CAR BONNET EVALUATION AGAINST PEDESTRIAN HEAD IMPACT BASED ON A LUMPED MODELING APPROACH

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ABSTRACT

Nowadays, physical models of head used in pedestrian head impact standard tests are not accurate enough to represent the human head behavior and to assess the head injury risk in case of impact in a realistic way. In order to remove this technological barrier, the Strasbourg University Finite Elements Head Model (SUFEHM) is used in conjunction with a lumped model of the impact point at bonnet level in the present study. The approach consists in proposing a lumped model of the bonnet based on the experimental response of a pedestrian ISO headform impacting the bonnet surface at a velocity of 11 m/s and an impact angle of 60°. During this experimental tangential headform impact, both linear and rotational headform acceleration are recorded, and these data allow to characterize the stiffness, plasticity, energy dissiparion as well as apparent mass of the bonnet lumped model. The model of the impact point at bonnet level consists of a rigid plate representing the bonnet impacted surface and connected to a fixed point by a general non linear spring. The non linear stiffnesse were implemented to the bonnet model in normal and tangential direction in terms of force-displacement. For this approach, the force was obtained by multiplying the acceleration by the headform mass and the displacement was derived from double integration of the headform acceleration. As a demonstrator the approach was conducted numerically on a car bonnet FEM which was impacted by an ISO headform FEM. The validation of the method consists in simulating the impact of the finite element model of the headform-bonnet lumped model and comparing its response to the headform FEM impact againstthe complete bonnet FEM simulation in terms of resultant linear and rotational acceleration. In a last step the SUFEHM is used for the simulation of the impact against the above defined bonnet lumped model in order to assess the injury risk for the impact point under study.

INTRODUCTION

In current standards and regulation, most head injury criteria such as HIC are based and developed from physical models that are now widely used [1,2,3].Indeed, for the pedestrian protection regulation, the European Enhanced Vehicle Safety Committee (EEVC WG10 and WG17) has developed test procedures to assess the level of pedestrian protection for vehicle fronts. The European directive (2003/102/EC) [1] consists of head impact, upper leg impact and lower leg impact.

The directive as well as the EuroNCAP pedestrian testing protocol [2] consider very simplified impactors, especially for the head. The headform used is a hemispherical object covered with an elastomeric skin. The injury criteria is the HIC (Head Injury Criterion) [4] is computed with the head linear acceleration components and the resultant value has to be below 1000 for an adult head for instance. Ueno and Melvin [5] as well as DiMasi *et al.* [6] found that the use of either translation or rotation alone may underestimate the severity of an injury. Zhang et al. [7] concluded that both linear and angular accelerations are significant causes of mild traumatic injuries. More recently, Deck *et al.* [8] conducted an in depth analysis on the contribution of rotational and linear acceleration under pedestrian accident conditions. It can be concluded that the rotational acceleration had a huge influence on both intracerebral loading and brain-skull relative motion, supposed to lead, respectively, to neurological injuries and subdural haematoma. As a conclusion, these authors unanimously suggested that any future head protection standard should integrate the rotational component in addition to the linear one in order to enable a realistic evaluation of the brain loading conditions and consequently of the head-injury risk prediction. A number of attempts towards improved head injury criteria have been reported in the literature both based on global parameters [9] and Finite Element (FE) modeling [10]. In the framework of EU project APROSYS SP5 'Biomechanics' in 2007 [11], improved head injury criteria based on a state of the art of head FE model have been developed in terms of skull strain energy, CerebroSpinal Fluid (CSF) pressure and brain VonMises stress respectively as injury parameters for skull fracture, subdural hematoma and neurological injuries.

The use of finite element models of the human head to test the pedestrian injury risk, will require characterization and modeling of the car bonnet. If this procedure is considered appropriate for use in standards and regulation, it reveals a major inconvenient about cost due to modeling and validation of the complet car bonnet. The aim of this study is to propose a lumped model of the impact point on the bonnet based on the experimental tests using a pedestrian headform. The final goal however is to include the numerical simulation using the finite element model of the head impacting the above defined lumped model for a more realistic head injury assessment..

MATERIAL AND METHOD

Insofar as the prediction of head injury is more accurate with injury criteria based on finite element modeling of the head, it is essential to have a model of the mechanical behavior of the impact point at bonnet. This mechanical characterization of the "bonnet point" will be a dynamic test using the ISO headform at an impact velocity close to the pedestrian standard tests, i.e. 11 m/s and an angle to define relatively to the impact surface. The ISO headform has to be equipped with a rotational velocity sensor in addition to the existing linear accelerometers. The idea in the present study is no longer having a biofidelic headform, but a reasonable mass, an inertia and a geometry with an initial velocity in order to characterize the impact point under shock conditions . A lumped model of the impact point is then developed from the headform experimental responses, in terms of inertia, elasticity, plasticity and absorbed energy along the normal direction and in term of friction along the tangential direction. In a final step, this lumped “bonnet point”model is coupled with the finite element model of the human head to assess the injury risk of the determined impact point.

