SOME ASPECTS OF DESIGNING AND NUMERICAL MODELLING OF GLASS RAILING EXPOSED TO IMPACT LOAD

Ondřej PEŠEK[1], *Jindřich MELCHER*[1]

[1]Institute of Metal and Timber Structures, Faculty of Civil Engineering, Brno University of Technology, Veveří 331/95, Brno, Czech Republic

pesek.o@fce.vutbr.cz, melcher.j@fce.vutbr.cz

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Abstract. *In recent architecture glass is widely used structural material of facades, walls, roof, stairs and other applications. Glass as a material is popular for its transparency, but it need to be carefully analysed for its fracture behaviour. This paper deals with some aspects of numerical modelling and designing of all-glass railings acting as cantilever element fixed at the bottom edge and with a handrail on the top edge. In the frame of study, number of different glass railings models were analysed to find out the best way how to simulate glass railing imposed to the impact load. The impact load is in most cases decisive load case acting on that type of structure. Variable parameters entering the analysis are the aspect ratio of glass railing pane, impact intensity, impact member hardness and finite element meshing. Finite element analysis of 250 models was performed in ANSYS Workbench.*

Keywords

Impact load, numerical modelling, pendulum test, railing, structural glass.

1. Introduction

Glass railings are modern architectural elements, but also structural elements which have to meet the requirements of static stability, reliability and safety in use according to the national and international standards. The basic purpose of railings is to secure safe movement of persons on floors and stairs and prevent falling down into free space. The secondary purpose is to carry a handle and tertiary purpose is to be an architectural element in building. The final shape and size of railings and handrails with exactly defined materials and anchoring and connection details resulting from the mentioned purposes.

Each railing has to be designed and realised according to the relevant codes on defined permanent and imposed loads resulting from the specified area of use (for example there are different requirements on railings in family house and in public terrace). Static load acting on the railings includes permanent loads (self-weight and other dead loads which are not significant in this type of structure) and imposed loads (live load due to use by persons, wind load only in the outside applications [1]). More important load in railings applications is dynamic load simulating moving (falling) person impacting on railing [2].

One way how to demonstrate the designed glass railing is safe is to carry out full-scale load test [3], which is expensive and long-term. The other way is to carry out numerical structural analysis. In both ways it is necessary to demonstrate the designed railing meets the requirements on structural stability (including sufficient strength of materials, dimensions, connections, anchoring) and maximal permissible deformations. The special attention must be paid on structural detailing (steel-glass connections, glass anchoring), which have significant influence on dynamic behaviour [4].

2. Methodology

Analysis and numerical modelling of glass railing was performed in ANSYS Workbench software [5] based on finite elements method [6]. The purpose of analysis is to find out the optimal way how to precisely and effectively design and model glass railings exposed to impact load. There are some aspects, which are listed below:

- Aspect ratio b/h of glass railing,
- finite element type and meshing,
- impact intensity and point of application,
- impact member hardness.

2.1. Geometry of analysed glass railing

For the analysis the simplest type of glass railing was chosen – rectangular glass pane fixed on bottom edge. It is of Type E according to the Czech national standard for design of railings ČSN 74 3305 [7]. The height *h* of glass railings was chosen by basic value 1000 mm (the distance between final floor and upper edge – handrail). The railing is without any steel or timber handrail, as handrail top edge of glass railing serves which is permitted by cited code [7]. Using steel or timber handrail is more practical due to possibility to join next glass panes together by handrail. The width *b* of railing is 1000, 1500 or 2000 mm (Fig. 1). These values give three aspect ratios b/h = 1.0; 1.5 or 2.0.

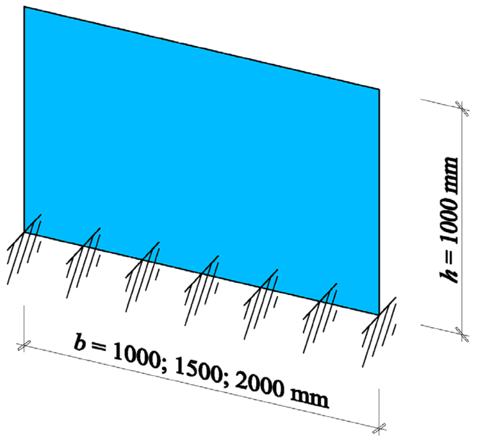

Fig. 1: Analysed glass railings geometry.

