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Simulation of Tram-Pedestrian Collision with Validated Windshield Material Model

ŠPIRK S.[1,a], ŠPIČKA J.[2,b], VYCHYTIL J.[2,c]

[1]Regional Technological Institute, University of West Bohemia in Pilsen, Univerzitni 8, 306 14 Pilsen, Czech Republic

[2]New Technologies - Research Centre, University of West Bohemia in Pilsen, Univerzitni 8 301 00 Pilsen, Czech Republic

[a]spirks@rti.zcu.cz, [b]spicka@ntc.zcu.cz, [c]jvychyti@ntc.zcu.cz

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Abstract. The rail industry has been significantly affected by the passive safety technology in the last few years. The tram front-end design must fulfil the new requirements for pedestrian passive safety performance in the near future. The requirements are connected with a newly prepared technical guide "Tramway front end design" prepared by Technical Agency for ropeways and Guided Transport Systems [1]. This paper describes research connected with new tram front-end design safe for pedestrian. The brief description of collision scenario and used human-body model "VIRTHUMAN" is provided. The numerical simulations (from field of passive safety) are supported by experiments. The interesting part is the numerical model of the tram windshield which is experimentally validated and completely described (even by table with material parameters). Some major simulations results are discussed at the end of paper.

Introduction

This paper is focused on the simulation of the pedestrian and vehicle collision. The legislation in this area is still under preparation, although there exists a significant pressure on the tram front-end design crashworthiness. The research is supported by the cooperation with the worldwide tram developer acting in Czech Republic. The main attention here is paid to windshield of tram as significant safety feature. The material model of windshield layers (glass, PVB foil, glass) is described with all material parameters. The behaviour of tram windshield model is compared with experiment to prove the model fidelity. The full-scale tram front-end collision simulations with pedestrian are also presented. The results of the simulations are significantly influenced by the windshield model, therefore it is necessary to have a precise material model, validated on an experimental data. The results can predict the crash performance of new tram front-end and consequently the injury risk of the pedestrian.

Collision scenario

The collision scenario defined in the technical guide is based on the statistical data of the tram to pedestrian collisions and also follows the automotive safety scenarios, defined in EuroNCAP [7]. The collision scenario is defined as a moving tram hitting the pedestrian (moving or standing) from his side. The pedestrian is moving perpendicular to the tram trajectory, in front of its front end. The technical report divides the impact into three phases, where the first phase is considered as an impact of the vehicle to the pedestrian. Second phase is an impact of the pedestrian onto the ground and the third impact phase deals with the scenario, where the pedestrian lays on the railway (ground) and can be overrun with the vehicle. The scope of the technical report is focused on the first and third phases. The second phases is connected mainly with urban engineering and material of the surroundings (grass, concrete, pavement, asphalt etc.)

For the first collision scenario (type A) the pedestrians involved in the collision are specified to be mid-size male (175 cm, 78 kg – 50th percentile) and 6 years old (YO) child (110 cm, 24 kg). The report also defines possible impact area and impact zones, with respect to the shape of the vehicle, for more specification, see [1].

The collision scenario evaluating of the first impact considers the tram moving with the initial velocity equals to 20 km/h and pedestrian standing still, left side to the vehicle, one step forward (not specified which leg to be forward) and the lateral position relative to the vehicle has two specifications (H-point with respect to the tram):

- 15 % value of half of the tram width
- 50 % value of half of the tram width

The vehicle does not stop (not loaded with any deceleration pulse) only energy lost due to the impact. The pedestrian injury risk is monitored only with the Head Injury Criteria (HIC), which should not exceed threshold 1000 [8].

Evaluation of the third impact, collision scenario type B, (overrun of the pedestrian) is tested via 4 scenarios (each of them with the adult and child dummy). For this particular test, the dummies are specified to be “adult rescue dummy” (183 cm, 75 kg) and “child rescue dummy” (122 cm, 17 kg). The testing scenarios are defined as follows:

- Test 1: transverse to the rail, centred
- Test 2: transverse to the rail, off centre (hip on the rail)
- Test 3: lengthwise on the rail, centred (feet pointing towards the tram)
- Test 4: lengthwise on the rail, off centre (hip on the rail, feet pointing towards the tram)

This technical report also describes the protective technology to be used and how to be used, the gaps between dummy and vehicle etc. The initial velocity of the tram in this scenario is 25 km/h and after reaching specified position it starts to break within emergency breaking until it stops. The objective of this test is to verify capabilities of the vehicle during crash, with the following parameters [1]:

- to stop any part of the rescue mannequin before the first wheel set
- not to jam the rescue mannequin at its thighs, chest, or head
- not to sever one of the rescue mannequin's limbs so that the rescue mannequin should remain intact
- to push the rescue mannequin away so that it does not come into contact with the wheels
- not to trigger any debris or fracture on impact with the rescue mannequin (risk of aggravating injuries)

The full test protocol is available in the technical report, where all settings of the test are specified. The conclusion of the test indicates whether it meets the objective or not. There is no threshold value specified to pass the tests. Only the position of the pedestrian with respect to the tram is monitored.

