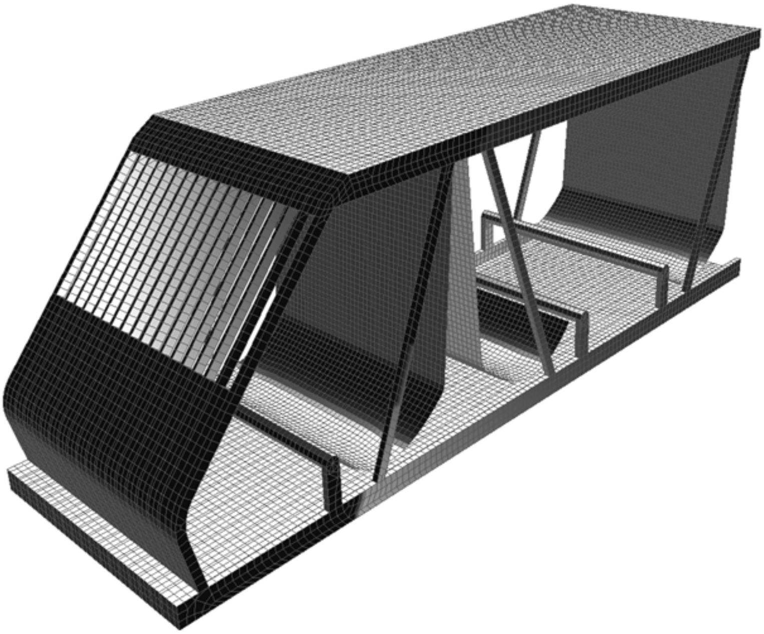

Fig. 6. FEM meshing of surface components in computational model of the carriage for transportation of people in a suspended monorail

Due to accepted simplifications, the computational model covered only a part of a real cabin. Non-deformable model of material was accepted. A model of ATB anthropometric features of different size i.e.: 5, 50 and 95 centiles, extended the computational model,. ATB model representing the ATD (*Anthropomorphic Test Devices*) real dummy of Hybrid III type, which consists of 17 body segments connected with each other by 16 articulated connections of different degree of freedom and representing the joints, was used (Cheng et al., 1998). These segments and joints created the kinematic chains. The example of 95-centile model of anthropometric features is presented in Fig. 7.

The following boundary conditions were defined:

- deceleration of braking: so-called crash impuls calculated with use of MBS simulation, for emergency braking,
- gravity: 9.81 m/s^2,
- definition of contacts: carriage – model of anthropometric features, seat – model of anthropometric features,
- inclination of working – downward or upward travel,
- forward-facing or rear-facing location of ATB model,
- time of simulation.

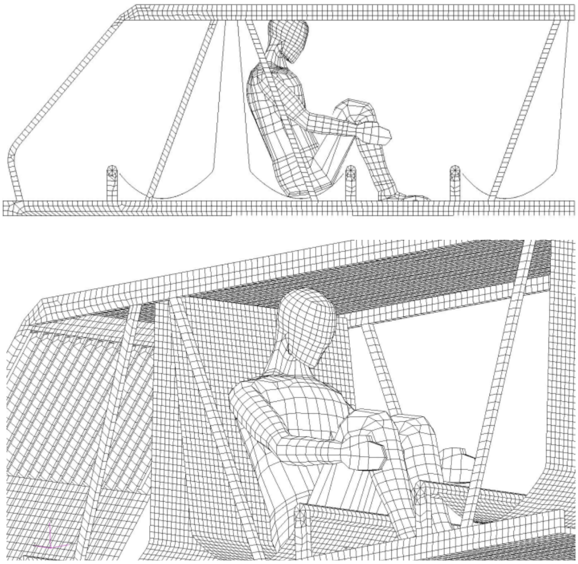

Fig. 7. ATB model of anthropometric features (95-centile) in carriage for transportation of people

The dynamic simulations, so-called explicit simulations, were made. Changeable parameters, including as follows:

- linear and angular position of each body segment,
- speed, acceleration, force and torque in joints of anthropometric model,
- force resulting from the contact between a given body segment and the obstacle,

were analyzed.

Animations presenting dislocation of ATB model were prepared on the basis of the obtained results. Dislocations in the case of 5- and 95-centile models for the same moment are compared in Fig. 8.

Simulation of 95-centile ATB model showed that the model hit the upper shitting of carriage; it was "stuck" and could not move towards front part of carriage. The results of dynamic overloads affecting the man were identified. The change of Head Injury Criterion parameter (HIC 36) (Cichos et al., 2005) in time for different size (in centiles) of ATB model is presented in Fig. 9.

