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LAMINATED WINDSHIELD BREAKAGE MODELLING IN THE CONTEXT OF HEADFORM IMPACT HOMOLOGATION TESTS

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The purpose of modelling a laminated windshield using the FEM is to provide a critical look on the way the adult headform impact tests are conducted in the process of motor vehicle certification. The main aim of the study is to modify the design of a laminated windshield in the context of a vehicle collision with vulnerable road users. The initial phase of the work was to develop a model of the adult headform impactor. The validation consisted in conducting a series of FEM analyses of the impactor certification testing according to the Regulation (EC) 631/2009. Next, the impact of the headform model on a windshield was analysed. The FEM model of laminated glass is composed of two outer layers of glass and an inner layer of polyvinyl butyral. FEM analyses of the impaction were performed at five points of the windshield characterised by various dynamic responses of the impactor and various patterns of glass cracking. In modelling the layers of glass, the Abaqus environment "brittle cracking" model was used. The following material models of PVB resin were considered: elastic, elastic-plastic, hyperelastic, and low-density foam. Furthermore, the influence of the mesh type on the process of glass cracking in a laminated windshield was analysed.

Key words: laminated windshield, polyvinyl butyral, fracture mechanics, pedestrian safety, dynamic analysis.

1. Introduction

Laminated glass is composed of two layers of glass and an inner layer of polyvinyl butyral (PVB) binder. Windshields are fixed to the car body by means of an adhesive. Their function is to remain harmless for the vehicle user in the event of a collision, but also to keep the body inside the vehicle during such an incident, even in the absence of seatbelts.

The Directive of the European Parliament and Council No. 2003/102 / EC of November 17, 2003, requires the designers of windshields to protect not only vehicle users, but also the so-called "vulnerable road users" such as pedestrians, cyclists and motorcyclists. Therefore, modelling of the behaviour of laminated glass in a collision with a pedestrian head became highly needed.

If we look at the structure of passenger cars, we can see that the way of designing the geometry and thickness of windshield layers is very diverse. In all windshields the thickness of the laminate layer is the same throughout the glass pane. In this case, the strength of the glass pane depends only on the geometry, thickness, and material strength of the laminate layers. In the present study, we will focus on the dynamic reaction of the glass depending on the point of impact. This shall allow the development of appropriate design modifications of the windshield in order to improve pedestrian safety.

Modelling the impact of the headform impactor on a windshield using the Finite Element Method is highly complicated. Dynamic collision during which the glass breaks requires a high-end model. In modelling, the following aspects are important: the rate of deformation of PVB material, glass cracking, and the connection between the layers of the laminate. The use of materials with high plasticity and resilience often causes instability of calculations. In addition, glass cracking is problematic for the FEM. Calculations with this method do not allow the loss of continuity of the geometry. After the simulated cracking a change

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in the strength parameters and geometry occurs. Nevertheless, the finite element mesh is continuous throughout the whole analysis.

In this article, we will focus on reflecting the laminated glass cracking process in the context of pedestrian head impact.

2. Headform impactor certification test

Conducting the test of the adult headform impact on a windshield in accordance with the Regulation (EC) 78/2009, requires prior certification testing of the impactor. The Regulation (EC) 631/2009 specifies the criteria for certification. The headform impactor test bench is shown in Fig.1.

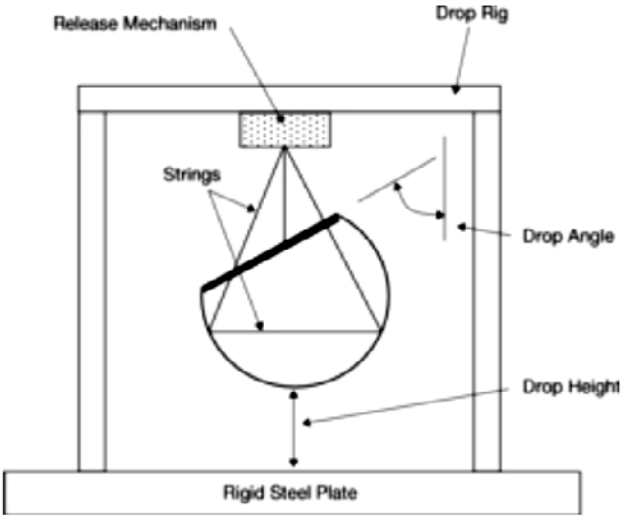

Fig.1. Headform impactor test bench.

