Reinforced glass beams - experimental and theoretical verification

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Summary

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.

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.

Testing specimens

Specimens of glass beams were of dimensions 1500 x 130mm and for their production laminated glass was used with a sheet thickness of 5mm and PVB foil with a thickness of 0,76mm. Therefore the theoretical thickness of laminated glass pane was 10,76mm. A reinforcing profile made of stainless steel profile of material quality EN 1.4301 was used. Profile 15 x 3mm 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.

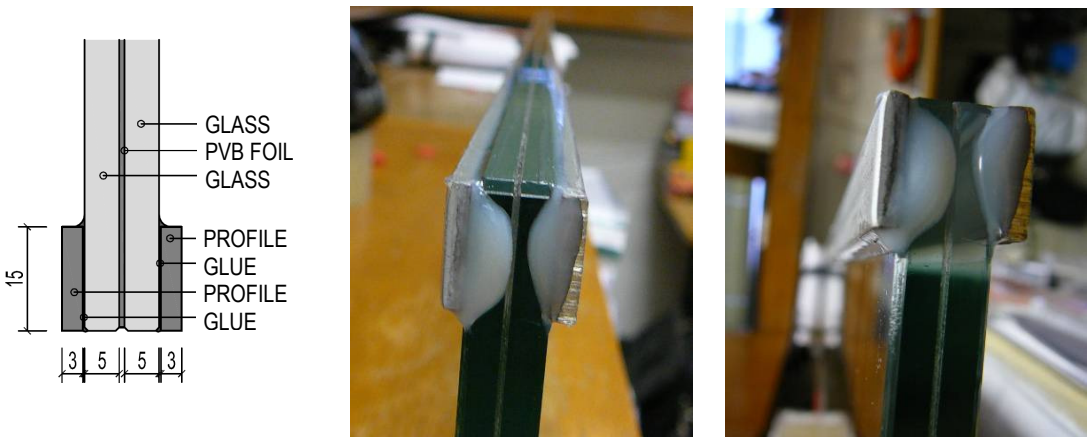

Fig. 1 : Glued reinforcing profile (detail), scheme and the real performance

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 100kN. 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).

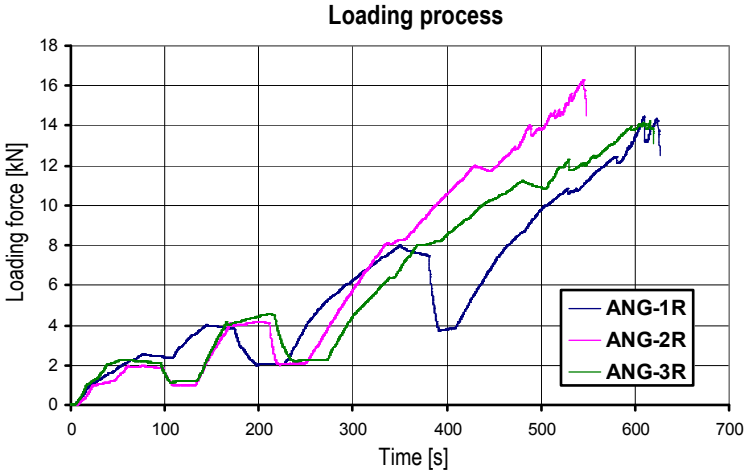

Fig. 2 : Loading diagram of the reinforced glass beams

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. 3. 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).

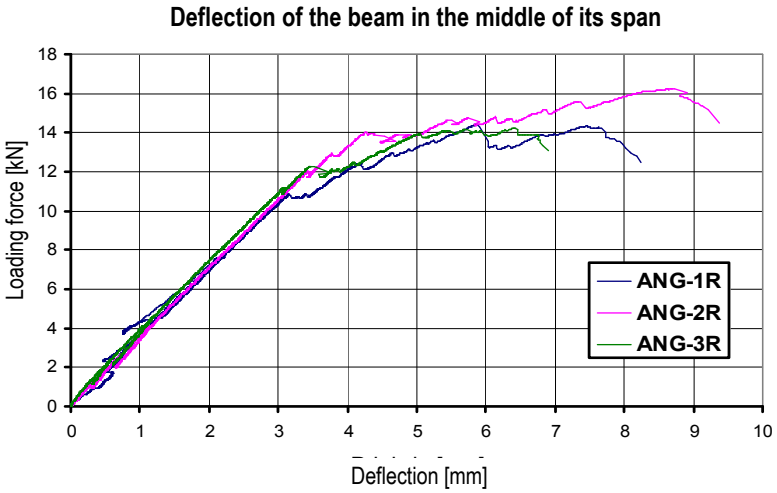

Fig. 3 : Diagrams of P – w relationship of the reinforced glass beams

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. 4 - 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. 4 - right picture).

