GUIDELINES FOR PEDESTRIAN FRIENDLY WINDSCREEN DESIGNS CONSIDERING PROBABILISTIC FRACTURE BEHAVIOR

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ABSTRACT

If adult pedestrians are being struck by passenger cars with short bonnets, head contact usually occurs in the windscreen area. In test procedures for regulation and consumer protection, this impact type is being assessed using so-called pedestrian head impactors. The head injury risk is being evaluated based on the acceleration signal using the so-called Head Injury Criterion (HIC). Corresponding experimental impactor tests in the windscreen center show large scatter. Main reason for the observed scatter is the fracture initiation of glass as already published in several studies [5]. Thus, for a head impact in the windscreen center an early fracture initiation results in a small head injury risk, while a late fracture initiation increases the injury risk significantly [14]. In the design of measures for the enhancement of vehicle sided pedestrian safety, this scatter is currently neglected.
Based on a theoretical description of the probabilistic fracture mechanics of glass, a methodology for designing pedestrian friendly windscreens considering the probabilistic fracture mechanics of glass will be described in the present paper. This methodology consists of two steps. First, the probability for certain fracture initiation times are assessed, considering probabilistic fracture mechanics and the tensile stress distribution on the glass surfaces during head impact. In a second step, the head injury risks for the different fracture initiation times are evaluated.
In order to show the potential impact of the described methodology, a windscreen of a vehicle model is being assessed and optimized. The findings of this optimization process are being used to derive guidelines for pedestrian friendly windscreens.

INTRODUCTION

In case of a vehicle-pedestrian collision the impact location of the head of the pedestrian is being mainly influenced by the vehicle speed, by the pedestrian size and the vehicle shape. For a combination of an adult pedestrian and a passenger car with a short bonnet, head contact usually occurs in the windscreen area (e.g. [8, 9]). If a pedestrian head impactor is being shot against the windscreen center, large scatter can be observed for the acceleration signal of the head impactor as shown by [5] and [14] (see Figure 1).

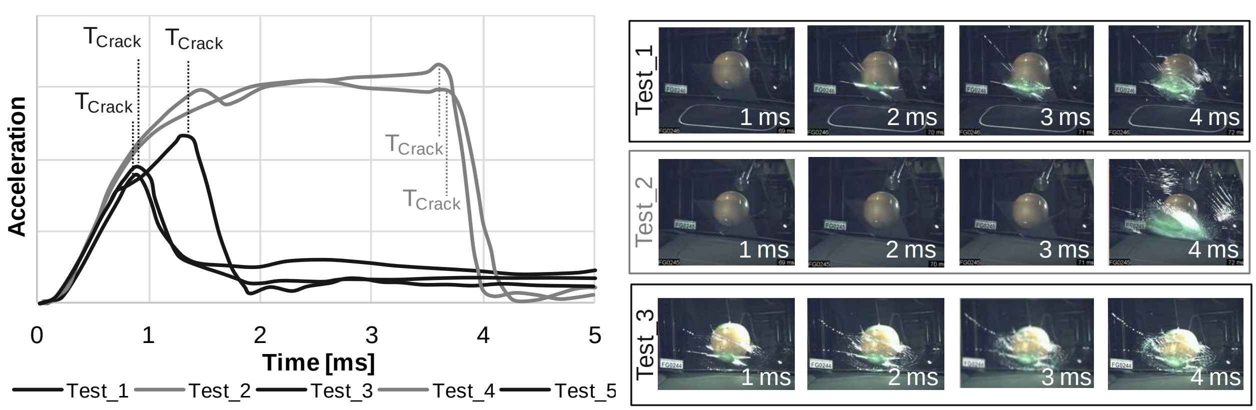


Figure 1. Acceleration signal and crack initiation times for head impact in windscreen center [14].

Since the boundary conditions are not changed and the windscreens are from the same batch, main reason for the scatter is the stochastic fracture behavior of the windscreen glass [14]. As can be seen in Figure 1, an early fracture initiation as in test 1, 3 and 5 results in lower accelerations and thus in lower head injury risks [14].
The stochastic fracture behavior of glass is a material dependent property, which cannot be changed easily. Due to the high viscosity of molten glass, the silicon dioxide molecules of glass cannot take the ordered structure of a crystal lattice during the cooling process, but solidify in a metastable order [4, 17]. Since the tensile stresses cannot be homogenized by plastic flow as within the elastic-plastic behavior of most metals [15], all glass components show a brittle fracture behavior.
Stochastically distributed material or surface defects influence the fracture behavior of glass [2]. In order to describe this stochastic behavior, the so-called Weibull-Distribution shown in Eq.1 is often used [10]. According to Eq.1 the fracture probability FP can be described by the current stress load σ, the characteristic strength σ_c and the so-called Weibull-Module m. σ_c and m can be assessed using quasi-static experiments like the double-ring (also called ring-on-ring) bending test.

$$FP(\sigma) = 1 - \exp\left(-\left(\frac{\sigma}{\sigma_c}\right)^m\right) \qquad \text{Eq.1 [10]}$$

In an approach with the title GLASPROB, the Weibull-Distribution has already been used for the design of windscreens focusing on endurance strength loads [1]. In [1] the stress state of the windscreen for different load cases is assessed based on Finite-Element (FE) simulations. Since the size of the loaded area strongly influences the fracture probability [19], [1] extended Eq.1 to Eq.2 in order to assess the fracture probability based on the stress loads for a certain area A for different endurance strength loads.

