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Full length article

Experimental investigation and finite element analyses of the car dynamic frontal crash

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ABSTRACT

Road accidents and passenger safety in passenger vehicles were a major concern for manufacturers. This has led to the integration and improvement of various safety systems with the ultimate goal of enhancing safety. From a practical perspective, laboratory crash tests were very complex and difficult to implement, and their cost was very high. Hence the importance of designing and developing numerical simulation models to address this issue. Nowadays, finite element methods were commonly used to analyze the crashworthiness and reliability of safety systems. These simulations have therefore become an essential tool for reducing development times in the automotive sector and, above all, reducing costs. In this research, the finite element model was developed using LS-DYNA software, and the reactions of the adult driver during a frontal collision on roads with a speed limit of 90 km/h were numerically studied using 3D mannequin models according to several scenarios. The ultimate objective of this work is to predict the behaviour of an individual inside a vehicle in the event of a collision. The results provide important information on the evolution of the passenger's position (hands, head, legs, neck, thorax, etc.) during a road accident. This study showed that only seat belt only can be restrains the upper torso and thighs and doesn't prevent forward movement of the head and neck in the event of a collision at very high speeds.

Introduction

Nowadays, road safety is one of the most important topics in the automotive industry because they were one of the leading causes of mortality in modern society. Thus, many engineers have increasingly carried out experimental studies to improve the road safety of their finished products incorporate a wide range of safety devices and features into their vehicles [1–3]. In order to better protect passengers, the safety rules developed for cars were increasingly strict. It has also become one of the key design considerations in the automotive industry and a powerful selling point [4–7]. Furthermore, the primary priority of the automotive industry is really to ensure that passengers do not suffer injuries caused primarily by very high inertia forces.

However, crashworthiness tests were often implemented for the automotive industry. They were intended primarily to represent most real-world situations, such as vehicle-to-fixed and vehicle-to-vehicle, with very significant frontal engagement [5,6]. However, these tests were required appropriate facilities, one or more cars with measuring devices, experienced staff and a long time to prepare. It means they were complicated, expensive, long-lasting and therefore not easy to realise (See Fig. 1). As a result, the numerical simulation of crash test procedures has become of primary importance. It allows the designer to predict the behaviour and optimise the structure performance on the very early stage of the development [7–11].

Therefore, finite element numerical simulation was becoming more and more essential in road safety, which replaces the majority of the vehicle destruction in crash tests. Therefore, finite element (FE) simulation was a valuable tool before real tests to study critical parameters, thus reducing the cost incurred on these tests [9,10]. It was used to precisely analyse road accidents in different situations and to model the resistance to different impacts of vehicles [11,12]. Nowadays, the finite element method was increasingly considered as the most appropriate analysis and calculation method to accurately provide the most accurate information on vehicle crash analysis. However, this less expensive approach now requires powerful hardware resources to produce accurate results [13–15].

Many research works have recently attempted to use different numerical simulations to model crash tests. Marler et al. (2006) performed

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a system identification for a frontal vehicle crash using a multi-objective optimisation approach using the front of the vehicle modelled as a 3-DOF system [16]. Then, Ofochebe et al. (2015) studied the performance of a vehicle front structure using a lumped mass-spring model. This model with a 5-DOF was composed of body, engine, the cross-member, the suspension, and the bumper masses [16]. This was also taken into account in our model that composed of mass-spring with 5 degrees of freedom.

Hickey et al. (2017) analysed several car crashes using their Ford Explorer model. The conclusion given in this study was to replace destructive vehicle testing with numerical simulations in terms of time saving and cost-effectiveness [17]. This was consistent with other scientific work showing that simulations were increasingly gaining ground in replacing destructive vehicle testing thanks to cost savings and reduced of development time. Klausen et al. (2014, 2015) introduced a firefly optimisation method to estimate parameters of vehicle crash test based on a single mass-spring-damper model [18,19]. These parameters were also directly estimated in our study via the FE model based on this mass-spring-damper system.

Recently, Mazurkiewicz et al. (2018) proposed models to improve the safety of children during a vehicle crash subjected to a side impact [20]. Gabler et al. developed also models for vehicle crashes using the commercial code to extract the influential parameters during crash test [21]. Safari et al. simulated a full-frontal impact, side-impact and roof crush for a Dodge Neon vehicle to assess the structural crashworthiness. They showed that Advanced High Strength Steel materials, due to their excellent properties, have considerable potential for assessing a vehicle's crash safety performance [22]. In our study, the proposed model is complex because it takes into account the presence of an adult driver, whether or not they were belted, in the driving position inside a passenger compartment. This has been done through the different materials used and their behaviour laws, the different possible contacts with the different elements of the passenger compartment, and the use of adaptive meshing, etc.

Vangi et al. proposed a new procedure to collect data for a both vehicles accident reconstruction [23].

Beik et al. assessed the effectiveness of tapering S-rails in the automotive application using finite element method. They showed the reinforcing and tapering S-rails both could improve the energy absorption and specific energy absorption in static and dynamic loading conditions [24].

Tso-Liang et al. analysed the response of a human body in a car accident. They were able to assess injuries sustained mainly in areas such as the occupant's head, chest and pelvic [25].

Muhammad et al. studied via an FE model, automobile crash tests using ANSYS Explicit for three different conditions (a car collides first with a wall, second with another parked car and finally with a moving car). They concluded that the use of aluminium alloy was is reliable and safe [26]. Ambati et al. studied frontal collisions with the rigid barrier of a Chevrolet C1500 type car using the LS-DYNA software. It was found that the internal chassis of the car allowed maximum energy to be absorbed with minimum deformation and that the latter was transferred to the passenger cabin [27]. Bruski et al. developed a numerical FE model and validated it with a large-scale crash test of a passenger car equipped with a 3-cable high-voltage barrier system [28]. Mazurkiewicz et al. proposed models to improve the safety of children during a vehicle crash subjected to a side impact [29].

The aim of our work, it's to analyse the behaviour of the perfectly belted driver during a car crash with fixed-object using finite element numerical models.

In this paper, LsDyna explicit code was used to numerically simulate frontal crash of vehicle with at the rigid obstacle.

This paper proposes an FE model to modelling a crash test when taking into account the presence of an adult driver. Using this approach was complex to analyse driver behaviour allows a better understanding of risks. The main contribution of this paper was our modelling of adult driver behaviour by analysing longitudinal and lateral displacements and also rotation angle of shoulders in different scenarios. The objective was to evaluate the effect of seat belts on the behaviour and posture adopted by the driver in several configurations (see Fig. 2).

We mainly wish to analyse the behaviour of the driver, whether perfectly belted or not, and also the influence of the collusion speed in this type of accident (see Figs. 2 and 3). In this study, the vehicle was assumed to move in right angle against the at the obstacle. The shape of the road, straight or curved road was not considered in this study.

The both main scientific contributions of this paper were summarised as follows:

(1) Model takes into account contact with any elements inside the simplified vehicle cabin. Different contact control cards have been identified and included in the model.

(2) Degrees of freedom of the 18 elements constituting the model driver have been carefully adjusted and imposed in order to reproduce reality as much as possible and facilitate the study of the driver behaviour, his reaction and his movement in the passenger compartment during the collision, i.e Increasing the degrees of freedom.

Finite element simulation of crash test

For allowed us to understand the possible injury mechanisms involved pf passengers in accidents, the FE methods has been used with LS-DYNA software was used. They were realised to simulate a real-life vehicle crash involving a belted driver or not belted.

However, numerical simulations of frontal collisions were simulated under different test conditions. These were used a passenger vehicle model with a dummy, either perfectly belted or unbelted, moving at a speed greater than or equal to 50 km/h.

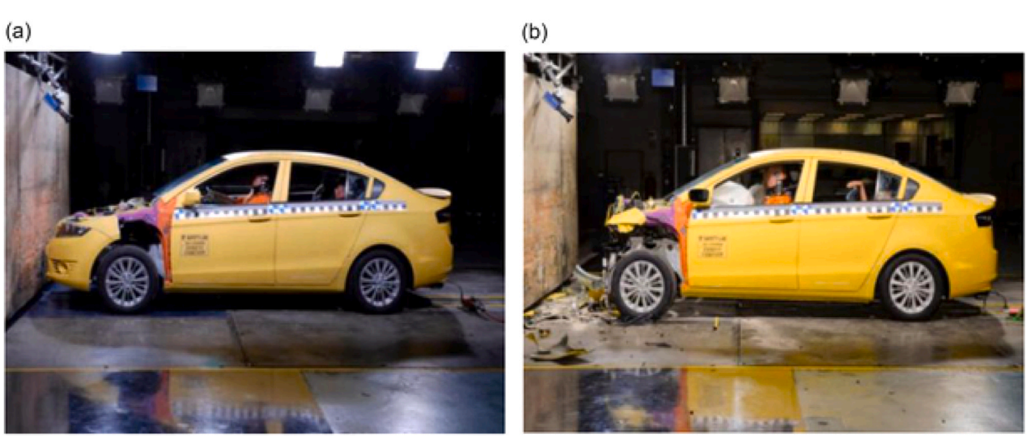

Fig. 1. Frontal Crash Testing [8].

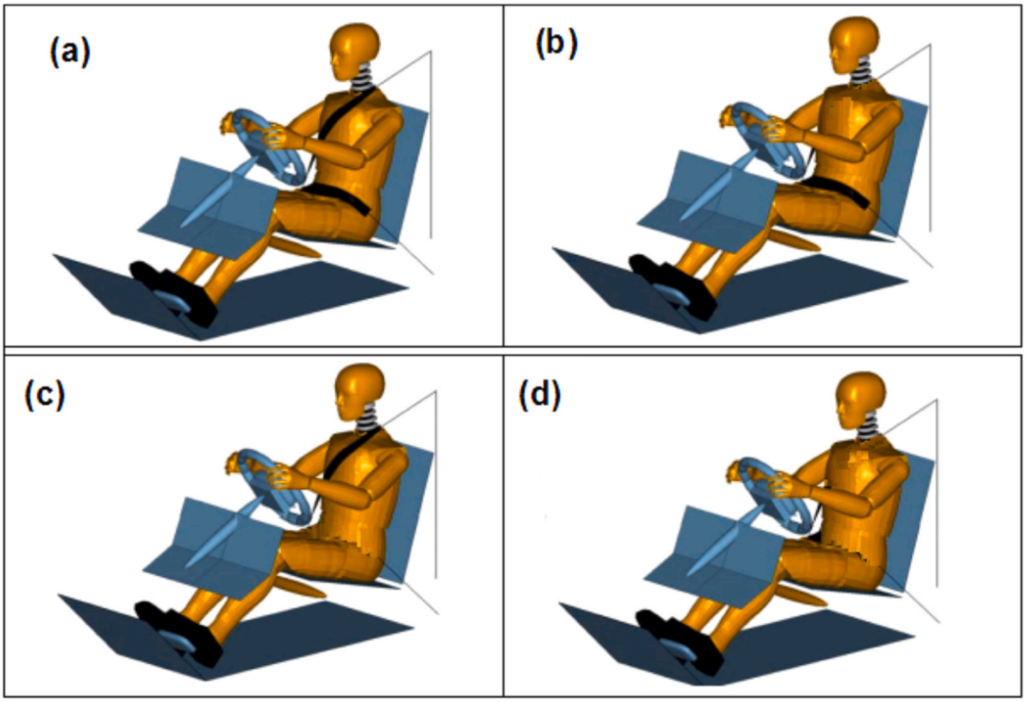

Fig. 2. Seating position of an adult driver: (a) belted, (b) and (c) secured with an high or low strap and (d) without seat belt.