The FEM analysis was performed for the drop of the adult headform impactor with the mass of *4.8 kg*. The drop height was *376mm* and the angle of fall equal to *65°*. The acceleration of the mass centre of the head during the test was calculated. A one-modal acceleration curve versus time was obtained as shown in Fig.2. The maximum acceleration was *234g*. The acceleration value is in the normative range *<225g*, *275g>*. The curve of the headform impactor mass centre acceleration during the certification test is shown below.

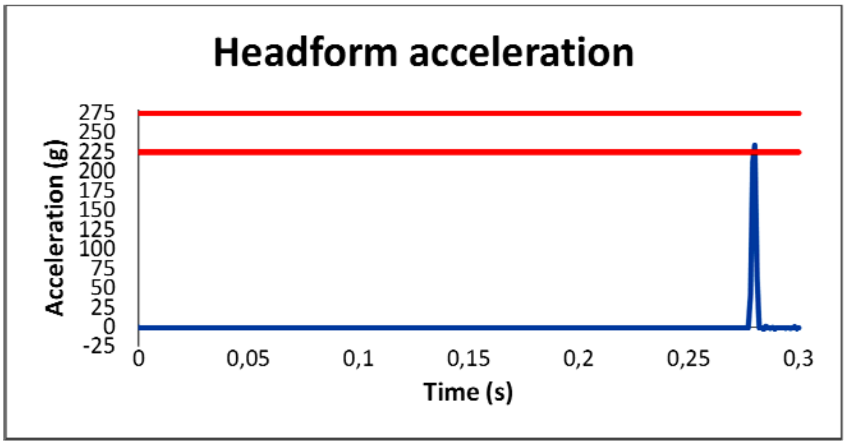

Fig.2. Headform certification test.

The material constants of the headform impactor section selected at the design phase and using the FEM analysis are shown in Tab.1.

Table 1. Material constants of the impactor components.

Material	E [GPa]	ν [–]	ρ [kg/m^3]
PVC	*0.02*	*0.42*	*1300*
Aluminium	*69*	*0.33*	*2720*

With the headform impactor certified according to the Regulation (EC) 631/2009 we can carry out the target test, namely the adult headform impact on the windshield. We will deal with this in the next chapter.

3. Headform impactor striking the windshield

The FEM analyses for the impact of the pedestrian headform impactor on the windshield were performed in accordance with the Regulation (EC) 78/2009. During the test the windshield rigidly attached to the vehicle was hit by the headform impactor at the velocity of *35 km/h*. The velocity vector is perpendicular to the windshield at the point of impact. The windshield is restrained at the edges, where all degrees of freedom were eliminated (Fig.3).

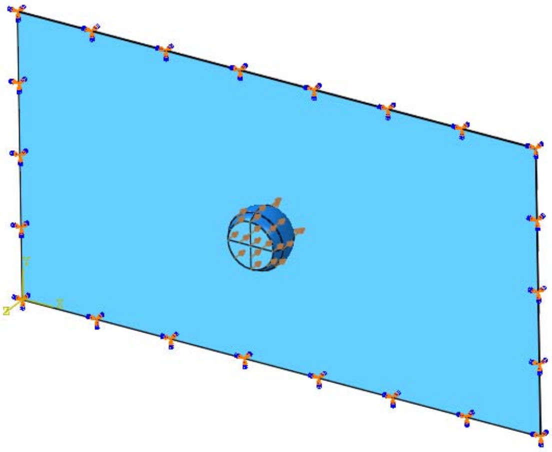

Fig.3. Headform impactor - boundary condition.

The impact occurs at five different points on the windshield (Fig.4). The points were selected to obtain a complete picture in the context of the dynamic response of the impactor and the nature of the windshield cracking.

