A Detailed Numerical Investigation of Insulated Glass subjected to the Standard Pendulum Test

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Abstract:
Structural glazing design must reliably withhold static loads e.g. hand rails loaded by crowds, as well as dynamic loads, e. g. impacting persons or objects. Due to the ideally elastic behavior up to the brittle failure of glass, the verification of the load carrying capacity has been regularly done by experimental studies. However, it seems that trusting experimental results has more and more stopped engineers from looking into other means to safe design of glass structures, e. g advanced finite element tools that are able to simulate the dynamic response of glass designs. In relying solely on experimental investigations, one should also be aware of the fact that a safety factor against glass failure can neither be gained nor be trusted from only a limited number – in most cases only a single test is done - of experimental investigations. The latter holds even more, since scatter in material strength and even worse of the experimental setup are predominant.

Contrary to the experimental result, that has to be obtained through thorough and complicated gauging of a 50ms impact test, the numerical investigation allows easy and comprehensive studying of all mechanical parameters that may or may not influence the overall results. Also, simple design changes, that would otherwise raise the question if another test should be made, can easily be accomplished when a suitable, validated numerical model is available. Finally, this will lead to safer and more economic glazing design.

The present paper will focus on a sophisticated finite-element pendulum model that has been validated through pendulum tests against a rigid wall (see [1]). Furthermore it is used to simulate the impact on monolithic and isolated glass structures. The results are compared to experimental test data. It is shown that state-of-the-art numerical models are not only capable of representing the correct load carrying capacity of glass structures and the correct acceleration characteristics of the pendulum but also allow a deep insight into the complete mechanical behavior and the whole impact process of such discretized structures. In the following the results of the numerical investigation on impact loading of glass structures as described in DIN EN 12600 will be discussed. The main part of the present paper will focus on the setup, validation and calibration of the finite element model. A state-of-the-art discretization of the pendulum, the loading frame and the glass itself s presented. A discussion will conclude the paper.

Keywords:
impact loading, pendulum test, glass structures, finite element investigation, model validation

1   Introduction

Glass structures need to be designed to withstand various load scenarios from static and dynamic loading, e. g. facade elements might be subjected to static loading by second order structures or dynamic loading from impacting persons etc. Due to the known sensitiveness of the material to support and boundary conditions, special care needs to be taken to find a good and reliable design. With the publication of the „Technische Regeln für die Verwendung absturzsichernder Verglasungen" (short: TRAV, see DIBT [16]) for safety design of glass structures in January 2003, legal minimum requirements were eventually defined. The acquirement of this regulation has taken several years and they are substantially based on the suggestions of Charlier [3] & [4]. After legal introduction of these rules to the engineering community (see [5] & [9]) glazing structures need to be designed accordingly in future: The load-carrying-capacity is not only to be shown for the static loading but also for dynamic loads, where both the glazing structure and the immediate glass fastening need to be considered. In the informative appendix E of the TRAV the possibility is pointed out, that the proof against failure due to dynamic loading can also be given by means of numerical simulation. At present, this approach is not very common.

In literature the principle applicability of numerical methods to investigate the load-capacity of structural glazing subjected to impact loading by a pendulum was shown in [11], [13], [14], [15] and [20]. However, these references are focused predominantly on monolithic glass components. The present paper is addressed to pendulum tests of insulated glass, where a very detailed mechanical model, discretized with the finite element method, is studied. Hereby the nonlinear, commercial software code LS-DYNA [22] is used, which offers a variety of different material models, element formulations and time integration schemes (explicit and implicit) to solve highly dynamic problems. Its widespread use in the automotive industry allows the application of non-standard methods in the present application, e. g. the air filled tires of the pendulum body and also the gap between the two insulating glass panels are modelled with the so called uniform pressure approach, that allows simulation of the physical forces on the structure more realistic.

The finite element pendulum model developed in the context of the present work has been validated by pendulum tests against a rigid wall. This model permits now the simulation of impact tests of arbitrary glass structures realistically. Any geometrical design can be investigated or the calculation results of third parties can be verified with the herein present finite element model.

2   State-of-the-art in designing glass structures against pendulum impact

In accordance with the TRAV, proof of the load carrying capacity of glass structures can be given according to one of the following alternatives:

1. By respecting design specifications like screw-diameters, border-spacing etc., allowable designs can be read from given tables.
2. By conducting an experimental pendulum test according to DIN EN 12600 at a technically accredited laboratory or agency.
3. An expert's statement which is based on existing component or pendulum tests can be present.
4. Tensional stresses can be read from a table which is based on the design and size of the supporting structure. Interpolations at inter-values are permitted. These tensions are compared to the short time strength of the corresponding, actual glass (see table 1).

