An Approach to Simulate the Residual Strength of Initially Damaged Laminated Safety Glass with LS-DYNA

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Abstract

Since March 2011, a newly released Federal Motor Vehicle Safety Standard 226 - Ejection Mitigation (FMVSS 226) shall help to reduce the complete or partial ejection of vehicle occupants through side windows during rollover or side impact accidents. The rules apply to laminated safety glass windows - sandwich structures made out of polyvinyl-butyral foil and regular glass panes and have to be verified experimentally by car manufacturers from the year 2017 onwards.

To be able to evaluate or even predict the experimental results with finite element analysis (FEA), a simulation model is built representing the material and structural behavior of the laminated safety glass during the testing procedures which include the impact of a regular head impactor at different velocities and positions on pre-damaged side windows. The main challenge for the model development is the consideration of a specific crack pattern on the in- and outside of the window given by a center punch procedure prior the impact test. In a first approach to understand the material behavior, full vehicle experiments are replaced by a simplified drop testing procedure. According to the FMVSS 226 rules, different velocities and impact positions are considered. In addition, a frame-like structure is built representing the constraints of a side window in a full vehicle testing procedure.

During the model development, different modeling techniques, element types and material models are tested. To analyze the dependency of the simulation results and the chosen mesh, different element sizes and orientations are considered. The simulation results gained with the finite element software LS-DYNA are compared with the results of drop tests performed on three different side window geometries.

Keywords:

Initial Damage, Laminated Safety Glass, Drop Tests, LS-DYNA, FMVSS 226

1 Introduction

Many deaths and injuries during rollover or side impact accidents are caused by the ejection of the vehicle's occupants through the side windows. To minimize the risk of being pulled out through the side windows, car manufacturers start to use laminated safety glass instead of regular safety glass for the construction of the side windows. So far, laminated safety glass was mainly used just for the car's windshield. To cover this development with appropriate verification tests, the National Highway Traffic Safety Administration (NHTSA) released a new Federal Motor Vehicle Safety Standard No. 226 (FMVSS 226) [1] in January 2011 which has to be fulfilled by car manufacturers from the year 2017 onwards to get clarification for new released car models.

The experimental testing procedures described in the FMVSS 226 rules include full vehicle impact tests with an 18 kg head impactor on initially damaged laminated safety glass side windows at different points of impact and with different velocities. Additional safety features such as side airbags are also considered in the regulations. Since nowadays experimental testing is usually accompanied by finite element analysis (FEA) to foresee upcoming difficulties during the experiments or to be able to predict the experimental results and even reduce the number of necessary tests, a modeling technique has to be developed being able to represent the material behavior of the laminated safety glass for the load cases defined in the FVMSS 226. Possibilities to model a three-layered material such as laminated safety glass which consists of two glass panes being hold together and supported by a polyvinyl-butyral (PVB) foil are already proposed by Kolling et. al. [2]. The more challenging problem is the consideration of the initial damage applied to the laminated safety glass side windows with a center punch procedure prior the actual impact test which leaves a random crack pattern on both the inner and outer glass panes of the side windows. To be able to develop an appropriate simulation model which is valid for different window geometries, various points of impact as well as for different impact velocities, several drop tests are performed on damaged and undamaged side windows helping to understand the material's behavior and avoiding the expensive costs of full vehicle tests. Nevertheless, the developed modeling technique will only be verified for the special punch pattern defined in the safety standard which consists of center punches every 75 mm, having an offset of 37.5 mm between the inner and outer punch pattern.

As reference, acceleration time curves gained with the simplified drop tests are used to evaluate the proposed modeling techniques with respect to accuracy, model pre-processing, geometry and mesh independency of the developed model and of course the calculation time needed. In total, three different side window geometries are tested, using the center of gravity as a reference point for all three geometries and lower and upper points of impact determined by the safety standard for further verification. The experiments and simulations are performed with two different impact velocities and a final experimental setup with a frame-like structure representing the constraints of the laminated safety glass during full vehicle experiments is used to verify the models validity for simulations according to the actual FMVSS 226 standards. For the simulations, LS-DYNA version 971 – R 5.1 is used.

2 Material properties of laminated safety glass

Laminated safety glass is mainly characterized by the adherence of the glass to the PVB foil. The glass material is usually a regular float glass which shows a brittle failure behavior in case of damage. Compared to a single layer safety glass which breaks into fine splinters once it is damaged, regular float glass is not thermally pretreated and therefore rather breaks into coarse pieces. The safety effect of laminated safety glass is given by these splinters being hold together with the PVB foil which in this case leads to a residual strength of the composite through the foil itself as well as through the splinters being able to support each other along the crack's edges. The glass's Young's modulus usually has values between 70.000 N/mm³ and 73.000 N/mm³ and a Poisson ratio of approximately $\mu = 0.23$ [3].