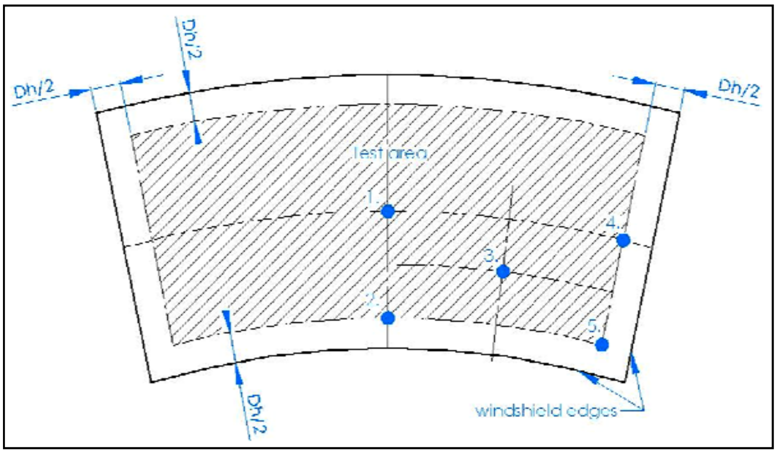

Fig.4. Points of impact of the headform impactor where: Dh-impactor diameter.

In modelling the glass layer, the Abaqus environment “brittle cracking” model was used. In previous publications (Kosiński and Osiński, 2014), the authors presented the pedestrian headform impact considerations for the following PVB resin material models: elastic, hyperelastic and low-density foam. The results in this chapter apply only to the elastic-plastic model of polyvinyl butyral. The tensioning characteristics of PVB and glass are taken from Peng (2013), Timmel (2007).

Figures 5-9 show the results of the impact at 5 selected points on the windshield. In all cases the fracture lines propagate from the point of impact and appear on the restrained edge nearest to it. The rate of crack propagation is the greater the more susceptible the windshield is at the given point of impact. The crack propagates the fastest for the impact at point No.1, and the slowest for the corner impact at point No.5.

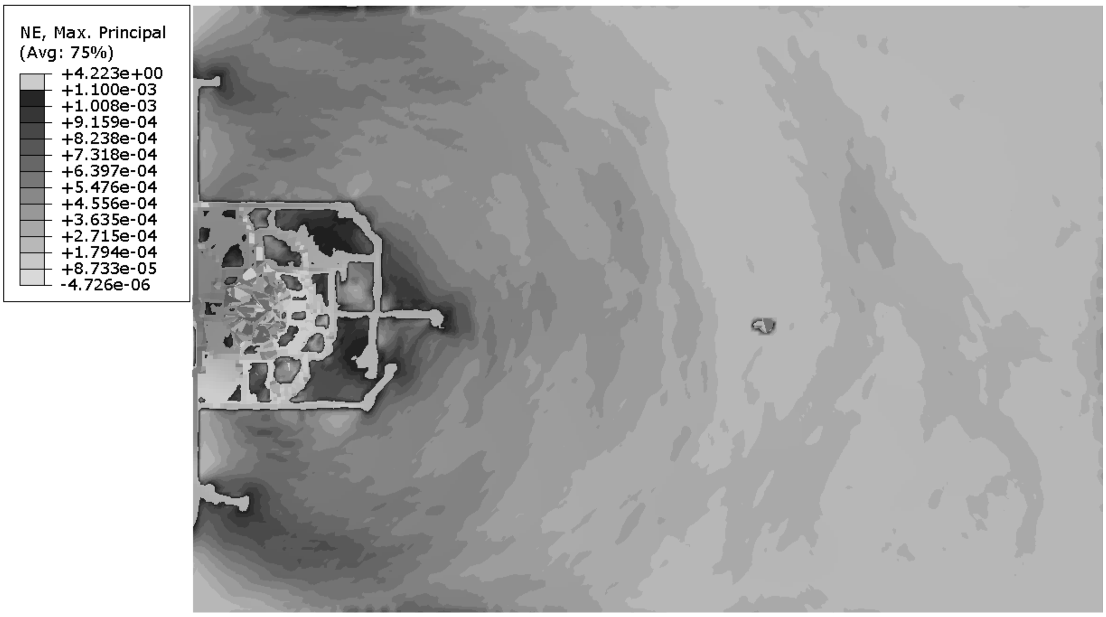

Fig.5. Windshield cracking process - point 4. (*t=8ms*)