2.2. Laminated structural glass

Glass railings have to be made of structural laminated glass composed of two (or three in extremely exposed cases) glass panes bonded together by interlayer. Glass panes should be of annealed glass, heat strengthened glass or fully tempered glass. The type of glass has no influence on behaviour under loading up to breakage because of the same linear elastic P-Δ diagrams for all glass types. The difference is in strength and post-breakage behaviour. The interlayer material could be based on PVB (polyvinyl butyral), EVA (ethyl vinyl acetate) or Ionoplast. All the materials are visco-elastic materials, this means that their physical characteristics (especially shear modulus *G*) depend on temperature and load duration. The value of interlayer shear modulus has strong influence on overall behaviour of laminated glass under loading. But in the case of impact load, the load duration is extremely short, that causes there is full interaction of glass panes while using any interlayer material and thus it is not necessary to calculate effective thickness of laminated glass according to the laminate theory [8, 9].

In the frame of parametric study, the following laminated glass compositions were analysed: 66.2, 88.2, 1010.2 and 1212.2. First digits (6; 8; 10 or 12) are thicknesses of glass panes and last digit after the dot is number of interlayer foils (where each one is 0.38 mm thick), e.g. glass 66.2 is composed of 6 mm glass + 2×0.38 mm interlayer + 6 mm glass = 12.76 mm overall thickness.

2.3. Impact load

According to the Czech national standard for design of railings ČSN 74 3305 [7], railing has to be able to resist impact load and thus prevent person to fall through railing. The impact load is defined according to the international standard EN 12600 Glass in building – Pendulum test – Impact test method and Classification for flat glass [10]. The code prescribes the weight and the shape of impact body. The body should be composed of double-tire with steel ballast or canvas bag filled with small glass shots. In both cases the overall weight of impact body is 50 ± 0.2 kg. The Czech standard prescribes use of double-tire impact body for glass railings and impact intensity is given by height from which the impact body falls according to the Categories of use defined in EN 1991-1-1 Eurocode 1: Actions on structures – Part 1-1: General actions – Densities, self-weight, imposed loads for buildings [11]. The double-tire impact body is shown in Fig. 2. Fall height and impact energy are listed in Tab. 1.

Tab. 1: Impact load intensity.

Category of use according to the EN 1991-1-1	Fall height *h* of impact body	Impact energy
A, B, C1, D1	450 mm	221 J
C2-C5, D2, E	950 mm	466 J
Stairs and ramps	200 mm	98 J

The Czech code [7] also prescribes the impact area on glass railing where the impact body should impact to verify the glass railing is safe. The impact area is defined between lines in distance of 250 mm from handrail (or from upper edge of glass pane when no handrail) and in distance of 500 mm from floor and in distances of 100 mm from free vertical edge of glass railing. Within impact area two impact points were chosen for analysis – first one in the middle of railing width and second one 100 mm from the vertical edge of railing – see Fig. 3.

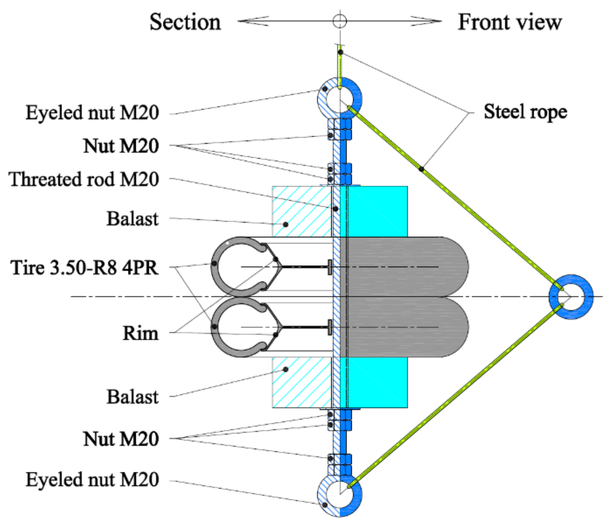

Fig. 2: Impact body.