The method mentioned in item 4 was introduced in [15] and [20] and was worked out with finite element simulations of the pendulum test. The simulation results were converted into the tabular values given in the appendix C of the TRAV and the data was verified with existing test results. These tensional stress values guarantee an unbroken glass panel. Additional load carrying capacity, that is available due to a PVB foil in laminated safety glass, is not taken into account. Hereby an engineering method is available, that allows the assessment of glass constructions in a way, which resembles the table methods of concrete slab design of earlier days. But while nowadays the finite element method is accepted as method of choice for slab and shell design, both for physically and geometrically nonlinear problems, its application to the transient pendulum impact problem is generally not accepted in practise. The latter holds even due to the fact, that numerical investigations with various different geometric or material parameters would allow a more thorough understanding of the load carrying mechanism and thus leading to safer design. At present, the proof of load-capacity is dominated by pendulum tests of the actual glass structure. However, often only one test is conducted, which in turn questions the reliability of the gained data. An over-estimation of the available safety against failure

due to material over-strength, climatic influence and support conditions of the structural elements can in almost all cases be assumed.

In addition to the experimental verification there is the possibility of verifying the load carrying capacity through numerical simulation techniques as mentioned earlier. At present the biggest criticism to their application is the fact, that manipulation of input data allows matching of any experimental data or approval of any design. In addition there are only a limited number of software codes available which are specifically tailored for the demands of the civil engineering industry (e.g. SJ MEPLA) and which are able to simulate the pendulum impact with a simplified mechanical model. The conclusion arises - and this approach is followed in this work - , that one of the major, multi-purpose finite element packages, where a detailed geometrical discretization of the experimental setup is possible, should be used. However such codes are usually not used in the civil engineering industry.

3 Glass strength under short-time loading

The pendulum test represents a short time impact load for the glass component. For glass different strengths values depending on the type of glass, environmental influences, scratches on the glass surface, load duration and velocity, are observed. With increasing load velocity the glass strength increases as for most engineering materials. In the literature models, based on experimental data and fracture mechanics theory, that estimate the short time strength for glass under impact loading, are available (see [11] & [15]). The TRAV lists allowable bending stresses at the upper and lower glass surface, which are applied in the following numeric examples (see table 1).

	Float glass	Semi-thoughened glass	thoughened glass
zul. σ	45 N/mm^2	70 N/mm^2	120 N/mm^2

Table 1 Maximum stress for impact loads according to TRAV
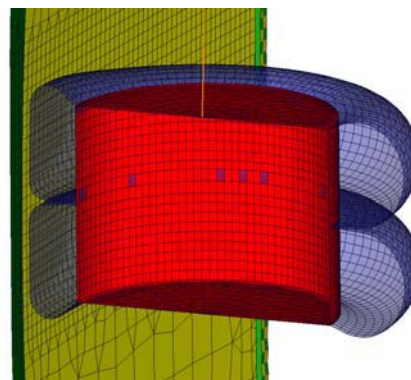

Figure 1:   Modelling of the pendulum; flattened tire geometry due to contact on the left

4 Finite element model and validation of the pendulum body

The pendulum in the present investigation is modelled according to DIN EN 12600 [7] (see figure 1). The individual parts of the pendulum, e. g. tires and massive steel corpus are modelled with shell elements of the Belytschko-Tsay formulation (see [22]). The steel corpus is set rigid and for the tires an elastic material is assumed. The internal pressure of 4.0 bar in the tires is simulated by the *control volume concept* with an equation of state for ideal gases. The model takes the pressure increase due to deformation of the tire into account and allows therefore a realistic reproduction of the physical behaviour of the pendulum. The same approach is being used for the gap between the two glass panels for the insulated glass structures. Thus not only a correct loading of the inner glass plate is guaranteed but also climatic effects (different ambient pressures between production and final location) can be simulated. The latter is usually not taken into account when experimental test are conducted. A detailed description of this approach can be found in [23].

