Influence of Side Windows Type on Occupants' Injury Response in the Cutaway Bus Rollover Analyses

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Abstract

In the rollover crash scenarios, occupants are often subjected to impact with interior parts of the bus, especially side windows which play the main role in ejection protection. In this study, we investigated the influence of the window's glass type and their modeling techniques into occupants' response during the rollover experiment. Rollover experiment of the cutaway bus was conducted in compliance with ECE R66, which is also known as a tilt table test. Two-point Hybrid III 50th male Anthropomorphic Test Device (ATD) was seated next to the window, on the impact side. Full scale numerical analyses were conducted with nonlinear explicit code LS-DYNA®. In the cutaway buses, a tempered glass is used commonly for the side windows. The effect of potential replacement with laminated glass was analyzed and its role in the ejection protection. Two common modelling techniques were used to represent a laminated glass, layered single-shell and double-shell model with coincident nodes. Also, the influence of yield stress was investigated, for both, laminated and tempered glass models. Head and chest accelerations and axial neck forces of the two-point belted ATD were presented and relevant injury criteria were compared. Results show the importance of using the laminated glass for the partial and full ejection prevention. Likewise, glass properties and modelling techniques can be meaningful in the validation process.

Keywords: tilt table test, cutaway bus, LS-DYNA, ejection protection, glass

Introduction

Cutaway busses are commercial vehicles designed to transport up to 22 passengers. Cutaway buses are usually built by two different manufacturers. In order to build a cutaway bus, first, a major and reputable manufacturer builds a chassis including driver cab. Secondly, the smaller manufacturer adds a passenger compartment and necessary equipment. It has to be noted that smaller manufacture has freedom in designing and manufacturing of the passenger compartment what results in a lot of variabilities among cutaway buses. In order to evaluate structural integrity, Florida Department of Transportation adopted few worldwide vehicle standards. In details, safety assessment and validation of the FE bus models were presented by Kwasniewski at el. [1] Bojanowski and Gepner at el. [2-4]. ECE R66 rollover standard, which is also known as tilt table test (Fig. 1) was developed to secure a residual space, zone that keeps passenger safe during the rollover event. It's suitability to represent a biofidelic rollover scenario crash scenario is questionable. However, some aspects of the rollover crash can be investigated, for instance, an ejection protection. In the tilt table test, the bus is located on the tilting platform at 800 mm above the ground, the upper part of the table slowly rotates causing the bus to freefall onto a concrete slab. The vehicle used in the presented test was built on 159" wheelbase chassis and accounted for 12300 lbs. The tested configuration included 1 Hybrid III 50th male ATD, 16 water ballasts, and wheelchair. The ATD was placed in the first row, behind the driver, on the impact side of the bus.
The prediction of ATD response in a rollover crash is challenging due to the complexity of rollover crash. There is no ATD prescribed to use in the rollover tests, but engineers and researches commonly choose hybrid III 50th male ATD thanks to its availability.

Fig. 1 Tilt table test according to Florida Standards and ATD's position.

Ejection has been recognized as the most fatality-risk that occurs during the rollover crashes [5]. It is known that the best ejection mitigation system is simply the usage of the seatbelt. However, partial ejection can still occur, especially when using common in buses, two-point restraint system. In this study, we presented associated with partial ejection results for upper body parts: head, chest and axial neck forces because of life threating injuries that they might be exposed to in the rollover accidents.

Head injury criterion (HIC) has been introduced to assess the probability of brain injury due to impact. HIC is computed based on head resultant acceleration, for a 15 millisecond time period.

$$HIC = max\left(\frac{1}{t_2-t_1}\int_{t_1}^{t_2} a(t)dt\right)^{2.5}(t_2-t_1) \qquad (1)$$

Similarly, chest acceleration curve is used to grasp the 3 ms clip that is used to calculate chest severity index. There is no standardized limit value for HIC and 3 ms clip for the rollover test, therefore we used corresponding values the frontal crash test of a passenger car (FMVSS 208). For the Hybrid III 50th male ATD limits are following: HIC-700, 3 ms chest acceleration clip cannot exceed 60 g and axial neck forces should be lower than -6160 N and 6806 N for compression and tension, respectively.