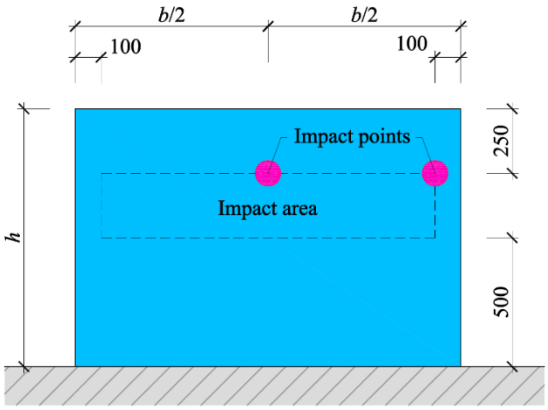

Fig. 3: Impact area and impact points.

The Czech code [7] allows use of numerical modelling of impact load instead of experimental testing. The numerical modelling has to demonstrate there will be no breakage of the glass railing to avoid injury due to glass shards and the deformations will be less than limit value.

In the case of double-tire impact body, the code [10] prescribes internal pressure 0.35 ± 0.02 MPa which defines impact body hardness. But in the ANSYS software, the impact body hardness is defined by Young's modulus *E*. Thus one goal of the FEA is to find out the influence of impact body hardness on deformations and stresses in glass railing at the time of impact.

2.4. Finite element analysis

Finite element analysis was performed in ANSYS Workbench software [5]. Laminated glass was modelled as one simple glass pane with nominal thickness as the sum of thicknesses of glass panes and interlayers (according to the laminated glass theory [8, 9]).

Two types of finite element models were analysed: volume models using spatial elements SOLID186 and shell models using planar elements SHELL181. In the case of volume model the influence of number of elements along glass thickness was analysed. The number of elements were 1, 2, 3 and 4. Impact body was modelled using tetrahedral elements in both cases.

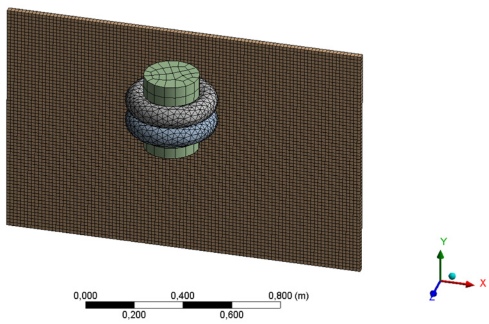

Fig. 4: Finite element model with element mesh.

Element size of glass pane was set to 15 mm. One of the goals of FEA was to find out the best way how to simulate glass pane – using planar or spatial elements and in the case of spatial elements, which number of elements along the glass thickness is necessary – in the frame of analyses five models with different mesh were performed for the same geometry.

3. Results and discussion

From overall results only following data are presented – maximal displacement of glass pane and maximum principal stress of glass pane (in both cases it is maximum value from all nodes of whole model, not for one specific node or element of model), because they are the only limitations in structural design – maximal principal stress should be less than design strength in ULS and maximal deformation should be less than limit value in SLS. Typical stress distribution and deformation of railing for impact point on the right edge is shown in Fig. 5.

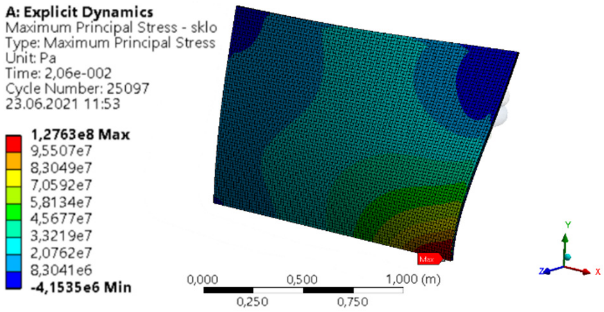

Fig. 5: Principal stress distribution on deformed geometry of glass 1010.2 with aspect ratio *b*/*h*=1.5 for impact point on the right edge and *h* = 450 mm.