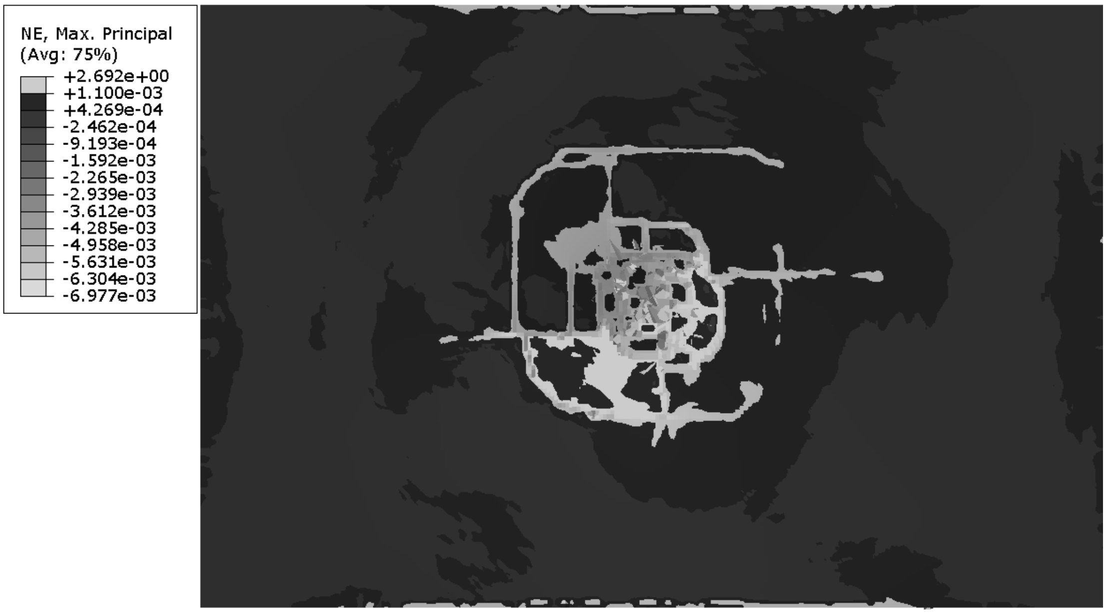

Fig.6. Windshield cracking process - point 1. (*t=8ms*)

Fig.7. Windshield cracking process - point 5. (*t=8ms*)