Characterization of “bonnet point”

To demonstrate the feasibility of this study, a validated finite element model of a car bonnet has been used and illustrated in figure 2. The model was used in Tinard *et al.* [12] study and is consisted of an upper panel modeled by shell elements and an engine block considered as a rigid body. The material law of the upper panel used for the model is an elastoplastic material whose mechanical characteristics are reported in table 2.

Table 1. Mechanical properties of the bonnet FFE model.

ρ [kg.m^{-3}]	E [MPa]	υ	σe [MPa]	b [MPa]	n	σm [MPa]
2700	50000	0.3	60	567	0.62	65

The standard ISO headform model is represented in figure 1. It consists of an aluminum sphere, an aluminum plate and a rubber skin. Each part is modeled with an elastic law with values reported in table 2 in accordance with Lawrence [13]. The head model is made of 3020 solid elements.

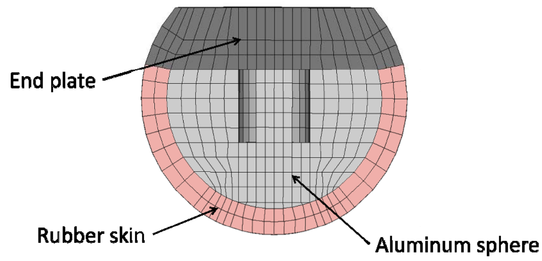

Figure 1. Standard ISO pedestrian headform model.

Table 2. Mechanical properties of the different parts of the pedestrian headform FE model.

	P [kg m^{-3}]	E [MPa]	υ
Rubber skin	1 950	7	0.4
Aluminum sphere	2 800	200 000	0.29
End plate	2 800	200 000	0.29

To illustrate the methodology allowing to develop the lumped parameter model of a "bonnet point", all data have been extracted from simulation based on finite element method. The numerical test consists in simulating the pedestrian standard test with an ISO headform as illustrated in figure 3.

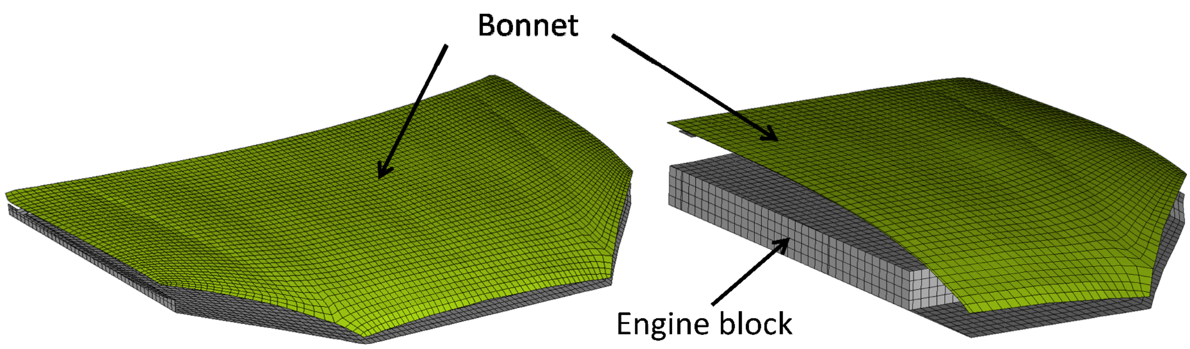

Figure 2. General view of the bonnet and the engine block.

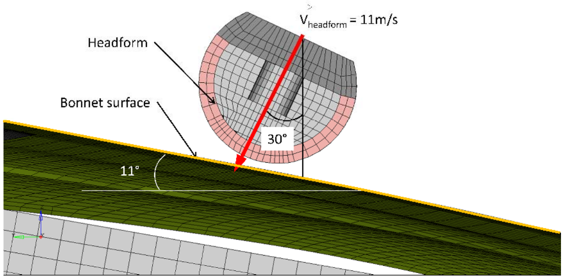

Figure 3. Illustration of the pedestrian standard test reproduce numerically.

As stated in the regulations, the headform impacts the bonnet surface with a 60° incline with horizontal. Considering the bonnet point as illustrated in figure 3, the tangent plane is 11° to the horizontal axis..