3.1. Influence of glass thickness

Glass railing stiffness depends on glass thickness. More thick and stiff glass results in less deformations and principal stresses under loading. Maximal deformations strongly decrease with increase of glass thickness, because there is nonlinear dependency of moment of inertia on thickness. The deformation of 1212.2 is 38 % in comparison with 66.2 and moment of inertia of 1212.2 is eight times greater in comparison with 66.2.

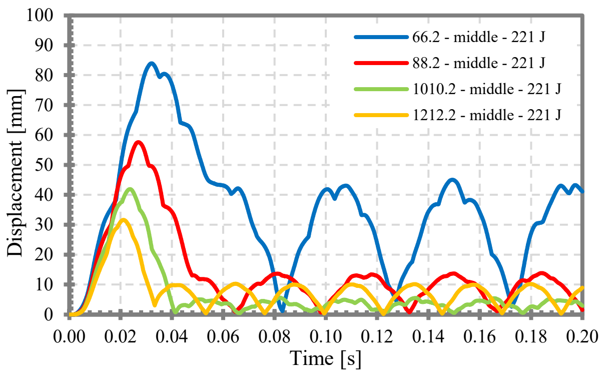

Fig. 6: Maximal displacement of glass railing depending on time for impact point in the middle and *h* = 450 mm.

On the other hand, the decrease of maximal value of principal stress is not so strong with glass thickness increase. The maximal value of principal stress of 1212.2 is on 75 % compared to 66.2. This phenomenon is caused by dynamic loading, in the case of static loading the stress decreasing would be stronger. The results of time dependent analysis are shown in Fig. 6 (displacement) and in Fig. 7 (principal stress) for aspect ratio *b*/*h* = 1.5.

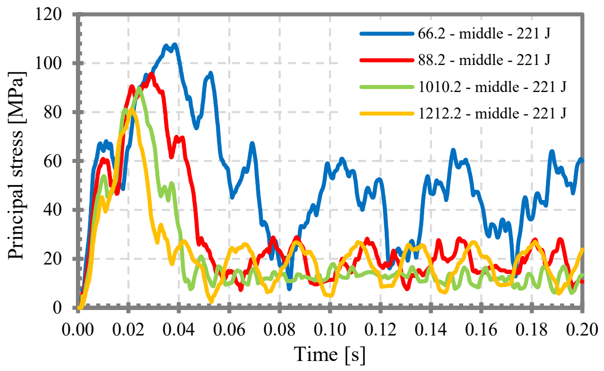

Fig. 7: Maximal principal stress in glass railing depending on time for impact point in the middle and *h* = 450 mm.

The relative expression of maximum displacement, maximum principal stresses and moment of inertia is in Fig. 8, where glass 66.2 is reference for displacement and stress and 1212.2 is reference for moment of inertia.

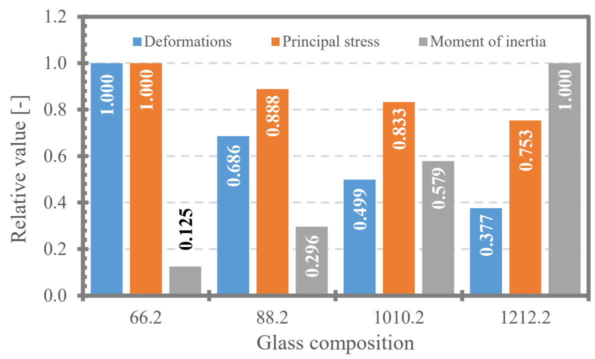

Fig. 8: Relative values of maximal deflections and principal stress in glass railing for impact point in the middle and *h* = 450 mm.

3.2. Influence of aspect ratio

Glass railings were analysed with different dimensions which gives three values of aspect ratio *b*/*h* = 1.0; 1.5 or 2.0. In the case of dynamic loading the inertia of mass is significant unlike of static loading. When impact body impacts on the glass railing in the middle, the left and right ends remain in place for short time and after some time they start to move in direction of impact, but at the same time the middle part of railing has already move in opposite direction. The time delay from impact to start moving of railing ends depends on railing stiffness and geometry. For the aspect ratio 2.0 the time delay is longer than for aspect ratio 1.0. The same principle applies to impact point on right end of railing and moving of left end of railing.