The PVB foil is an amorphous thermoplastic material and is usually produced with a thickness of 0.76 mm or a multiple of that. The material shows a viscoelastic stress-strain behavior which is highly temperature and strain rate dependent [4]. Due to that, environmental standards such as temperature and humidity are defined in the FMVSS 226 rules for the experimental testing to ensure reproducibility. Storing the side windows in a climate chamber until short before the drop tests, this is also guaranteed in the experiments described here.

3 Experimental tests according to FMVSS 226

The experimental tests described here are performed according to the FMVSS 226 rules. Nevertheless, the full vehicle tests are replaced by a simplified drop testing procedure to avoid the expensive costs of such experiments in this first model development step. Using a crane, the 18 kg head impactor mounted onto a slide is carried into a height so that after its ejection, the impactor will hit the laminated safety glass side windows at either a speed of 3 m/s or 5 m/s. An accelerometer is mounted on top of the head impactor, being activated by a light barrier just short before the impactor hits the side window. The three different side windows must be placed onto individually manufactured shoulders made out of steel on the basis and polyethylene (PE) in the areas, where the windows are placed. With clamps holding this construction together, it is reasonable to use rigid body formulations for this part of the experimental setup during simulations. Cameras are used to capture the deformation of the laminated safety glass at the point of impact. The complete experimental setup is shown in figure 1.

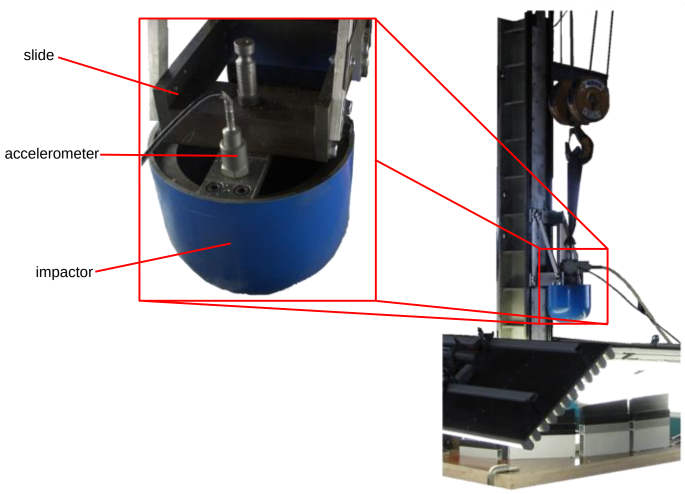

Fig. 1: Complete experimental setup..

As already mentioned, the side windows are undertaken a center punch procedure creating a random initial crack pattern on the in- and outside of the laminated safety glass. As reference point, the center of gravity (COG) of the so called daylight opening on the outside of the window is chosen and the points for the crack initiation are found 75 mm in vertical and horizontal direction from the COG. The daylight opening is defined as the area where no surrounding material of the car such as rubber or carpeting can be found – simply spoken: the area where the vehicle occupants can look through. The punch pattern applied to the inside of the side window is moved 37.5 mm in horizontal direction from the outside punch pattern. The drawing given in the FMVSS 226 rule explaining the identification of the center punch points is given in figure 2 as well as a laminated safety glass window right after the center punch procedure.

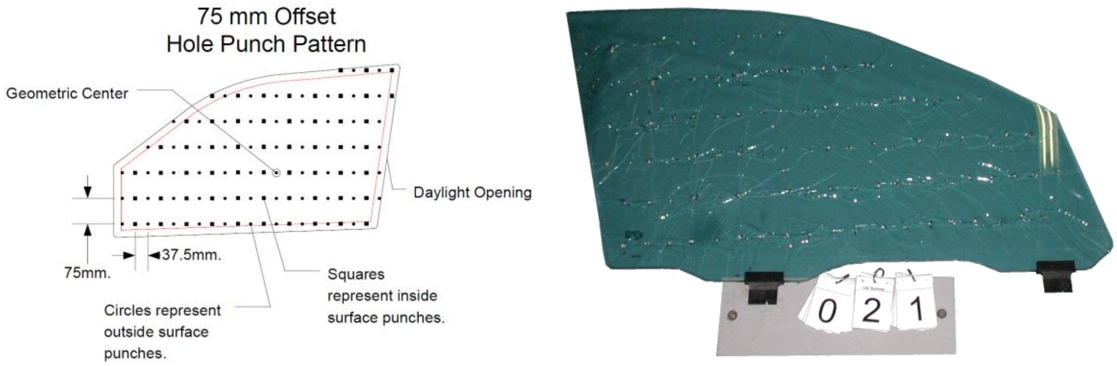

Fig. 2: Punch pattern defined in FMVSS 226 [1] and an initially damaged side window according to these rules.