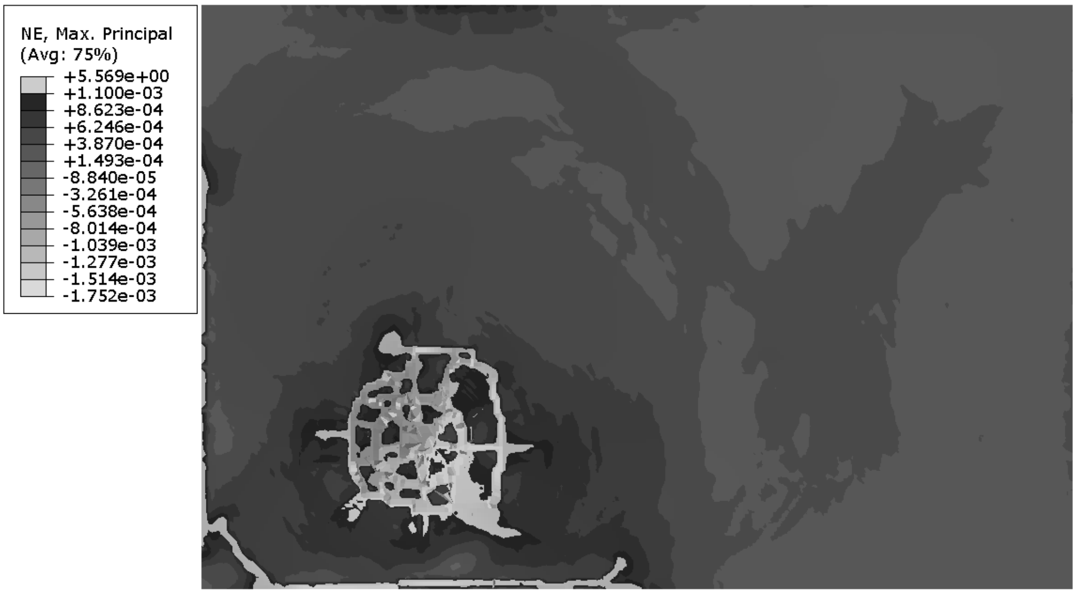

Fig.8. Windshield cracking process - point 3. (*t=8ms*)

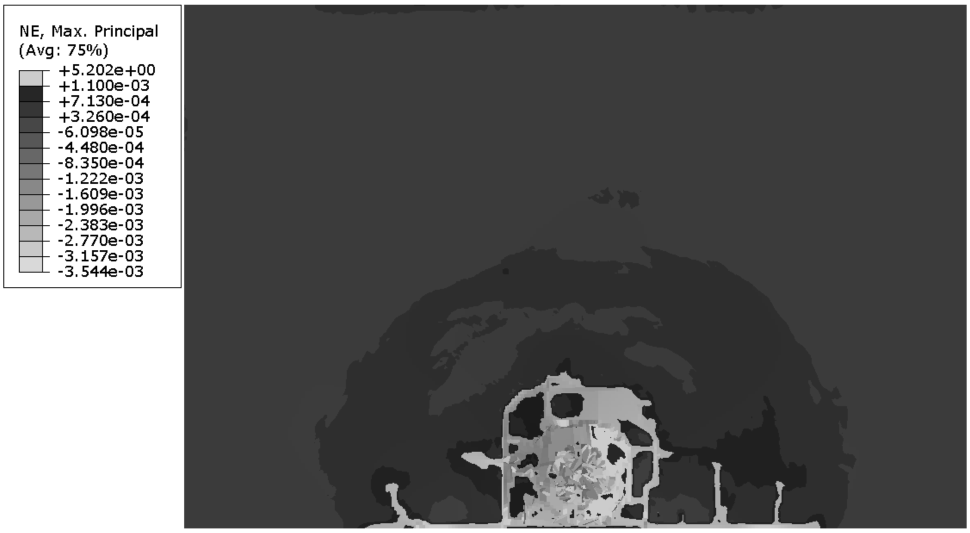

Fig.9. Windshield cracking process - point 2. ($t=8ms$)

The most important results from the point of view of safety of the pedestrians are the head's centre of mass acceleration values during the impact. We can thus classify the windshield areas as more or less safe. Calculating the head performance criterion (HPC) based on acceleration, expressed by Eq.(3.1), it can be stated that the vehicle fitted with such a windshield can be approved for traffic.

$$HPC = max\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} adt\right](t_2 - t_1). \tag{3.1}$$

Figure 10 shows the HPC results of the headform impactor during the impact for the five cases under analysis.