Wide range of numerical models were carried out within parametric study. Glass composition 66.2, 88.2, 1010.2 and 1212.2 with impact point in the middle and on the edge by impact energy of 211 J and 466 J (in total 48 different models). In tFig. 9 and 10 the results of glass railing of composition 1010.2 loaded by impact energy 221 J are shown as example.

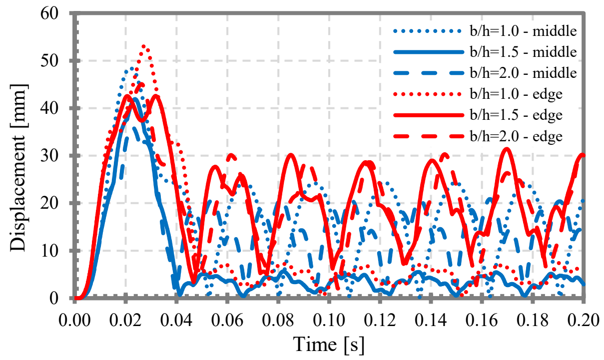

Fig. 9: Maximal displacement of glass railing depending on time for impact point in the middle and on the edge and *h* = 450 mm.

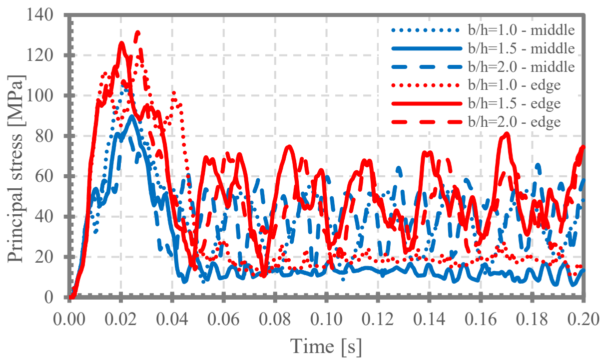

Fig. 10: Maximal principal stress of glass railing depending on time for impact point in the middle and on the edge and *h* = 450 mm.

The influence of aspect ratio is described in Fig. 11. The maximum displacements of railings with greater aspect ratio (1.5 and 2.0) are less than for aspect ratio 1.0 for both impact points – in the middle and on the edge. On the contrary, principal stresses of railing of aspect ratio 2.0 are higher than for aspect ratio 1.0, but aspect ratio 1.5 gives lower values of stresses than for 1.0.

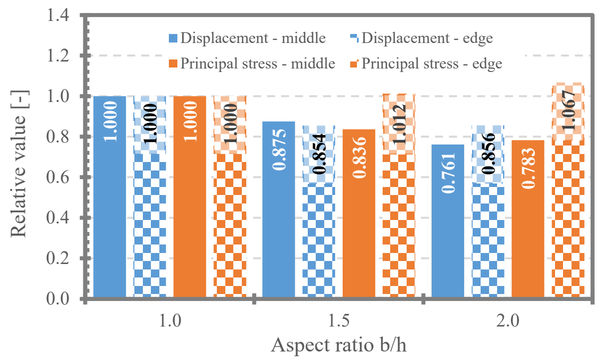

Fig. 11: Relative values of maximal displacement and principal stresses in glass railing for impact point in the middle and on the edge.

3.3. Influence of finite element type and mesh

For each case of glass railing (railing aspect ratio $b/h = 1.0$; 1.5 or 2.0, different impact point and intensity, glass composition 66.2; 88.2; 1010.2 or 1212.2) five different FE models were carried out – in total there were 240 different models. The difference between them is in the different FE meshing: in one case the shell model was performed using shell finite elements (marked $n = 0$), in other four cases solid models were performed using solid finite elements (marked $n = 1$; 2; 3 or 4 for number of finite elements along the glass thickness).

From the charts in Fig. 12 and 13 (for displacement and stress) it can be concluded that solid model of glass with only one finite element along the thickness is very inaccurate and gives invalid results. Solid model with three elements along the thickness gives acceptable results.