Glass modeling

Tempered glass, knows also as the toughened glass is a type of safety glass manufactured with controlled chemical or thermal treatment to increase its strength and change the failure mechanism. When glass breaks, it crumbles to into small pieces instead of jagged shards. Tempered glass is used for plenty safety applications, for instance, architectural windows and vehicle side windows.

The strength of the glass is not a material parameter however it depends on processing quality and damage that occurs at the glass surface. Therefore, there's a lot of variability in reported characteristic strength. Veer at el. [6] presented comprehensive experimental studies of annealed, heat strengthened and fully tempered glass. Average failure stresses were noted as 26.5 MPa, 71.3 MPa and 98 MPa with 20.1%, 15.8%, and 13.7% standard deviations, respectively. Tempered glass was modelled with MAT24 conservative 70 MPa and 80 MPa were chosen as yield stresses criteria, and failure plastic strain was set to 0.0012.

The other safety glass, laminated glass, is typically used in automobiles for windshield application. Laminated glass typically consists of two layers of tempered or annealed glass separated with a thin layer of viscoelastic

polyvinyl butyral (PVB). Pieces are firmed together at a high pressure and temperature that results in effective bonding. Splinters remain on the middle layer in the event of breaking, thus occupants are protected from sharp flying pieces. In the literature, several modeling techniques of the laminated glass can be found: single layer shell, double-layer with coincident mesh [7, 8], solid and combined solid-shell models [9].
In this paper, two common and simply approaches were used to create represent laminated glass, single-layer and double-layer with coincident mesh. Single-layer model of shell elements defined as *MAT_LAMINATED_GLASS (MAT_32) predetermines shells to work on glass basis upon the plastic strain failure criteria is reached for the glass, afterwards, shell elements are driven by the elastic behavior of PVB layer. Particular properties are prescribed to shell's integration points. Shell elements are not getting deleted at any point during the simulation.
Double-shell models are constructed by placing shells of glass and PVB layer on the coincident set of nodes. Glass was represented with *MAT_PIECEWISE_LINEAR_PLASTICITY, and the effective plastic strain was set to 0.001. Mooney-Rivlin rubber-like material model (*MAT_MOONEY_RIVLIN_RUBBER) was assigned to set of shells representing PVB layer because of the expected small deformation. For both models, three yield stresses of the glass were tested, 30 MPa, 50 MPa, and 70 MPa, respectively. Total shell thickness for tempered and laminated glass models was set to 5 mm.

Results

Plots in this section represent the resultant head and chest acceleration and neck forces for different glass models. Underscore values denote yield stress value of glass (in MPa) used in the simulation.