	Pendulum	Glass	Steel frame	EPDM
Young's modulus [N/mm²]	27.0	70000.0	21000.0	15.0
Poisson's ratio	0.40	0.23	0.30	0.23
Density [N/mm³]	-	2.5e-5	7.85e-6	-
Thickness [mm]	4.00	7.75	see [11,17]	see [11,17]

Table 2 Material properties for the simulation with LS-DYNA

Experimental investigations of pendulum bodies impacting a rigid wall have been reported in [2], [15] and [20]. There the acceleration of the pendulum was measured. This data is used to verify the

pendulum discretization in the present application and also to validate the necessary constitutive data. Thorough examination of the experimental data shows, that the readings of the accelerations show significantly lower impact energy than what would be expected from the potential energy at the beginning of the experiment. The reason for this effect may be sought in a wrong estimation of the centre of gravity and deferred release of the pendulum. Thus in the present contribution the velocity of the pendulum just before the impact is calculated from acceleration data from the experiment assuming a fully elastic impact:

$$F^* = \int_{\Delta t} F(t)dt = \int_{0}^{t=t^*/2} m \cdot a(t)dt = m \cdot \Delta v \tag{1}$$

Figure 2 depicts the pendulum accelerations for different drop heights (FH in *mm*) compared to experimental data; the constitutive parameters are given in table 4. The calculated curve plots are not filtered, thus oscillations due to the discretization of the tire and due to axial and tangential contact forces in the contact algorithm can be observed. Another verification of the developed pendulum model is show in figure 3. Here the results of the software code SJ MEPLA, which is widely used in civil engineering practise, are compared to the solutions with LS-DYNA with drop heights of 450 mm and 900 mm. The software code SJ MEPLA has been validated in [2]. The maximum forces are depicted in table 3.
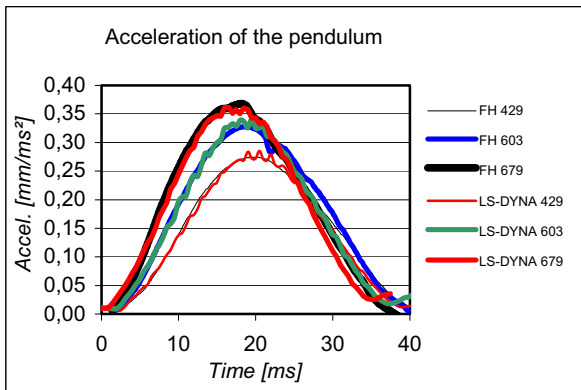

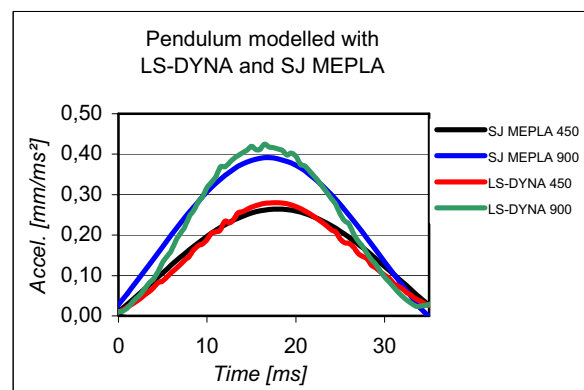| Figure 2: | Comparison of experiments and results from LS-DYNA | Figure 3: | Pendulum acceleration at different drop heights when modelled with LS-DYNA and SJ-MEPLA |

Drop height [mm]	Part	Max. force of pendulum [kN]
450	Rigid wall	13.9
900	Rigid wall	18.7
450	ESG 8[*]	8.68
450	MSI 8/16/8[*]	9.03

Table 3:   Maximum force of the pendulum   [*] Impact of pendulum in centre of panel according to [11]

Investigated glass designs	Toughened glass [mm]	Air gap [mm]	Toughened glass [mm]	Drop height [mm]
ESG 8	7.75	-	-	450
MSI 8/16/8	7.75	16.00	7.75	450

Table 4:   Investigated glass designs

5   Simulation of the pendulum impact on toughened and insulated glass

5.1   General considerations

The validated pendulum body is now being used to simulate the pendulum test on toughened glass (ESG) and air-filled insulated glass (MSI). The exact glass set-up can be gathered from table 4. The investigated insulated glass panel is built up from two monolithic ESG plates. Both glass set-ups would not be approvable due to the TRAV, since this demands a glass construction with at least one

composite glass panel (VSG). They offer, however, the advantage that possible side effects due to the unknown shear stiffness of the PVB foil are not present.