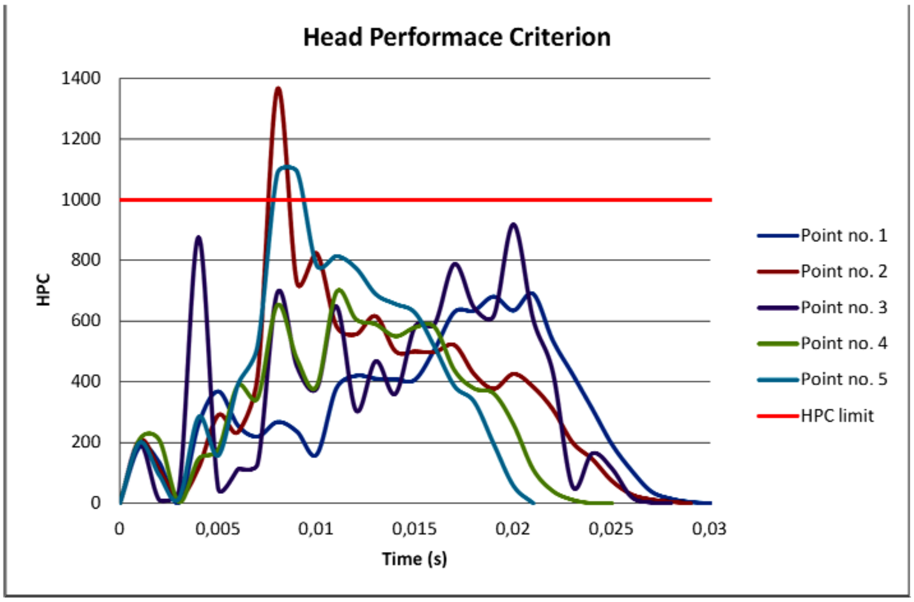

Fig.10. Head performance criterion.

It can be seen in Figure 10 that the head performance criterion exceeded the limit value equal to 1000 in two cases. Currently, the impact tests of the adult headform impactor on the windshield are performed solely for the purpose of monitoring, but in the near future it will probably be a mandatory test. Summarizing the results of calculations it should be noted that the tested laminated windshield does not pass the head impact test. Therefore, there is a great need for designing safer windshields.

4. Analysis of the influence of the FEM mesh on the process of laminated windshield breakage

4.1. Analysis of the influence of the FEM mesh type

Laminated windshield cracking phenomenon is rather complicated to model due to the irregular nature of the crack propagation. In this section, we will compare the behaviour of the windshield model when different types of mesh are applied: concentric, rectangular and tetragonal.

The results showing the effect of the windshield cracking obtained from FEM calculations are presented below.

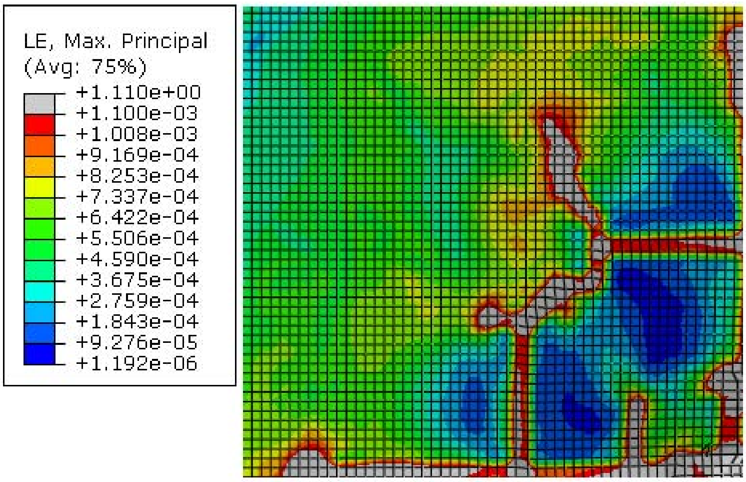

Fig.11. Rectangular mesh.

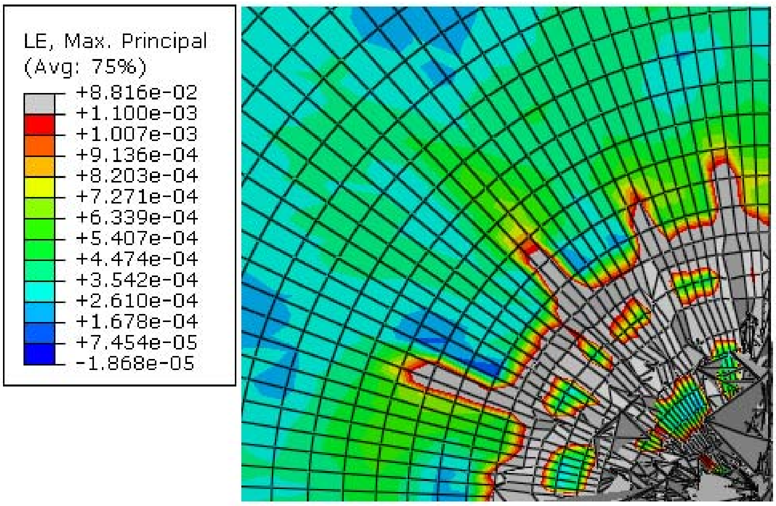

Fig.12. Concentric mesh.