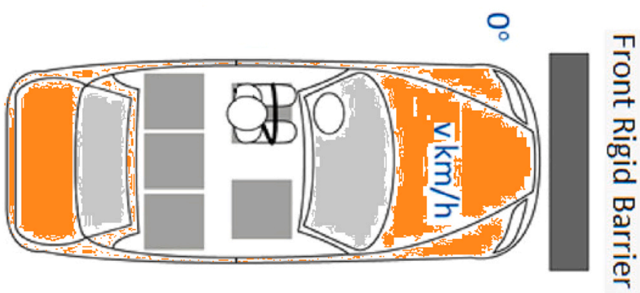

Fig. 3. Frontal collision with a rigid barrier.

In this study, the FE analysis carried out includes different stages: the creation of the geometric model, the discretization, the specification of the constitutive laws of the material, the definition of the contact elements, the boundary and initial conditions and the insertion of the dummies in the vehicle.

The modelled vehicle essentially consists of only the parts likely to be in contact with the driver (see Fig. 4). However, in this case, explicit LS-DYNA should be used, due to the highly nonlinear transient dynamics phenomenon during crash tests. (see Fig. 5).

The statistical human geometry models developed predict thousands of points that define the body posture [31,32], the size and shape of the external body surface [34], and rib cage [33–35] and lower extremity bone geometries [36]. It has been scaled to match the body morphology of an adult used for the crash test. These dimensions were measured on a 35-year-old adult that was 1.74 m for 70 kg (See Fig. 6). This made it possible to define the external dimensions for our dummies by palpation. In total, about 50 measurements were taken of the seated posture. The FE dummies model was consisting of 19 rigid bodies (see Fig. 7).

The dummies and the vehicle were meshed separately then assembled and the complete model includes in total more than 111 components, 54,000 elements and 11,060 nodes with a characteristic size of 0.8–1 mm (see Fig. 8). Different contacts were defined between the head and the different elements of the dashboard and/or the windshield. This contact was defined under Lsdyna by a Coulomb type contact with a

Fig. 4. Comparison between the geometry of the vehicle and its simplified 3D digital model.

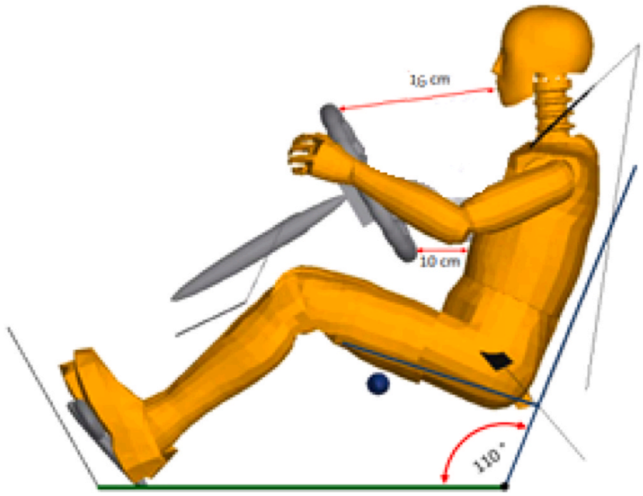

Fig. 5. Descriptive diagram of an adult driver in a seated position facing an airbag [30].

coefficient of friction of 0.2.

In addition, the mechanical behaviour of the seat belt was reproduced by a MAT_060 type material. The chassis, the backrest, the seat and the roof as well as the windshield were modelled using a material of type MAT_RIGID and MAT_BRITTLE, respectively. A MAT_004 type material was also selected to model the behaviour of the thermoplastic polymer conductor.

These FE dummies can have been then be placed inside in the vehicle, the same posture i.e., sitting position and then the crash-simulation has been performed. They can provide various insights into the dynamic behaviour of the human body in the event of a crash. It was considered that the driver was completely belted or not belted. The complete 3D model was as shown in Fig. 8.

The simulations have been performed in a standard shock configuration with dummies perfectly belted or not at a speed greater, when impacted by the front of a vehicle at different speeds between 50 km/h and 90 km/h.

The advantage of such a modelling was to make it possible to simulate the overall behaviour of the system with simplified geometries. They allow also to confront qualitative elements such as the kinematic behaviour of a victim driver (body movement, impact points …).

Materials and experimental set-ups

Tensile tests were carried out on the Lloyd EZ20 universal tensile machine at the mechanical testing laboratory of the University of Constantine (Algeria). They were realised to determine the thermophysical properties of several elements such as the seat belt, the mannequin, and the metal chair stands. They were also used to identify the behavioural law parameters used to develop our simulation model.

The material chosen of the car parts as the bumper was AISI 304 L steel which was the most widely used among all steels due to its weldability and excellent toughness. Then, the chassis cover and the roof were used an AA5052 aluminium for its lightness, excellent mechanical characteristics and recyclability. Finally, the car's dashboard and windshield were supposed to be made of polypropylene and glass, respectively. The mechanical properties of the materials were related in Table 1.

Different samples were cut according to certain standards from the base material. For example, the specimens were cut from an aluminium or steel plates using water jet technology with a dimension of 200 mm × 20 mm × 3 mm rendering to ASTM E8M standard. Each tensile test for a given material was conducted on five samples at room temperature. Then, the seat belt, rectangular samples with a length of 200 mm and a width of 40 mm were cut. Seat belt straps were made of polyester and polyamide fibres was gripped between the clamps and subjected to quasi-static axial tensioning. It was increased until they broke.

Axial force and displacement acquired during a tensile test were converted into stress and strain from a continuous recording of tensile tests was carried out during the loading and unloading phases (see Fig. 9). These tests were conducted at a crosshead speed of 1 mm/min using max 100 kN.

The tensile results were illustrated in Fig. 10 which present the standard mechanical behaviour obtained from tensile tests on aluminium AA5052 or steel AISI 304 L specimens cut from thin sheets. From these curves, the mechanical properties ($\sigma_{0.2}$, s_{ut} and e_f) have been extracted. Fig. 11 shows the tensile fractured specimens.

The results of measurements of the breaking strength of seat belt straps were presented. During the tests, the force-displacement curves were plotted (see Fig. 12).

Identification methodology and comparison between experiment and modelling

One part of the initial kinetic energy was transformed into elastic and plastic energy due to the frontal impact following a collision of the vehicle with an obstacle. This deformation can be taken into account via several behaviour laws with parameters to be identified and then validated using experimental tests to be set up. In our study, the Johnson-Cook model was used [36].

$$\sigma = (A + B\varepsilon^n)\left[1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon_0}}\right)\right]\left[1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right]$$

In this equation, *A, B* and C were the initial yield stress, strain hardening coefficient and reference strain rate coefficient, n was the strain hardening exponent, $\varepsilon_p^{\cdot}$ was the rate of plastic strain. The thermal softening parameter was denoted by *m*. The Johnson-Cook model parameters for AA5052 and AISI 304 L, which were listed in Table 2.

The fitness function of the genetic algorithm was obtained from the least squares principle as follows [37]:

$$(A, B, n, C, m) = \kappa_1\left(\sum_{\iota=1}^{N}\left[\frac{A + B\varepsilon_{AB}^n(\iota)}{\sigma_{AB}}\left(1 + C\ln\left(\frac{\dot{\varepsilon}_{AB}(\iota)}{\dot{\varepsilon}_0}\right)\right)\left(1 - \left(\frac{T_{AB(\iota)} - T_r}{T_m - T_r}\right)^m\right) - 1\right]^2\right)$$

N represents the experimental groups number, k1 refers to a proportionality constant value −1 and i expresses the experimental sequence number.

At the end of the identification process, a set of parameters was determined and then validated (see Table 2). For monotonic tensile loadings, both experimental and modelling approaches provide fairly similar responses in terms of stress evolution versus function of strain,

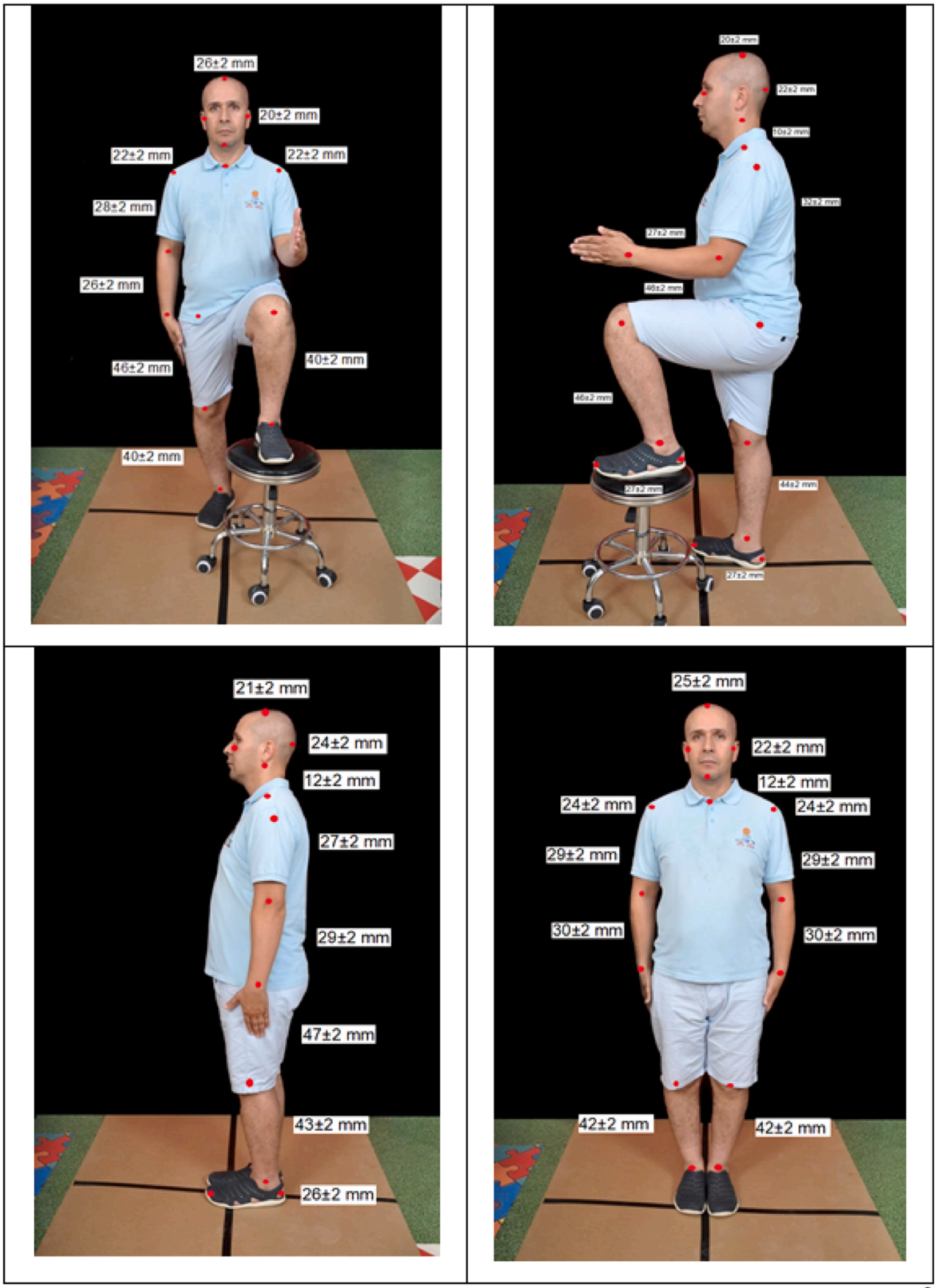

Fig. 6. Photographs of an adult driver in calibrated space.

with better prediction in the elastic part. For example, the modelling data shows that the law of elastoplastic behaviour makes it possible to correctly reproduce the mechanical response obtained on DP steel specimens with a maximum average gap of 8 % (see Fig. 13). On the elastic part the model was perfectly accurate with respect to the experimental data. Some discrepancies were observed at the beginning of the inelastic behaviour. However, we can therefore admit that these results were valid.