Human body model VIRTHUMAN

To represent a pedestrian in the collision scenario, Virthuman (Fig. 1) model is considered. It is a virtual human body model which skeleton is formed of multi-body structure (MBS). Outer surface of the model is formed of deformable segments that are connected to the skeleton via nonlinear springs and dampers to account for deformability of soft tissues. Individual rigid bodies of the MBS structure are interconnected via kinematics joints. Moreover, additional "breakable" joints are considered in lower extremities to account for possible fractures of both femur and tibia of the pedestrian in the collision scenario. The model has been validated extensively to ensure its biofidelity [6]. The basic referential model (50^{th} percentile male) can be scaled using the parameters of height, weight, age and gender. In this case, the 50^{th} percentile male was used corresponding to the Hybrid III dummy (male, 172 cm, 78 kg). Due to the MBS structure, the model is easy to position. In this case, the positions as defined in the chapter "Collision scenario" were considered for the model. There is an embedded algorithm in the model to evaluate standard injury criteria for individual body parts as defined by EuroNCAP testing procedures [7]. In particular, Head Injury Criterion is used in this study to predict injury sustained by the pedestrian in the collision with the tram.

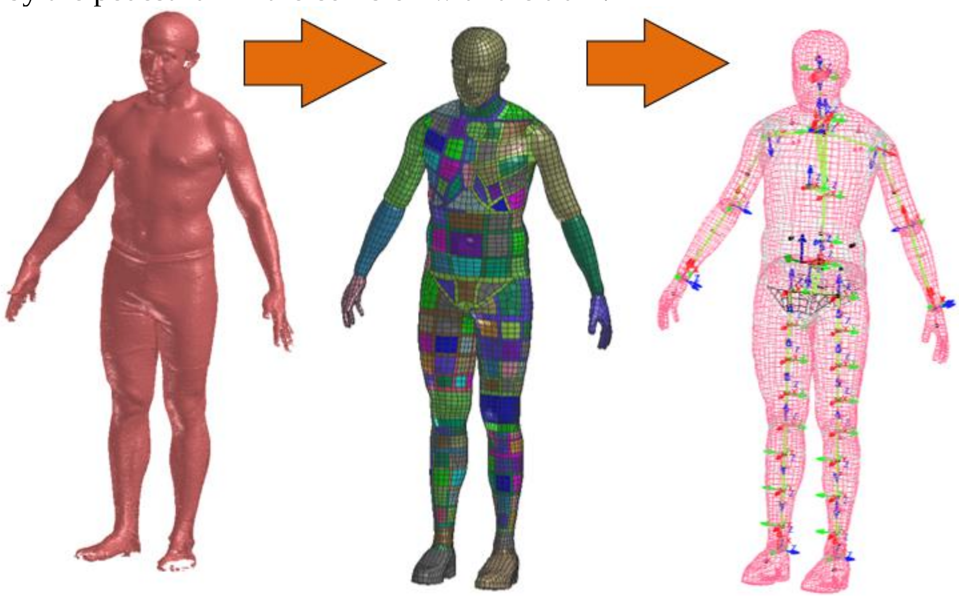

Fig. 1: VIRTHUMAN model CAD data, FE model and Multibody structure

Numerical model of collision

The tram-pedestrian collision is modelled with numerical software (Visual Performance Solution) and human body model described above (Fig. 2). For the dynamic structural analysis (with significant nonlinearities) the explicit integration method is used. The model of the vehicle is created mainly with quad and brick elements with one gauss integration point. The contacts and links (node to segment connection) are realized by penalty algorithm. The model was discretised into 1.6 million elements with the smallest element characteristic length 2 mm (leading to a time step 5e-6 ms). The simulation time of the defined scenario is 390 ms. Mechanical properties of steel S235 and 1.4301 are used from literature. The top shell cover is made from polymer (acrylonitrile butadiene styrene) with acceptable fire protection and recycling possibilities. Unfortunately mechanical properties of this material used in simulation are confidential (courtesy of the company).