$$FP = 1 - \exp\left(-\int_A \left(\left(\frac{\sigma}{\sigma_c}\right)^m\right) dA\right) \qquad \text{Eq.2 [1]}$$

By considering the increase of the tensile strength in case of dynamic loadings [7], [3] has further extended Eq.2 for dynamic load cases as well. As shown in Eq.3 the fracture probability depends now on a Dynamic Factor DF, a reference area A_{ref} as well as the tensile stress and the size of the N FE-elements of the windscreen glass.

$$FP = 1 - \exp\left(-\frac{1}{A_{ref}}\sum_i \left(\frac{\sigma_i \cdot A_i}{\sigma_c \cdot DF}\right)^m\right) \quad \text{for i = 1 to N} \qquad \text{Eq.3 [3]}$$

Scope of this study is to use the findings from [3] for the assessment of the probabilistic fracture mechanics of glass in order to design a pedestrian friendly windscreen geometry for a head impact against the windscreen center.

METHODS

For the evaluation of the head injury risk for an impact against the vehicle windscreen, a method considering the probabilistic fracture mechanics is proposed (see Figure 2). This procedure consists of two steps.
In the first step, which in part is already be published in [3] and [11], the probability for certain fracture initiation times is assessed. Within this step, a FE simulation of a head impactor being shot against the center of a vehicle windscreen is calculated. The windscreen center is being chosen in order to minimize the influence of the windscreen adhesive and of the glass edges. For these impact simulations an adult head impactor with a mass of 4.5 kg is used. The impact conditions are chosen based on the latest Euro NCAP test procedure. Since vehicle windscreens are made of laminated safety glass, consisting of two 2.1 mm thick float glass plies being attached by a 0.76 mm thick intermediate layer of polyvinyl butyrale (PVB), a three layered approach is being chosen. For the windscreen model a so-called Shell-Solid-Shell-approach is being used. The material data for glass is chosen based on literature values for not-pre-stressed glass, which is usually the case for the windscreen center. During this first step, the glass is modeled without fracture. More detailed information about the validation of the glass model is given in [11]. The windscreen is modeled to be attached to an adhesive layer, while the degrees of freedom of the adhesive surface being usually attached to the vehicle body is being blocked in the global coordinate system.

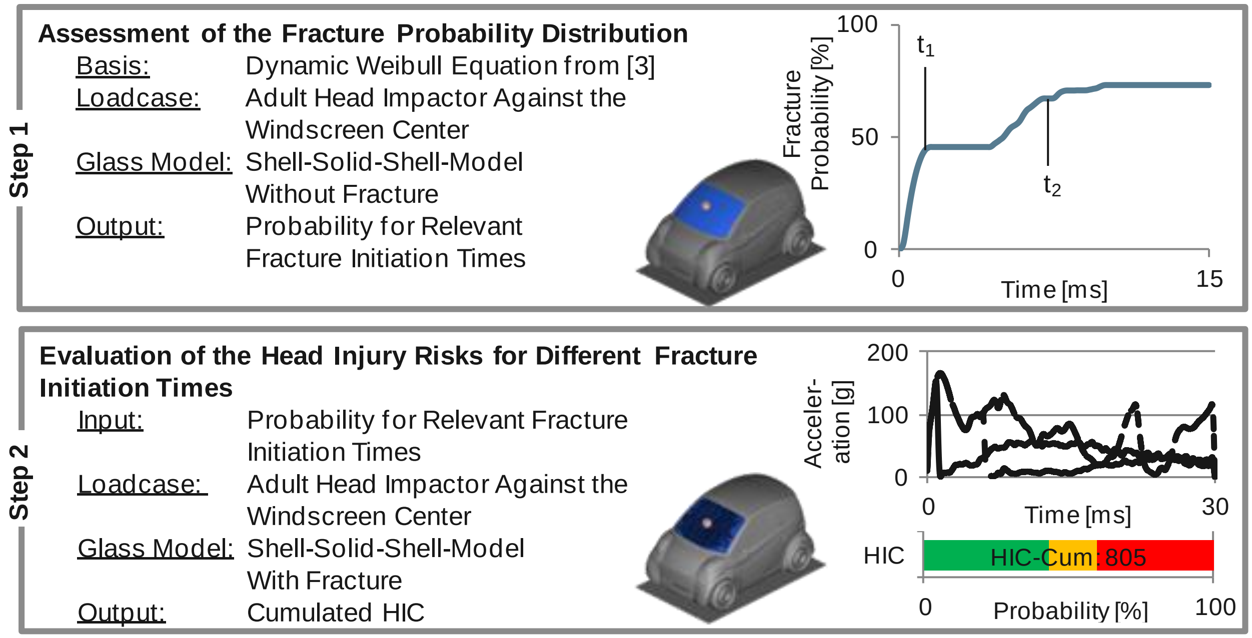


Figure 2. Methodology for Evaluation of Head Injury Risk Considering Probabilistic Fracture Mechanics.