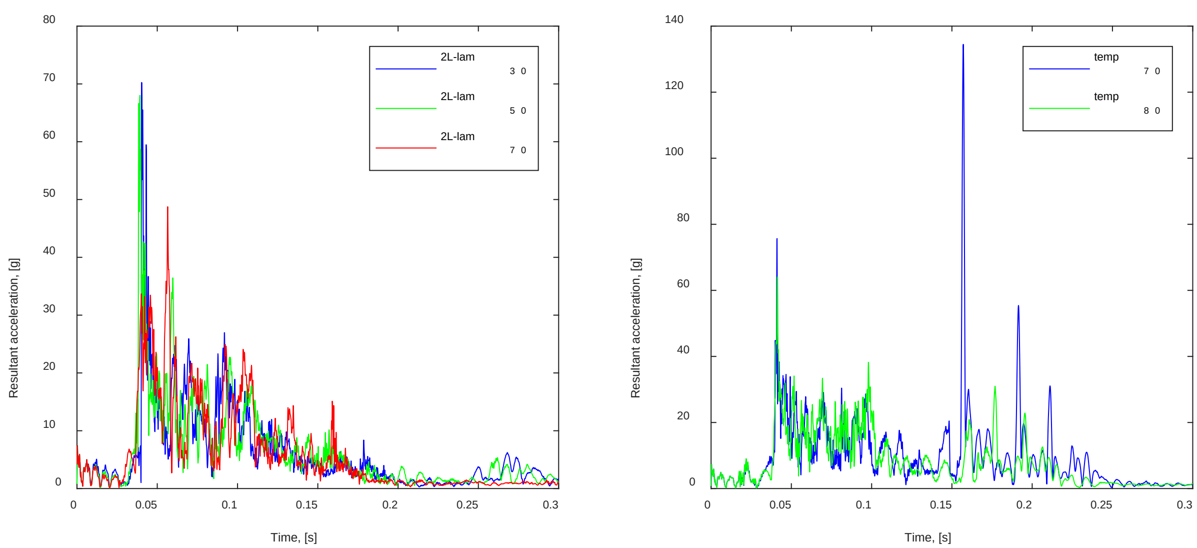

Fig. 2 Resultant acceleration plots of head acceleration for double-layer laminated and tempered glass.

Good representation of discrepancies that can occur during simulation was observed on the head acceleration plot for tempered glass (Fig. 2 –right plot). Tempered glass breaks immediately when the bus hits the ground what allows the ATD to exhibit a partial ejection from the bus. For the glass with 70 MPa strength limit, ATD's head slips over the window's rail and hits the ground more severely.
Peaks of maximum accelerations for the strongest laminated glass is shifted when compared to other ones. (Fig.2 – left plot) Most of validation and verification tools are phase sensitive, therefore it can be another source of error.
Magnitudes of accelerations and HIC values (Table 1) are low due to several factors. Tilt table drop test wasn't designed to assess occupant response during the rollover event and its nature determines low final deceleration.

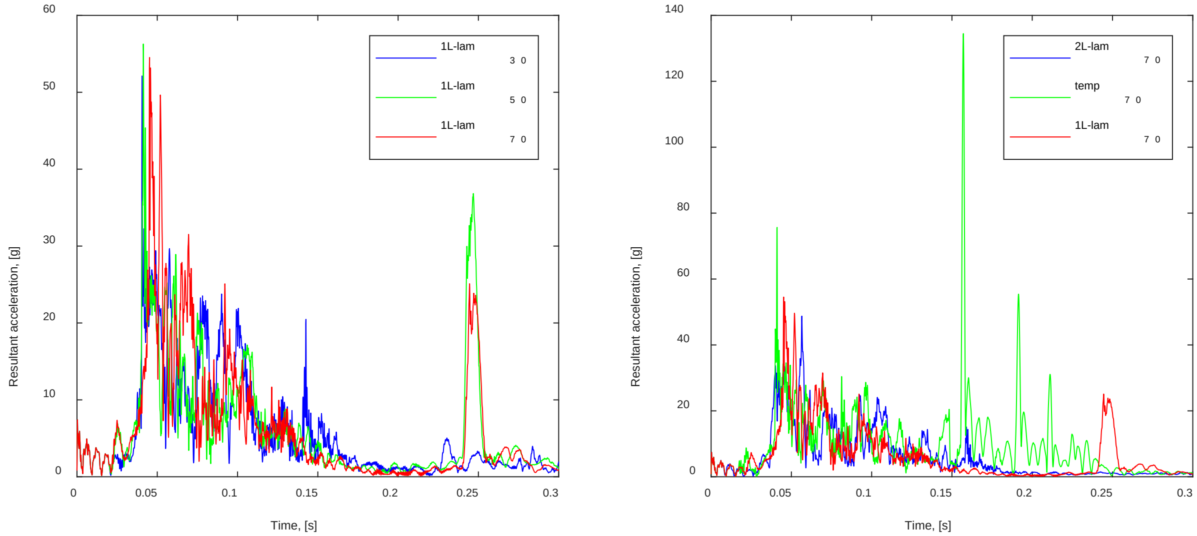

Fig. 3 Resultant acceleration plots of head acceleration for single-layer laminated glass and a mixed plot that represents models of each type.