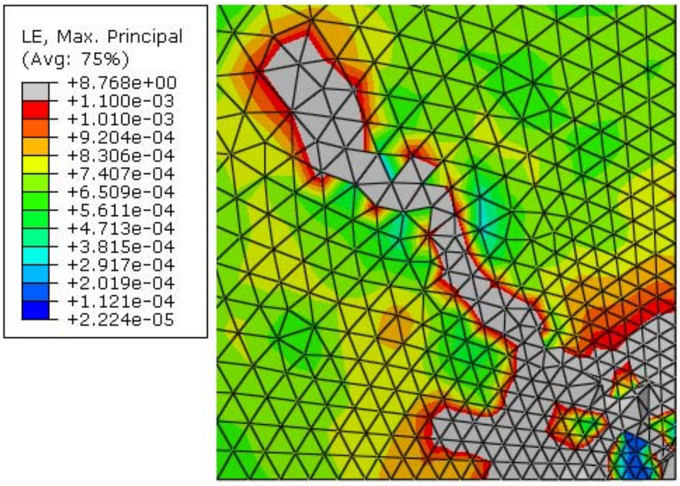

Fig.13. Tetragonal mesh.

The model which is better at reflecting the phenomenon of propagation of the laminated windshield fracture lines is undoubtedly the one with the concentric mesh. Regarding the cracking as a process we find that the circumferential crack lines appear at first, and then crack propagation proceeds further through the radial lines.

4.2. Analysis of the mesh size influence on the cracking process of the glass layer

In this section, we will compare the behaviour of the glass layer model subject to a dynamic load depending on the size of the FEM mesh. The windshield model with a thickness of *1 mm* was divided into rectangular mesh with a length of element edge: *2 mm*, *1 mm* and *0.5 mm*. The Abaqus environment "brittle cracking" model was used in modelling the layers of glass.

The results of FEM simulation are shown below.

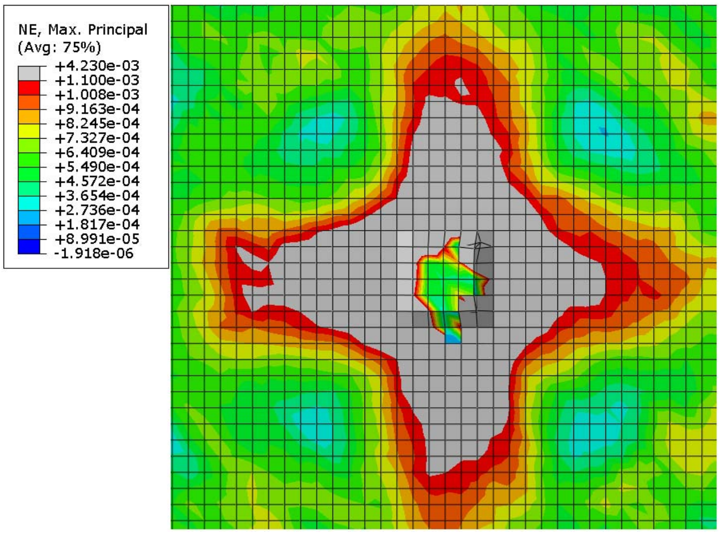

Fig.14. Rectangular mesh – *2mm*.