Similarly, we also simulated the mechanical behaviour of a seat belt experimentally characterised by hyper-elastic behaviour. Fig. 14 illustrates the stress-strain curves from the constitutive law model used in this study and compared with the experimental results from tensile tests. The result of the evolution of stresses as a function of deformation was satisfactory and in good agreement with experiment with a maximum average gap of 3 %.

Numerical results and discussions

The numerical simulations were carried-out according to the different scenarios proposed previously on Fig. 2 using finites elements LS-DYNA software to simulated a driver behaviour, these reactions and the possible injuries risk. Moreover, different simulations were compared to provide a clear overview of the differences in posture taken by a driver following a frontal collision using at different impact speed of

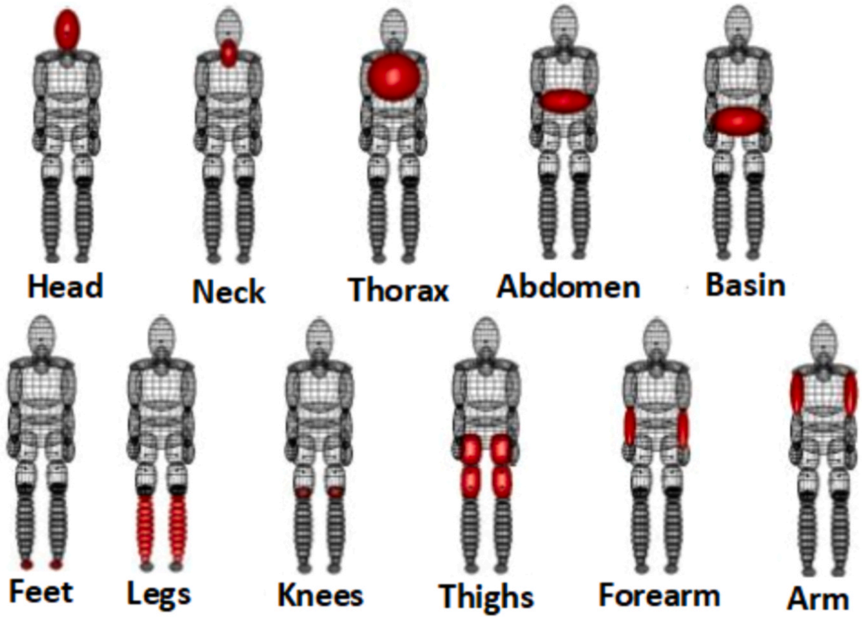

Fig. 7. Decomposition of the multi-body model of the vulnerable user.

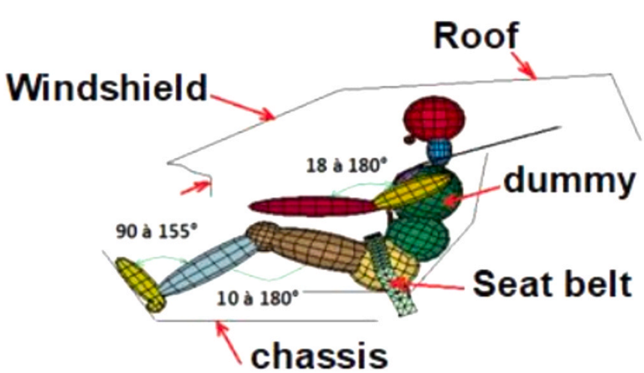

Fig. 8. Full-scale crash simulation in LsDyna Explicit at car crashes at different speeds between 50 km/h and 90 km/h.

Table 1
Comparison of properties between AL-AA5052 and other materials.

Materials	Density [kg/ m^3]	Elasticity modulus [GPa]	Yield stress [MPa]	Poisson's ratio	Elongation at break [%]
AA5052	2700	69	320	0.34	10
AISI 304 L	7800	210	340	0.29	15
PP plastic	1400	1.6	14	0.40	300
Glass	2230	69	80	0.30	3
Polyester	1200	10.6	8.3	0.38	2.5

50 km/h, 70 km/h or 90 km/h.

Driver without a seatbelt

In a driving situation without a seatbelt, the vehicle driver can easily interact and dangerous unsafely with the vehicle's interior while trying to resist the forward movement during frontal crash. We can clearly see the risks of driving without a seatbelt. The body of the unbelted passenger moves dangerously inside the vehicle, the head violently hits the rigid windshield, as illustrated in Fig. 15. The passenger risks being thrown out of the vehicle at any time, which could aggravate their injuries.

Driver with low strap of seatbelt

To follow up on this firstly analysis, a second scenario was simulated with this time a driver partially belted at the pelvis (low strap, see Fig. 16). But in the case, it was observed that the head took a more dangerous posture because it was positioned very forward until dangerously collide with the rigid windshield. The impact of the head clearly results in a higher acceleration of the passenger's head even though his abdomen was well held by the lower part of the seat belt throughout the entire phase of the accident (see Fig. 16). At around 122 ms, we can also see that the driver's head risks violently touching his knees. Therefore, the importance of the presence of the seat belt only on the abdomen was evident while driving the vehicle. In fact, this partially ensures the driver but in no case can it alone ensure the total protection of the driver inside the vehicle.

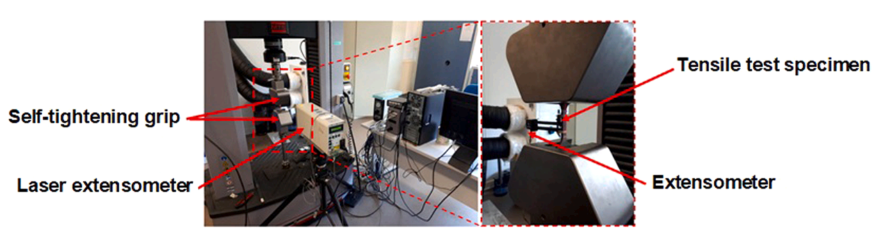

Fig. 9. A photograph of Lloyd EZ20 universal testing.

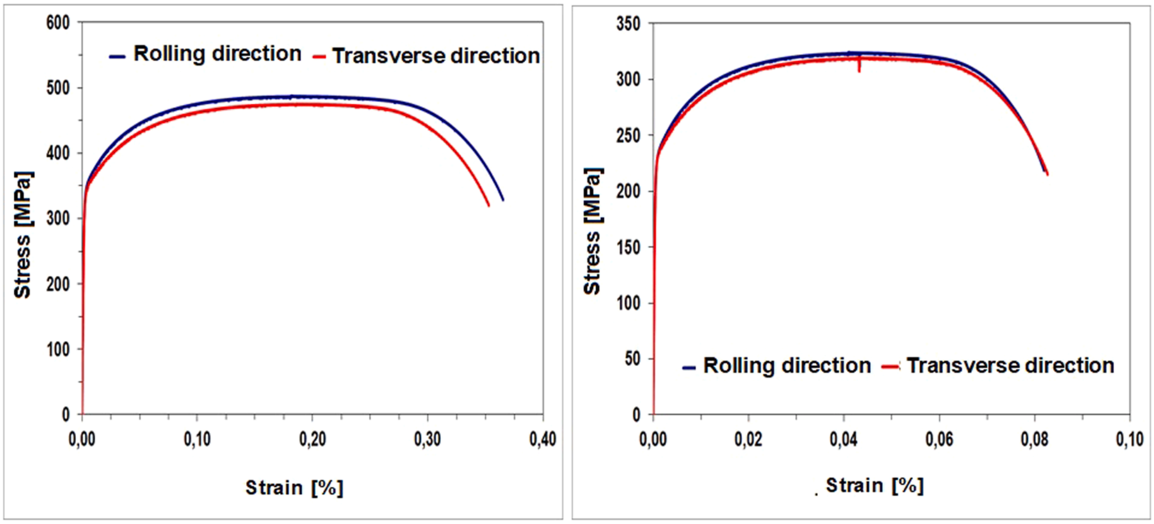

Fig. 10. Stress versus strain using Lloyd EZ20 machine for: (a) aluminium AA5052 and (b) AISI 304 L.

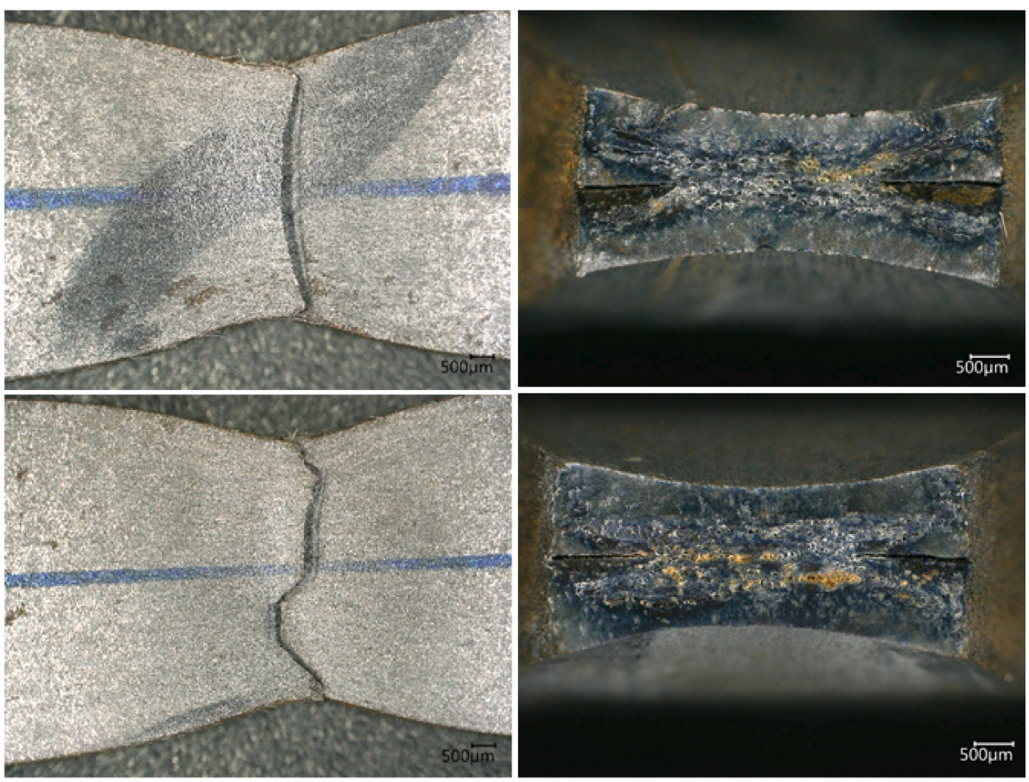

Fig. 11. The photographs of fracture specimens of AISI 304 L.