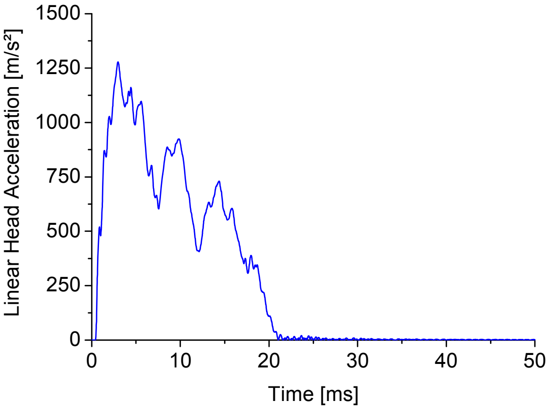

Figure 4. Representation of linear acceleration of the headform.

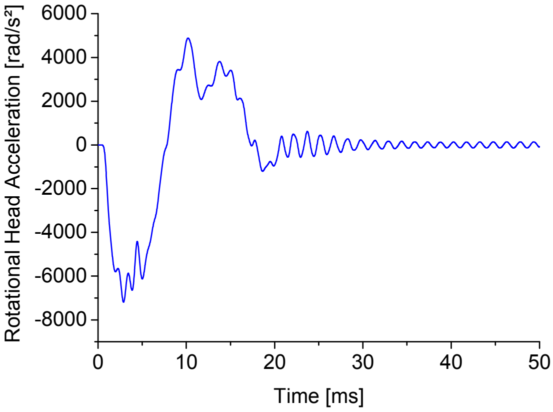

Figure 5. Representation of rotational acceleration of the headform.

The output data are extracted from the simulation in terms of linear and rotational accelerations at the headform center of gravity as plotted in figure 4 and figure 5. It should be recalled that in the final methodology this step will obviouselly be conducted experimentally only.

Subsequently, these output data are the components that constitute the input to the characterization and modeling step of the lumped "impact point"model.

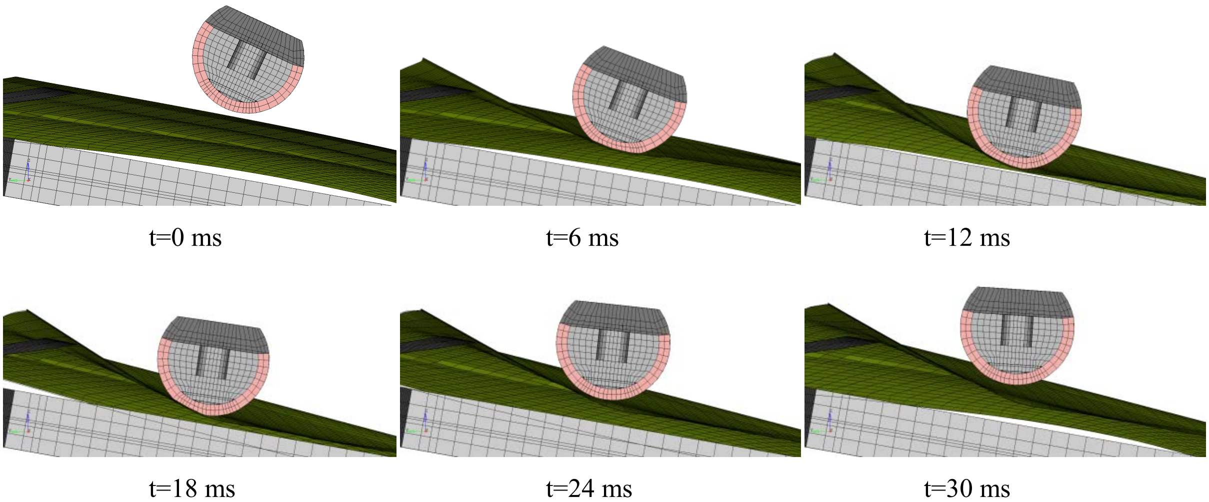

Figure 6. Simulation of the standard test using a pedestrian ISO headform on a bonnet.

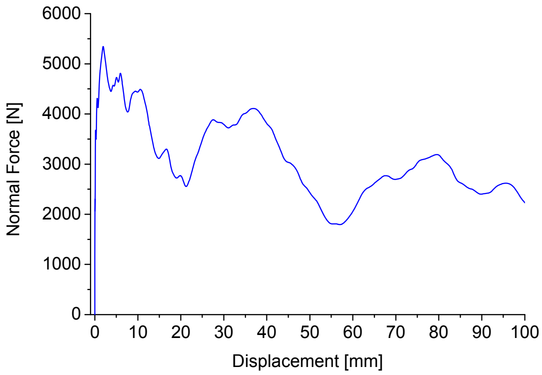

Figure 7. Representation of the normal force-displacment behavior of bonnet impacted by a headform of 4.5 kg at 11 m/s inclined of 19° with normal of the impacted surface.