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

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

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.

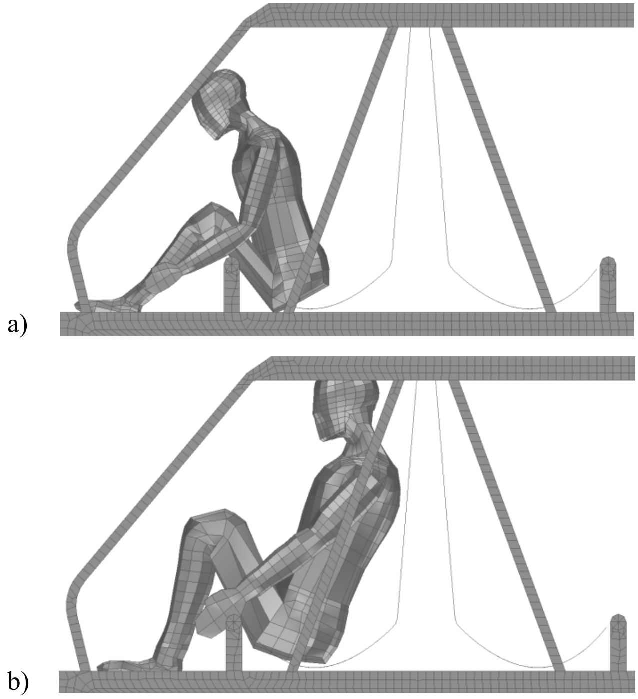

Fig. 8. Comparison of dislocation for 5-centile (a) and 95-centile (b) ATB models at the same moment

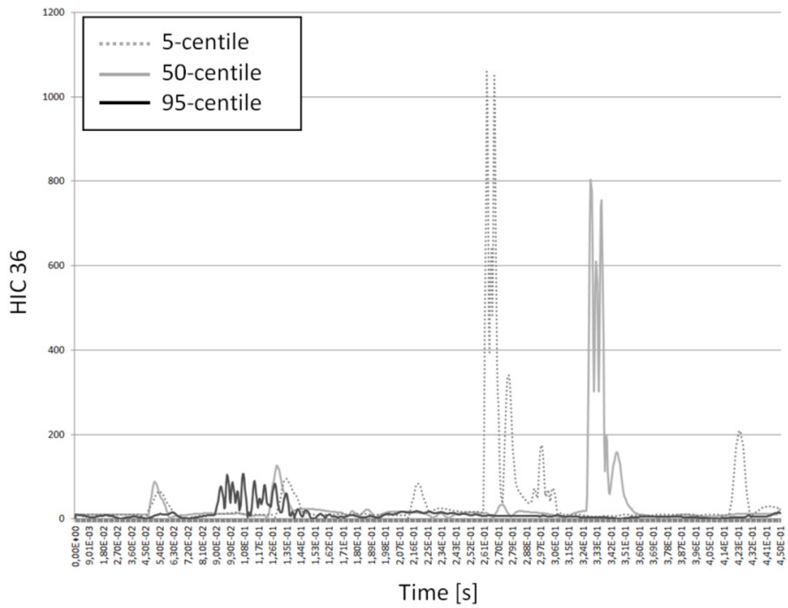

Fig. 9. Change of HIC 36 parameter in time for different size of ATB model

Calculated change of HIC 36 parameter in time for three sizes of ATB model, i.e.: 5, 50 and 95 centiles, is presented in the diagram. The results are different both as regards the value and moment at which the value is maximum. The differences are associated with the size of ATB model, its weight and behaviour in a confined space. In this case modification of carriage for transportation of people, to improve the safety for 5-centile model, could result in a decrease of safety for 50- and 95-centile models. Due to this, after modifications of geometrical features of carriage, each time they should be assessed as regards three sizes of models of anthropometrical features.

ATB dummy models apart from head injury criterion, the parameters referring to the potential injuries of cervical spine, chest and joints as well as break of lower limbs are possible to calculate (Cichos et al., 2005).

The results for variant 1 and variant 2 are consistent. It means that speed of train does not have a significant impact on deceleration during emergency braking. Higher speed causes elongation of braking time and braking distance. The results of simulation of ATB dummy behaviour show that during emergency braking, the passenger hits the front part of carriage just after about 0.18 s, what can lead to an injury, Fig. 10.