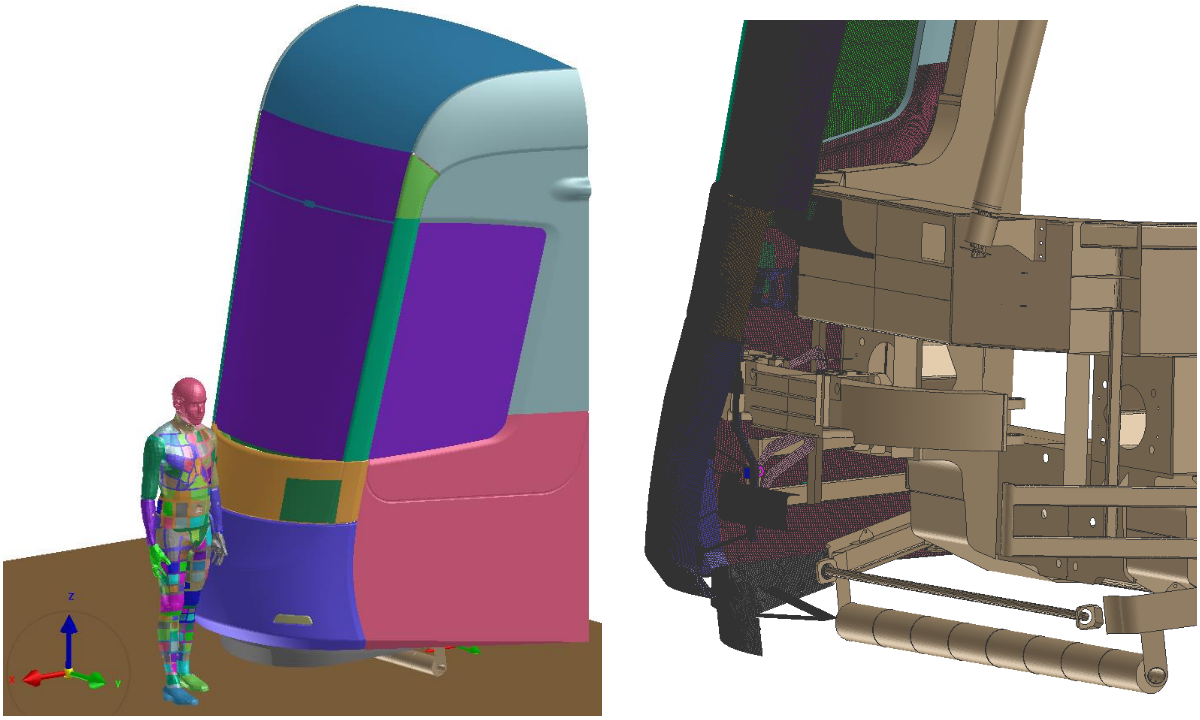

Fig. 2: Numerical model of the collision (left) and detail of tram FE structure (right)

Windshield material model

The approach for windshield modelling is based on the studies connected with automotive industry. The FE model of laminated glass is composed of two outer layers of glass and one inner layer of polyvinyl butyral (PVB) [3]. All layers are modelled with shell elements connected by *tide* node-segment link. The linear acceleration of the head-form impactor were determined by the critical fracture stress [4]. The aim of this work is to build a standard tram windshield model and to experimentally validate this model. The main difference (between road and rail vehicle) is mainly in the thickness of glass and PVB layers. The initial prediction is, that the material behaviour of layers is very similar for the tram and road vehicle. The PVB foil is modelled as an isotropic nonlinear viscoelastic shell element of Maxwell type:

$$\sigma = k(1 - e^{-w\varepsilon})(1 + h_1\varepsilon + h_2\varepsilon^2)\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{ref}}\right)^m \qquad (1)$$

Where $\dot{\varepsilon}$ is the plastic strain rate, $\dot{\varepsilon}_{ref}$ is the reference strain rate, and k, w, m, h_1, h_2 are material constants. The glass is modelled as linear elastic material with a brittle failure criterion. For the fracture definition the Rankine criterion is used and the fracture occurs when the maximum principal stress exceeds the critical value.

$$\sigma = \begin{bmatrix} (1-d_1)\sigma_{11} & (1-d_{max})\sigma_{12} & (1-d_{max})\sigma_{13} \\ (1-d_{max})\sigma_{12} & (1-d_2)\sigma_{22} & (1-d_{max})\sigma_{23} \\ (1-d_{max})\sigma_{13} & (1-d_{max})\sigma_{23} & 0 \end{bmatrix} \qquad (1)$$

where σ is the damaged stress tensor, $\sigma_{11}, \sigma_{12}, .., \sigma_{23}$ are components of undamaged tensor, d_1 and d_2 are damage values in two directions and d_{max} is maximum of d_1 and d_2.

The detailed description of material model parameters is presented below (units mm kg ms). These material parameters are used for tram windshield in simulation with three layers (3 mm outside glass, 0.9 mm PVB foil, 3 mm inside glass) connected with TIED links.

