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Theoretical verification of the reinforced glass beams

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Abstract

Designing with glass, demands a detailed knowledge of the mechanical properties of the material. There are various ways of describing the mechanical behaviour of glass as a structural material. Some of these methods are also used in the design of constructions made of materials like steel, aluminum, concrete, reinforced concrete and timber. Nevertheless the designing with glass is still an under-developed area. Intensive theoretical and experimental research is therefore essential for ensuring the reliability and efficiency of modern structural glass systems.

Keywords: structural glass, laminated glass, beams, reinforcement, post-breakage structural capacity, FEM analysis, crack, fracture

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1. Experimental verification

Experimental testing of reinforced beams made of annealed glass has focused on the ways how to improve the load-bearing resistance of glass by coupling with steel materials and how to ensure the post-breakage capacity of the partly damaged load-bearing glass element.

1.1. Testing specimens

Specimens of glass beams were of dimensions 1500 x 130 mm and for their production laminated glass was used with a sheet thickness of 5mm and PVB foil with a thickness of 0,76 mm. Therefore the theoretical thickness of laminated glass pane was 10,76 mm. A reinforcing profile made of stainless steel profile of material quality EN 1.4301 was used. Profile 15 x 3 mm was attached to both surfaces of the glass pane along the tension edge (Fig 1). Two-component epoxy adhesive Loctite Hysol 9466 was used for bonding the reinforcing profile.

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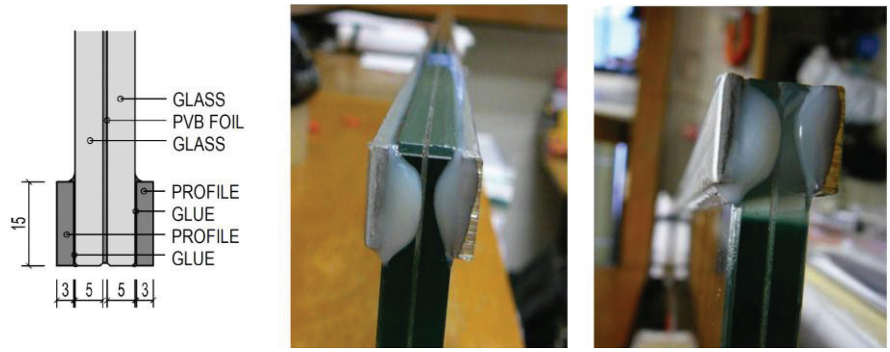

Fig. 1 Glued reinforcing profile (detail), scheme and the real performance

1.2. Loading process

All specimens of glass beams were tested in 4 - point bending test in a stationary hydraulic testing machine with a maximum loading force of 100 kN. The increase of the loading force in time was approximately linear, so the loading speed was approximately constant. The loading process was divided into several loading cycles (increasing load - constant load - decreasing load) before the total collapse of the glass beam occured (Fig. 2).

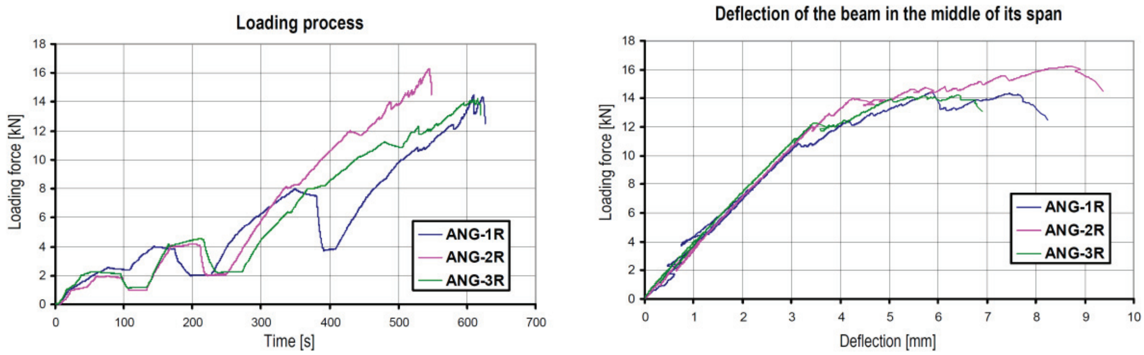

Fig. 2 Loading diagram of the reinforced glass beams (left) and diagrams of $P – w$ relationship of the reinforced glass beams (right)

1.3. Deformation behavior and load-bearing resistance

Comparison of the experimental results of vertical deflection in the middle of span for selected specimens is shown in Fig. 2. It is obvious, that the relationship between the loading force and the vertical deflection is up to a certain level of loading almost perfect linear (initial straight function of the P - w relationship diagrams).