The method used to identify the target points for the head impactor is shown in figure 3. Thereby, an offset-line of 10 mm towards the daylight opening is used to ensure that the head impactor does not get in contact with the vehicle's interior carpeting. It can be seen that for a front side window, primary targets are a lower-front and an upper-back position – for a back side window, the primary targets are an upper front and a lower back point of impact. Main difference between the experiments presented here compared to the actual rules defined in the FMVSS 226 considering the target identification is that the COG will be used as a reference point of impact for all three geometries tested during the model development. The other target points are chosen in a way that they are similar or at least close to the ones defined in the testing requirements, even though only the primary targets are considered. The target points used for the experimental results presented here are shown in figure 3 as well.

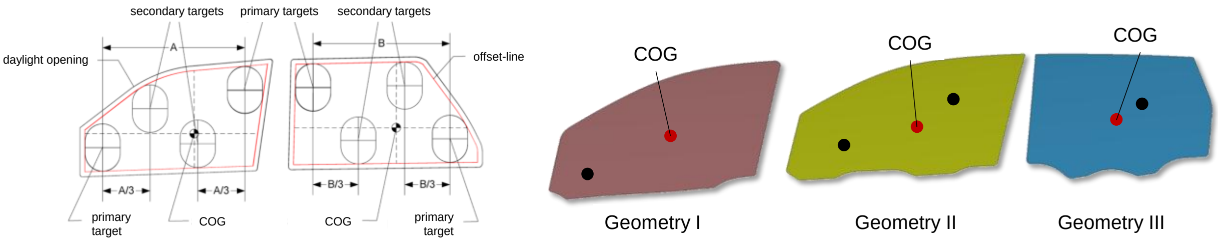

Fig. 3: Target identification according to FMVSS 226 [1].

Additional experiments performed only on the COG of geometry I include drop tests on undamaged side windows, side windows damaged only with one center punch at the center of gravity and besides the punch pattern defined in the FMVSS 226 rules, also side windows damaged on the same positions on the in- and outside of the safety glass with either a horizontal offset of 50 mm or an offset of 100 mm. These tests are preformed to gain a better understanding of the material behavior of the damaged side windows.

Further experiments are performed in order to identify the material parameter used for the initially damaged area of the laminated safety glass (also see [5]). Therefore, tensile specimen such as they are shown in figure 4 are cut out from laminated safety glass side windows and the area of interest is damaged to see how the glass splinters attached to the PVB foil do influence the remaining strength of the material. Tests are performed quasi-static and with velocities of 1.0 m/s, 1.2 m/s, 2.0 m/s and 4.5 m/s to consider the PVB foils' rate dependency. Using an equivalent specimen model, the material's parameters are adapted in a way that all the experimental tests can be simulated properly.

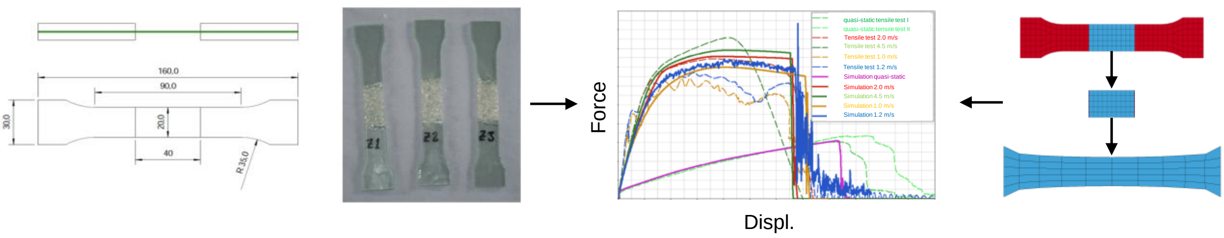

Fig. 4: Material parameter identification [5].

4 Finite element modeling

There are several modeling techniques conceivable to model the composite layup of the laminated safety glass windows as well as for the modeling and consideration of the initial damage applied to the side windows. Some of the techniques were already introduced by Kolling et. al. [2], others are being improved or tested to fit to the requirements of the load cases considered here.

4.1 Modeling of laminates

A simple way to model the three-layered laminates is to use solid elements for each one of the layers. To avoid unnecessary contact formulations, the element's nodes should be identical at the boundary layers of the different materials so that the nodes can be merged. Using this modeling technique such as it is show in figure 5, it is recommended to use element formulation ELFORM = -1 in the *SECTION_SOLID card which is able to simulate solid elements with a poor aspect ratio in a proper way [6]. The main disadvantage of this model setup is the higher amount of calculation time for the solid elements

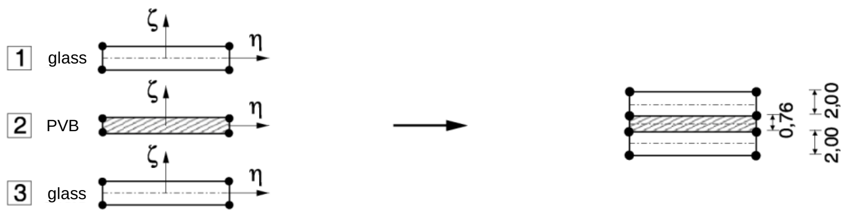

Fig. 5: Solid element layup.

compared to the calculation time for shell elements. Using thick shell element formulations might reduce the calculation time and makes it still possible to use three dimensional material formulations if requested, but this is not tested here.