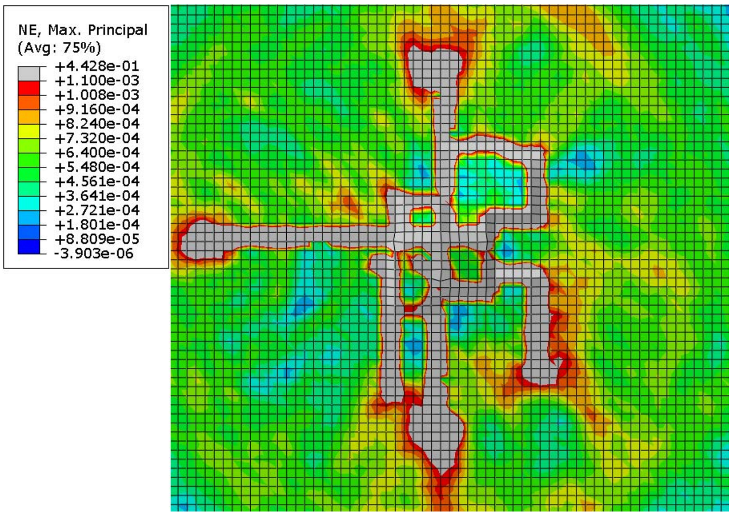

Fig.15. Rectangular mesh – *1mm*.

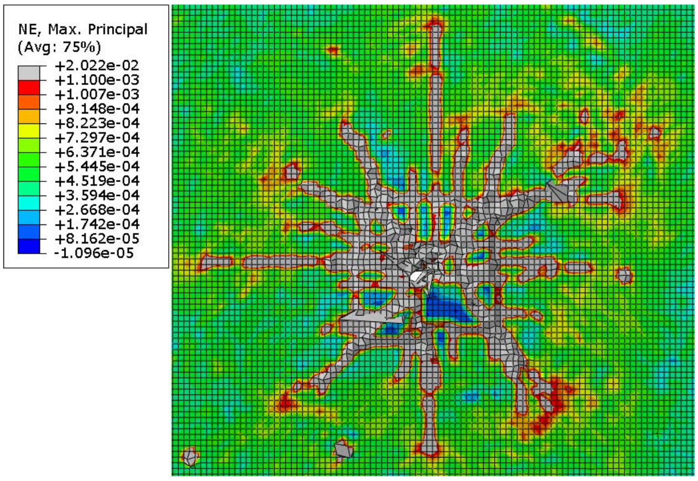

Fig.16. Rectangular mesh – *0.5mm*.

The results of impact to the glass layer illustrate that modelling the glass cracking process depends largely on the density of the FEM mesh. For the rectangular mesh of *0.5 mm* edge the radial nature of the glass cracking process was obtained. But there are no circumferential cracking lines which occur in a real impact.

5. Conclusions

The study on pedestrian headform striking a laminated windshield rendered it possible to determine how to model this type of material using the Finite Element Method. The following conclusions were drawn:

1. The value of acceleration of the centre of mass of the headform impactor differs depending on the place of impact. The limit value of the head performance criterion (HPC) was exceeded in areas with greater rigidity, at the edges of the glass.
2. The nature of the glass cracking depends strongly on the type of the FEM mesh used. The concentric mesh is the best at modelling the process of the windshield cracking during pedestrian head impact. The

peripheral crack lines initiate destruction, and then crack propagation occurs through the radial lines. The finite element mesh on the edges should be similar to a concentric mesh.

3. Reflecting the glass cracking process also depends on the size of the FEM mesh. When using a sufficiently small mesh, where the element edge was *0.5 mm*, the radial nature of glass layer cracking was obtained for the square mesh.
4. The elastic-plastic material model of polyvinyl butyral gives the best results in simulating the pedestrian head impact to the laminated windshield.
5. The brittle cracking material model of Abaqus system allows the glass breakage to be reflected during the impact loads.

Pedestrian safety should be improved in the area of increased rigidity of the windscreen. One way is to reduce the windshield thickness from centre to edge. From a technological point of view, the execution of such windshield is more difficult, but possible. Another very effective way to improve safety is to increase the thickness of the PVB layer, as described in Kosiński and Osiński (2014). Laminated windshields with a variable thickness of the constituent layers would be an innovative trend and a new concept in designing.

In current solutions of the construction of automotive windshields the outer layer of glass is thicker than the internal one. This direction in design is related to the driver and passenger protection in the event of a collision with a small object, e.g., a stone. To improve pedestrian safety, laminated windshields should have a thinner outer layer. A more susceptible outer layer would absorb more energy by plastic deformation of the PVB resin.

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