Fig. 4 : 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.

The comparison of the experimental results and theoretical analysis (Finite Element Method = FEM) is given in a chapter below.

2. Theoretical analysis

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 5mm were identical for all of the FEM models (Fig. 6). The basic mechanical properties of the used materials are given in Tab. 1.

Tab. 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 constant	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. 5). The first linear partition, i.e. the yield strength f_y = 210MPa corresponds to the Young modulus E_s = 200GPa.

Layered nature of the laminated glass (5mm 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 10mm and a pair of reinforcing profiles of dimensions 15 x 3mm was replaced by one shell element of thickness 6mm. Both glass and reinforcement lay together in one common plane.

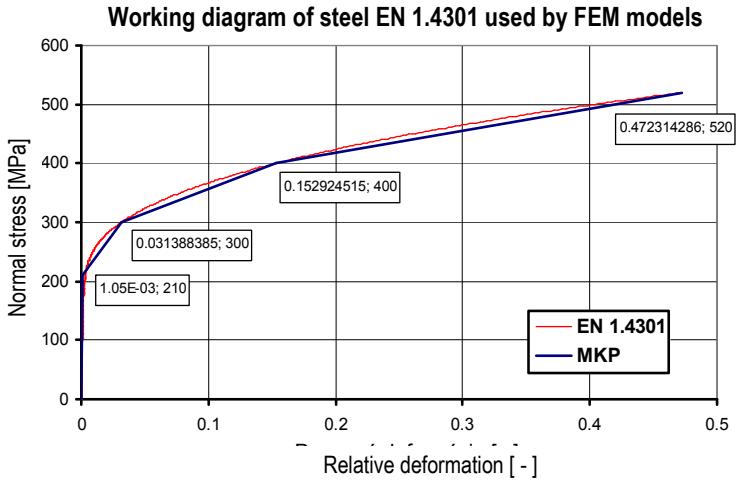

Fig. 5 : Non-linear material model of stainless steel (σ – ε relatioship diagram)

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

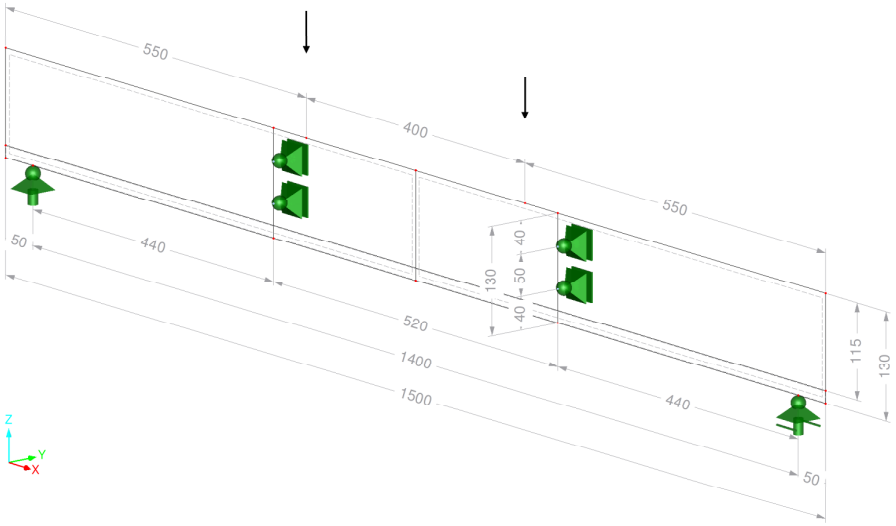

Fig. 6 : Geometry and boundary conditions of the FEM model

Overview of the theoretical results

Evaluation of the FEM calculations has focused primarily on a comparison of the vertical deflection U_z, normal stress $Sigma_x$ 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. 7 - Fig. 9 to illustrate the theoretical results for different FEM models.