In order to use only shell element formulations, it is necessary to use the NLOC – Function available in the *SECTION_SHELL card in LS-DYNA. This flag allows to fully consider the thickness of the shell elements but to move the shell's mid-surface along its normal. As shown in figure 6, the mid-surface of the shell elements representing the float glass attached to the PVB foil is moved to be identical to the mid-surface of the PVB foil itself. With this option, the nodes of three-layered shell elements can be merged which leads to a higher numerical stability since no usage of further contact formulations is required. The value for NLOC can be calculated using a formulation given in [6], where "offset" describes the distance between the mid-surfaces of the shell elements and the average shell thickness of the elements of which the reference plane is moved has to be known:

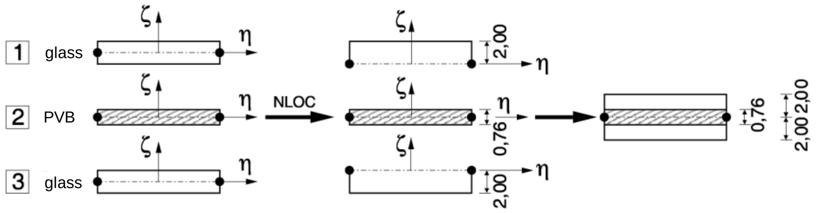

Fig. 6: Shell element layup.

$$offset = -0.5 \times NLOC \times (average\ shell\ thickness) \quad (1)$$

Another modeling option shown in figure 7 might be the usage of contact formulations instead of the identical nodes. This makes the usage of the NLOC – flag unnecessary but proper parameters have to be found for the contact formulation. A *CONTACT_..._TIEBREAK - formulation can be recommended for such a modeling technique since it is used quite often for laminate modeling [7]. Another modeling possibility is to merge the elements representing the float glass with cohesive elements representing the PVB foil in the way being shown in figure 5. It is also conceivable to use zero thickness cohesive elements to separately combine the two glass panes with the PVB foil. These methods are just mentioned here for integrity reasons but will not be tested in the following. Nevertheless, all the modeling techniques just described allow the consideration of the material's characteristically properties for both the PVB foil and the float glass which is in particular the brittle failure behavior of the glass panes compared to the strong viscoelastic material behavior of the PVB foil.

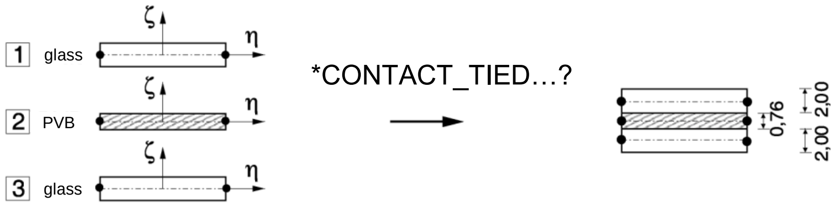

Fig. 7: Shell element layup with contact interface.

4.2 Material models

To be able to consider the material properties of the PVB foil, the unbroken float glass and the areas where the laminated safety glass is considered as being damaged, a total of three different material models or at least different input parameters for the material cards are necessary. The following will shortly describe the available material formulations in LS-DYNA for the rubber-like PVB foil and the float glass.

4.2.1 Rubber-like materials

An easy to use material model is the so called *MAT_BLATZ-KO_RUBBER (*MAT_007). It only requires the input of only one parameter – the shear modulus. A value for the material's Poisson ratio is already implemented in the LS-DYNA material routine and is μ = 0.463, making it nearly incompressible. Another option is the *MAT_SIMPLIFIED_RUBBER/FOAM (*MAT_181) material card which needs a little more input data such as the linear bulk modulus, a damping coefficient and a limit stress value for frequency independent frictional damping. Also the shear modulus has to be given and the Poisson ratio can be user-defined. Otherwise a fixed value of μ = 0.495 will be used. In

addition, element failure can be activated with this material model, even though this is not necessary here since a breaking of the PVB foil cannot be observed during the experiments.
Finally, the often used LS-DYNA standard material *MAT_(MODIFIED)_PIECEWISE-_LINEAR_PLASTICITY (*MAT_024 or *MAT_123) is a also good option allowing the consideration of a rate dependency such as it can be observed for the PVB foil. Rate dependency is considered with tabulated effective stress vs. effective plastic strain data and the further necessary material parameters are a Young's modulus, the Poisson ratio as well as the yield stress and a tangent modulus [8]. Failure can also be considered which is not necessary here.