Table 1: Parameters of material model GLASS

MAT TYP	RHO	BELYTS.-TSAY REDUCED INTEGRATION	STIFFNES ELASTIC HOURGLASS	QUADRATIC VISCOSITY MULTIPLY	
126	2.5e-6	0	0	1	
E	NU	MEMBRANE HOURGLASS	OUT OF PLANE HOURGLASS	ROTATION HOURGLASS	TRANS SHARE
70	0.2	0.01	0.01	0.01	0.8333
SIGMAC	TIME FILTER	STIF DAMPING			
0.031	0.01	0.1			

Table 2: Parameters of material model PVB-foil (nonlinear viscoelastic model)

MAT TYP	RHO	BELYTS.-TSAY REDUCED INTEGRATION	STIFFNES ELASTIC HOURGLASS	QUADRATIC VISCOSITY MULTIPLY	
121	1e-6	0	0	1	
E	NU	MEMBRANE HOURGLASS	OUT OF PLANE HOURGLASS	ROTATION HOURGLASS	TRANS SHARE
9	0.39	0.01	0.01	0.01	0.8333
G-SHELL PARAM	k	m	h1	h2	w
	0.007	1.33	1.35	0	3

Experimental validation of windshield numerical model

In order to validate the material model, the simple pendulum test and its numerical simulation (Fig. 3) is used. The pendulum is made of steel profile (50x30 mm, thickness 2 mm, length 2000 mm and 4.41 kg of mass) and the ball (150 mm of diameter and 4.7 kg of mass). The part of windshield is placed on the extruded polystyrene (with known properties) with circular opening with diameter 300 mm. More than 10 tests was performed to get statistically significant results. In most of the tests, the ball was falling from full height (2000 mm). Few tests were executed from a smaller height and also with initial crack on glass or different shape and size of glass. These experimental results are not described here, but significant difference was observed only in the condition of smaller initial height, that theoretically allow the validation for range of initial velocities. The windshield model was validated only for full height with the impact velocity 6 m/s. The acceleration was recorded with accelerometer (PCB 352C33 S/N 120471) and displacement was recorded with high-speed camera (Photron fastcam SA X2 RV). This kinematics conditions are similar to pedestrian head impact during collision with tram (initial speed 20 km/h). The impactor is considered as a rigid to validate the glass model (not for head injury prediction where biofidelic impactor is necessary).

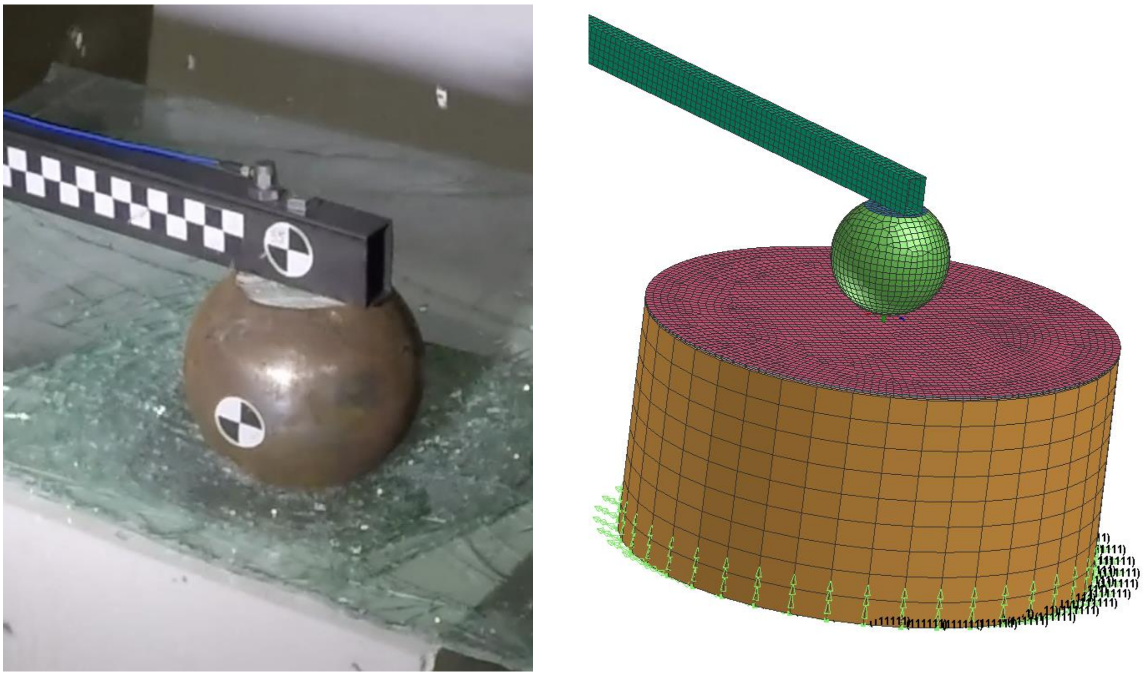

Fig. 3: Experimental test of windshield (left) and simulation for material validation (right)

It is clear that this model cannot exactly predict the crack shape in detail, but it has been discovered that in repeated experiments and simulations the influence of crack shape difference is insignificant. In this phenomena the crack shape has some general similarities in radial and circular direction (Fig 4). Moreover, the acceleration results are influenced by the steel rod oscillations. This is one of the possible improvements for the further experiments.