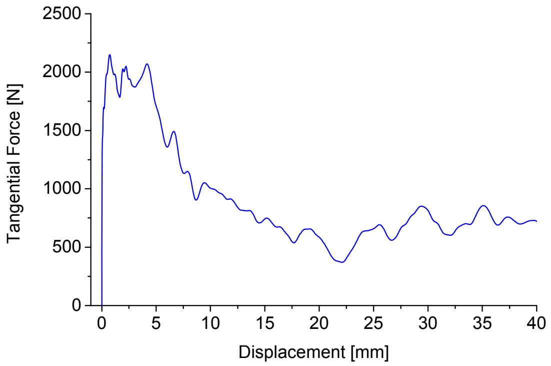

Figure 8. Representation of the tangential force-displacement behavior of bonnet impacted by a headform of 4.5 kg at 11 m/s inclined of 19° with normal of the impacted surface.

For the lumped model parameters identification, first the normal behavior of the impact was obtained by projecting the headform acceleration to the normal axis of the bonnet surface and multiplying it by the head mass of 4.5 kg. The normal acceleration was double integrated to get the bonnet deflection. The force-displacement curve can then be plotted as shown in figure 7 and represents therefore the normal behavior of the bonnet. In a similar way, the tangential behavior is extracted from the linear acceleration projectedon the tangential axis and plotted in figure 8.

Lumped model of "bonnet point"

The modeling of the "bonnet point" by a lumped parameter model consists of a rigid plate with a mass located at its center of gravity linked to the reference space by a generalized nonlinear spring, as illustrated in figure 9. The rigid panel is constrained in rotation in three axes and in translation along the transversal axis. At the spring element, only normal and tangential linear stiffness are implemented in the model. Those stiffnesses are extracted from the force-displacement behavior of the bonnet point after the headform impact experiment (or simulation in this tudy). Concerning the rigid panel, it is modeled in shell elements with a thickness of 0.1 mm and a concentrated mass at the node linked to the spring element of 1e-7 kg. The choice of a low mass was done to avoid an initial force caused the inertia effect of the panel at contact moment of the head on the plate. Nevertheless, it is needed to adapt the force-displacement curves for the spring element to apply due to non-zero mass at the rigid panel recommended for the finite element computation. The simplified force-displacement curves modeling the "bonnet point" are represented in figure 10 and figure 11.

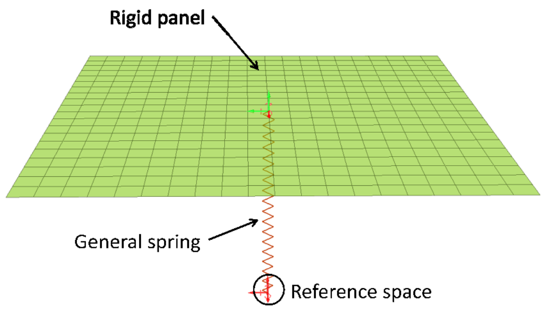

Figure 9. Illustrationof the « bonnet point » lumped model.

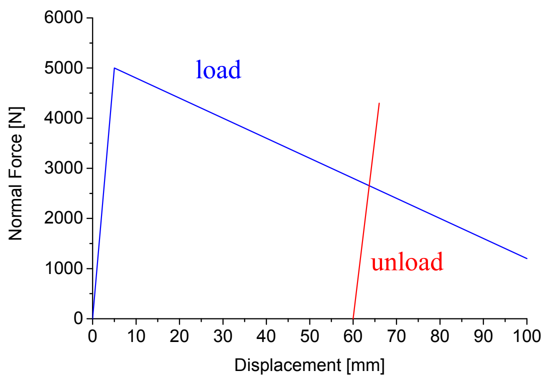

Figure 10. Representation of the normal force-displacement curve implemented in the spring element.