As a result of the simulation the tensile stress over time distribution of each element on the glass surface is stored in a separate file. Due to the layered set-up of laminated safety glass, four glass surfaces have to be differentiated. The tensile stresses are combined with the test results from specimen tests using the Weibull-Distribution. Similar to windscreens of series vehicles, the windscreen is assumed to be in FTTF-design. This refers to the production process of float glass, in which the glass melt floats on a tin bath. The glass side floating on the tin bath is called tin side (T), while the other surfaces pointing to the atmosphere is called fire side (F). In an FTTF-design, for the outer and inner surface of the windscreen the fire (F) side of the float glass is chosen, while the surfaces attached to the PVB-foil are the tin (T) side of the float glass. In general, the fire side has a higher tensile strength than the tin side, since in the tin side some tin molecules are diffused in the glass structure. More specific information on the chosen material parameters as well as the dynamic factor is given in [3]. Result is a graph showing the fracture probability over time. In this graph, the probability for certain fracture initiation times can be assessed.

These fracture initiation times are used as input for the second step, which is not been published before. By integrating a failure criteria, the so-called 'non-local failure criterion' developed by [13], in the glass model, the head acceleration curve as well as the so-called Head Injury Criterion (HIC) can be determined. One simulation has to be conducted for each combination of fracture initiation time and fracture probability. Thus, the failure criterion parameters have to be adapted for each fracture initiation time. Further information on the validation of this failure criterion is given in [11]. Finally a cumulated HIC can be determined using Eq.4.

$$HIC_{cum} = \sum_i FP_i \cdot HIC_i \quad \text{for i = 1 to N} \qquad \text{Eq.4}$$

A sequence of the further work being described in the present paper is shown in Figure 3. The methodology and results of this work is also not been published before. The work is being conducted within a European research project named 'SafeEV', which is co-funded by the European Commission within the Seventh Framework Programme (2007-2013) (see http://www.project-safeev.eu/).

In order to show the potential impact of the described methodology, the head injury risk during an impact on a windscreen of a vehicle model is being assessed using the methodology described above. For the vehicle model the so-called REVM1 is being used. A description of the vehicle model is included in [12]. The resulting cumulated HIC is being used as reference.

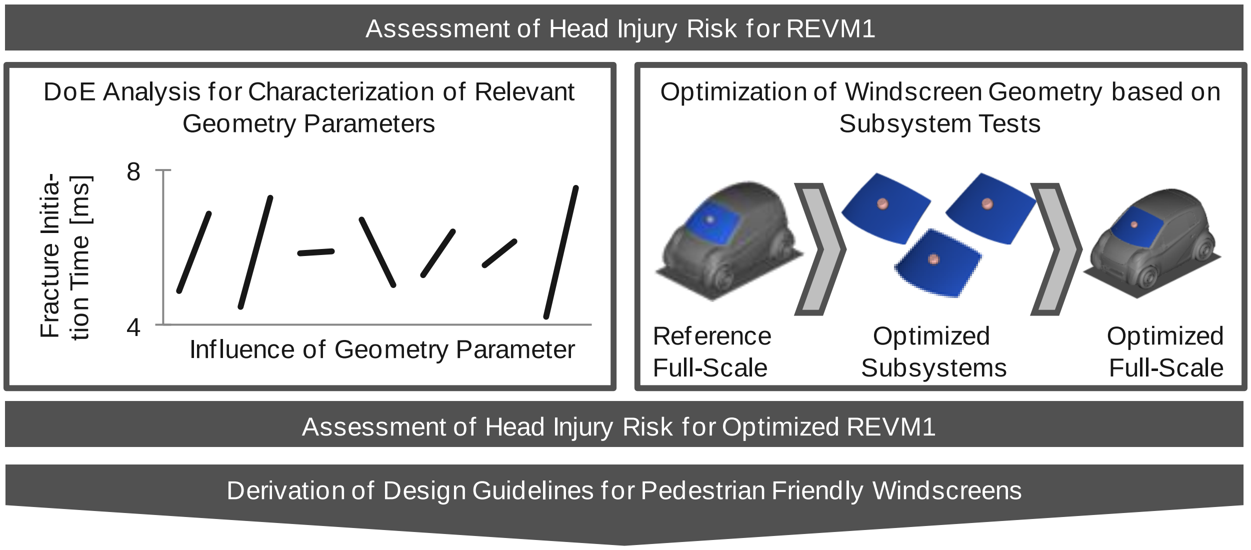


Figure 3. Work Sequence of Present Investigation.

Afterwards a "Design of Experiment" (DoE) analysis is conducted, in order to analyze the influence of the windscreen geometry on the fracture probability respectively the fracture initiation time. Seven of the eight geometry parameters shown in Figure 4 are included in the DoE analysis. Only the so-called end tangent angle is not included, since the windscreen side is assumed to have only a minor effect during an impact in the windscreen center. As a consequence a test plan including 64 windscreen designs is developed (see Figure 10). The according maximum and minimum values for the seven parameters are chosen based on series production vehicles (see Figure 11). In order to determine the fracture probability for certain fracture initiation times, the first step of the methodology shown in Figure 2 is being conducted for each of the 64 windscreens.