The test framework, which was supported with diagonals in approx. 1.6 m of height (see figure 5) consisted of U50 and U100 profiles (screw distance 250 mm). With these rectangular test bodies of the size 1050 mm x 2056 mm (width x height) numerous pendulum tests were carried out [17]. Experimental pendulum accelerations and deformations given in [10] and [17] are compared to the simulation results introduced in the following.
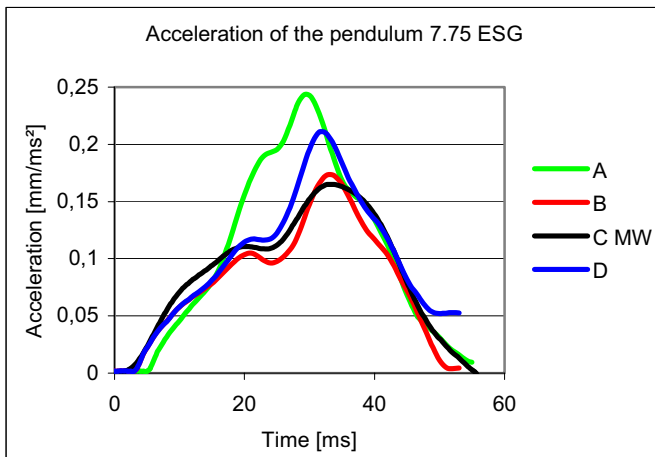
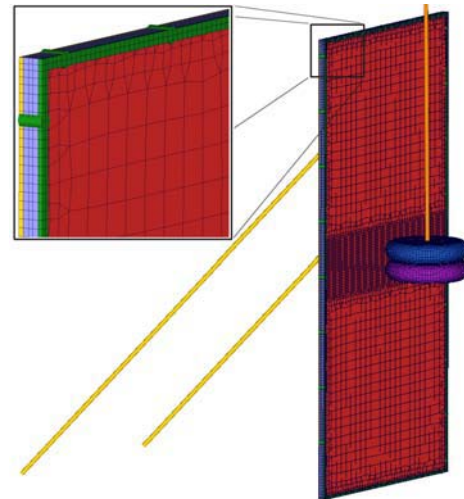

Figure 4: Accelerations of ESG-model

Figure 5: Total view of numerical model and detailed view of corner region

5.2   Results of ESG 8

The result of the aforementioned simulation model is depicted in figure 4, curve B. Here the drop height was set to 450 mm and the experimental data of [10] is given by curve MW. It can be seen that the characteristics of the accelerations fit very well. In principle one could study any of the given mechanical properties (e. g. stresses, strains, deformations) of the numerical test setup. With the present approach any unsafe design of the structure or unknown sensitivities (e. g. due to geometry or material choice etc.) due to DIN EN 12600 can be investigated and economic pitfalls may be found at an earlier stage of the design phase.

Of course, critics warn, that finite element results will always fit to given experiment results, since the experimental data is used to fit the simulation. This shall not be contradicted since finite element models can be built and also modified in various ways of course. On the other hand a numeric solution of the problem is often regarded rashly as inadequate as soon as the measure data does not agree with the simulation results congruently. A proper simulation shall be able to describe the principle characteristics of the test according to an approximate solution and deliver thus assessment relevant quality of data in the range of available experimental measurements. By a further gradual improvement of the numerical model the quality can be increased further.

In the present case the finite element model of a simple plate model used at first could not deliver satisfactory agreement with the measurements. Eventually, more detailing (i.e. a finer mesh including more geometrical details) could describe the complex event satisfactorily. The introduced simulation model of the glass panel contains now all geometric details of the actual testing structure, including the support situation, in the testing frame, existing stiffening profiles, screws and diagonal stiffeners.
The set up of the model followed the specifications in [10] and [11] as far as documented. Aspects not documented have been chosen adequately according to engineering judgement. Further model improvement can be done by taking into account physical nonlinearities, particularly for the rubber materials. For the present application the use of linear elastic material models exclusively is sufficient, since experimental data for material model characterization was not available.

The impression shall not arise, however, that the simulation shows the reality identically and in any case without deviations. The experimental data shows great scatter, too. Departing of acceleration-

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and displacement-gauges makes measuring often extremely difficult. The described problems with the experimental setup and the low number of samples can feign an apparent safety at the test that is not existent in the real built structure.