4.2.2 Glass materials

LS-DYNA provides several possibilities to describe the material behavior of glass. The ones that are tested here are *MAT_ORIENTED_CRACK (*MAT_017) – an isotropic, elastic-plastic material model failing under tensile stress, *MAT_BRITTLE_DAMAGE (*MAT_096) considering both, tensile and compression failure with an anisotropic material formulation and *MAT_JOHNSON_HOLMQUIST_CERAMICS (*MAT_110) which accumulates the damage created in the material and calculates the remaining residual strength as a function of compression and the actual damage. A complete set of material parameters for *MAT_110 is given by [9]. Also a good option is to use *MAT_(MODIFIED)_PIECEWISE_LINEAR_PLASTICITY (*MAT_024 or *MAT_123) for the simulation of the glass material. This is easily done by not defining any rate dependency or a tangent modulus which finally leads to a linear-elastic material behavior. Additional element failure can be activated with the *MAT_ADD_EROSION – material card.

4.2.3 Models for the damaged material

Basically, all material models described for the PVB foil or the float glass are also conceivable to describe the material behavior of the area considered as damaged. Therefore, material parameters have to be varied, either by decreasing the data used for the intact float glass or by an increase of the parameters used for the PVB foil modeling. Nevertheless, the tensile tests mentioned above show that a rate dependency should be considered at the elements representing the damaged areas of the laminated safety glass and therefore *MAT_024 or *MAT_123 are the best options of the above described materials.

4.3 Consideration of pre-damage

Several options are available to consider the pre-damage of the laminated safety glass. An easy way is to consider some elements as damaged and provide them with rate dependent and lower material data compared to the regular glass material. Depending on the number of elements being assigned with such material data, the simulation shows a weaker or stronger response to the impact of the head impactor. To identify the elements being considered as damaged, an artificial punch pattern has to be added to the laminated safety glass during the side window's pre-processing. The punch patterns tested for the simulations here are shown in figure 8. One considers the damage as element strips onto the surface of the safety glass windows, being offset 37.5 mm between the inner and outer safety glass pane. The other possibility is a star pattern applied at the identified center punch positions to the laminated safety glass. Both models offer the possibility to vary the number of damaged elements, either by choosing a higher number of elements in the width of the element strips or through a higher number of rays or a larger radius of the star pattern.

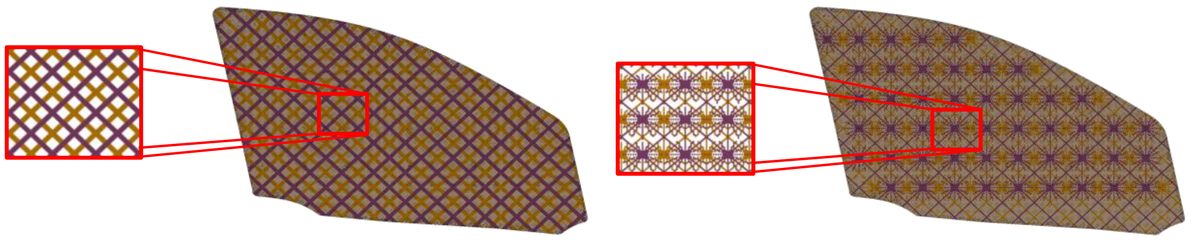

Fig. 8: Different punch patterns representing the initial damage of the laminated safety glass.

Compared to the real crack pattern which can be seen in figure 2, the star pattern seems to be more realistic and offers a little more variability compared to the element strip model which therefore is easier to generate during pre-processing. Both models can be generated using the command-files and scripting language of LS-PrePost, but also a program written in Python or FORTRAN generating such patterns is a good option.

Further options considering the initial damage are the use of *Initial_Stress or *Initial_Strain cards for the identified elements instead of weakened material parameters for the glass material. Another option for the element identification would be to project black/white data from pictures taken of the damaged safety glass onto the simulation model. The accuracy of such a method is highly dependent on the element size and is therefore not considered in this study.

4.4 Complete simulation setup

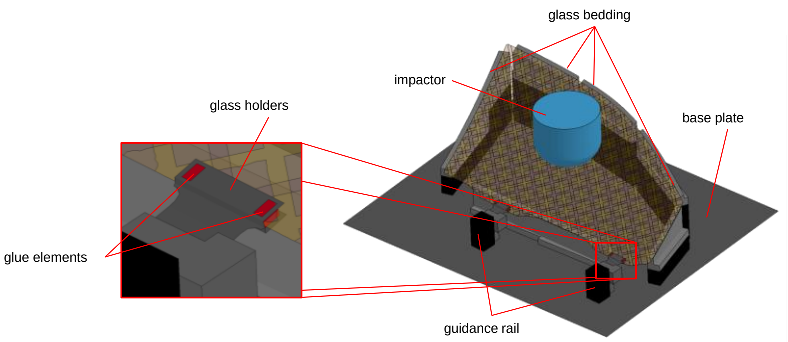

Fig. 9: Complete model used for the simulations.