Driver with high lap of seatbelt

Thirdly scenario was considered for this crash test which consists of simulating the behaviour of a partially belted driver. Fig. 17 illustrates the response given by the numerical simulations for the case of a vehicle driver attached only at the shoulder and chest by the upper part of the seat belt (diagonal seat belt) i.e. without the strap low.

We see that during the first 20 ms, the driver risks sliding slightly forward. At approximately 57 ms, this driver was restrained only by the upper portion of the seat belt, which holds the upper body toward the seat. While the passenger's head tilts dangerously forward. At around 90 ms, we can clearly see that the vehicle passenger risks sliding under the seat belt while their legs risk hitting the dashboard violently.

Driver with seatbelt

The images succession at time intervals 0, 0.05, 0.10 and 0.15 s illustrated below represents the moments numerical results given by the FE model on the driver reactions during the phase of accident, shown for example in Fig. 18. We were noted that the position and kinematics of the driver correct-belted during the accident remained stable inside the passenger compartment and secure at all times for a ride to 50 km/h (no contact with a rigid obstacle).

We can also see that the movements of the driver's body for a ride to

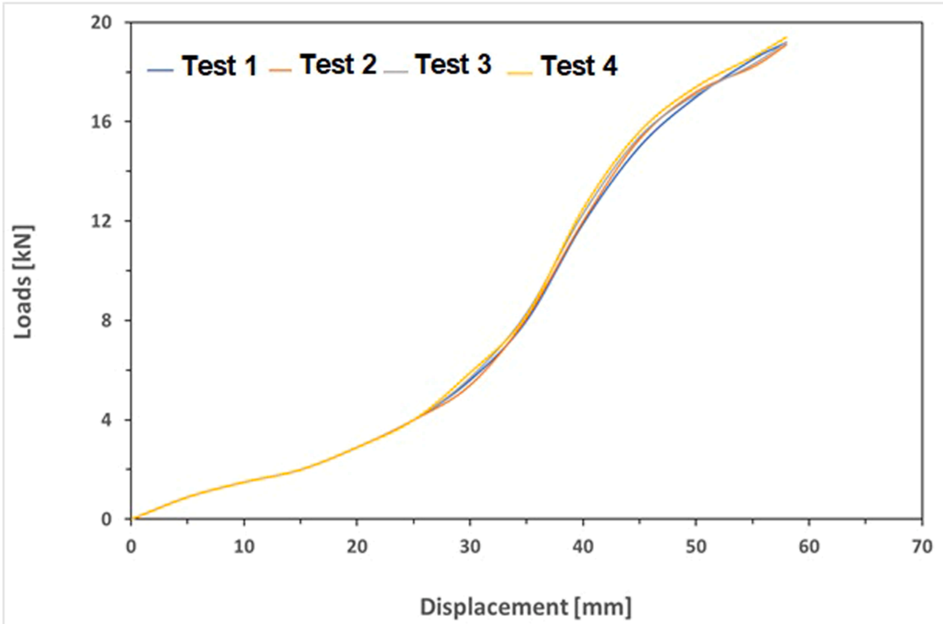

Fig. 12. Load versus displacement using Lloyd EZ20 machine.

Table 2
Johnson-Cook strength model parameters for AA5052 and AISI 304 L.

Parameters	Values	
	AA5052	AISI 304 L
Initial Yield Stress A	176.6	239
Hardening Constant B	289.4	522
Hardening exponent N	0.3712	0.65
Strain Rate Constant C	0.001	0.02
Thermal Softening Exponent m	1	1
Reference Strain Rate (/sec)	1	1

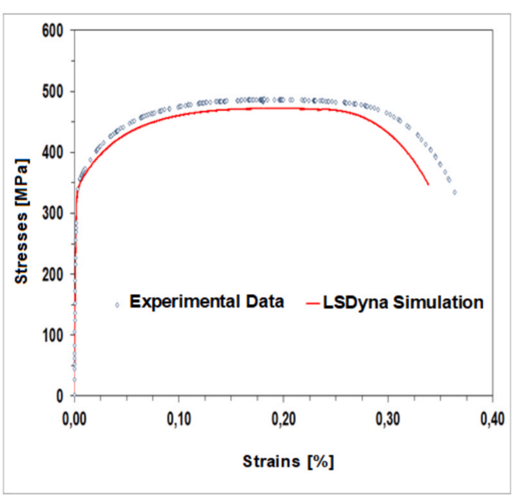

Fig. 13. Comparison of results between experimental and simulation at room temperature in the rolling direction of a DP steel specimen.

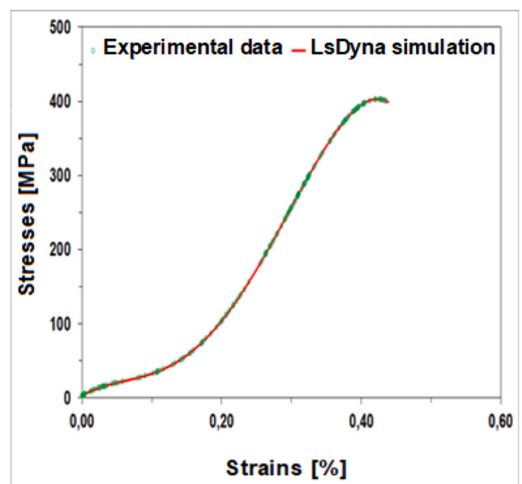

Fig. 14. Stress vs strain curves of seat belt compared to the experimental results under large deformation.

70 km/hm have an identical overall appearance, only the angle of inclination of the head, the torso and the angle of rotation of the upper part of the body differ (see Fig. 19). They were proportionally sensitive to the value of the impact speed. For example, the frontal collision at 90 km/h, the angle of inclination of the head and torso equal to 33° and 37° respectively. This phenomenon was naturally observed in real driving during a sudden frontal collision. At the moment of impact, it was accompanied by a forward separation of the driver's torso from the seat back. This was mainly due to the inertia of the vehicle at the time of impact and the presence of the seat belt, which acts backwards during this phase.

The use of the seat belt provides only limited assistance in positioning or retracting the occupant in the driver's seat.

By comparing different situations, it was clear that the use of the belt with its two lower and upper parts presented as the most likely secure Finally, the analysis also showed that under the same conditions, the dynamic behaviour of the driver was completely different in the case of a vulnerable or poorly belted user.

The effective strain results of the FE simulation during braking before frontal collision show that the safety belt for assures controllable absorption of vehicle's energy during braking, which increases the safety of the vehicle occupants (see Fig. 20).

The belted were designed to provide an acceptable level of safety for the occupant, cannot guarantee the safety in all real-world collisions.

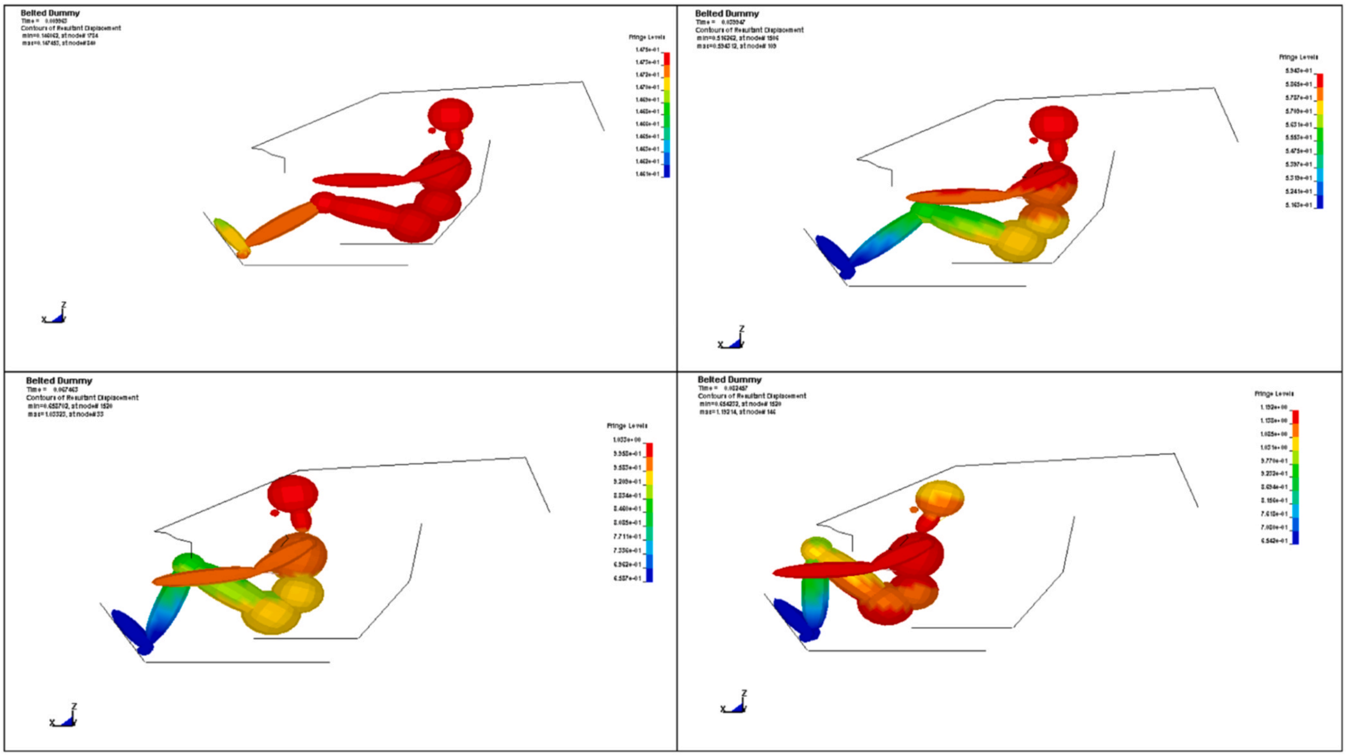

Fig. 15. Frontal-crash simulation in which dummy model is without a seatbelt.