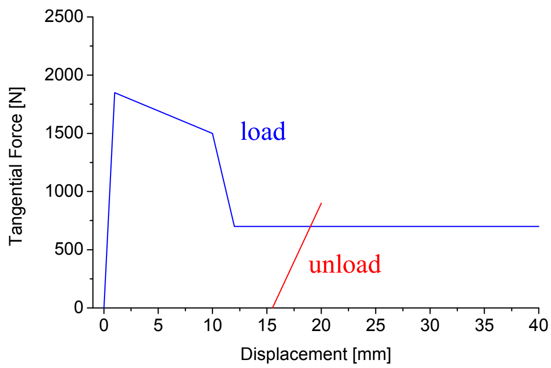

Figure 11. Representation of the tangential force-displacement curve implemented in the spring element.

The validation of the lumped parameter model of the "bonnet point" was carried out by impacting the headform inclined of 60° with the horizontal axis on the rigid panel with a velocity of 11 m/s as illustrated in figure 12. The computed responses are the linear and rotational accelerations of the headform as well as the plate deflection and the headform velocity.

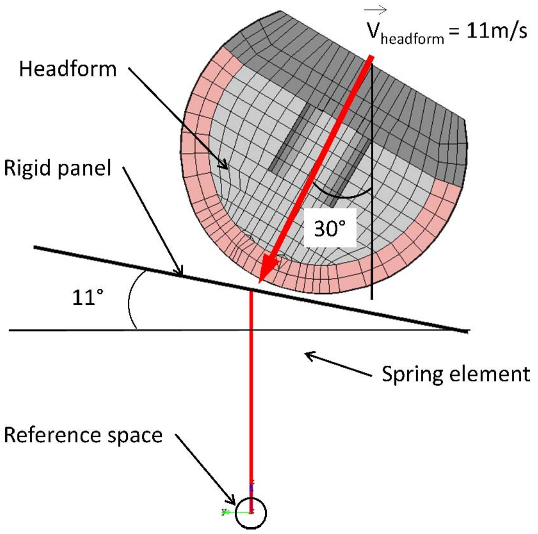

Figure 12. Representation of initial conditions of the headform to validate the "bonnet point" lumped model.

RESULTS

Figure 15 shows the simulation animation of the impact. The linear and rotational accelerations of the headform are superimposed on those extracted from the numerical simulation of thel standard test with the finite element model of the complete bonnet and are plotted in figure 13 and figure 14. A good accordance of the headform accelerations can be observed, demonstrating a realistic lumped model of the "bonnet point). The linear acceleration pulse is a little bit shorter for the lumped model compared to the finite element model one. The maximum linear acceleration is 134 g for the lumped model compared 130 g for the finite element model, i.e. a 3 % deviation. Both calculated HIC are also veryclose with a HIC of 938 for the lumped model against a HIC of 927 for the finite element model, i.e. a 1.2 % deviation.

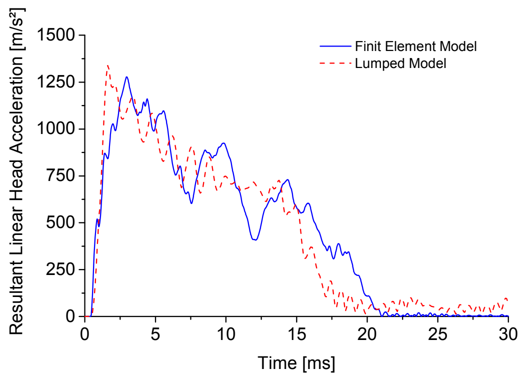

Figure 13. Superimposition of the linear headform accelerationscomputed with the FE and lumped bonnet model.

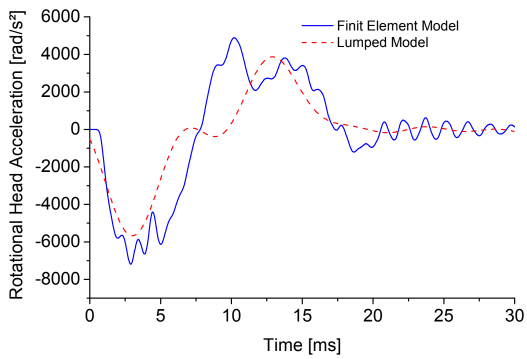

Figure 14. Superimposition of the rotational headform accelerations computed with the lumped and FE bonnet model.