Further decrease of carriage speed does not result in an injury. The results refer only to possible effects of emergency braking and do not cover other emergencies such as brake of track and fall of train or hitting the obstacle.

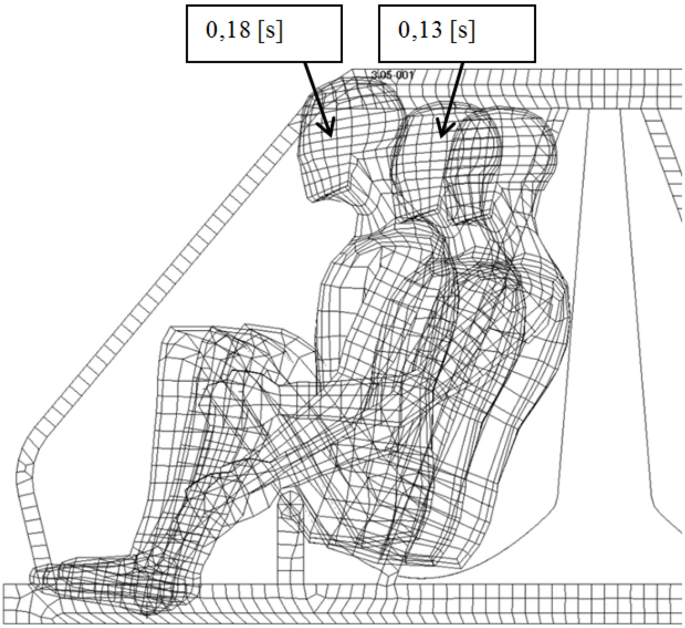

Fig. 10. Successive phases of dislocation of ATB model (50-centile) in time

5. Generator of computational models with use of remote starting the numerical analyses

Author's generator of computational models for identification of results of dynamic overloads acting on a man was built within the project. The generator aids creation of computational models with use of ATB models. Its main task is to automate the process of building the computational model (operators' carriages, carriages for transportation of people), i.e. to prepare the input files for computational software programme and then start the computational tasks remotely. The generator integrates the environment of MSC.Dytran computational software programme (MSC. Software, 2013) with the internet platform (Tokarczyk, 2015). The generator of computational models is an interface between FEM pre-processor and a computational programme (solver).

The computational programmes most often are started at workstations used for preparation of computational models. To shorten the time of calculations the generator starts the numerical calculations out of the workstation at which they were prepared. There are the following methods for remote starting the computational tasks:

- computer cluster – a set of computers connected with each other (or one of very high calculation power) in a local network. The computer clusters are the sub-group of the efficiency clusters. They significantly speed up the computational tasks through their division into the computational nodes (Németh & Sunderam, 2003),
- grid computing – are the extension of computer clusters. The computational tasks are solved on the separated computers, i.e. the computers that are located in a high distance from each other or have different operational systems (Pfister, 1997),
- cloud computing (Foster et al., 2008) – computational service including access to the special software programme with indispensable infrastructure. Calculations in the cloud, as it is in the case of network processing, can be made only when functionality of the software programme allows them to do that. However, calculations in the cloud are associated with losing the control over sent computational models. Due to this, methods for verification and protection of data transferred to the computational cloud are under development at present (Fernandes et al., 2014; Gouglidis et al., 2014).

So-called Amdahl's law presents theoretical, maximum speed up of calculations (shortening the time of calculations) at increase of number of processors (Amdahl, 1967):

$$S = \frac{N}{(B*N)+(1-B)} \tag{2}$$

where:

S — calculations speedup,
N — number of processors,
B — part of code that cannot be realized in parallel.

The structure of computational software programmes can be optimized due to the fact that present computers are multi-processor ones. This structure takes into account not only the number of processors in a local computer (server), but also in computers, which communicate with each other.

The generator of computational models sends the computational tasks to the computational server (Tokarczyk et al., 2014). Input data for the calculation tasks are prepared with use of internet forms in the following five steps:

- STEP 1: preparation of input files – files including FEM meshing for the carriage, ATB model, seat and safety belts,
- STEP 2: defining the physical properties of ATB model: 5, 50, 95,
- STEP 3: defining forces and accelerations: components of gravity force and direction of acceleration associated with vehicle movement, crash impulse, Fig. 11,