Non-linear increasing of the vertical deflection starts after the tensile cracks in the glass part of beam is formed. Extension of the size and number of cracks results in a decrease of the bending stiffness and an increase of the vertical beam deflection (irregular redented function of the P - w relationship diagrams).

Initial cracks were formed on the tension edge of the beams. Cracks had a slightly branched shape and were oriented perpendicular to the edge of the beam (Fig. 3 - left picture). They formed in both layers of laminated glass almost simultaneously, in most cases in the area of the maximum bending moment. Initial crack length was limited to a maximum 3/5 of the total height of the beam's cross-section. Under an increasing load, new cracks were formed and the existing initial cracks grew. Total collapse of the beam was caused in most of the specimens by a collapse of the compression edge, which was corrupted with a large number of cracks (Fig. 3 - right picture).

Fig. 3 Initial cracks on the tension edge of the reinforced glass beam, the irregular cracks pattern immediately before the final collapse of the reinforced glass beam

Experimental results proved that total bending resistance of the reinforced beams was from 2,5 to 4 times higher comparing to the resistance of the unreinforced beams made of annealed glass and the typical brittle breaking behavior of the glass elements has transformed to a ductile (plastic) behavior, which showed a gradual decline in bending stiffness of the beam. Decrease in bending stiffness of reinforced beam is caused by two crucial factors - the formation and progress of tensile cracks in the glass and plastic deformation of the reinforcement in the crack.

2. Theoretical analysis

2.1. FEM models

In the FEM calculations the total number of 16 models was analysed using the software Dlubal RFEM 4. This paper deals only with the models in which the 2D elements for glass and also for reinforcement were used. The behavior of beam was analysed both in terms of the extent of damage of the beam (without crack, one crack, a number of cracks) and in terms of the working diagram of the reinforcement material (linear and non-linear relatioship of σ - ε). The boundary conditions, geometry of the beam and regular square FEM mesh of 5 x 5 mm were identical for all of the FEM models (Fig. 4, left picture). The basic mechanical properties of the used materials are given in Tab. 1.

Table 1 Material constants (linear material model)

Material constant	Symbol	Unit	ANG	PVB foil	Stainless steel
Young modulus	E	MPa	70 000	3,00	200 000
Shear modulus of elasticity	G	MPa	28 000	1,00	76 900
Poisson's ratio	ν	-	0,23	0,49	0,30

Non-linear material model of stainless steel EN 1.4301 used a simplified working diagram according to EC 1993-1-4: 2006 (E). The original continuous dependence of σ - ε was replaced in the FEM calculation by a polygonal (Fig. 4, right picture). The first linear partition, i.e. the yield strength f_y = 210 MPa corresponds to the Young modulus E_s = 200 GPa. Layered nature of the laminated glass (5 mm glass + 0,76 mm PVB foil + glass 5 mm) was neglected in the FEM models, laminated glass was replaced by one layer (shell) element of thickness 10 mm and a pair of reinforcing profiles of dimensions 15 x 3 mm was replaced by one shell element of thickness 6 mm. Both glass and reinforcement lay together in one common plane.

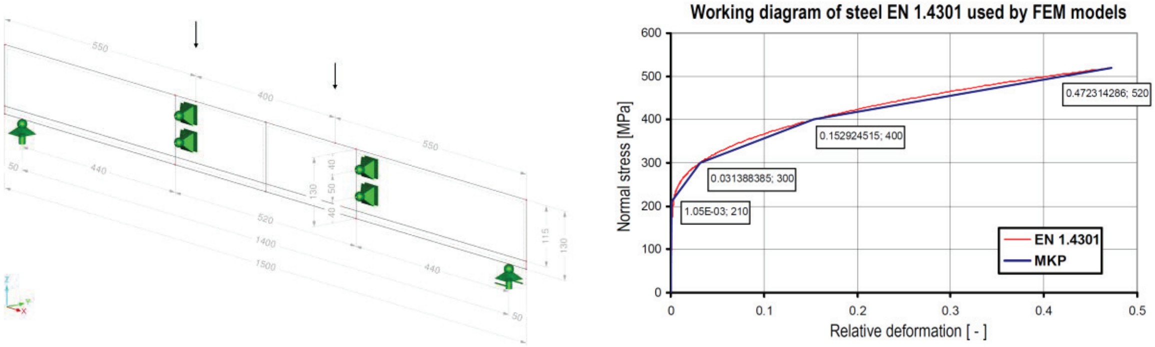

Fig. 4 Geometry and boundary conditions of the FEM model (left) and non-linear material model of stainless steel (σ – ε relatioship diagram, right)

In the case of cracked glass beams, the tensile crack/craks were defined as FEM elements of width 5 mm and the non-linear working diagram of glass. Exceeding the normal stress in tension over the 1 MPa caused a rupture of the material and these elements were no longer capable to carrying any tension forces. In case of compressive normal stress, there was defined an unlimited linear behavior of the material.