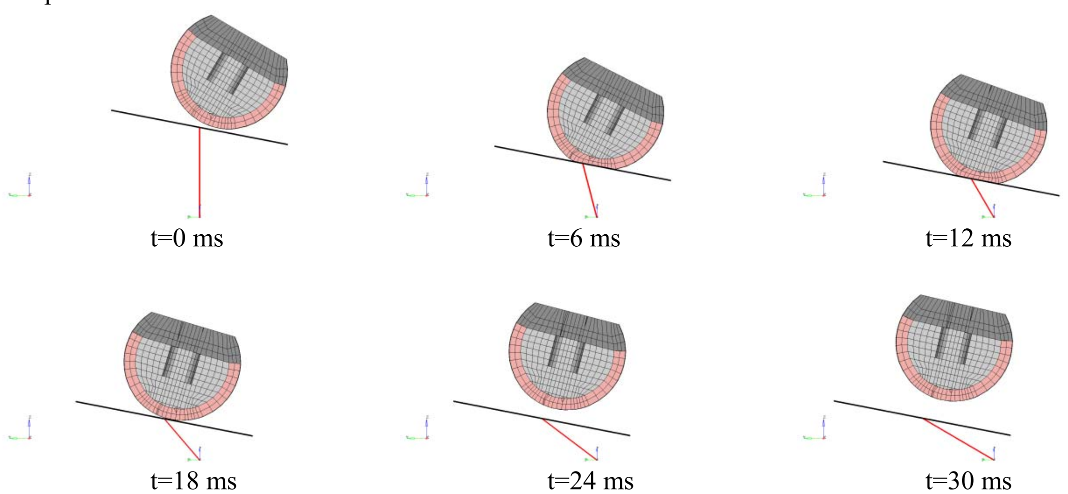

Figure 15. Simulation of the headform impact with the lumped "bonnet point" model.

Concerning the rotational acceleration, the deviation is slightly higher(about 10%) as illustrated in figure 14. This difference can be observed in figure 16 in terms of rotational velocity. However the shape of the curve is in accordance with the result from the full finite element simulation. The final rotational velocity is about 5 rad/s for the lumped model compared to 6 rad/s for the finite element model. The deflection of the rigid panel reached 65 mm which is in accordance with the result from the complete bonnet, as illustrated in figure 17.

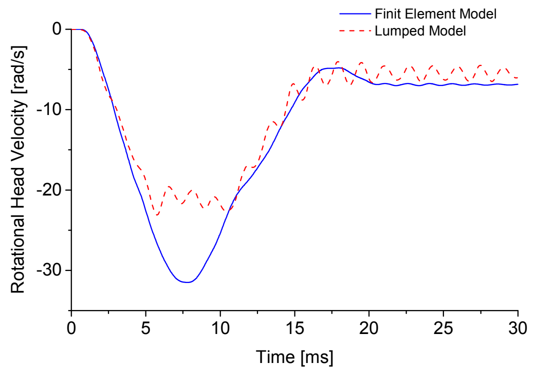

Figure 16. Superimposition of the headform rotational velocity computed with the FE and lumped bonnet model..

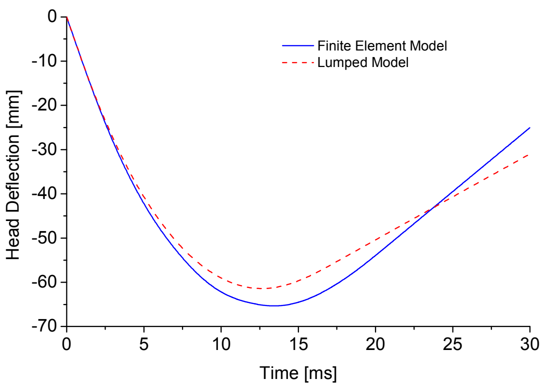

Figure 17. Superimposition of the headform displacement computed with the FE and lumped bonnet model.

The final step step of the novel methodology presented in this study is to use the head finite element model of Strasbourg University (SUFFEHM) to compare the lumped model of "bonnet point" with the complete finite element model of bonnet in terms of intracerebral injury risk. This step aims at validating fully the lumped model as the bonnet FE model is only a research step which will not be conducted in the test method under devlopment. The SUFEHM model developed by Kang *et al.* [14] and validated by Willinger *et al.* [15]was propelled frontally against the finite element model of the full bonnet at the same impact point as previously with ISO headform as illustrated in figure 18.

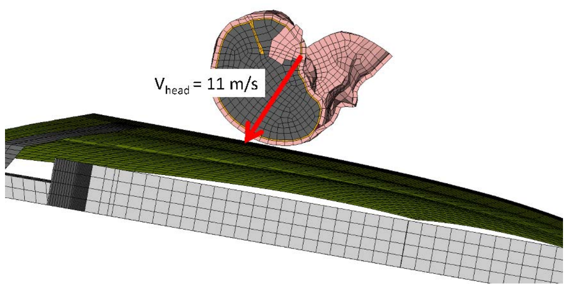

Figure 18. Initial condition for the impact of the SUFEHM on the finite element model of the bonnet.