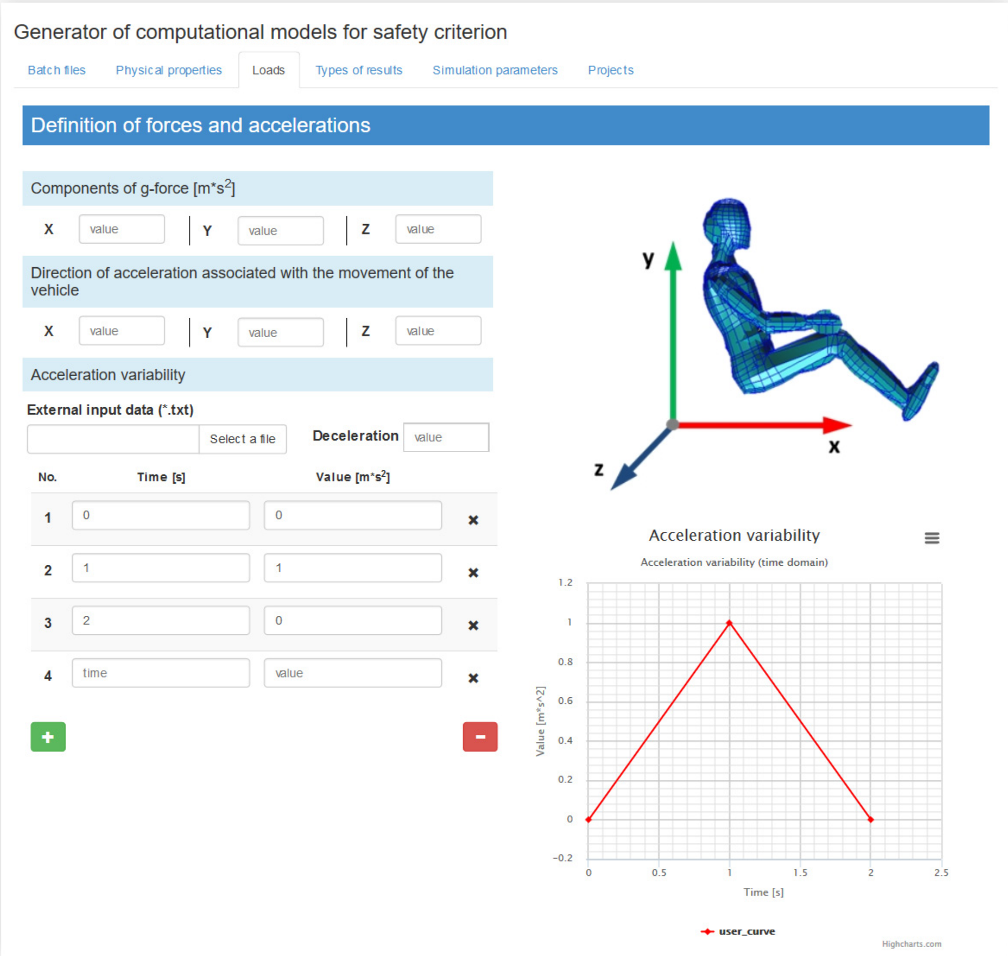

Fig. 11. Internet form for defining the boundary conditions (an example of STEP 3)

- STEP 4: defining the results:
  - head injury criterion,
  - dislocations, speed and linear or angular acceleration for each segment,
  - forces or moments of forces for each joint,
- STEP 5: defining other input parameters – time of simulation, initial and minimal integration step, number of textual results and results required for animation, presence of safety belts.

The use of generator enables to vary the computational tasks and to speed up the preparation of data for calculations.

6. Conclusions

Suspended monorails and floor-mounted railway used for transportation of materials and people are dynamically developing part of auxiliary underground transportation. Analysis of accidents that occurred on transportation routes of Polish mines indicate for presence of overload. There are the following reasons of overload:

- sudden braking or acceleration,
- derailing,
- crash of train,
- hitting the obstacle on the transportation route.

Due to increased weight of transported loads, it is required to use more powerful braking systems in railway vehicles to ensure proper coefficient of braking reliability (Rozporządzenie, 2002).

The suggested method used already at the stage of designing the auxiliary mine transportation system allows for:

- increasing the safety of people maintaining the auxiliary mine transportation system,
- calculating the dynamic overloads that can occur during emergency situations,
- identifying the design elements increasing the risk of injury to make changes in the cabin structure e.g. modification of space for feet, change of seats position or use of safety belts,
- identifying the hazards results in a function of centile measure (5, 50, 95).

Integration of FEM pre-processor environment, computational programme as well as possibility of remote start-up of calculations is the innovative feature of the method. Scope of its use covers the passenger area of any people transportation vehicle and simulated overloads can be a result of both crashes and collisions as well as of hit by falling objects.

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