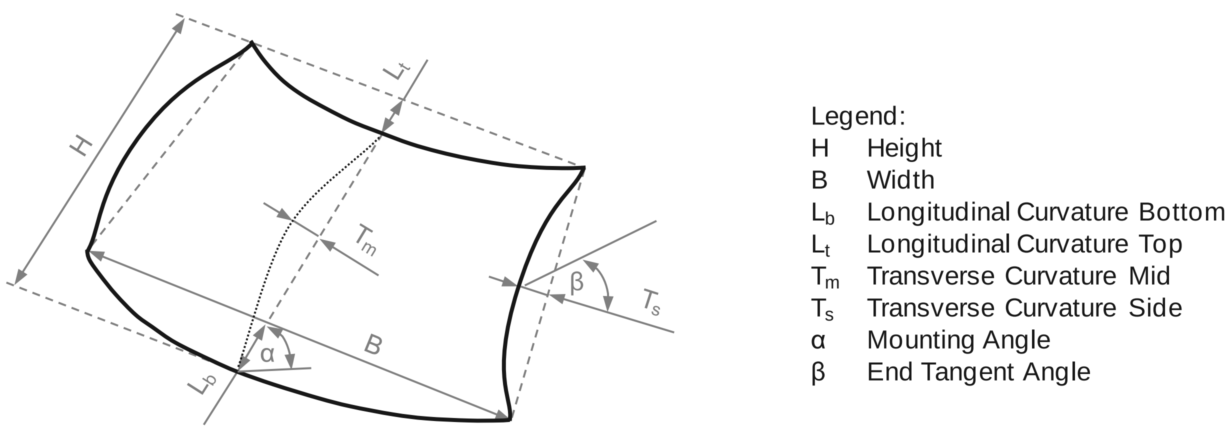


Figure4. Geometrical Characterization of Vehicle Windscreens.

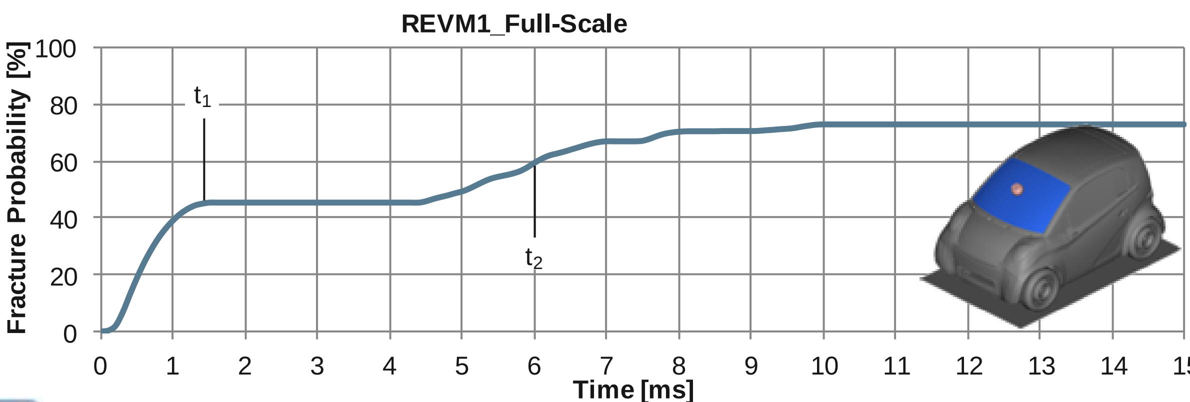
Assuming that during a head impact in the windscreen center an early fracture initiation time results in low injury risk, the windscreen geometry of REVM1 can be optimized using the results of the DoE analysis. Since the integration of a redesigned windscreen in an existing vehicle geometry is very time-consuming, the effect of the redesigned windscreen is first investigated in a subsystem environment. Thus, the redesigned windscreens are only attached to a constrained windscreen. Since this new constraint is stiffer, the original windscreen is also being investigated as a subsystem. After the optimization process results in a satisfactory change of the fracture probability distribution, the windscreen flanges of the vehicle model are being updated for the new windscreen geometry, so that a full-scale model is available.
This full-scale model is being assessed using the methodology described in Figure 2. By comparing the cumulated HIC of the reference and the optimized vehicle, the benefit can be shown.

Finally, design guidelines for pedestrian friendly windscreens considering the probabilistic fracture mechanics of glass are being derived.

RESULTS

Assessment of Head Injury Risk for REVM1

Figure 5 shows the fracture probability over time curve for REVM1. Using the graph shown in Figure 5 a probability for three fracture initiation time periods are determined. The number of different periods is set to three periods in order to limit further necessary calculations to a reasonable number. For a first period from first impact to 1.5 ms after first impact, the windscreen will fracture with a probability of 43%. In a second time period between 1.5 ms and 6 ms after first impact, the windscreen will fracture with a probability of 17% (relative probability being calculated by subtracting 43% from 60%). Considering a worst case approach and assuming the head injury risk will decrease with an earlier fracture, the third period is being defined from 6 ms until the end of the impact. During this period the windscreen will not fracture with a probability of 40%.



43% fracture probability for $t < t_1$; 17% fracture probability for $t_1 < t < t_2$; 40% probability of no fracture

Figure 5. Fracture Probability over Time Curve for Head Impact in the Windscreen Center of REVM1.

By integrating a fracture criterion in the windscreen model, the head injury risk can be determined. The failure criterion is chosen in order to initiate the fracture at the end of the time period for the first two periods, while the windscreen should not fracture for the third period. Figure 6 shows the corresponding acceleration curves and the HIC-values. The cumulated HIC, which can be calculated using Eq.4, is 805.