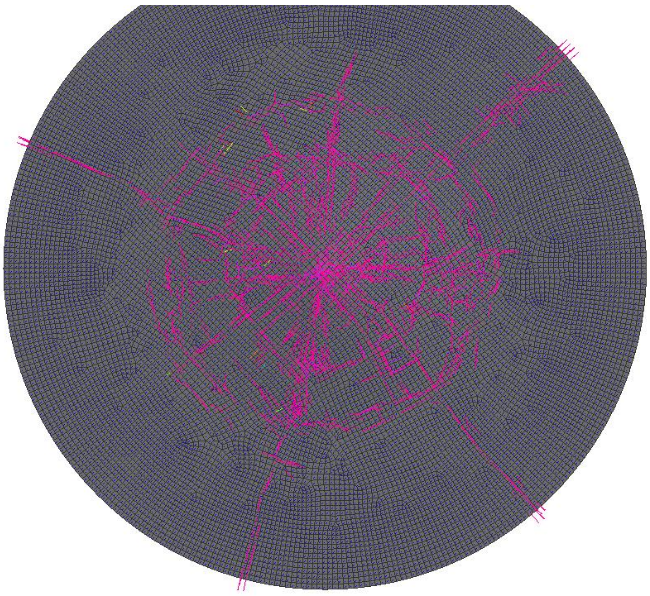

Fig. 4: The windshield glass with damage tensor directions

The comparison of the experimental data and validated numerical model (described above) shows very good coincidence. This coincidence is adequate and good enough for safety simulations and for head impact injury predictions in case of windshield-head impact. The acceleration-time curves are very close to each other (Fig. 5) what indicates similar result of HIC criterion. The deformation characteristics result in a good agreement of an experimental and simulation curves (Fig. 6).