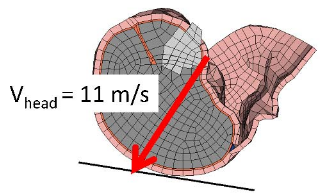

Figure 19. Representation of the initial condition for the impact of the SUFEHM on the lumped model of the bonnet.

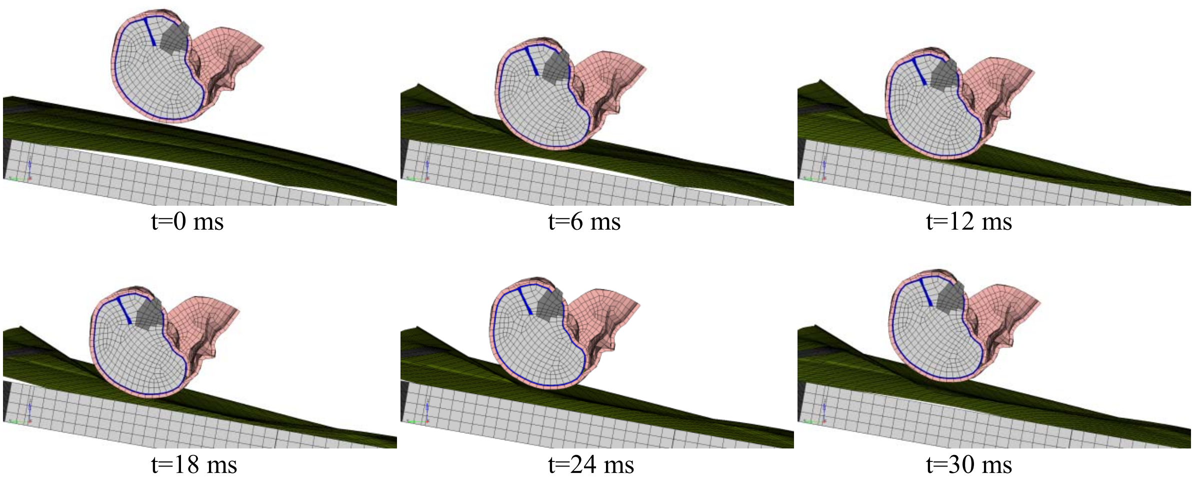

Figure 20. Simulation of the SUFEHM impact against the bonnet FE model

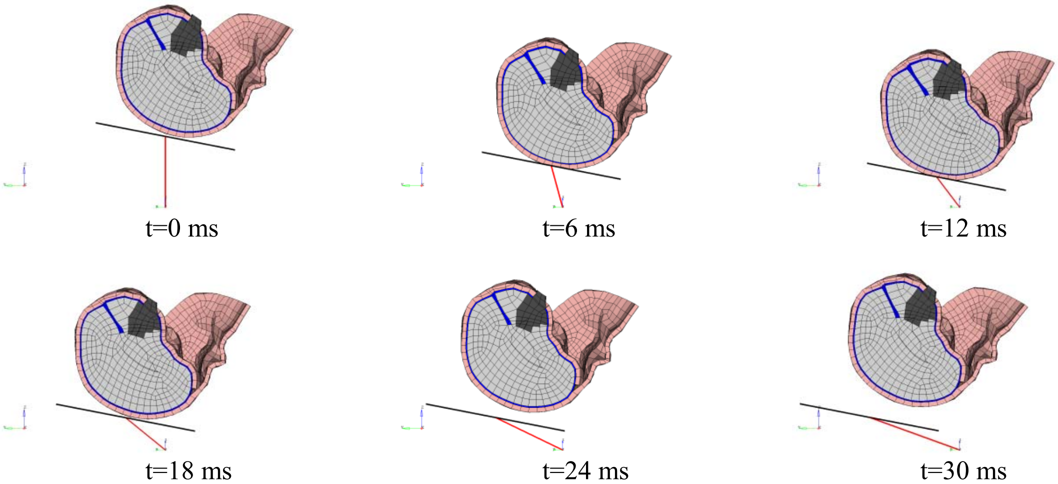

Figure 21. Simulation of the SUFEHM impact against the lumped bonnet model

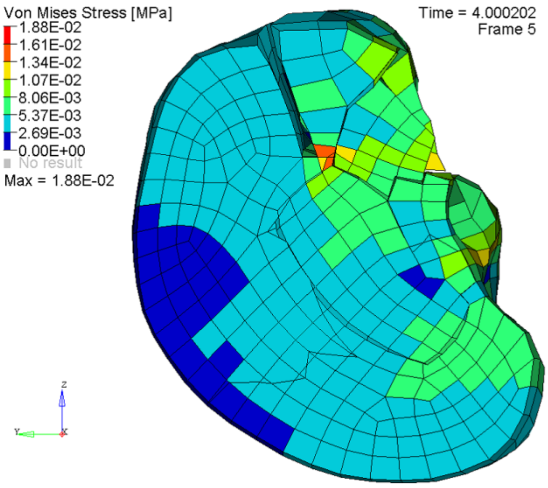

Figure 22. Representation of intracerebral Von Mises Stress in case of impact of the SUFEHM with FE bonnet model.