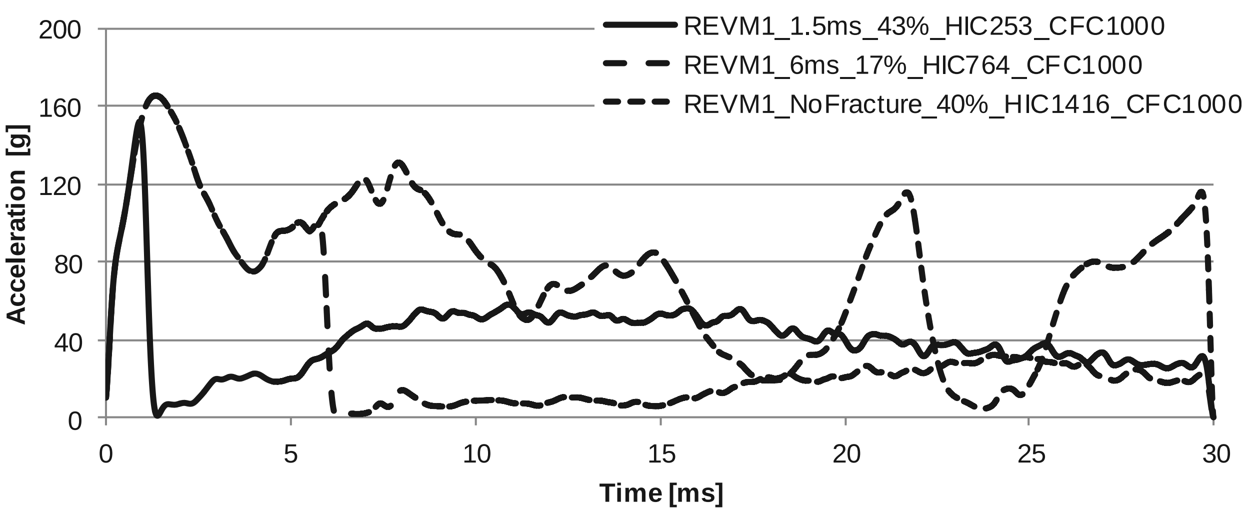


Figure 6. Head Impactor Acceleration for REVM1 for Three Different Fracture Times.

Similar to the results from [14], the head injury risk increases with later fracture times (see Figure 6). Since the stiffness of the windscreen strongly decreases after the fracture is being initiated, the acceleration signal rapidly decreases as well. After glass fracture, the head impactor is being further decelerated by the PVB-foil and attached glass fragments.

DoE Analysis for Characterization of Relevant Geometry Parameters

In Figure 7 the result of the DoE analysis is shown. The lines displayed in Figure 7 represent the influence of each windscreen parameter. A positive slope implies a small fracture initiation time for the corresponding minimum value of the parameter, while a negative slope implies a small fracture initiation time for a maximum value respectively. The absolute value of the slope gradient can be used to describe the impact of this parameter. According to this, the mounting angle, the windscreen width as well as the windscreen height have the largest influence on the fracture initiation time.

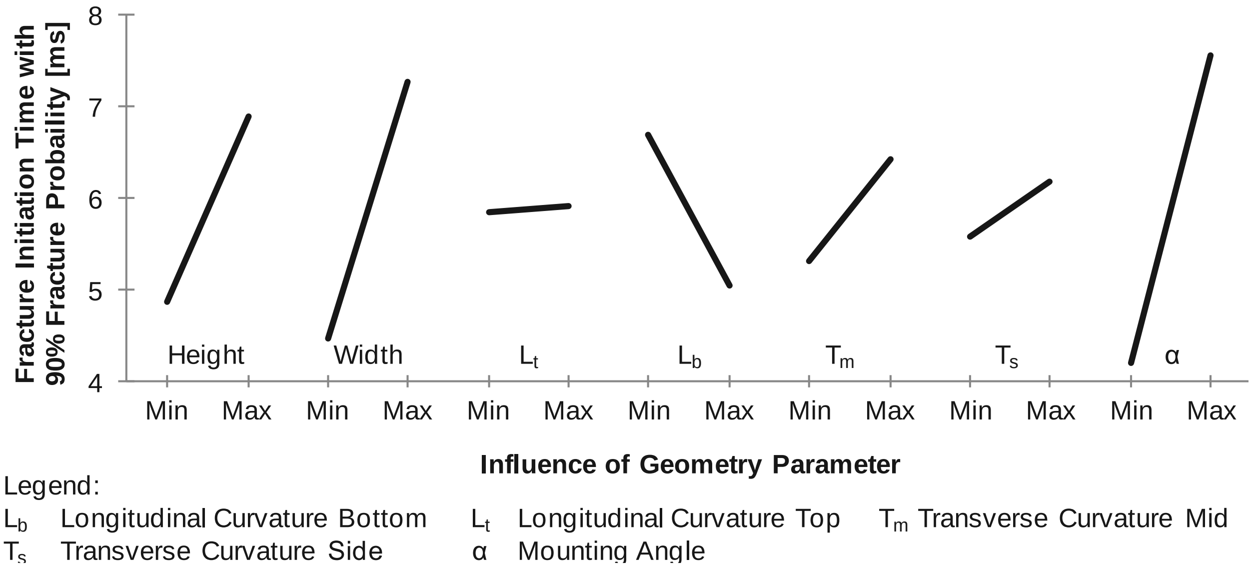
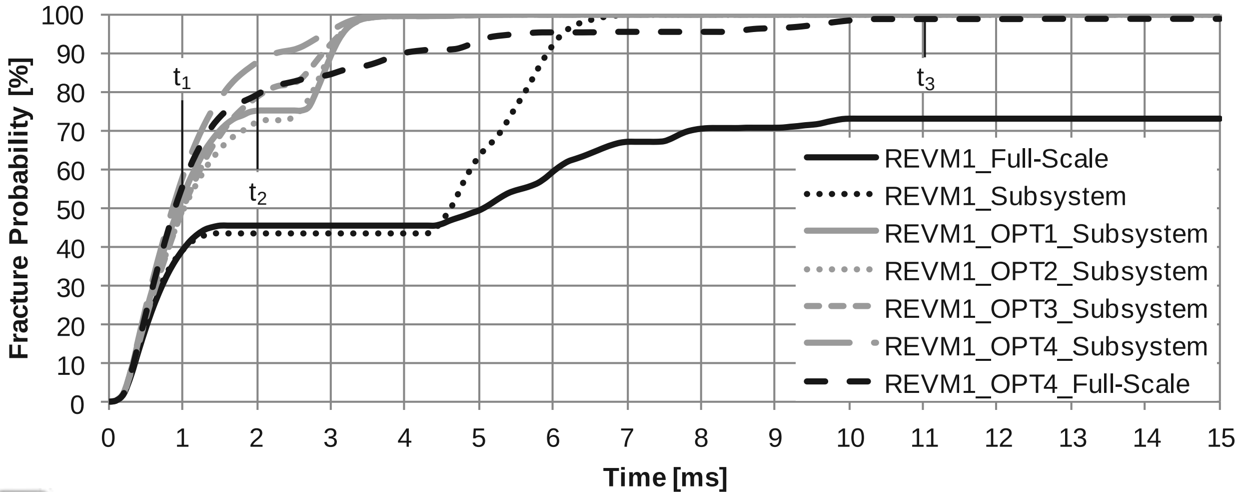