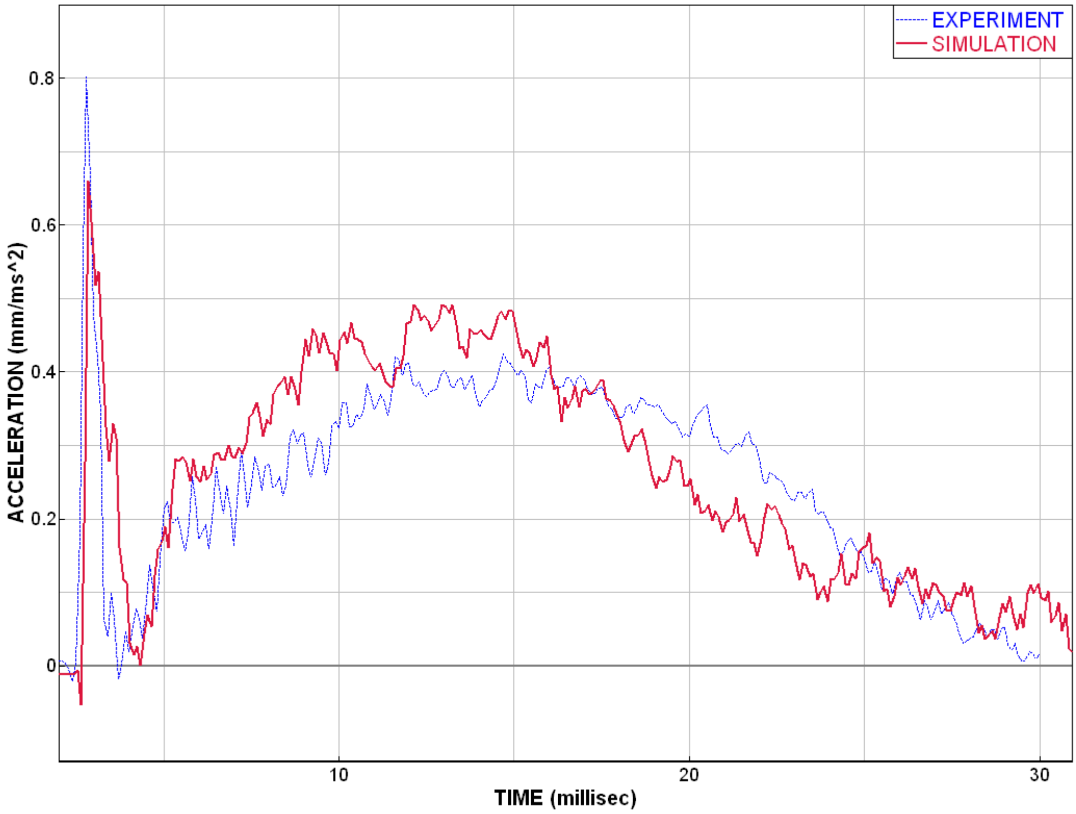

Fig. 5: Plot of the acceleration vs time

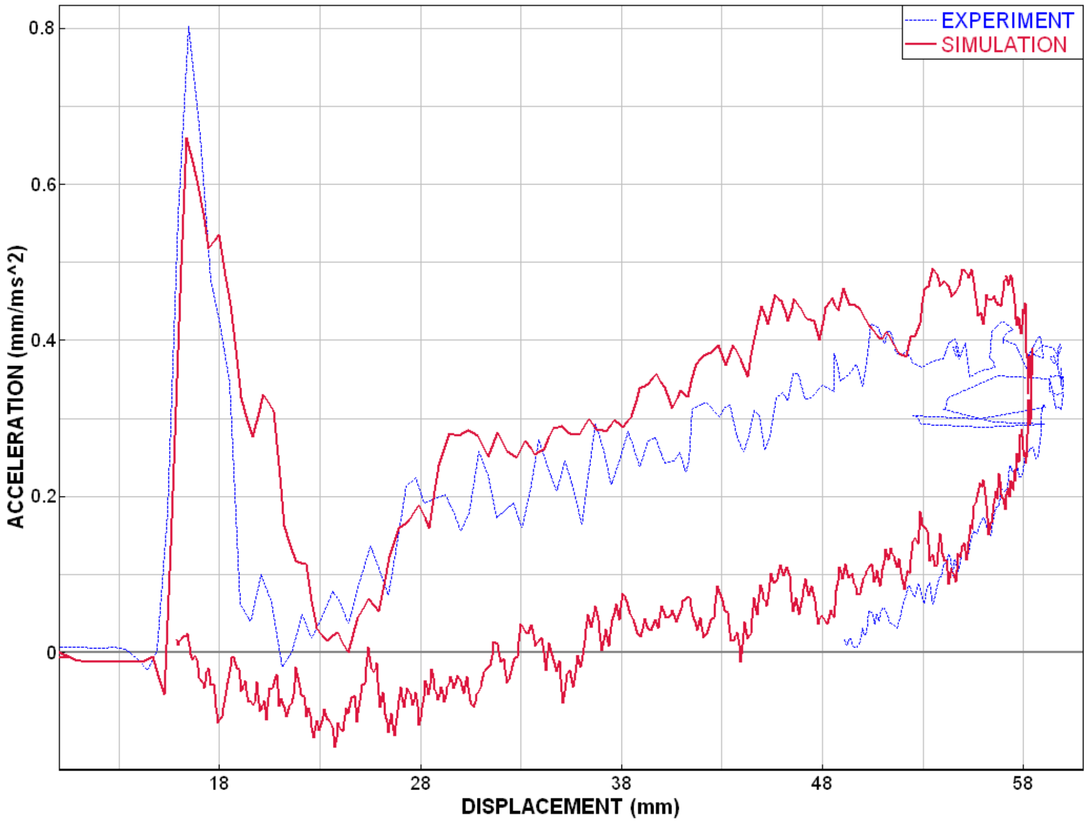

Fig. 6: Plot of the acceleration vs displacement

Simulations results

There are two different set-ups of the simulations. The first type is a collision with standing pedestrian. The second one is a collision with laying pedestrian. All simulations are performed with the same model. The main reason for material model validation is the simulation from field of passive safety. The sequence figures in the time (Fig. 7) shows the detail of the head impact to the tram front-end. This part of collision is the most important, since the head injury connected with significant severity occurs here. It is clearly visible, that the head impact occurs directly to the windshield. However, the head acceleration does not exceed limit of 0.8 mm/ms^2 and the HIC criterion is only 234 (bellow the threshold 1000). This indicates low injury risk of the head.