The complete model which is used for the impact simulations is shown in figure 9. The base plate, the steel parts of the glass bedding as well as the glass holders and the impactor are modeled as rigid material, reducing the calculation time. The impactor is surrounded by zero-thickness shell elements due to contact reasons. For the glue elements at the glass holders, an easy to use *MAT_ELASTIC formulation is chosen in combination with a *CONTACT_…_BEAM_OFFSET formulation. The solid elements representing the PE shoulders are modeled with a *MAT_024 formulation and with …_AUTOMATIC_SINGLE_SURFACE and …_AUTOMATIC_SURFACE_-TO_SURFACE contacts, the model setup is complete. As a solid element formulation, the LS-DYNA default constant stress solid element is chosen and a Belytchko-Lin-Tsay formulation is used for the shell formulations, using three integration points for all the shell elements belonging to the general experimental setup and five integration points for the elements representing the laminated safety glass.

5 Experimental and simulation results

The first interesting results are given in figure 10 and were obtained prior this work by [5] in order to understand the material behavior of initially damaged laminated safety glass. Drop tests on undamaged safety glass (blue) show a characteristic peak in the acceleration-time curve's progression, just right after the impactor hits the side window. This can be explained by a high resistance of the undamaged safety glass which after the breakage leads to a decline of the measured acceleration and finally, the acceleration measured is highly dependent on the material parameters of the PVB foil. Having only one center punch applied to laminated safety glass (light green) already leads to a lower progression of the measured acceleration-time curve and the peak which can be obtained during the tests with undamaged material is not visible anymore.

Figure 10 also shows that the measured acceleration–time curves are almost independent of the degree of damage. Considering the 100 mm (lilac), the 50 mm (red) and the FMVSS 226 punch pattern (green), the increase of the acceleration is almost similar, even though a higher maximum of

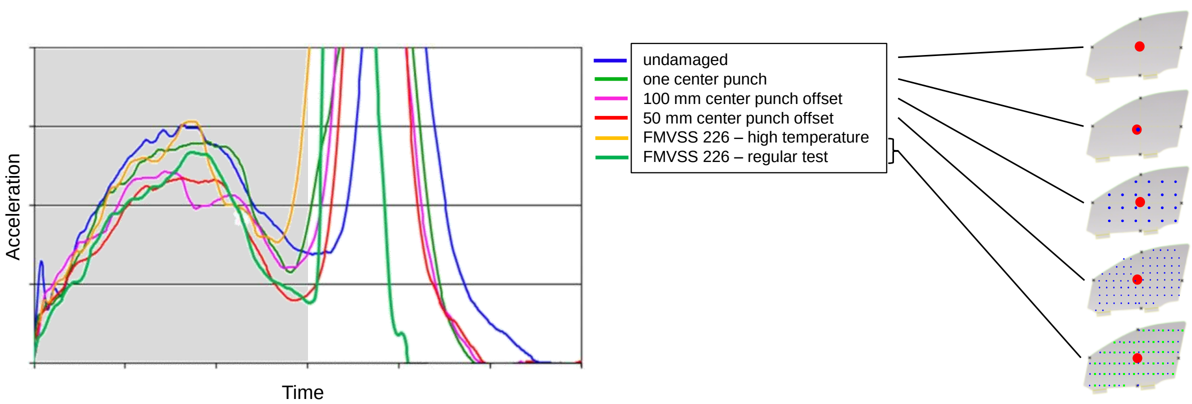

Fig. 10: Drop tests on different punch patterns for geometry I.

the acceleration measured for the FMVSS 226 punch pattern is visible and reasonable since the center punch positions are not equal on the in- and outside of the side window and therefore, the highly damaged areas on the in- and outside of the laminated safety glass are separated from each other (also see figure 2). The yellow curve was measured on a day having higher temperatures than the others and the side window lay outside of the climate chamber for a while prior the testing. This lead to a different acceleration-time curve due to the PVB foils temperature dependency. Finally, it has to be mentioned that the high increase and the drop of the values at the end of the curves shown in figure 10 characterize the event of the impactor hitting the base plate of the experimental table.

The simulation results which can be gained with the modeling techniques proposed above are given in figure 11. Using an element strip width of 3 elements or a star pattern with an 85 mm ray radius, good results can be gained, speaking in terms of the maximum acceleration reached and the time the impactor hits the base plate. Using only an element strip width of one element predicts too high accelerations but this example also shows how the artificial crack pattern can be easily adapted without much extra time during the model pre-processing.

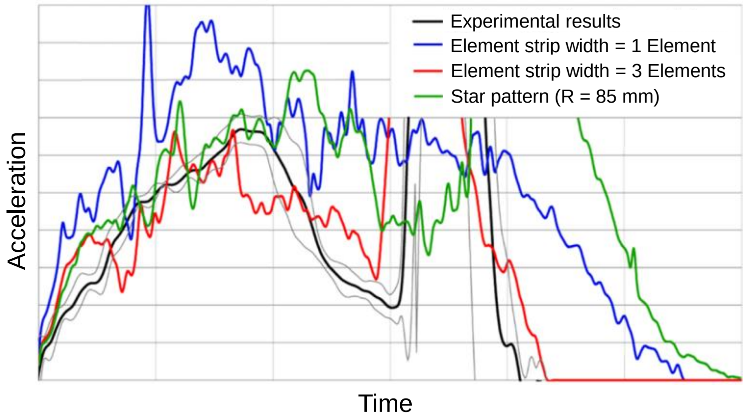

Fig. 11: Simulation results for geometry I, COG.