Figure 7. Effect of Windscreen Characteristics on Fracture Initiation Time.

Optimization of Windscreen Geometry based on Subsystem Tests

Assuming that during a head impact in the windscreen center an early fracture initiation time results in low injury risk, the windscreen geometry can be optimized using the results from the DoE analysis. According to the DoE analysis especially the windscreen mounting angle, height and width influence the fracture probability (see Figure 7). But since these parameters are usually defined by the vehicle designers, they were excluded from the optimization process in order to minimize the change of the vehicle design.

Other parameters influencing the fracture probability are the transverse curvature at the middle of the windscreen, the transverse curvature at the windscreen side as well as the longitudinal curvature at the bottom. In order to show the influence of these parameters, the windscreen geometry is changed. The fracture probability over time curves for the full-scale and subsystem tests are shown in Figure 8. As expected, the stiffer constraint influences the subsystem test of the original windscreen, so that the fracture probability for the subsystem test is being increased from 4 ms after first impact onwards. In the first optimization step (OPT1) only the transverse curvature at the middle of the windscreen is being reduced. In the second optimization step (OPT2) the transverse curvature at the middle of the windscreen as well as the transverse curvature at the windscreen side are reduced. In the third optimization step (OPT3) both transverse curvatures are reduced and the longitudinal curvature at the bottom is increased.



55% fracture prob. for $t < t_1$; 25% fracture prob. for $t_1 < t < t_2$; 20% fracture prob. for $t_2 < t < t_3$

Figure 8. Fracture Probability over Time Curve for Optimized Windscreen Designs of REVM1.

As can be seen in Figure 8, the fracture probability increases for OPT1, OPT2 and OPT3. Especially for the first 2 ms the fracture probability is larger compared to the original windscreen geometry. It seems that the influence of the transverse curvature at the side shows the largest effect, since either OPT2 as well as OPT3 show only a minor increase compared to OPT1.

In the fourth optimization step (OPT4), the effect of the positioning of the float glass within the laminated safety glass is considered. Thus, the windscreen geometry OPT3 is assessed in the so-called TFFT-design. Here, the inner and outer surface of the windscreen glass are chosen to be the tin side (T) of float glass, while the intermediate surfaces are made of the fire side (F). OPT4 shows a further increase of the fracture probability. By analyzing the corresponding tensile stress distribution, it seems that the combination of large tensile stresses and the corresponding area loaded by these stresses is especially for the glass surface directing to the vehicle compartment. The largest fracture probability results, if the tin-side is chosen for this surface. Thus, it is expected that a FTFT-design could lead to similar results. But this assumption is not further specified.

Since OPT4 shows the largest fracture probability, OPT4 is chosen to be integrated in the vehicle model. As can be seen in Figure 8, the fracture probability of OPT4 assessed in the Full-Scale model decreases due to the softer constraints as expected. But still, the improvement in comparison to the original windscreen is significant.

In order to calculate the head injury risk in the next step, three time periods have to be chosen based on the fracture probability curve for the Full-Scale model of the optimized windscreen geometry OPT4. Since the fracture probability curve changes due to the redesign, this step is necessary. The first period is defined to be between first impact and 1 ms after first impact with a probability of 55%. The second period with a probability of 25% is defined between 1 ms and 2 ms and the third period between 2 ms and 11 ms with a probability of 20% respectively.