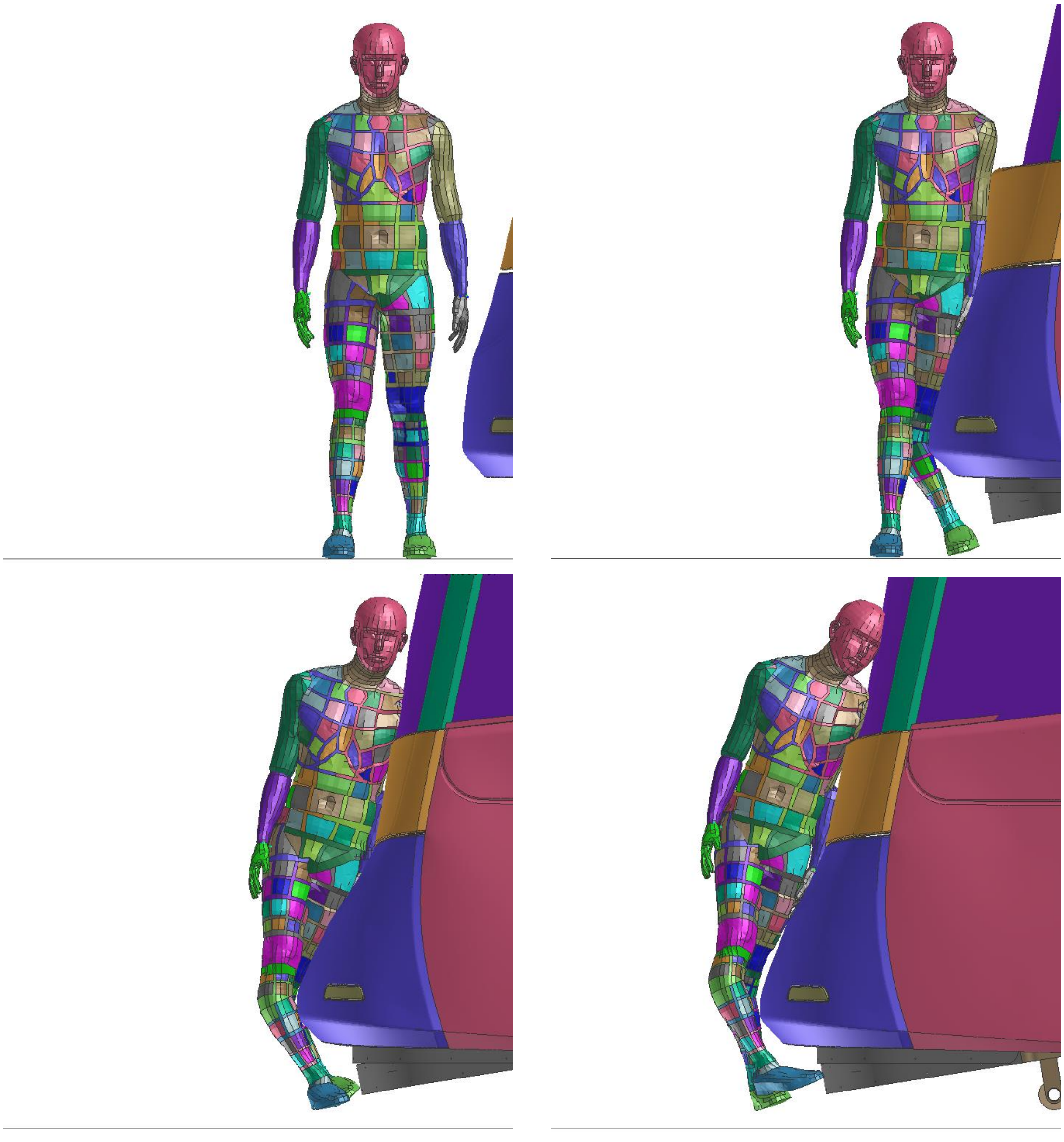

Fig. 7: The results of simulation (in time 0, 25, 50, 75 ms), where the head impacts the windshield