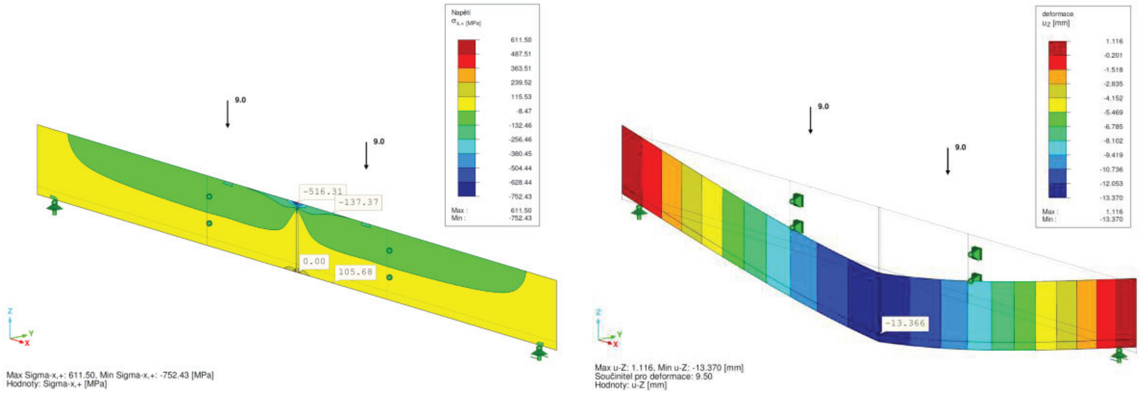

Fig. 5 Normal stress σ_x in the glass and vertical deflection U_z for loading force P = 18 kN one crack, non-linear material model of the reinforcement

2.2. Overview of the theoretical results

Evaluation of the FEM calculations has focused primarily on a comparison of the vertical deflection U_z, normal stress σ_x and the distance between compression edge and the neutral axis x. These results were evaluated for several levels of loading forces P in the typical cross-sections of a glass beam. Several of graphic outputs from software RFEM 4 are shown in Fig. 5 and Fig. 6 to illustrate the theoretical results for different FEM models.

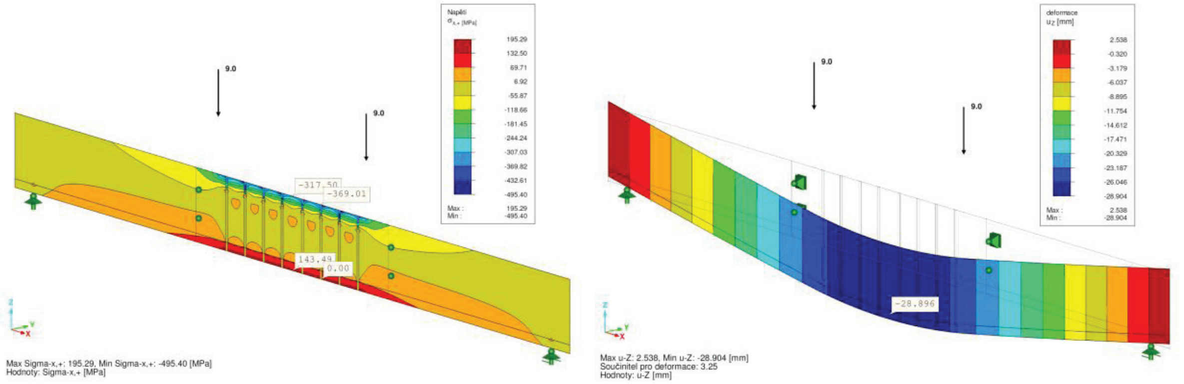

Fig. 6 Normal stress σ_x in the glass and vertical deflection U_z for loading force P = 18 kN eight crack, non-linear material model of the reinforcement

2.3. Results comparison

The results of FEM calculations proved - the number and extension of cracks do not affect the bending stiffness of the reinforced glass beam significantly in case of unlimited linear behavior of the reinforcement material (dashed traces show a slight variance, Fig. 7, left picture). On the other hand, the effect of the number and extension of cracks in the glass is strongly manifested for a non-linear material model of the reinforcement (continuous traces). Glass beam has a very small bending stiffness and the vertical deflection increases because of a plastic deformation of the reinforcement in the crack.