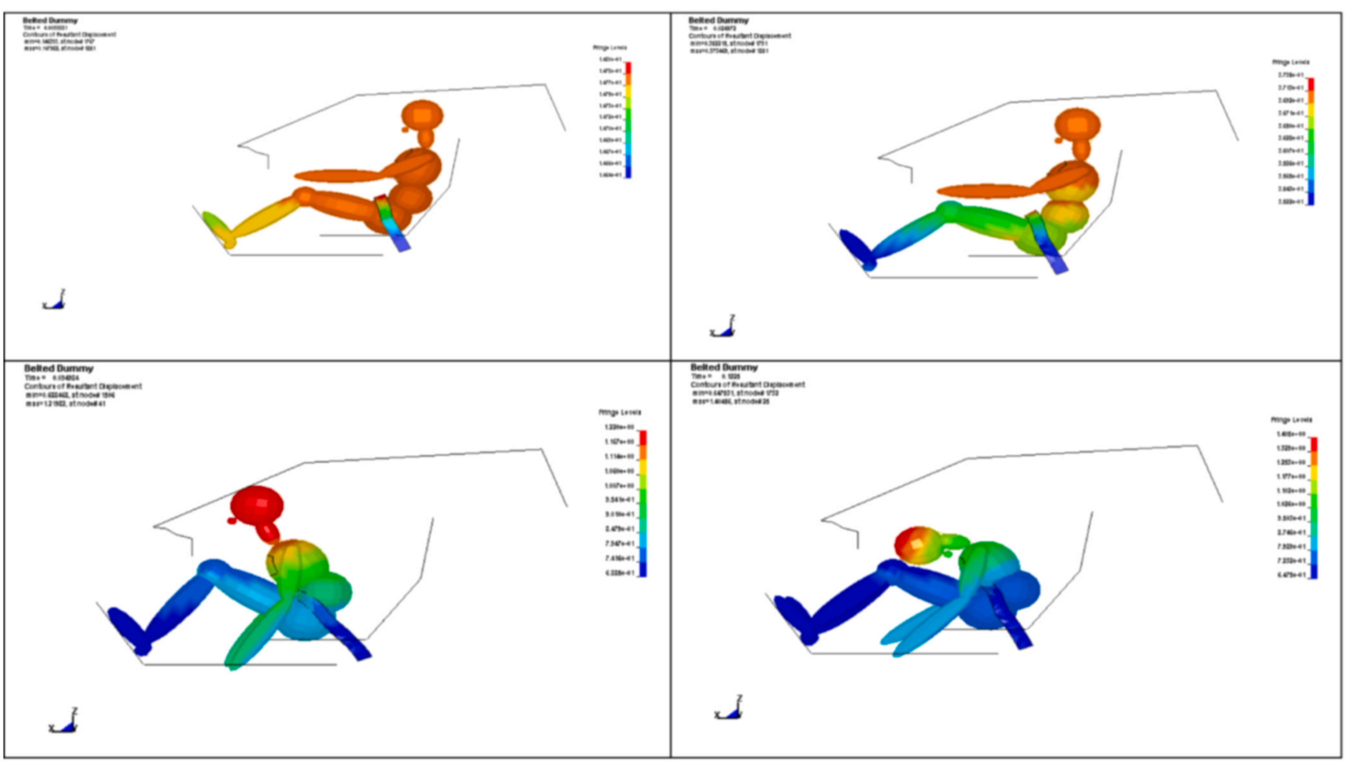

Fig. 16. Frontal-crash simulation in which dummy model was with a low strap.

The following figure shows the driver belted position to the abdomen and the thorax before the moment of impact at 70 km/h. The results of the study demonstrate that the vehicle passenger don't interact with the vehicle interior when braking. The safety belt assures maintaining the passenger position during braking, but doesn't guarantee the protection of the head nor avoid serious head injuries as whiplash injuries associated with auto collisions (see Fig. 21).

The energy balance of a system in an impact was governed by the law of conservation of energy. In case of an impact the kinetic energy possessed by the system in motion was converted into potential energy,

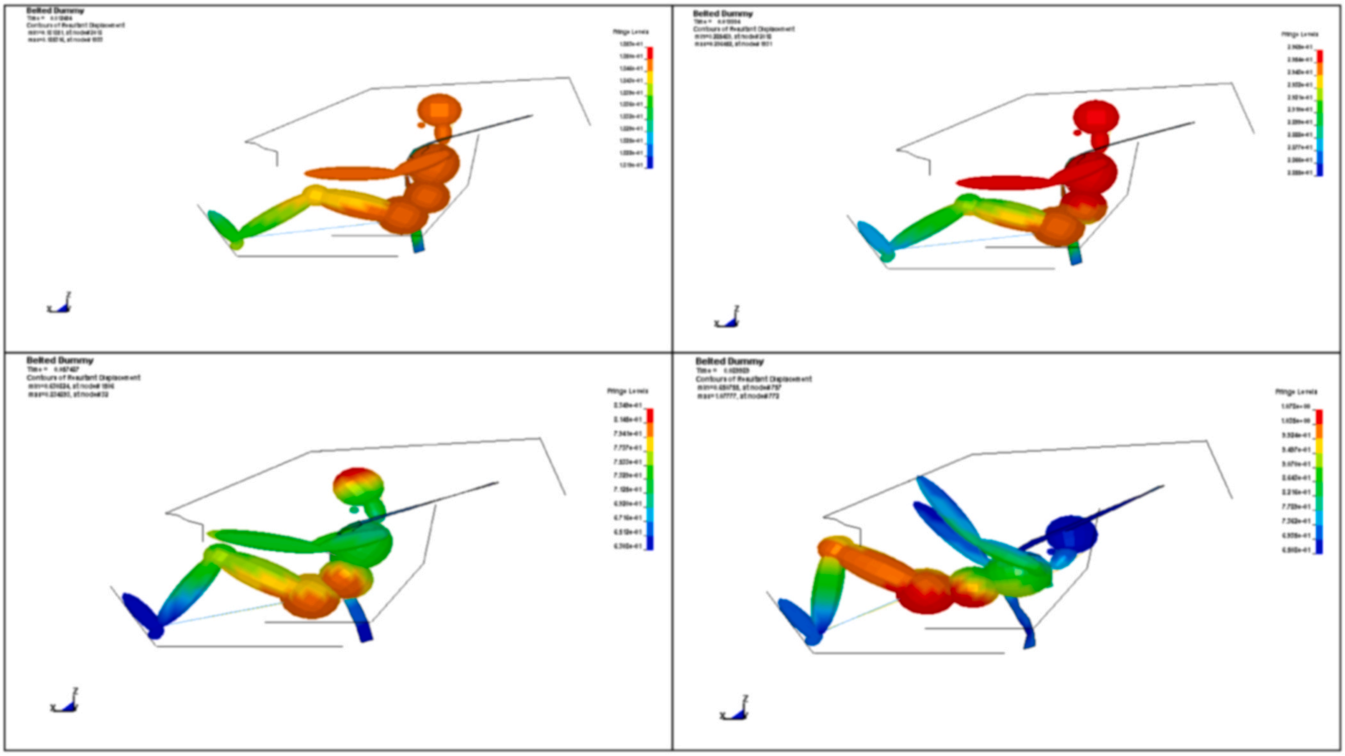

Fig. 17. Frontal-crash simulation in which dummy model was with the seat diagonal belt without the strap low.

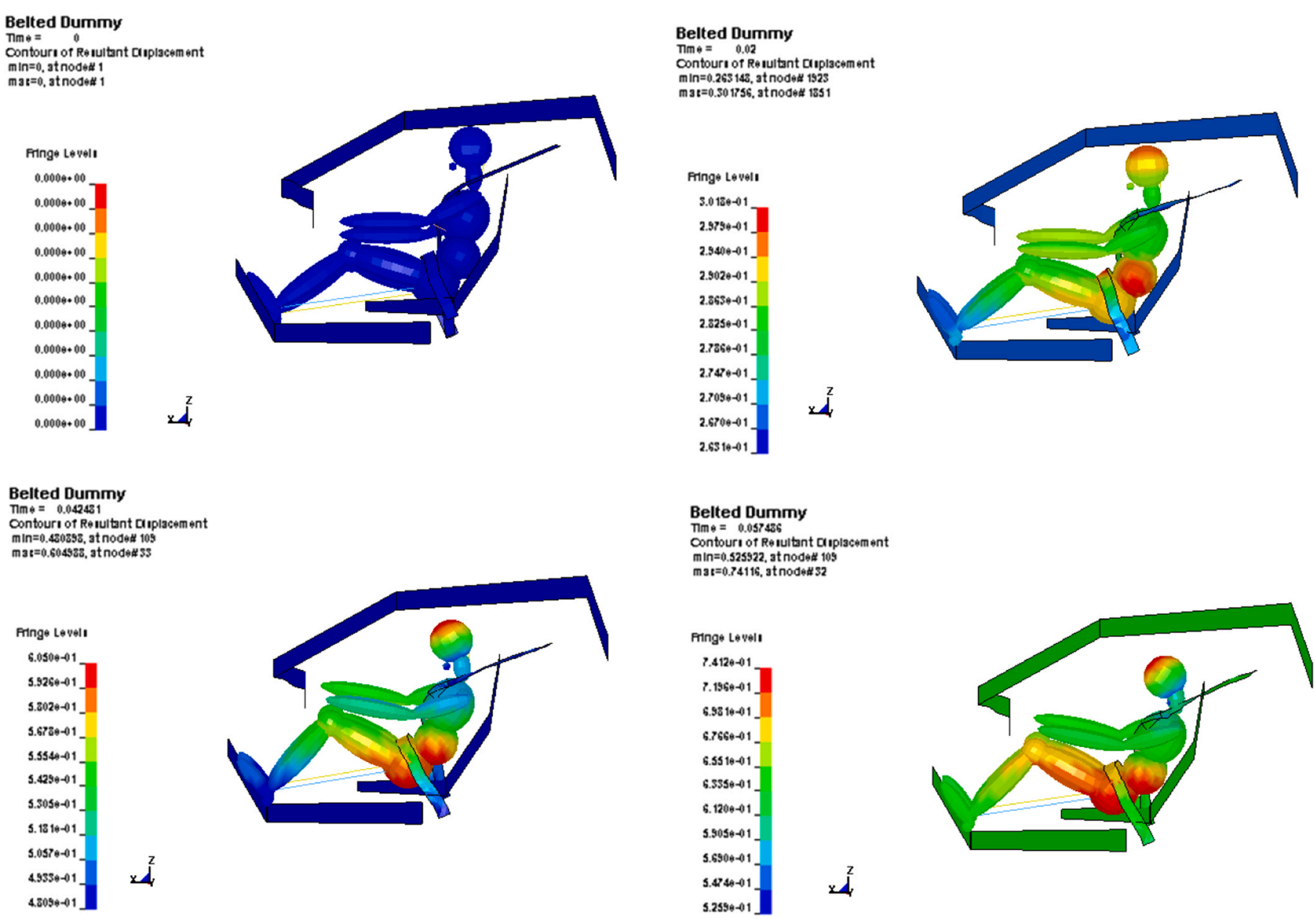

Fig. 18. Dynamic behaviour of fully belted adult driver during a collision at 90 km/h.