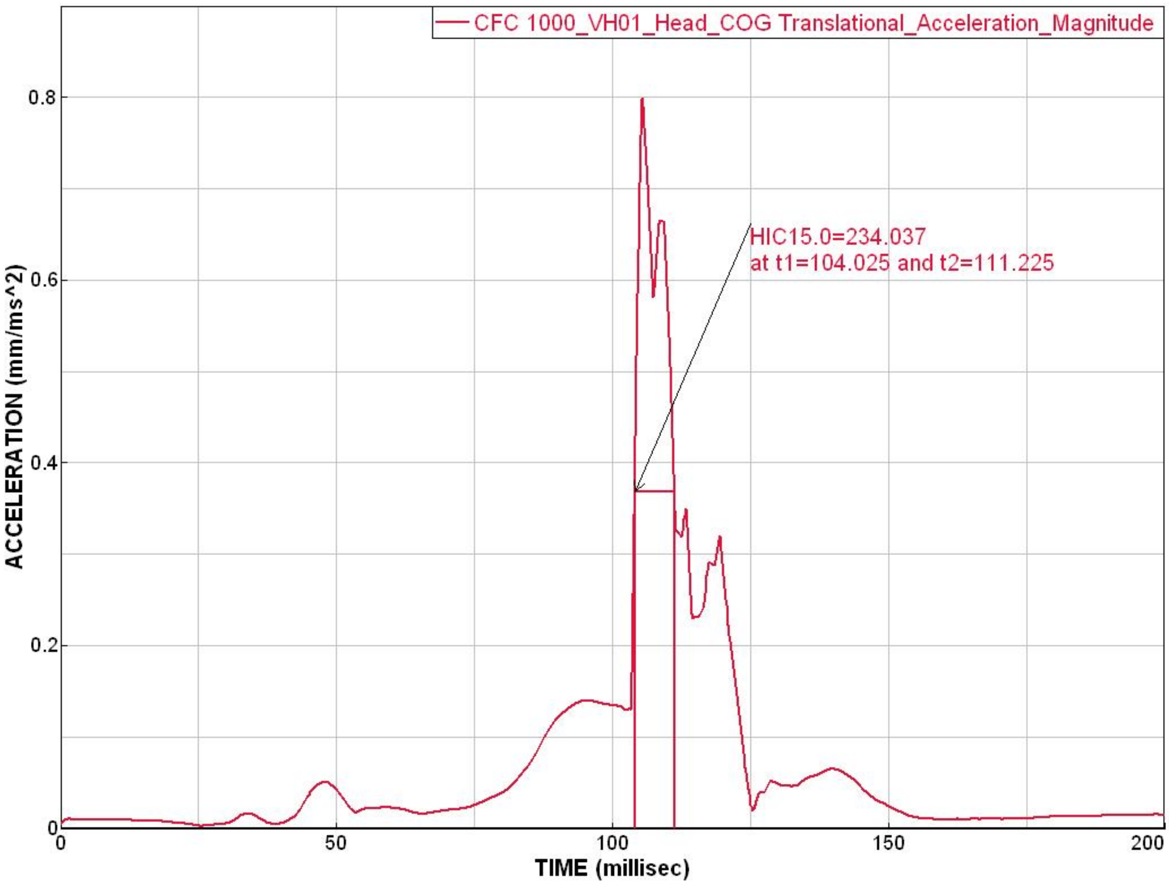

Fig. 8: The acceleration of the COG filtered by CFC1000 filter with HIC15 injury criterion assessment

The collision of tram and laying pedestrian (Fig. 9) shows how the requirements for the pedestrian anti-crush mechanism are met. With the advantages of the simulations the effect of mechanism with correct clearance (100 mm) is visible. It can be said that the injury of laying pedestrian during collision with tram without pedestrian anti-crush mechanism are absolutely fatal (the most of trams has no pedestrian anti-crush mechanism). The design of new tram can save a lot of lives and significantly reduce number and severity of injuries.

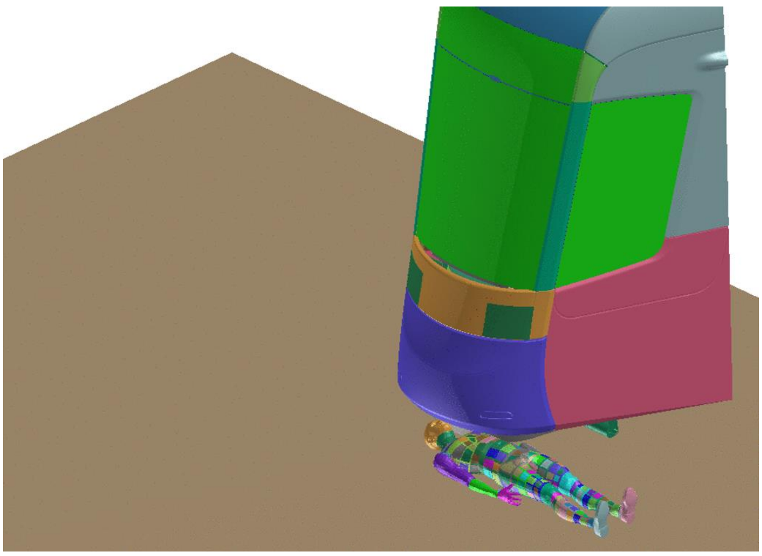

Fig. 9: The result of simulation of tram and laying pedestrian (90 ms)

Conclusions

The collision of tram-pedestrian described in paper was simulated with the advantage of the human body model “Virthuman”. The injury of the pedestrian head (HIC) is highly influenced by the windshield behaviour. The simulation indicates that the defined tram to pedestrian crash scenario results in the HIC value (234) significantly smaller than the threshold limit of 1000. The first results of the experiments suggest very similar material behaviour of tram and road vehicle windshield. Therefore it is possible to use the material model of glass and PVB foil from an automotive industry with modified thickness. The paper contains description of experimental material validation and also material model of windshield (with detail material parameters). The simple pendulum test has some inaccuracies (see above), which can be further improved, but the experimental observations are acceptable for material validation. The results of the simulation (with experimentally validated material) indicate that the windshield is feature with good crashworthiness. The design of tram with low height of bottom windshield is feasible.

Acknowledgment

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