Assessment of Head Injury Risk for Optimized REVM1

Figure 9 shows the resulting acceleration curves and the HIC-values for the optimized windscreen geometry. Similar to the results shown in Figure 6, the head injury risk increases with later fracture times due to the significant reduction of the windscreen stiffness after fracture initiation. Comparing Figure 6 and Figure 9 shows that the HIC values for the three periods of the original and the optimized windscreen are in a similar range. Due to the changes of the geometry design, the probability for the first two periods are increased for the optimized windscreen, which results in the reduction of the cumulated HIC from 805 to 577.

But Figure 9 reveals as well that a higher fracture probability for short fracture initiation times results in a higher acceleration peak. So, it seems that the windscreen stiffness has to be increased for a higher fracture probability.

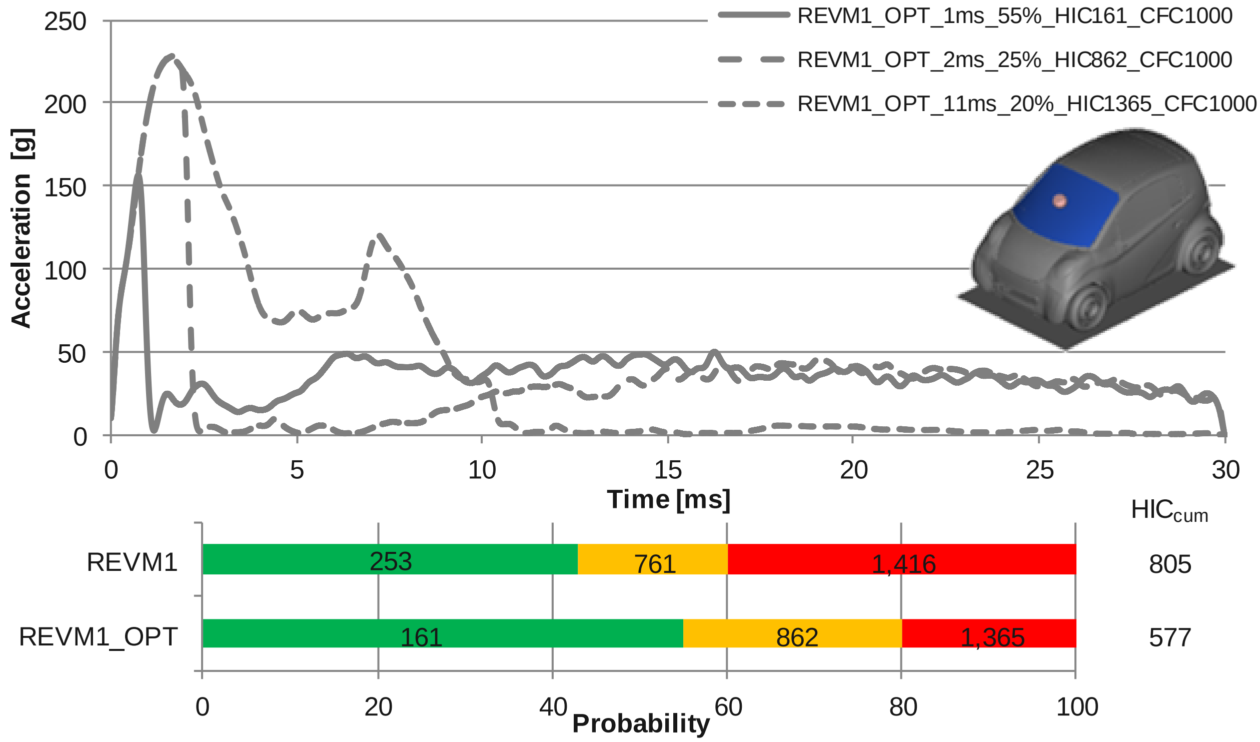


Figure 9. Head Impactor Acceleration for REVM1 and Optimized Windscreen.

Derivation of Design Guidelines for Pedestrian Friendly Windscreens

Based on the work described in the present paper some guidelines for a pedestrian friendly windscreen design can be derived. These guidelines are only valid for a head impact in the windscreen center and are based on an evaluation of the HIC using an adult head impactor.

First, probabilistic fracture mechanics shall be considered within the design process of the windscreen geometry and associated injury risks, since an early fracture initiation seems to result in low injury risks.

Second, in order to increase the fracture probability for an early fracture initiation time, the mounting angle, the windscreen width, the windscreen height, the transverse curvature at the middle of the windscreen as well as the transverse curvature at the windscreen side shall be reduced and the longitudinal curvature at the bottom increased.

Third, the positioning of the float glass influences the fracture probability as well. In the present case it seems that a TFFT- or a FTFT-design is more beneficial for pedestrian safety.

LIMITATIONS

The presented study can be separated in two main sections. First the limitations of the methodology for the assessment of the fracture probability over time curve are discussed. Afterwards the limitations of the optimization process will be given.

Input for the fracture mechanical analysis are mainly material data based on a literature study. If this approach is being considered in the design phase of series vehicles, the material data should be updated in cooperation with the windscreen manufacturer. Thus, the specification sheet for the windscreen manufacturer should be expanded e.g. by Weibull-Module, characteristic tensile strength and Dynamic Factor.