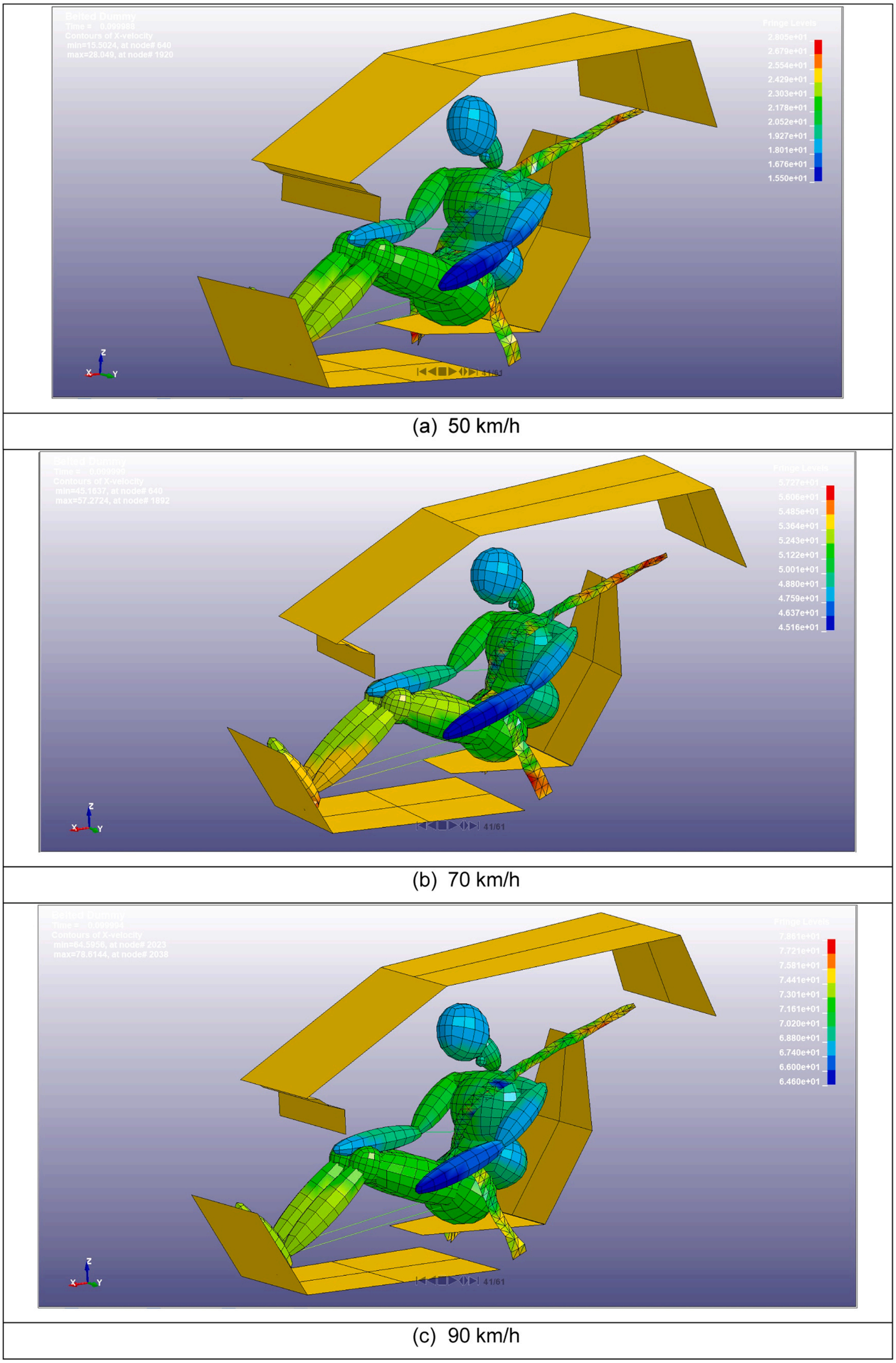

Fig. 19. Dynamic behaviour of an adult driver obtained following a frontal collision at different collision velocity.

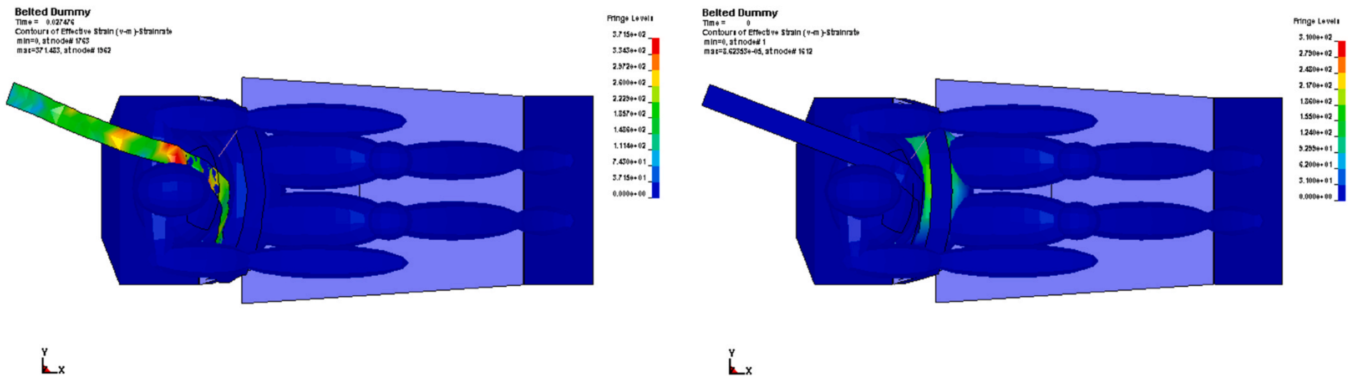

Fig. 20. Iso-values of effective strain results at the two stages of the FE simulation.

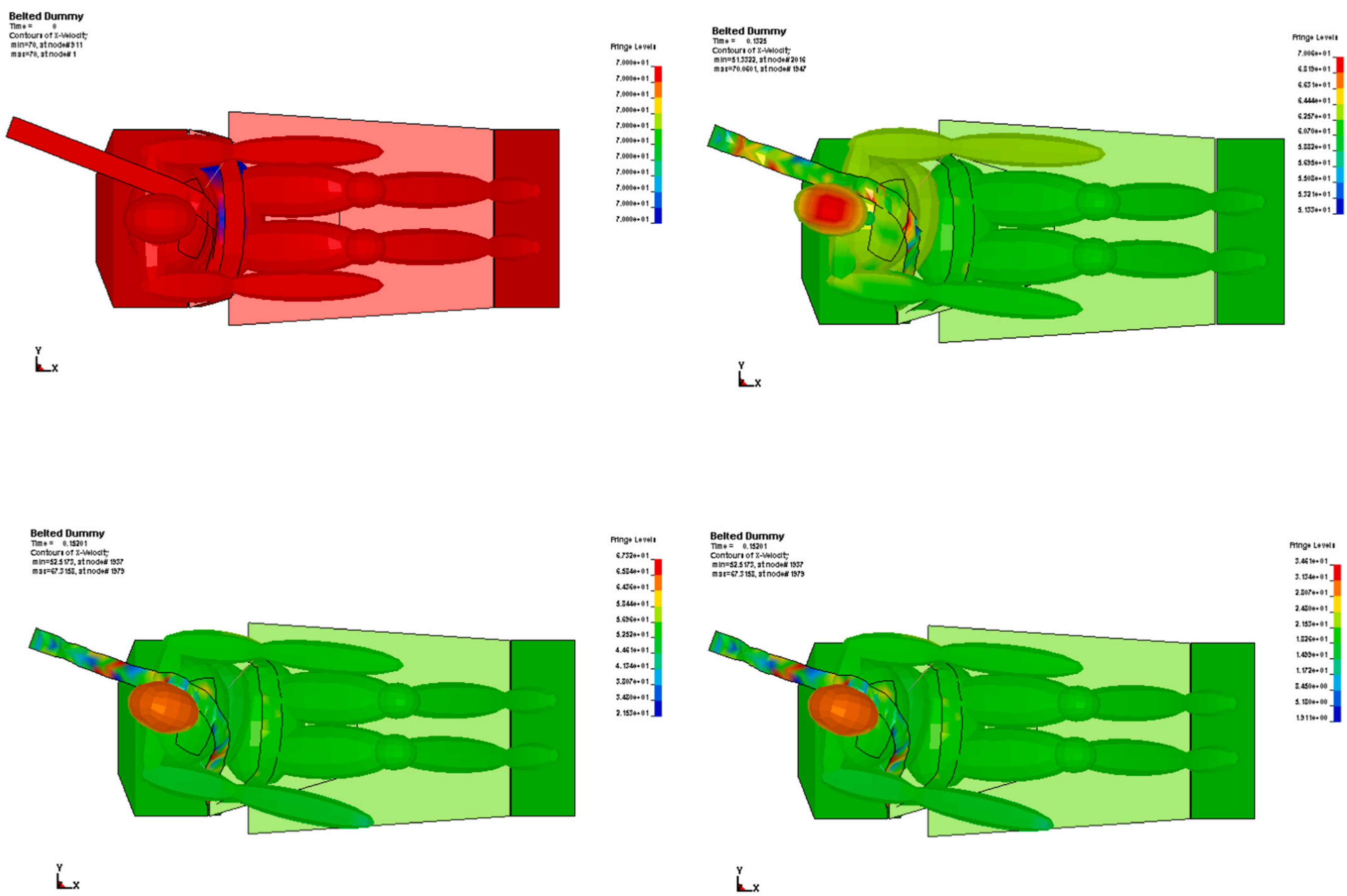

Fig. 21. Iso-values of x-velocity results at the different stages of the FE simulation.

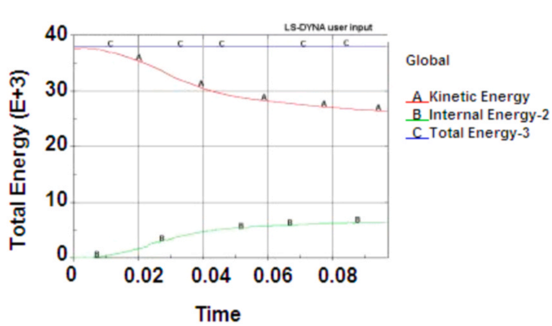

Fig. 22. Total energy balance graph of test model.

sound energy and heat energy. The majority of the converted energy was the potential energy. In other words, the total kinetic energy was absorbed by the structure of the vehicle, since the energy must be conserved. Fig. 22 showing the kinetic energy, internal energy and the total energy versus time obtained after the simulation of crash test. The maximum value of kinetic energy of the test model was 37.26 kJ.

The presence of a seat belt was therefore clearly essential or even obligatory for driving a vehicle. In fact, the driver will be safe and well held by the seat belt which holds the passenger's body to the vehicle seat, thus protecting his body against all dangerous elements on the dashboard. Alvarez et al. (2017) proposed a numerical study of a collision without and with an active safety system [38]. This study made it possible to carry out a comparison of the different results and therefore to give an evaluation of the attenuation caused by the presence or absence of this system. Based on the attenuated values, the assessment of injury reduction and severity through an active safety system was possible. Furthermore, these analyses allow us to conclude that the use of the seat belt ensures absorption of the energy due to an accident, which increases the safety of the vehicle passengers.

The likelihood of a vehicle passenger being seriously injured in a road accident was significantly reduced by the use of seat belts. All these trends obtained in our study in terms of risk of injuries and serious injuries were generally consistent with the majority of previous studies on road accidents [39–41]. These results clearly indicate that restraint systems were largely capable of adapting to several situations such as the occupants age, gender, overall stature and body shape of the passengers. These systems have great potential to improve occupant protection for people of different body sizes and shapes.

Furthermore, the likelihood of the driver or vehicle passengers sustaining injuries or serious injuries during a traffic accident was significantly reduced when these passengers were properly belted. This confirms the robustness and effectiveness of our FE model to correctly reproduce different scenarios. This model will be improved to study other scenarios in the presence of the airbag or even study the behaviour of two passengers during a collision.

The collision speed has a significant impact on the driver's body position in terms of shoulder rotation, lateral displacement, and longitudinal displacement, which increases the risk of injury to vehicle passengers (see Fig. 23). During the collision, it was observed that both legs were generally extended forward or each was resting on an accelerator or brake pedal. The driver moved primarily longitudinally, moving dangerously close to the steering wheel, with the risk of their knees hitting the space under the steering wheel.