The results shown in figure 11 are gained with an element size of 3 mm. In order to safe calculation time and costs, simulations are also performed with elements of a size of 10 mm and 7 mm. Therefore, only an element strip width of one element is chosen. Also the results of the modeling technique using solid elements and *MAT_096 for the material properties of the glass are shown but it has to be mentioned that using a complete solid element modeling leads to calculation times more than six times higher than with a shell modeling technique. Nevertheless, the results are comparable to the ones shown in figure 11, the acceleration predicted for a modeling with 7 mm shell elements is a little higher than the measured values. Using 10 mm shell elements is not recommended since the calculated acceleration is far too high.

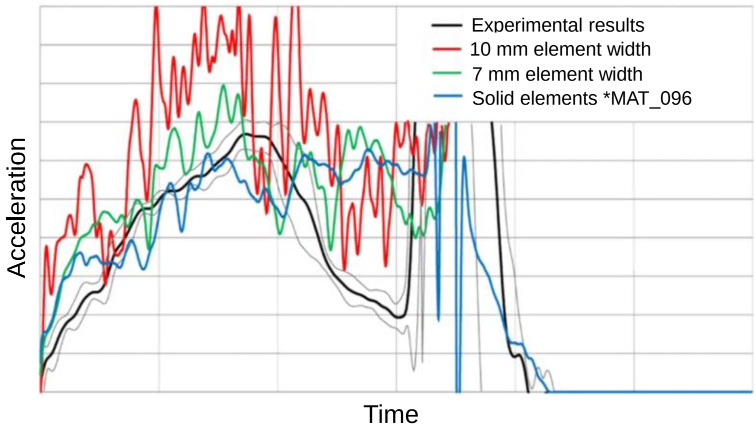

Fig. 12: Different element sizes & types - geometry I, COG.

Another criterion which is used to evaluate the quality of the developed modeling technique is the necessity of a structured mesh. The results presented so far consider that the elements are oriented along lines connecting the initial center punch positions such as shown in figure 8. Since the modeling of the damaged laminated safety glass shall not be too time consuming during the pre-processing, an unstructured mesh is desired which is still capable to represent the load case defined in the FMVSS 226 rules. The simulation results gained with such an unstructured mesh with QUAD and TRIA elements are shown in figure 13. Especially the simulation results gained with QUAD elements seem not to be influenced by the random element distribution. Using TRIA elements, the first disadvantage is that the calculated accelerations are higher than the ones gained with QUAD elements; the second disadvantage is that the calculation time increases to up to more than four times of the calculation time needed for the pure QUAD element mesh.

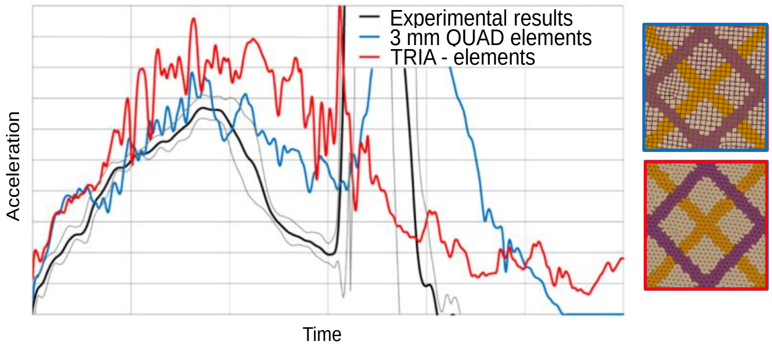

Fig. 13: Unstructured mesh with QUAD- & TRIA elements, geometry I, COG.

Since the developed model shall be valid for different side window geometries and different points of impact, the simulation results for these load cases are shown in the following. Figure 14 shows the results considering the upper back point of impact found according to the FMVSS 226 rules for geometry II (see also figure 3). All the methods which show good results for geometry I at the COG as point of impact are also capable to generate good simulation results for this second geometry at a different point of impact. All the modeling techniques more or less predict the maximum of the measured acceleration, even though only the shell element modeling using an element strip width of three elements shows that the acceleration is decreasing after the maximum is reached whereas the other models keep the maximum acceleration almost constant before the values decrease. Reason for this might be a non proper consideration of the friction between the safety glass and the shoulders supporting it during the experiment. In this case, a too high chosen friction coefficient could keep the side window from sliding down the support during the simulation.