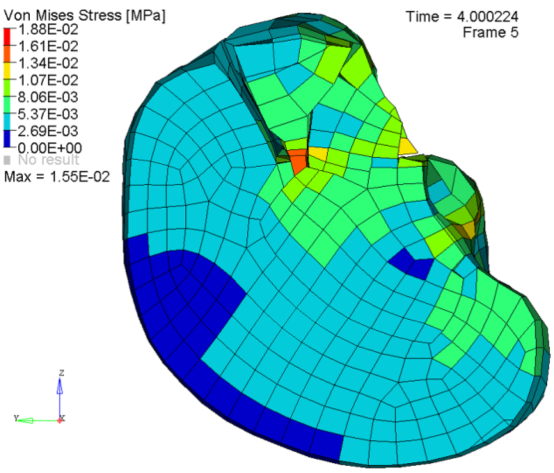

Figure 23. Representation of intracerebral Von Mises Stress in case of impact of SUFEHM with lumped model.

Figure 20 and figure 21 show the simulations of the impact between respectively SUFEHM vs bonnet finite element model and SUFEHM vs lumped bonnet model. Both simulations are in very good accordance. It can be observed that the Von Mises Stress distributions are very similar. The maximum stress appears at same location and at same moment, as illustrated in figure 22 and figure 23. The stress is slightly lower for the lumped model of the "bonnet point" than for the full FE bonnet model as reported in table 3. Consequently, the risk of neurological injury is slightly underestimated 0.9% for bonnet point against 3.4% for FE bonnet.

On the contrary, the intracranial pressure for cerebrospinal fluid is higher leading to a risk of hematroma injury of 22.1% for the lumped bonnet model compared to 19.6% for FE bonnet model, as reported in table 4.

Table 3. Comparison of neurological injury risk computed with FE and lumped bonnet models.

	Brain Von Mises Stress [kPa]	Neurological Injury Risk [%]	
		Moderate	Severe
FE Bonnet	18.8	3.4	1.5
Bonnet Point	15.5	0.9	0.5

Table 4. Comparison of hematoma injury risk computed with FE and lumped bonnetmodels.

	CSF Pressure [kPa]	Hematoma Injury Risk [%]
FE Bonnet	-115.5	19.6
Bonnet Point	-117.6	22.1

DISCUSSION

Limitation of the existing head pedestrian standard test is often discussed as it is carried out with a very simple headform and a calculated injury criterion (HIC) which doesn't take account rotational effect. An intensive use of the head finite elements modelling allowed to propose more accurate injury criteria of the head . This model can be coupled to the impact point models in order to simulate the direct impact for a more realistic head injury assessement. This novel approach needs to characterize and model the impacted structure.

In the present study it is proposed to model the bonnet impact point by a lumped model. This modeling is based on the experimental standard test including a rotation velocity sensor fitted to the headform. In order to check the feasibility of such a procedure, this experimental step has been simulated numerically only in the present study In a further step a complete experimental versus numericall approach of he method should be conduced..

The main limitation of the study is the surface contact which does not represents the real contact caused due to the fact that the normal direction is unchanged. It results to a tangential effect which is not perfectly reproduced and has to be improved. Nevertheless, the linear components from the lumped model simulation are in accordance with the complete bonnet one with a 3% deviation only.

The fact that this feasibility is only carried out with finite elements modeling constitute another limitation of this study. To complete this work, the use of experimental data from test carried out on real bonnet has to be done.

CONCLUSION

The approach which consists in modeling the impacted "bonnet point" by a lumped parameter model whose properties areidentified from the standard experimental headform tests with will contribute to evaluate more realisticaly the bonnet protective performance through the coupling of the method with the human head associated with more accurate injury criteria.

The first results are very encouraging since the impact simulation of a head finite element model on both, the full FE and lumped models of the bonnet lead to a very similar head injury risk assessment. The next step will be to conduct a full experimental versus numerical evaluation of a given bonnet, before going further towards a new test method proposal.

Acknowledgement

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