As shown in Fig. 24, the driver's head acceleration curves under the four scenarios. In the case of the belted driver, the head acceleration curve evolved smoothly for the first 10 ms, without any sharp peaks. However, after 13 ms, the head acceleration value increased rapidly and sharp peaks appeared. In the case of the unbelted driver (Case 4), the peak head acceleration was lower than in the previous case; however, the acceleration amplitude after the peak gradually decreased and persisted for an extended period. In the case of the improperly belted driver (Case 2), the dummy's head acceleration briefly peaked before rapidly decreasing in the opposite direction. Finally, for the last case, also with an improperly belted driver (Case 3), the dummy's head acceleration peak was similar to that of Case 2, but the acceleration decreased more significantly after the peak.

After the collision, the dummies subjected to the four restraint strategies exhibited completely different kinematic responses in their posture changes (Fig. 25). Overall, the unbelted dummies displayed a pronounced tendency toward forward movement with a greater downward pelvic shift due to the absence of a seat belt. It was concluded that the driver's posture, whether or not they were wearing a seatbelt, has a very decisive influence on the safety of vehicle occupants. Furthermore, without a seat belt, the dummies' heads struck the windshield. When driving with a seat belt, the anterior pelvic displacement was actually minimal. This demonstrated that seat belt application could effectively limit the driver's body displacement, thereby further limiting pelvic movement and improving occupant safety.

Conclusion

Improving road safety will remain a major challenge. In this context, this article focuses on the numerical modelling and simulation of road accidents on roads with a speed limit of 90 km/h. The main results of this article were as follows:

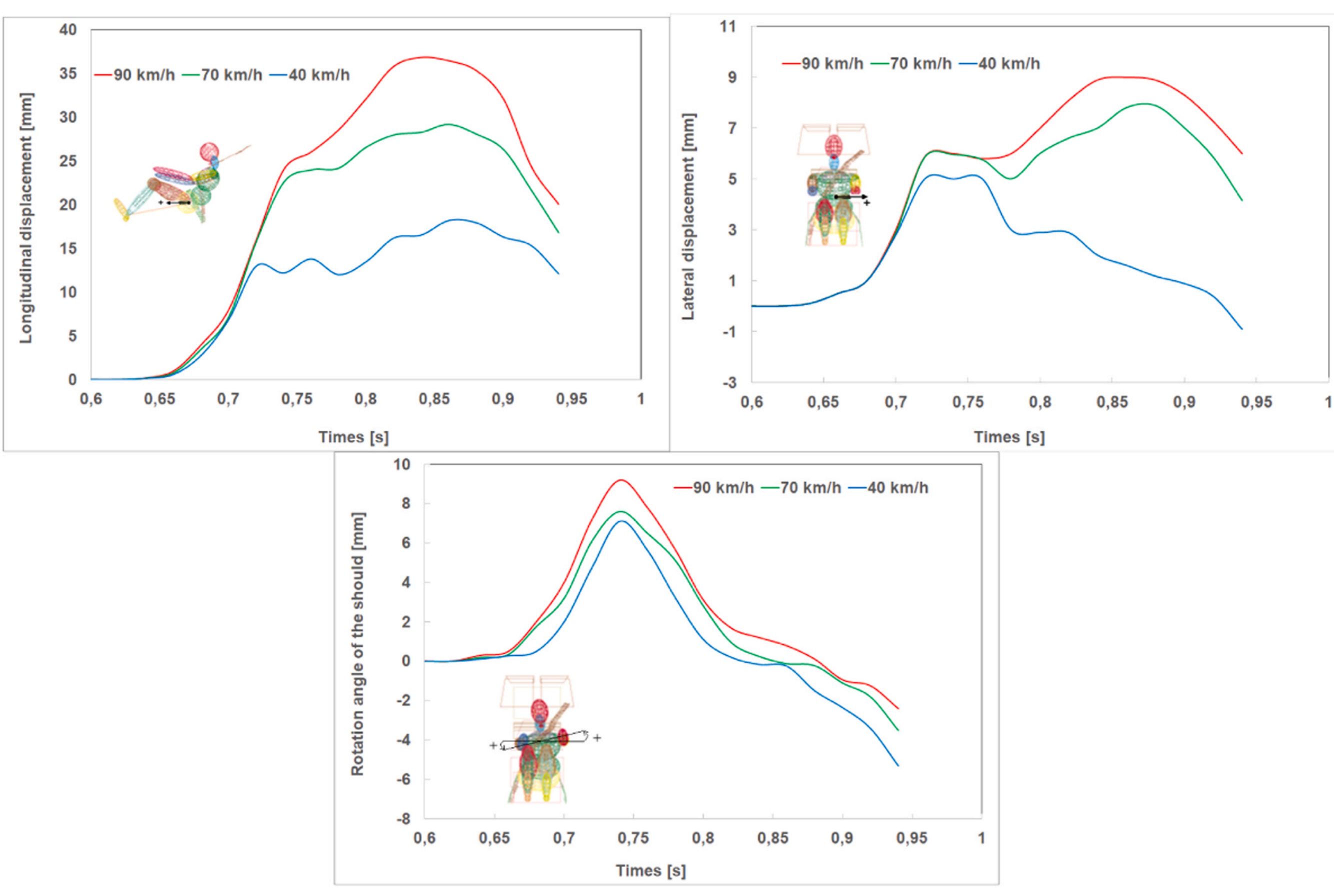

Figure 23. (a) longitudinal displacement of dummy, (b) lateral displacement of dummy and (c) Rotation angle of the shoulders.

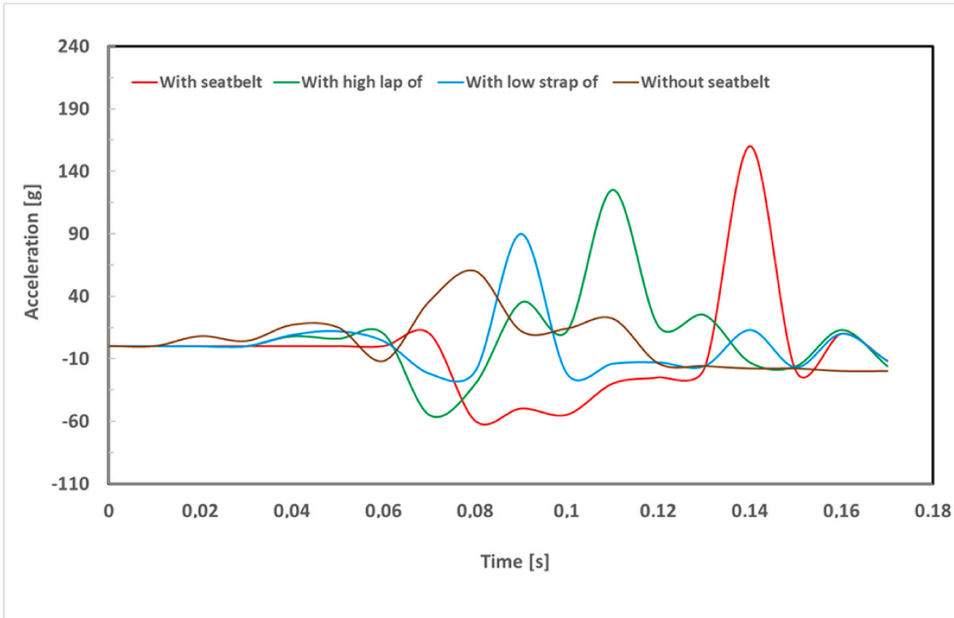

Fig. 24. Acceleration evolution of dummy head vs. times during frontal collision for different driving situations.

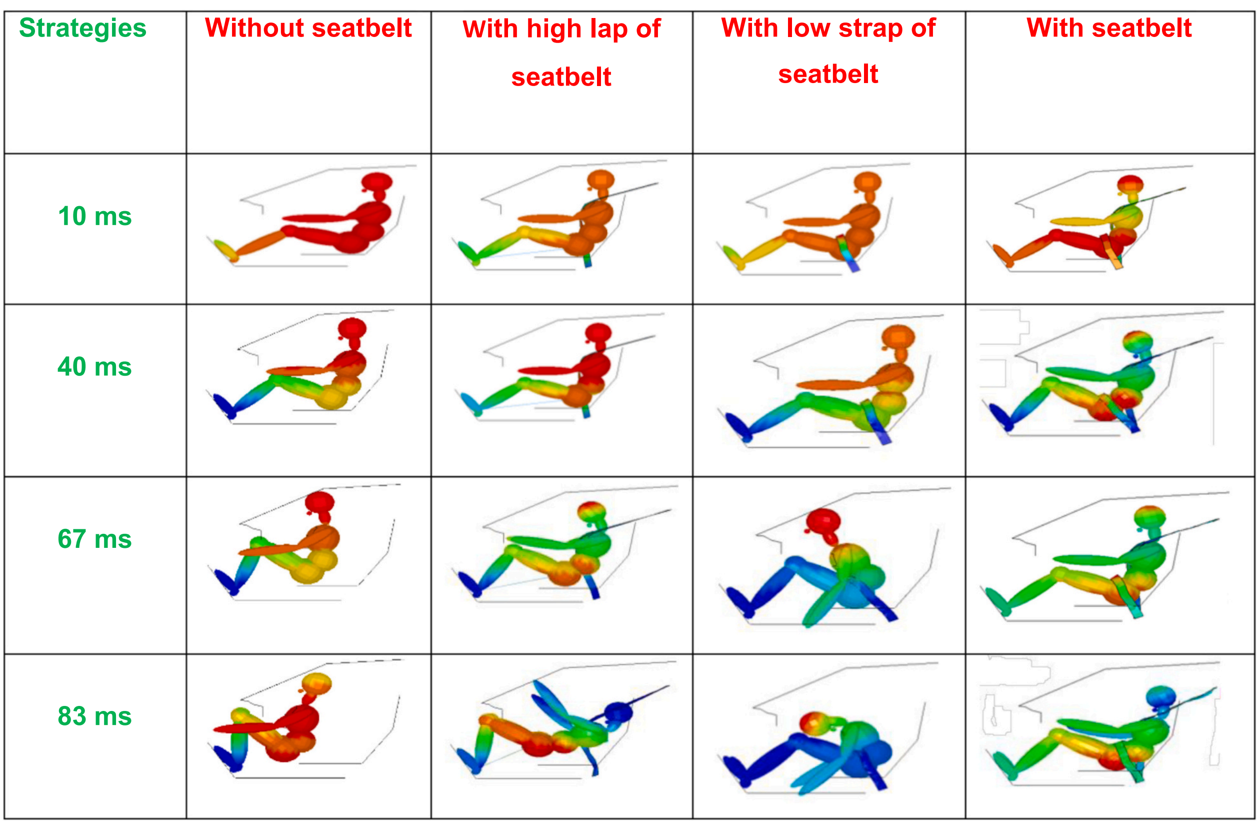

Fig. 25. Kinematic response of dummy.

1. Driver behaviour was numerically evaluated under several scenarios. This study showed that seat belts only restrain the upper torso and thighs and do not completely prevent forward movement of the head and neck in the event of a very high-speed collision.
2. The results also provide important information on the changes in the driver’s position (hands, head, legs, neck, thorax, etc.) during a road accident.