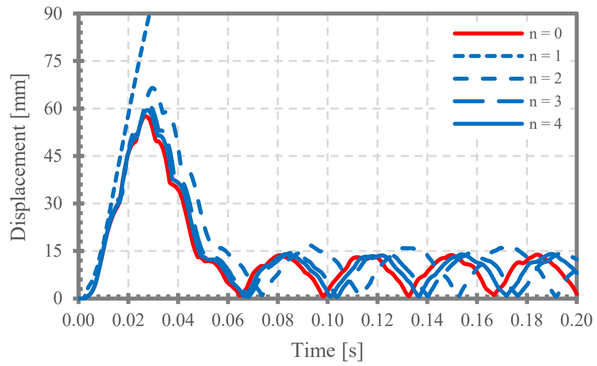

Fig. 12: Maximal displacement of glass railing 88.2 depending on time for impact point in the middle and $h = 450$ mm.

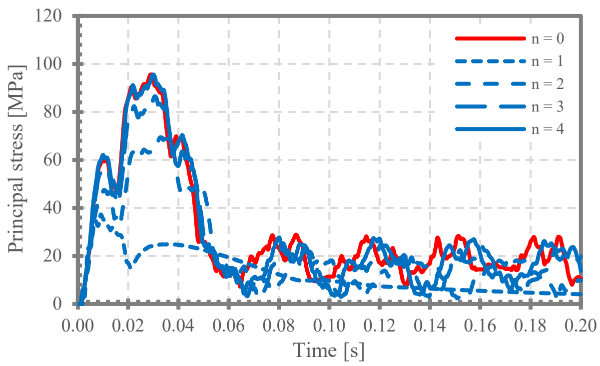

Fig. 13: Maximal principal stress of glass railing 88.2 depending on time for impact point in the middle and $h = 450$ mm.

Generally, the higher number of finite elements gives more accurate results – smaller displacements and higher stresses. On the other hand, numerical model with higher number of finite elements requires higher computing power or takes longer computing time.

Fig. 14 shows relative values of maximum values of displacement and normal stress where shell model is taken as reference. In the case of displacement, the solid model with two elements along thickness gives relative error +15 % and in the case of stress the error is -23 %. Model with four elements gives error +3.4 % and +1.6 %. On the other hand, the computing time of solid model with two elements along the glass thickness is 3.6 times shorter (28 % of time for $n = 4$) than for four elements along thickness and is similar as for shell model (24 % of time for $n = 4$). For computing time, the solid model with $n = 4$ is taken as reference.

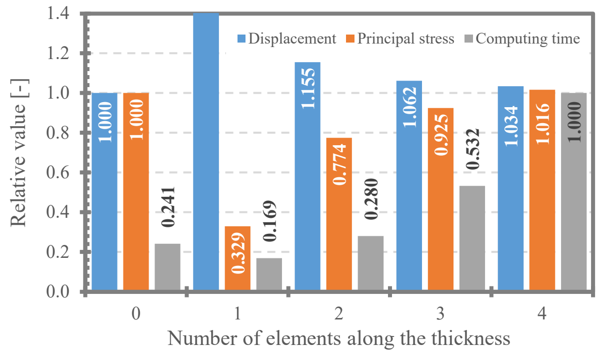

Fig. 14: Relative values of maximum displacement and principal stresses in glass railing in comparison with computing time.

3.4. Influence of impact intensity

In Fig. 15 and 16 the time depending results of glass railing of composition 1212.2 with aspect ratio $b/h = 1.5$ are shown as example.

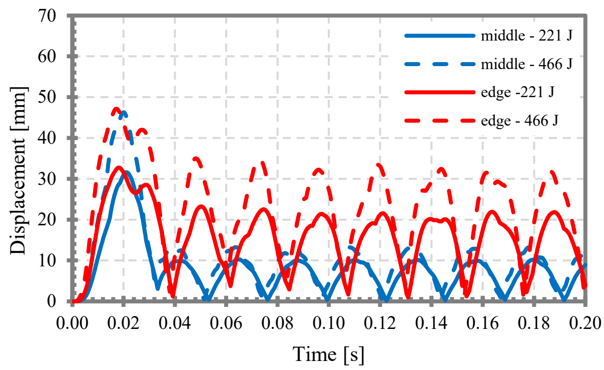

Fig. 15: Maximum displacement of glass railing 1212.2 depending on time.