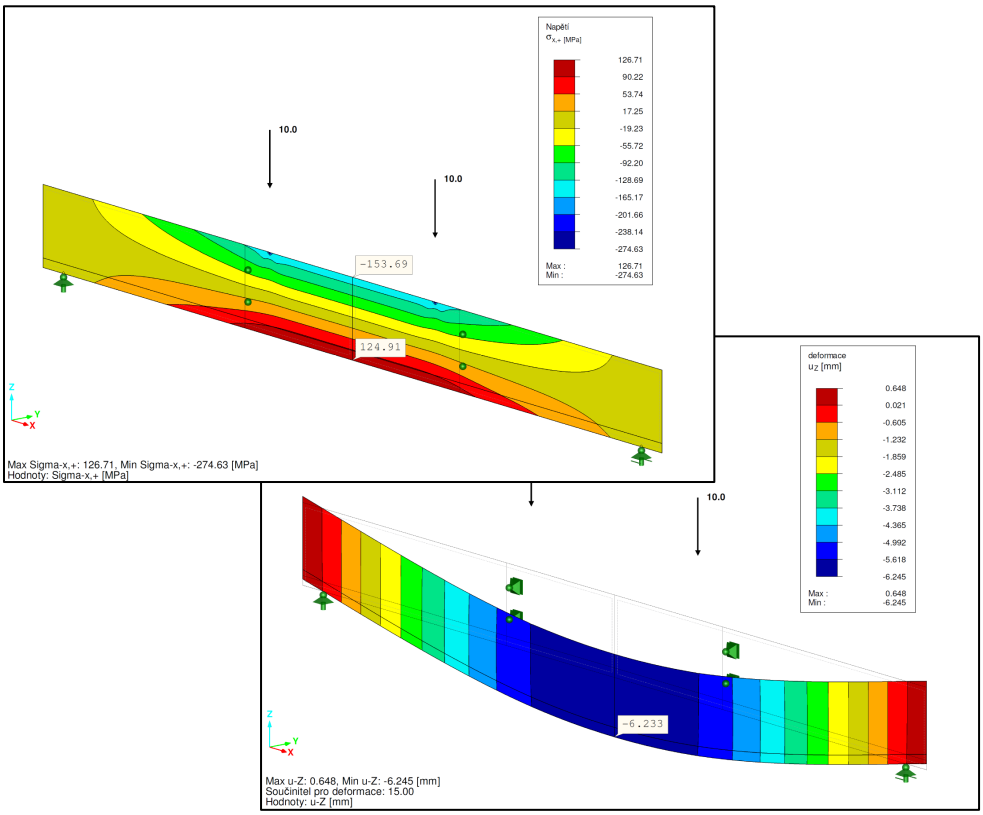

Fig. 7 : Normal stress Sigma$_x$ in the glass and vertical deflection U$_z$ for loading force P = 20kN, with no crack, non-linear material model of the reinforcement