The main findings and perspectives were as follows: The numerical simulation results show the risks to an improperly belted driver inside the passenger compartment during a collision on roads with a speed limit of 90 km/h. The initial results show good consistency with the expected results and those described in other studies. They can serve as a reference and database for us during the development phase of our new model and can be further developed through the results of physical crash test validations, which will be implemented shortly as part of a future collaboration.

Moreover, additional data will certainly be necessary to properly interpret this type of result; namely, the body shape of passengers, very late braking for reasons of vision and/or visual acuity, even driving with glasses, fog, driving at night, etc. It was important to remember that the higher a vehicle's speed, the more the driver's visual capacity decreases. Another issue to take into account to have an overall look at the behaviour of passengers during a collision was the muscle stiffness

Variations in muscle stiffness in the body of the models have been scarcely analysed, as have their effects on the overall behaviour and safety of the driver and/or occupants. Moreover, different sleeping postures of vehicle occupants can be to taking into account in our studies in the future. Another factor to consider was gender equality, with some studies suggesting that women may suffer different injuries in the event of an accident. The proposed FE model therefore proved insufficient for this type of situation. Several avenues for improving the model were currently being studied and refined with several models present inside the passenger compartment with different body shapes. Nevertheless, the numerical simulations have proven to be a very useful and valuable source of information. The developed model could be successfully used in the future for other road safety studies. Future studies plan to also include seat belt slack and different seating postures, such as forward leaning of the driver and/or passengers.

Future work will also focus primarily on extensive validation of the model in different scenarios taking into account the elements mentioned above to better understand its limitations, particularly its limitations.

CRediT authorship contribution statement

T. Barrière: Writing – original draft, Visualization, Supervision, Software, Resources, Methodology, Investigation. **sahli Mohamed:** Visualization, Validation, Supervision, Methodology. **D. Bendjaballah:** Writing – original draft, Validation, Software, Resources, Investigation, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] H. Chan, D. Albert, F. Gayzik, A. Kemper, Assessment of acclimation of 5th percentile female and 50th percentile male volunteer kinematics in low-speed frontal and frontal-oblique sled tests, SAE Int. J. Trans. Saf. 9 (2021) 3–103.

[2] C. Gong, Z. Bai, Y. Wang, L. Zhang, On the crashworthiness performance of novel hierarchical multi-cell tubes under axial loading, Int. J. Mech. Sci. 206 (2021) 106599, https://doi.org/10.1016/j.ijmecsci.2021.106599.

[3] K. Podosek, D. Frej, A. Górniak, N. Elvira, 50 percentile dummy movement analysis using TEMA automotive software, Arch. Automot. Eng. Arch. Motoryz 97 (2022) 25–50.

[4] M.M. Aydin, The modeling of effective parameters on public bus passengers' boarding time prediction, J. Eng. Res. (2021), https://doi.org/10.36909/jer.10079.

[5] D. Frej, K. Podosek, T. Kelvin, Overview of design solutions for child seats, Arch. Automot. Eng. Arch. Motoryz 92 (2021) 33–47.

[6] S. Kongwat, P. Jongpradist, H. Hasegawa, Lightweight bus body design and optimization for rollover crashworthiness, Int. J. Automot. Technol. 21 (2020) 981–991.

[7] P. Kunakorn-ong, P. Jongpradist, Optimisation of bus superstructure for rollover safety according to ECE-R66, Int. J. Automot. Technol. 21 (2020) 215–225.

[8] Ying Lu, Yufa Liu, Yu Shu, Yuezhou Yin, Injury prediction algorithm for rear-seat occupants in advanced automatic crash notification systems, IET Intell. Transp. Syst. (2021) 421–570.

[9] A.S.M. Fathalla, et al., A numerical study of the effect of bolt thread geometry on the load distribution of continuous threads, J. Eng. Res. 10 (2022) 158–173.

[10] B. Beylergil, Design and discrete optimization of hybrid aluminum/composite drive shafts for automotive industry, J. Eng. Res. 9 (2021), https://doi.org/10.36909/jer.v9i3B.8815.

[11] M.R. Seyedi, et al., Experimental assessment of vehicle performance and injury risk for cutaway buses using tilt table and modified dolly rollover tests, Accid. Anal. Prev. 132105287 (2019), https://doi.org/10.1016/j.aap.2019.105287.

[12] P. Jongpradist, et al., Crash analysis of sandwich composite electric microbus, IOP Conf. Ser. Mater. Sci. Eng. 1137012048 (2021), https://doi.org/10.1088/1757-899X/1137/1/012048.

[13] U. Idrees, S. Ahmad, I.Alam Shah, M. Talha, R. Shehzad, M. Amjad, S.-S.R. Koloor, Finite element analysis of car frame frontal crash using lightweight materials, J. Eng. Res. 11 (2023) 100007, https://doi.org/10.1016/j.jer.2023.100007.

[14] U. Idrees, S. Ahmad, I. Shah, M. Talha, R. Shehzad, M. Amjad, S.S.R. Koloor, Finite element analysis of car frame frontal crash using lightweight materials, J. Eng. Res. 11 (2023) 100007, https://doi.org/10.1016/j.jer.2023.100007.

[15] R.T. Marler, C.H. Kim, J.S. Arora, System identification of simplified crash models using multi-objective optimization, Comput. Methods Appl. Mech. Eng. 195 (2006) 4383–4395.

[16] S.M. Ofochebe, C.G. Ozoegwu, S.O. Enibe, Performance evaluation of vehicle front structure in crash energy management using lumped mass spring system, Adv. Model. Simul. Eng. 2 (2015) 1–18.

[17] A. Hickey, S. Xiao, Finite element modeling and simulation of car crash, Int. J. Mod. Stud. Mech. Eng. 3 (2017) 1–5.

[18] A. Klausen, S.S. Tordal, H.R. Karimi, K.G. Robbersmyr, M. Jecmenica, O. Melteig, Firefly optimization and mathematical modeling of a vehicle crash test based on single-mass, J. Appl. Math. (2014) 1–10.

[19] A. Klausen, S.S. Tordal, H.R. Karimi, K.G. Robbersmy, Mathematical modeling and numerical optimization of three vehicle crashes using a single-mass lumped parameter Model. In: Proceedings of the 24th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Gothenburg, Sweden, 8-11 June 2015, 44-49.

[20] L. Mazurkiewicz, P. Baranowski, H.R. Karimi, K. Damaziak, J. Malachowski, A. Muszynski, A. Muszynski, K.G. Robbersmyr, D. Vangi, Improved child-resistant system for better side impact protection, Int. J. Adv. Manuf. Technol. 97 (2018) 3925–3935.

[21] H.C. Gabler, W. Hollowell, S. Summers, Systems modeling of frontal crash compatibility. In proceedings of the 2000 SAE international Congress and exposition, Detroit MI USA (January 2000) 13–15, 1-8.

[22] H. Safari, H. Nahvi, M. Esfahanian, Improving automotive crashworthiness using advanced high strength steels, Int. J. Crashworthiness (2017) 1–15.

[23] D. Vangi, C. Cialdai, M.S. Gulino, K.G. Robbersmyr, Vehicle accident databases: correctness checks for accident kinematic data, Designs 2 (2018) 1–11.

[24] V. Beik, M. Fard, and R.N. Jazar, Crashworthiness of tapered beams in automotive application, In Nonlinear Approaches in Engineering Applications, 2016. pp. 3-62, DOI:10.1007/978-3-319-27055-5_1.

[25] T.L. Teng, F-A. Chang, Y-S. Liu, C-P. Peng, Analysis of dynamic response of vehicle occupant in frontal crash using multibody dynamics method DOI: 10.1016/j.mcm.2007.10.020.

[26] A. Muhammad, and I.H. Shanono, Simulation of a Car crash using ANSYS. In: Proceedings of the 15th International Conference on Electronics, Computer and Computation (ICECCO), IEEE. 2019. DOI: 10.1109/ICECCO48375.2019.9043275.

[27] T. Ambati, K.V.N.S. Srikanth, P. Veeraraju, Simulation of vehicular frontal crash-test, Int. J. Appl. Res. Mech. Eng. (IJARME) ISSN: 2, 2012. pp. 2231-5950.

[28] D. Bruski, S. Burzyński, W. Witkowski, Analysis of passenger car crash with a cable barrier installed with anti-glare screens on a horizontal convex road curve with 400 m radius, Int. J. Impact Eng. 173 (2023) 104486.

[29] L. Mazurkiewicz, P. Baranowski, H.R. Karimi, K. Damaziak, J. Malachowski, A. Muszynski, A. Muszynski, K.G. Robbersmyr, D. Vangi, Improved child-resistant system for better side impact protection, Int. J. Adv. Manuf. Technol. 97 (2018) 3925–3935.

[30] M. Ostmann, L. Jakobsson, An examination of pre-crash braking influence on occupant crash response using an active human body model, IRCOBI Conference, 2016. pp. 275-283.

[31] M.P. Reed, M.A. Manary, C.A. Flannagan, L.W. Schneider, A statistical method for predicting automobile driving posture, Hum. Factors 44 (2002) 557–568.

[32] J. Park, M.P. Reed, J.J. Hallman, Statistical models for predicting automobile driving postures for men and women including effects of age, Hum. Factors 58 (2016) 261–278.

[33] M.P. Reed, M.B. Parkinson, Modeling variability in torso shape for chair and seat design. Paper presented at: ASME International Design Engineering Technical Conferences; NewYork, NY. 2009. pp. 561-569 https://doi.org/10.1115/DETC2008-49483.

[34] X. Shi, L. Cao, M.P. Reed, J.D. Rupp, C.N. Hoff, J. Hu, A statistical human rib cage geometry model accounting for variations by age, sex, stature and body mass index, J. Biomech. 47 (2014) 2277–2785.

[35] Y. Wang, L. Cao, Z. Bai, et al., A parametric ribcage geometry model accounting for variations among the adult population, J. Biomech. 49 (2016) 2791–2798.

[36] G.R. Johnson, W.A. Cook, Constitutive model and data for metals subjected to large strains, High. Strain Rates High. Temp. (2018).

[37] N. Tounsi, J. Vincenti, A. Otho, M.A. Elbestawi, From the basic mechanics of orthogonal metal cutting toward the identification of the constitutive equation, Int. J. Mach. Tools Manuf. 42 (2002) 1373–1383.

[38] S. Alvarez, Y. Page, U. Sander, F. Fahrenkrog, T. Helmer, O. Jung, Prospective Effectiveness Assessment of ADAS and active safety systems via virtual simulation: a review of the current practices, National Highway Traffic Safety Administration NHTSA, editor. In: Proceedings of the The 25th International Technical Conference on the Enhanced Safety of Vehicles (ESV) (2017) 05-08.

[39] J.D. Rupp, C.A.C. Flannagan, A.J. Leslie, C.N. Hoff, M.P. Reed, R.M. Cunningham, Effects of BMI on the risk and frequency of AIS 3+ injuries in motor-vehicle crashes, Obesity 21 (2013) 88–97.

[40] D. Bose, M. Segui-Gomez, J.R. Crandall, Vulnerability of female drivers involved in motor vehicle crashes: an analysis of U.S. population at risk, Am. J. Public Health 101 (2011) 2368–2373.

[41] S. Zhu, J.E. Kim, X. Ma, et al., BMI and risk of serious upper body injury following motor vehicle crashes: concordance of real-world and computer-simulated observations, PLOS Med. (2010) 1000250.