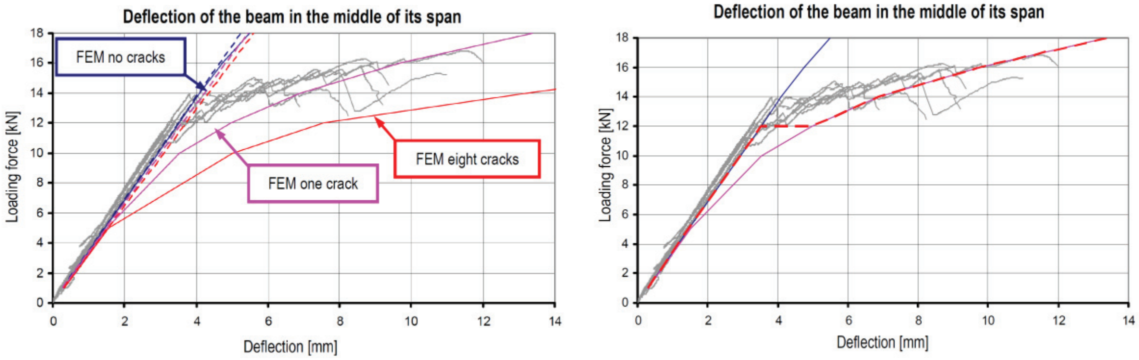

Fig. 7 Diagrams of P – w relationship of the reinforced glass beams, comparison of the theoretical and experimental results (left) and interconnection of the FEM results in the point of initial crack propagation (right)

The comparison of the theoretical (FEM analysis) and experimental results indicates a plastic deformation of the reinforcement during the experiment after the cracks were formed, otherwise the ductile (plastic) $P - w$ relationship of the real diagram (with almost horizontal secondary partition) is not possible (Fig. 2 and Fig. 7). In most cases the reinforcement works elastic before the initial crack formation, therefore the results of theoretical and experimental research on the reinforced glass beams without cracks are similar.

A complete theoretical relationship/function $P - w$ is a sort of combination of the results for glass beam without and with the tensile cracks and the point (moment) of initial crack propagation is crucial. Increase of the vertical deflection after crack propagation is caused by the two main factors - progressive crack extension of the glass and plastic deformation of the reinforcement. If the reinforcement works still elastic after occurance of cracks, the vertical deflection increases slightly. Vertical deflection starts to increase rapidly from the moment of the plastic deformation of the reinforcement and the horizontal "bonding trace" (increase of vertical deflection under constant loading force) between $P - w$ relationship diagrams of uncracked and cracked beam is significant (Fig. 7, left picture).

3. Conclusion

The issue of glass beams is a relatively novel field for load-bearing structures. Experimental research at the Department of Steel and Timber Structures has shown that the reliability of glass structures can be significantly improved by means of combinations with metallic materials. Reinforcing glass with a glued stainless steel profile increases its total resistance and supplies a very important residual resistance to the damaged glass structure (post-breakage load-bearing capacity). The application of the reinforcing profile by means of epoxy adhesives is technologically a very simple and relatively inexpensive process, which is not contradictionary to the appearance of a glass element. The unpredictable and dangerous brittle breaking behavior of the glass elements is modified towards the ductile (plastic) behavior. The significant damage of the glass and large deformations is noticeable before the final collapse of the reinforced glass element occurs. The application of the reinforcement in combination with fully tempered glass has no practical importance, because it immediately breaks into many small pieces; thus, there is no possible redistribution of the internal forces, which leads to a sudden failure of the beam without any post-breakage load-bearing capacity.

The theoretical analysis provided helps in understanding the operation of reinforced glass beams in a general way. The deviations between the results of the FEM calculations and the experimental data mainly occur because the mechanical material properties of the stainless steel were considered according to the theoretical EC values, and the real working diagram of the reinforcement was not experimentally tested. The results of the experimental testing of the reinforced glass beams showed that the real elastic working interval of the EN 1.4301 stainless steel used was probably higher than the theoretical nominal value of the yield strength $f_y = 210$ MPa, according to the EC.

The computational FEM models used are generally applicable in the design of reinforced glass beams despite the deviations listed above. Using the nominal material properties, the theoretical results (total bending resistance, vertical deflection, normal stress) represent safe values.

References

[1] Slivanský, M.: *Experimental and theoretical verification of the resistance of glass beams. Dissertation work SvF - 3237 - 3702*, Civil Engineering, SUT Bratislava 2010

[2] Louter, C.: *Adhesively bonded reinforced glass beams*, HERON Vol. 52, No. 1/2, 2007

[3] Ølgaard, A. B., Nielsen, J. H., Olesen, J. F., Stang, H.: *Properties of an Adhesive for Structural Glass Applications*, Challenging Glass, Conference on Architectural and Structural Applications of Glass, 2008