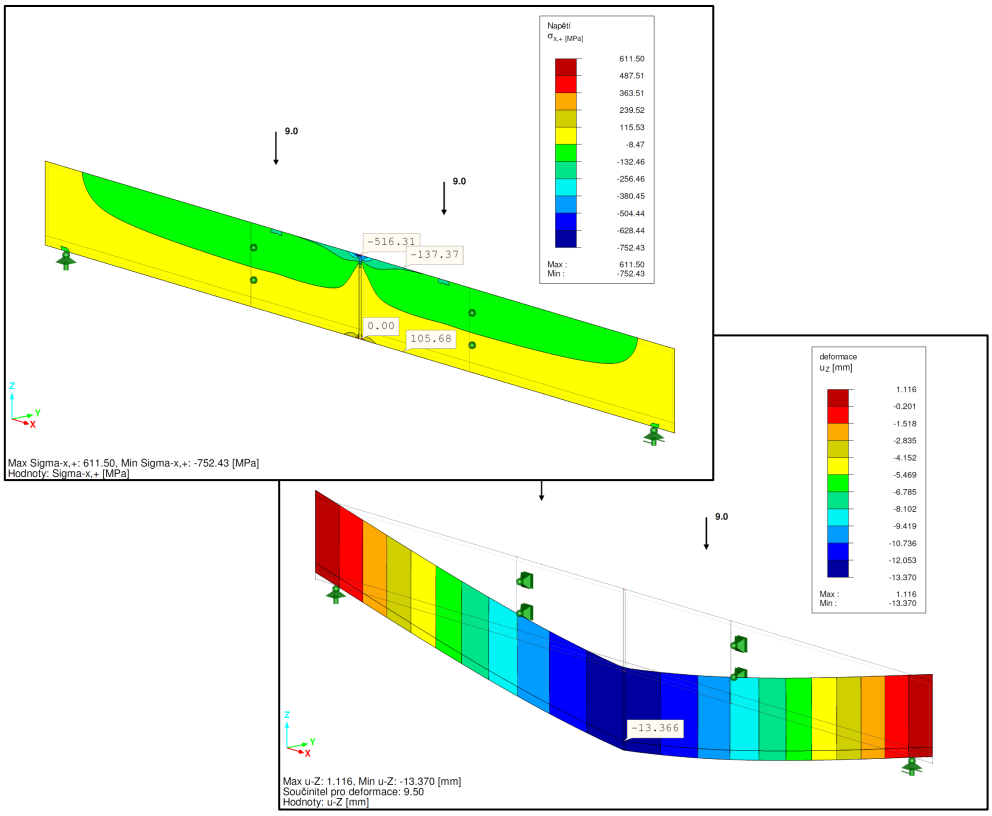

Fig. 8 : Normal stress Sigma$_x$ in the glass and vertical deflection U$_z$ for loading force P = 18kN, one crack, non-linear material model of the reinforcement

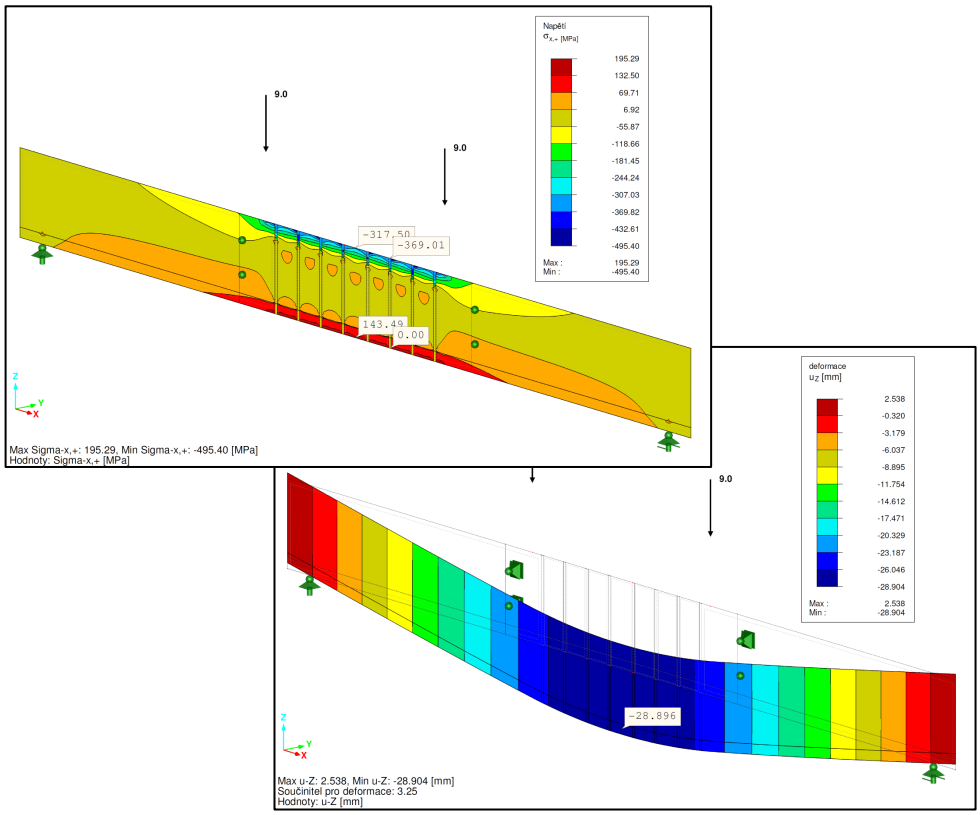

Fig. 9 : Normal stress Sigma$_x$ in the glass and vertical deflection U$_z$ for loading force P = 18kN, eight cracks, non-linear material model of the reinforcement

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. 10). 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.