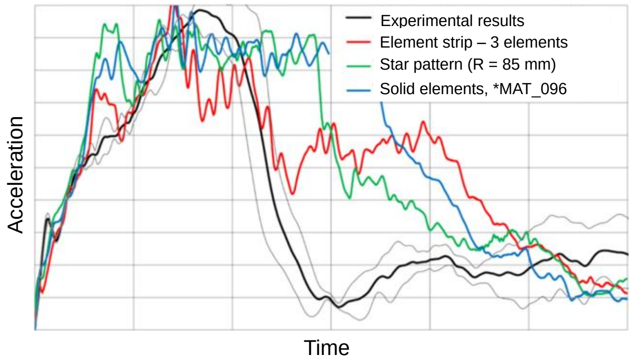

Fig. 14: Simulation results geometry II, upper point.

The last results which shall be given here are the ones using a frame like structure representing the side window's surroundings and carpeting during a full vehicle experiment. As a modeling technique, a shell element modeling using a star pattern with an 85 mm radius is chosen due to its relatively short calculation time and the good results gained so far. The geometry chosen for these experiments is geometry III, using the upper point of impact for the experiments such as shown in figure 3. As one can see when taking a look at figure 15, it is necessary to consider element failure throughout the simulations representing the experiments with such a structure. The *MAT_ADD_EROSION – card which adds element damage and failure is adapted twice to be at least able to calculate the maximum of the measured acceleration. As figure 16 shows, this additional failure consideration is reasonable since the safety glass pane shows a high damage at the areas where the boundaries of the frame structure hold the side window in its position. This can be validated when comparing this picture with the simulation model: besides the element failure at the point where the head impactor hits the laminated safety glass, elements do fail at the lower left corner of the side window. Further parameters that might

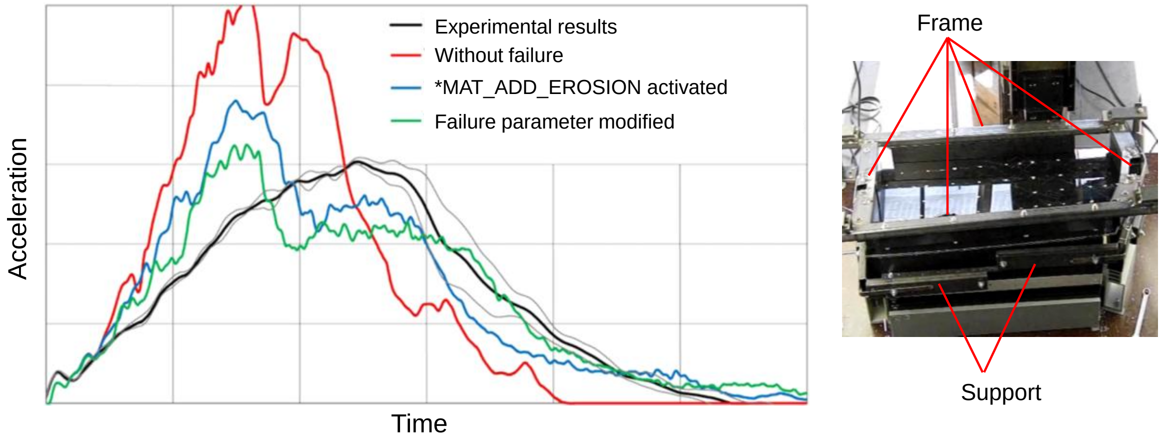

Fig. 15: Drop tests with frame on geometry III, upper point.

Fig. 16: Real and simulated material failure for the frame tests.

lead to the simulation results for this load case are that the friction between the side windows and the frame/support might not have been considered properly. Videos of the experiments also show a slightly upward movement of the frame structure which does not allow the assumption of a rigid body frame structure being constrained in all transversal and rotational directions. Nevertheless, the actual displacement of the frame is nearly impossible to be read out as additional boundary information from those videos.

6 Conclusion and Outlook

Several modeling techniques were proposed being able to represent initial damage on laminated safety glass side windows and therefore can be used for the simulation of the load cases defined in a newly released FMVSS 226 – Ejection Mitigation. In order to understand the material behavior of damaged laminated safety glass, simplified drop testing procedures on damaged and undamaged side windows were defined allowing evaluating and improving the proposed modeling techniques. Models using shell elements with identical nodes for each material layer and the NLOC – flag in the *SECTION_SHELL – card considering the respective layer's thickness showed a numerically stable behavior during calculations and good results for both, a star pattern and a pattern made out of element strips with a different number of elements defining the width of the element strip. For the cases considered here, three elements were in general sufficient enough and the main advantage of the element strip pattern compared to the star pattern is its simple pre-processing. Nevertheless, the last load case defined here using a frame like structure to model the surroundings of the vehicle once the side window is build into the car showed that additional element failure might have to be considered in the simulation model as well. Full vehicle experiments and simulations will have to be performed to gain further information on that topic.

7 Literature

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