On Fig. 3 we can observe the positive effect of using the laminated glass over tempered glass. For the tempered glass simulation, we could observe the straight contacts between shoulder and ground, consecutively, between head and ground. (Fig. 4 – shattered glass is turned off for a better view)

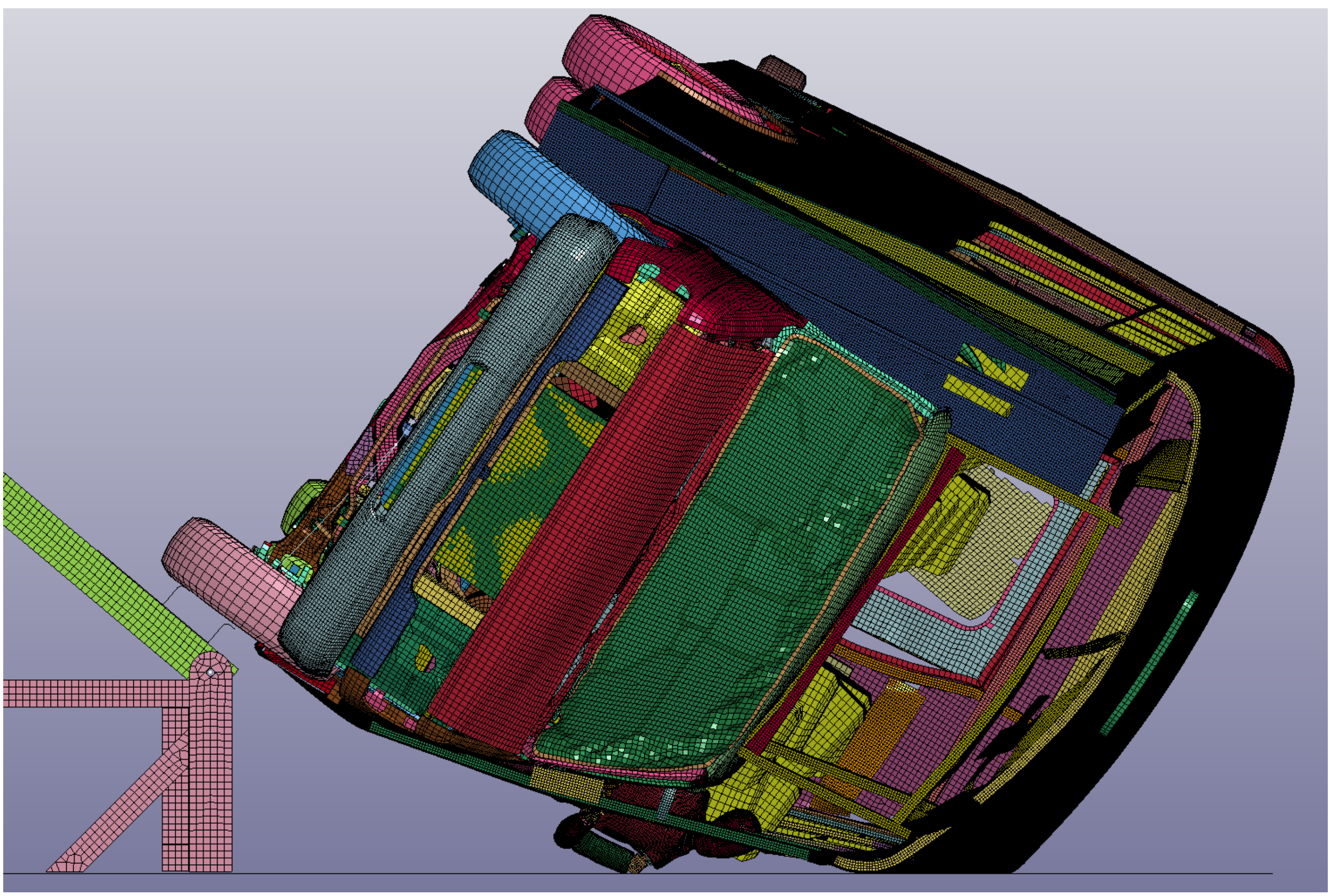

Fig. 4 . Partial ejection through the tempered glass

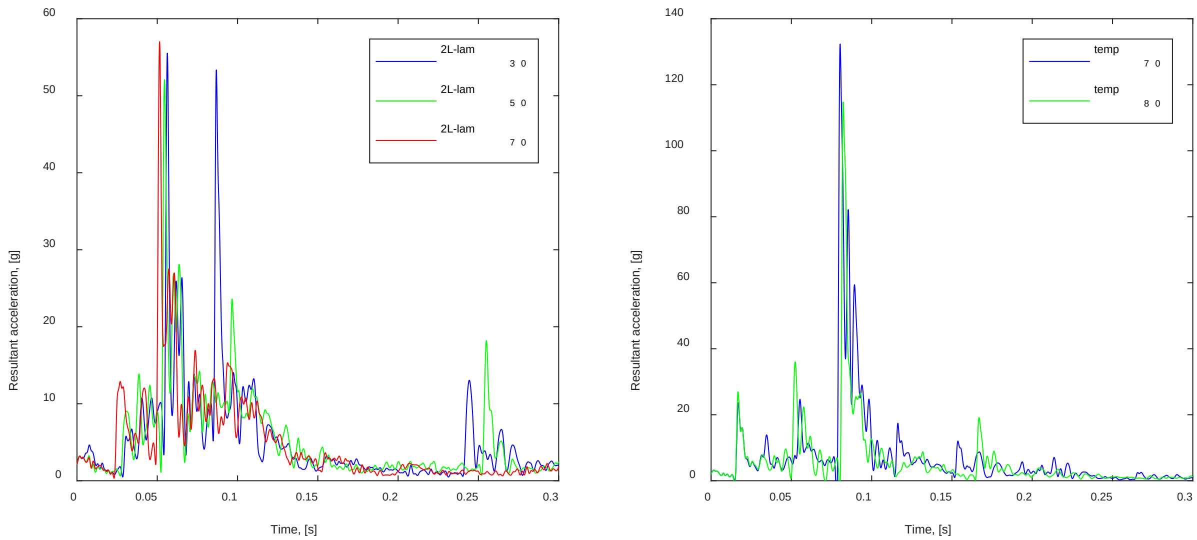

Fig. 5 Resultant acceleration plots of chest acceleration for double-layer, single-layer laminated glass, tempered glass, and a mixed plot that represents one of each type.

Single-layer laminated model results show a linear correlation between strength and ATD's response (Fig. 5). Stronger glass determines a higher response in magnitude. A similar observation can be found in different studies. Peng at el. [10] presented a parametric study of glass properties. Good matching between experimental and numerical data of linear acceleration and crack propagation was found for glass failure stress at 50 MPa.