Especially, the Dynamic Factor should be investigated in more detail. At the moment, the Dynamic Factor is defined based on Split Hopkinson Pressure Bar tests for laminated safety glass from [18] and the resulting strain rate during head impactor simulations in the windscreen center. Unfortunately, the analyzed strain rates in [18] show a large gap in the relevant strain rate field during head impact. Thus, the chosen Dynamic Factor is a rough approximation. In order to specify the Dynamic Factor further tests in the relevant strain rate field should be conducted.

Main input for the calculation of the fracture probability over time curve is the tensile stresses on the glass surfaces. These tensile stresses are being determined using FE simulations. An experimental verification of the resulting tensile stresses is according to the opinion of the authors not possible. Using polarization filters results only in a qualitative stress state, while instruments using the scattered light method cannot be conducted without contact to the glass surface and thus would influence the test results.
Nevertheless, the combination of stress state during head impact in the windscreen center and probabilistic fracture mechanics are verified using internally available test results. Thus, the authors are confident, that the effects and tendency shown in the present paper are reasonable.
The optimization steps currently focus on head impacts in the windscreen centre. In case of a head impact being close to the scuttle area, an early fracture initiation might result in a more severe impact with the instrument panel. This effect has to be investigated in future studies.
Furthermore, the pedestrian friendly windscreen design is evaluated using the HIC value. According to [16] the larger acceleration peak shown in Figure 8 can also result in a higher skull fracture risk. This risk will be integrated in the further course of the SafeEV-project. If the results from [16] are confirmed, further optimization criteria should be included in the optimization process.
For the validation of the windscreen model including failure, experimental tests of a middle class vehicle are used. Since no test results for the REVM1 are available, the windscreen model for the original and for the optimized windscreens could not be validated. Nevertheless based on the expertise of the authors, the calculated acceleration signals and fracture behavior seem reasonable. Main scope of the present paper is to show that the probabilistic fracture behavior of glass could be considered during the design of a pedestrian friendly windscreen. Thus, using reasonable, but not fully validated windscreen models is assumed to be acceptable. If this approach will be further evaluated, a broad experimental testing verification should be done.
The windscreen is optimized in order to minimize the head injury risk for pedestrians. In this context an early fracture is beneficial. Nevertheless, the windscreen shall fulfill further requirements as well. Main tasks for windscreen are protection against external events, optically faultless vision, prevention of serious injuries and sufficiently long service life [6]. None of these main tasks are negatively influenced by an early fracture initiation. In addition, the windscreen shall support the correct unfolding process and position of airbags for occupants. For this task a late fracture initiation is required. According to the opinion of the authors, the presented methodology could also be used to assess the corresponding effects.

CONCLUSIONS

In the present paper a methodology for designing pedestrian friendly windscreens is described. Main advantage of this methodology is that the probabilistic fracture behavior of glass, which strongly influences the injury risk during head impact in the windscreen center, is considered within the design process. The methodology consists of two steps. In the first step, the probability for certain fracture initiation times is assessed. Therefore, a FE simulation of a head impactor being shot against a vehicle windscreen without fracture criteria is calculated. The resulting tensile stress over time distribution of each element on the glass surface is used to calculate the fracture probability. Result is a graph showing the fracture probability over time, in which the probability for certain fracture initiation times can be assessed. These fracture initiation times are used as input for the second step. By integrating a failure criteria, the so-called 'non-local failure criterion' developed by [13], in the glass model, the head acceleration curve as well as a so-called cumulated Head Injury Criterion (HIC) can be determined.
In order to show the potential impact of the described methodology, a windscreen of a vehicle model is being assessed and optimized assuming a short fracture initiation time results in a small injury risk. By changing the transverse curvature, the longitudinal curvature at the bottom of the windscreen and the set-up of the laminated safety glass of the windscreen, the cumulated HIC value could be significantly decreased from 805 to 577. This refers to a reduction by 28 %. Finally guidelines for pedestrian friendly windscreen designs are derived.

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APPENDIX

Windscreen Design	Height [mm]	Width [mm]	Longitudinal Curvature Bottom [mm]	Longitudinal Curvature Top [mm]	Transverse Curvature Mid [mm]	Transverse Curvature Side [mm]	Mounting Angle [°]
1	-	-	-	-	-	-	+
2	+	-	-	-	-	-	-
3	-	+	-	-	-	-	-
4	+	+	-	-	-	-	+
5	-	-	+	-	-	-	-
6	+	-	+	-	-	-	+
7	-	+	+	-	-	-	+
8	+	+	+	-	-	-	-
…….							
63	-	+	+	+	+	+	-
64	+	+	+	+	+	+	+

Figure 10. Parameter Set-Up for DoE Analysis based on 64 Windscreen Designs.

Parameter	Maximum Value (+)	Minimum Value (-)
Height [mm]	1,000	600
Width [mm]	1,600	1,100
Longitudinal Curvature Bottom [mm]	150	0
Longitudinal Curvature Top [mm]	75	0
Transverse Curvature Mid [mm]	100	0
Transverse Curvature Side [mm]	40	0
Mounting Angle [°]	70°	25°

Figure 11. Maximum and Minimum Value for DoE Analysis.