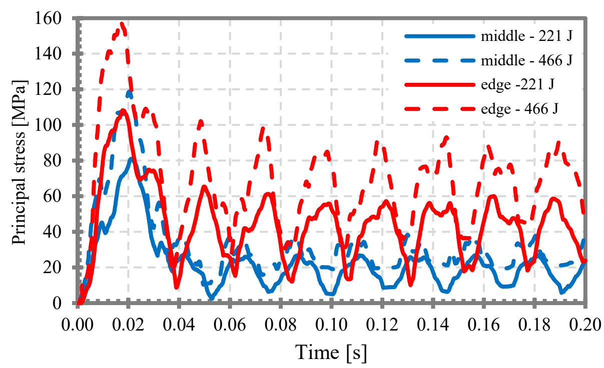

Fig. 16: Maximum principal stress of glass railing 1212.2 depending on time.

Two impact intensities were analysed: first one in value 221 J (which corresponds to the impact of 50 kg body from 450 mm height) and second one in value 466 J (which corresponds to the impact of 50 kg body from 950 mm height). These two impact intensities were applied on glass railings with aspect ratio b/h = 1.0; 1.5 and 2.0, and with impact point in the middle or on the edge. Also different glass compositions were analysed – 66.2, 88.2, 1010.2 and 1212.2. From the results it can be concluded that the relative difference between maximum deflections and stresses of railing impacted by energy 221 J or 466 J is the same for whole range of analysed railings. The relative values of maximum deflections and stresses are shown in Fig. 17 where the 211 J impact energy was taken as reference. For the impact energy 466 J the deflections are about 45 % higher for both impact point in the middle and on the edge. In the case of principal stress and impact energy 466 J the stresses are higher about 47 % for impact point in the middle and about 50 % for impact point on the edge. The deflection and stress increase is lower than impact energy increase 211 %.

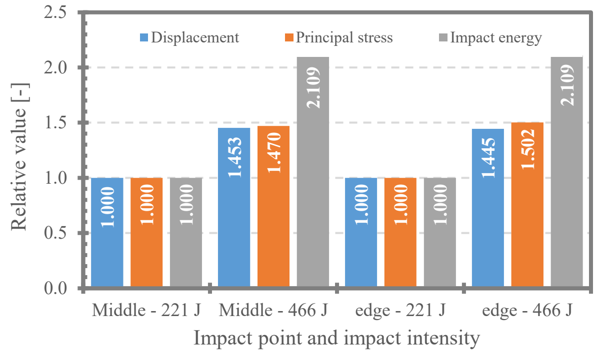

Fig. 17: Relative values of maximum displacement, principal stresses and impact energy in glass railing.

3.5. Influence of impact body hardness

Impact body hardness is defined in the code by internal pressure in tires, but in the numerical model its defined by Young's modulus of tires volume. In the Fig. 18 and 19 results are shown for impact body hardness with E_{tire} = 2, 5, 10, 20 or 50 MPa.

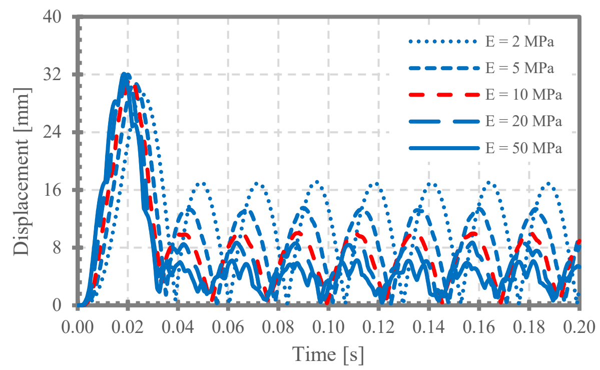

Fig. 18: Maximum displacement of glass railing 1212.2 depending on time for impact point in the middle and h = 450 mm.