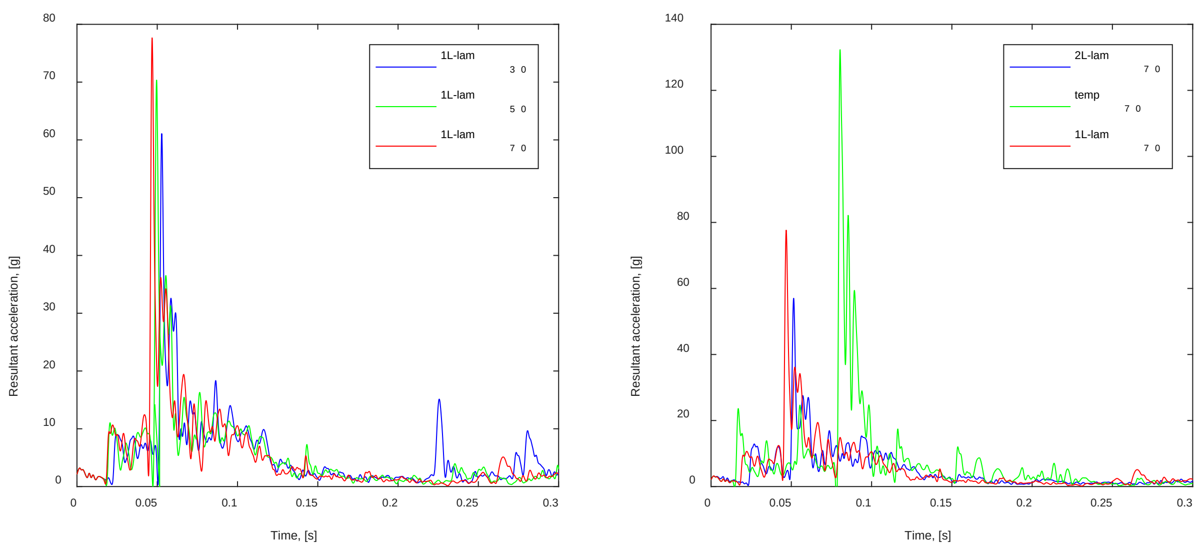

Fig. 6 Resultant acceleration plots of chest acceleration for double-layer, single-layer laminated glass, tempered glass, and a mixed plot that represents one of each type.

Axial forces are more consisted among the models. It implies that the main source of potential error might be associated with the first contact between ATD and glass. For the laminated glass models, first compression peak is associated with a contact between the head and window frame. For tempered glass model, we can observe the second peak when ATD hits the ground through the broken glass.

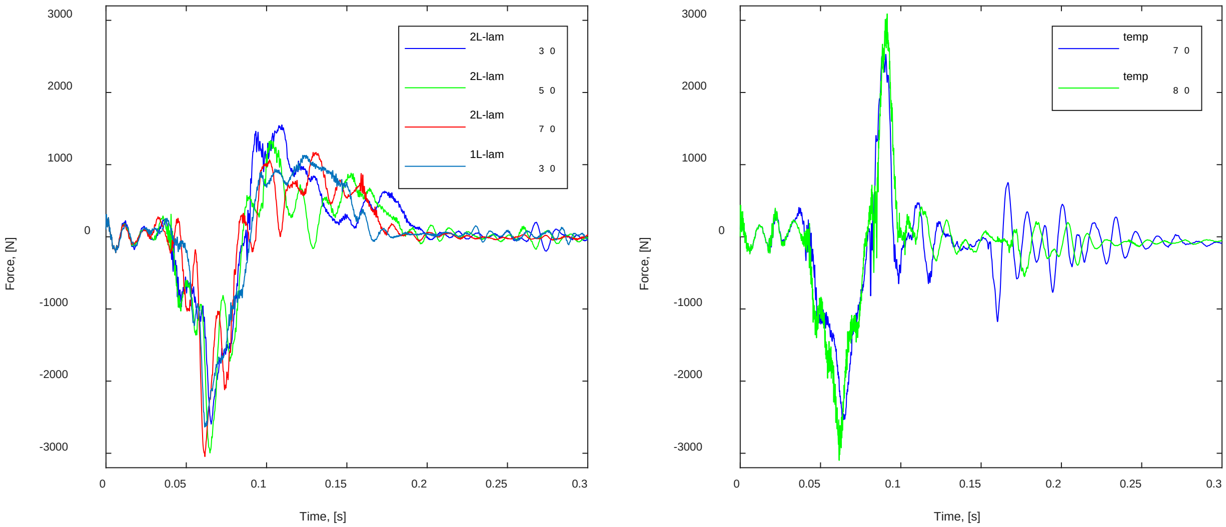

Fig. 7 Axial force plots of the upper neck for double-layer laminated glass and tempered glass.

In Table 1, we summarized obtained injury criteria values. Presented experimental values were obtained for the different bus which exhibited higher deformation during the test, therefore it cannot be used for validation purposes. It has to be noted that 3.5 mm thick tempered glass was used in the experiment.