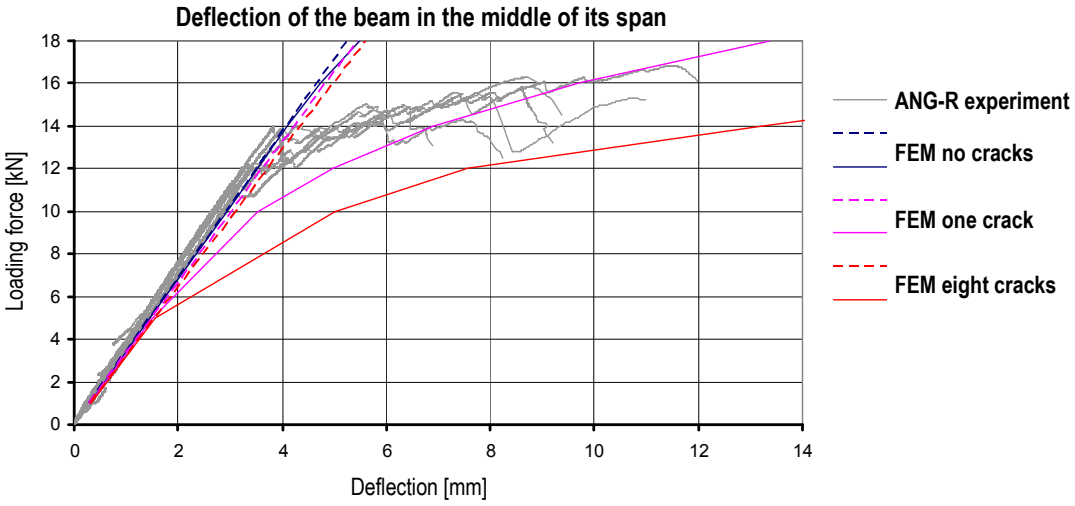

Fig. 10 : Diagrams of P – w relationship of the reinforced glass beams, comparison of the theoretical and experimental results

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. 3 and Fig. 10). 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 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. 11).

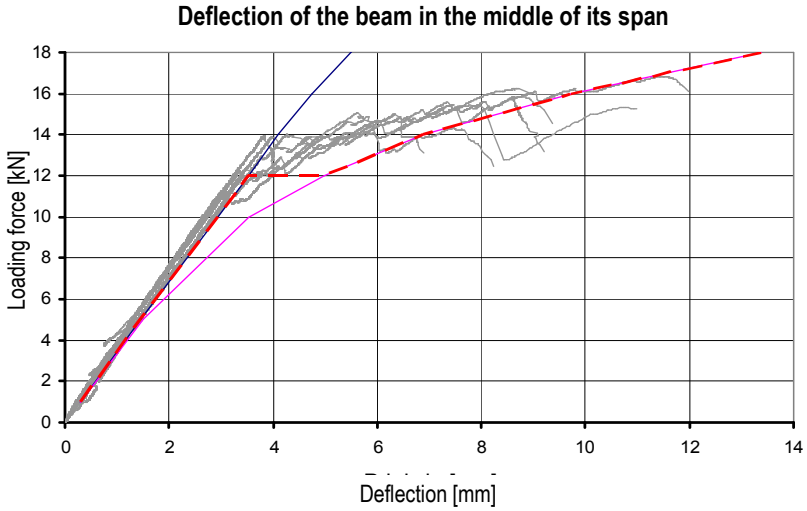

Fig. 11 : Diagrams of P – w relationship of the reinforced glass beams, interconnection of the FEM results in the point of initial crack propagation

3. Conclusion

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

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

References

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