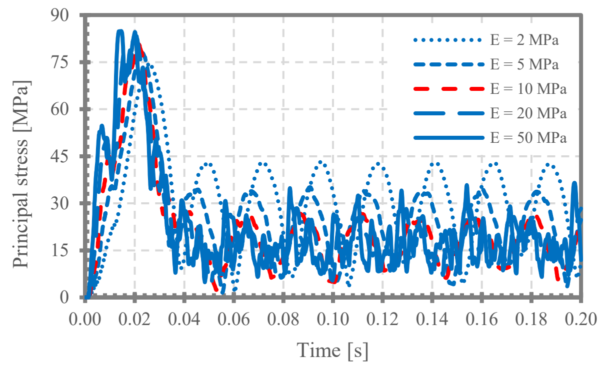

Fig. 19: Maximum principal stress of glass railing 1212.2 depending on time for impact point in the middle and h = 450 mm.

Influence of impact body is not significant according to the relative expression of results shown in Fig. 20, where maximal displacements and stresses are compared. Results of model with E_{tire} = 10 MPa (this value of tires hardness was considered in all others models) was taken as reference. Displacements and stresses are about 1.5 % and 4.7 % higher for five times E_{tire} value higher (50 MPa), for E_{tire} value five times lower (2 MPa) the displacement and stresses are about 17 % and 18 % lower in comparison with reference case (10 MPa). General conclusion is that the harder impact body gives slightly higher displacements and stresses than softer one.

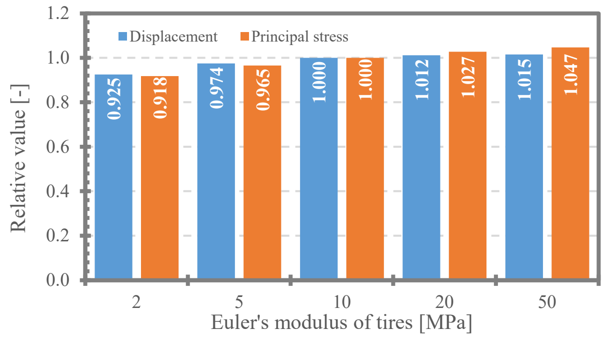

Fig. 20: Relative values of maximal displacement and principal stresses in glass railing for impact point in the middle and h = 450 mm.

4. Conclusion

The wide range of numerical models were carried out to find out the practical and accurate way how to model impact loaded glass railings – the total number of analysed numerical models is 250. From presented results the following conclusions can be drawn:

- In the case where the stresses are decisive in structural dynamic analysis, the influence of glass thickness increase is not significant in comparison with static analysis.
- Wider glass railings (with great aspect ratio) have, in general, less displacements and stresses under static loading but in the specific cases of very wide glass with impact point on the edge there could be

greater principal stress than for the narrow one (with low aspect ratio).

- From the point of view of computation effectiveness and accuracy the use of shell model is favourable. If the use of solid model is necessary, the finite element mesh requires three elements along the glass thickness for satisfactory results, for exact results it need four elements along glass thickness. The computing time is then four times longer than for shell model.
- Impact energy has influence on railings behaviour, but for double the value of impact energy, the deflections and stresses are only about 50 % higher.
- Impact body hardness has a relatively low influence on railings behaviour under loading. Generally, the harder impact body gives slightly higher displacements and stresses than softer one.

Further research could be focused on: analyses and more detailed investigation of adjacent glass panes joined together by handrail and their interaction (influence of adjacent glass stiffness and stiffness of handrail); the investigation of different types of glass anchoring and fixing (influence of anchoring stiffness, glass is fixed through steel parts using rubber or polyamide pads or silicone sealant which all allow large deformations); experimental analysis of exact double-tire impact body properties (impact body hardness); evaluation of numerical analyses results with experimental analysis.

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About Authors

Ondřej PEŠEK was born in Vysoké Mýto, Czech Republic. He received his Ph.D. from Structures and traffic constructions (with thesis Stability problems of laminated structural glass members) on Faculty of Civil Engineering, Brno University of Technology, Brno, Czech Republic in 2018. His research interests include design and stability problems of steel structures, glass structures, GFRP structures and numerical modelling.

Jindřich MELCHER was born in Brno, Czech Republic. He received his Prof. from Structures and traffic constructions in 1989 and his DrSc. in 1991. His research interests include design of steel structures and bridges, stability of steel members and experimental verification of load bearing members.