Table 1: Summary of the injury criteria

	HIC	**Clip 3 ms**	**Axial Upper Neck Force**
Glass Type	**700 [-]**	**60 g**	**-6160/6806 N**
2L-30	49.22	30.35	-2620/1564
2L-50	56.84	22.89	-2995/1336
2L-70	44.76	19.26	-3095/1202
1L-30	35.39	25.79	-2703/1158
1L-50	38.43	28.51	-
1L-70	63.1	33.78	-
Temp-70	208.2	76.55	-2694/2598
Temp-80	46	28.12	-3099/3090
Experiment	29.72	21.6	-1385/391

Discussion

Obtaining a good correlation of occupant response during the crash scenario still remains challenging. Out of all type crashes rollover are the most hazardous and complex. There are few sources of error spotted in the simulations. The window frame was clamped to the bus structure resulting in the active load bearing during the rollover simulation. Therefore, failure criteria for the glass were achieved immediately after the impact with ground what was not observed in the experiment. As a result, ATD jammed into membrane-like PVB layer (Fig. 8), therefore, authors recommend considering different approaches with non-local failure criteria that can represent post-breakage behavior [11]. Likewise, the boundary condition of the glass might be crucial in the multi-body and oblique loading simulations. Finally, mechanical properties of the glass can highly affect the ATD's responses and its variability should be considered in the rollover simulations.

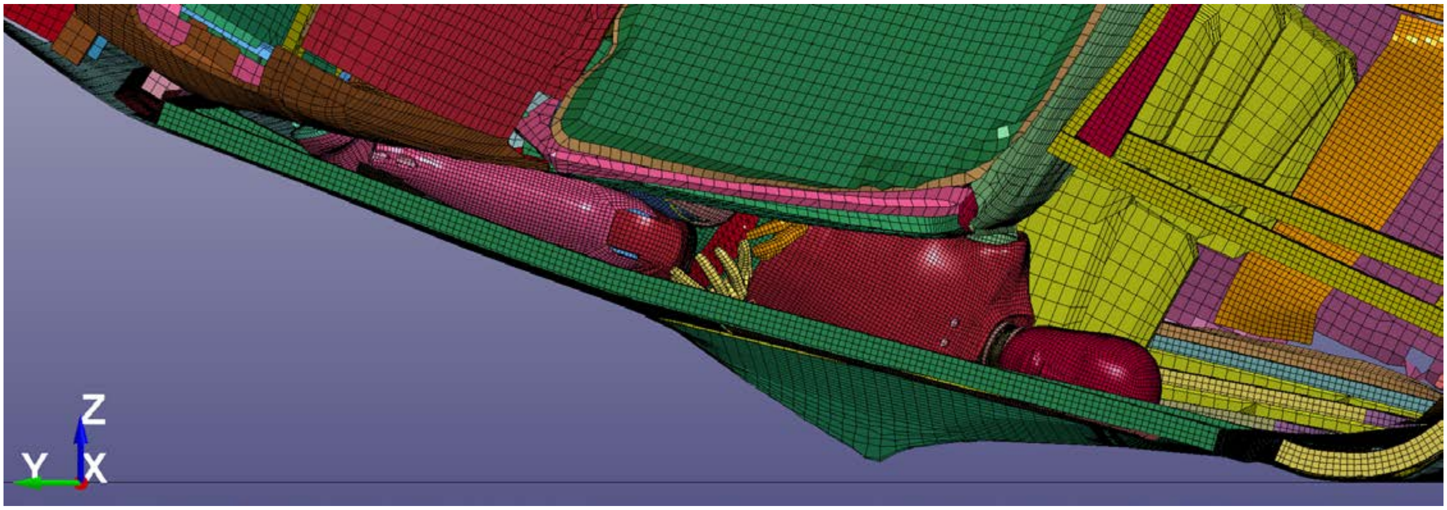

Fig. 8 Limitation of the single-shell laminated glass model.

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