5.3   Results of MSI 8/16/8

The insulated glass (MSI) was discretized (compare figure 5) in the finite element model including the air-filled gap between the two glass panels, spacers and comprehensive support conditions of the testing frame. The model is able to assign the stresses due to the changing of the enclosed gas volume to the adjacent components (glass and spacers). The panel surfaces are numbered beginning with the number 1 for the outside face. The pendulum body therefore hits surface 4 (inside face). At a drop height of 450 mm the deformations depicted in figure 6 represent surface 1 and 4. The simulation results are compared to the experimental values, characterized with MW, from [11]. It is recognizable that the deformation maxima of the individual panels appear at different times as expected.
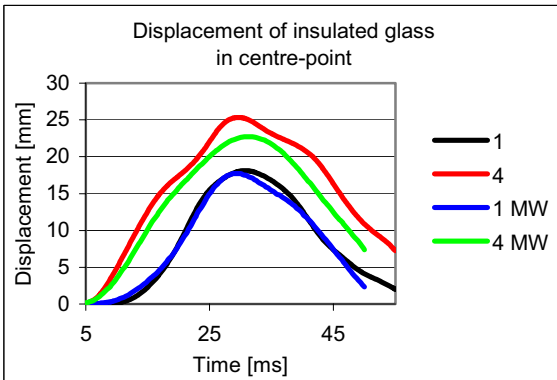
Figure 6:   Simulation data of surface (1) and (4) compared to experimental data (MW)
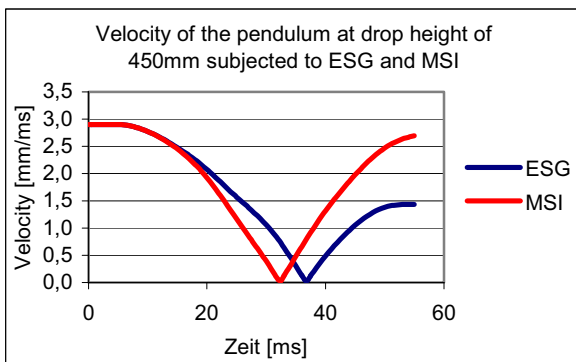
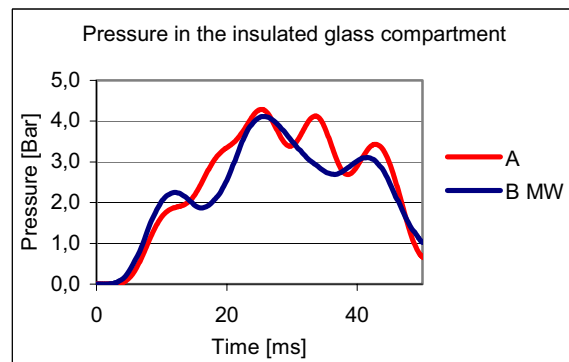Figure 7:   Velocity of pendulum at drop height of 450 mm subjected to ESG and MSI

Figure 8:   Pressure in the insulated glass glass compartment: (A) simulation and (B) experiment

Furthermore the simulation offers advantage over the test such that the impact event and the reactions of the glass panel can be studied in detail. The impacted surface 4 is immediately loaded by the pendulum body at the very beginning of the simulation. The complete compression phase only lasts for approx. 30 ms until the pendulum body comes to a stop and the movement reverses (figure 7). By swinging back of the glass panel elastically, the elastic energy stored in the panels and the air-filled tires accelerates the pendulum again. Until approx. 2.5 ms after the initial impact the loaded first glass panel starts carrying substantially. Within the next 20 ms the second glass panel is also involved in the load carrying process through the compressed air subjected to the panel as uniform load. This can be observed on the basis of the pressure in the gap between the panels. The simulation values are plotted in figure 8 against the experimental measurements.

6   Summary and outlook

It was shown that a state-of-the-art numerical model is capable of representing all major effects of real world experimental pendulum tests. It was also emphasized that such models need thorough validation against suitable test data to be able to predict correctly the load carrying behaviour of structural glazing. It should, however, be prudently mentioned that any finite element model is only able to represent the reality as good as underlaying mechanical assumptions allow. In order to correctly simulate the pendulum test in the prescribed manner, considerable efforts in detailing the

discretization, gaining constitutive parameters and investigating existing, published pendulum results have been made.

It should also be mentioned that only tests carried out after the numerical simulation has been conducted can create the necessary confidence in the existing and meanwhile matured numerical simulation models. In future it would be helpful if any simulation results would be handed in to the responsible authority before experimental tests are conducted. This would increase the quality of simulations and they could eventually be assessed by an independent authority only. Thus expensive component tests would be carried out only if the numerical simulation shows significant sensitivity to critical parameters.

With the introduced modeling technique in LS-DYNA it is possible to change the pendulum body arbitrarily. Thus the numerical simulation of a hard impact could be realized accordingly e.g. vehicles or dummies. At present, corresponding investigations are carried out by the authors.

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