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Structural Behaviour of Hybrid Steel-Glass Beams

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Steel-glass beams consisting of steel flanges and a glass web connected by bonding represent a new kind of transparent structural members. This paper deals with the particular structural behaviour of flexible composed hybrid beams regarding specific material characteristics of steel, glass and particularly adhesive, which is decisive for structural behaviour.

Keywords: Hybrid steel-glass beam, flexible composed beam, full scale bending tests

1. Introduction

Nowadays modern buildings are unimaginable without glass. Hybrid beams consisting of steel flanges and a glass web provide a fine balance between high load carrying capacity, easy connection feasibility and high transparency. These hybrid beams are new, innovative constructional elements, applicable as structural members such as girders, façade elements or even columns, see Figure 1. Due to the contribution of steel flanges hybrid beams have higher carrying capacity than pure glass fins.

Hybrid steel glass beams were investigated during the current European research project INNOGLAST [1]. This paper focuses on the specific structural behaviour of hybrid beams without instabilities. With the knowledge on stress distribution and deformation behaviour well utilized beams with an optimal structural interaction between steel and glass can be developed by choosing appropriate dimensions and materials.

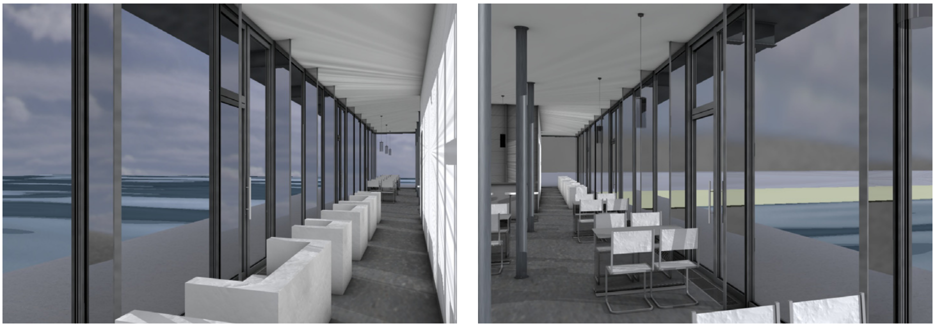


Figure 1 a and b: Application example of hybrid steel-glass beams [7].

2. Composition and structure

Hybrid beams presented in this paper are composed of a glass web and steel flanges to I-shaped profiles. These components are linked with a linear load bearing bonding, which provides constant stress propagation at the edge of the glass pane. The bonded joint can be shaped in different ways (see [6]). This paper presents beams with a simple joint bonding the face of the glass to the flanges as shown in Figure 2.

Other configurations of the linear bonded joint are possible and do not effect the principle structural behaviour. Therefore these considerations can be applied to other configurations considering the modified connection stiffness.

3. Structural behaviour

3.1. Preliminary considerations

The hybrid steel glass beam is composed with flexible joints. Carrying capacity of the pure glass can be enhanced significantly by adding flanges, with high normal forces at the flanges. Bending resistance of the steel flanges has only little influence on carrying capacity. Normal forces are inserted into the flange via the bonded joint. Therefore characteristics of the whole beam significantly depend on the connection stiffness.

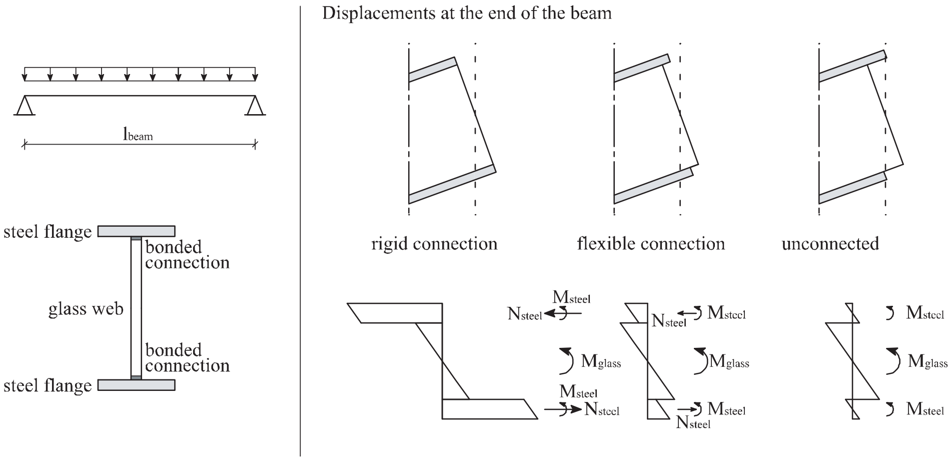


Figure 2: Behaviour depending on joint flexibility.

Figure 2 presents the distribution of internal forces and stresses and the deformation behaviour of beams with different connection stiffnesses. Normal forces at the flange have high contribution on load transmission when the section is connected rigidly. The unconnected section is loaded with bending moments only. The behaviour of the flexible connected beam is located between these two cases. The load carrying capacity generally increases with the increase of the connection stiffness, because of the higher normal forces in the flanges.

The external moment on the hybrid beam is distributed into internal moments of the glass web and the steel flanges and normal forces on flanges, see equation (1). As a specific characteristic of flexible connected beams, the distribution of normal forces does not correspond to the external moment as presented in Table 1.

The analytical solution for flexible composed beams with different load types and positions was developed by Pischl [5] for timber structures. These results were adjusted to a beam composed of different materials [4], resulting in the following equation (2) for a simple beam with uniform load, see Figure 3. Knowing the normal forces of the steel flanges N_{steel} the distribution of internal moments can be calculated regarding different bending stiffnesses of flanges and web according to (3) and (4).

Table 1: Distribution of internal forces of simple beams with flexible composed sections

Load	Sinusoidal	Uniform	Concentrated
External moment M_E	Sinusoidal	Parabolic	Linear
Normal force (flange)	Sinusoidal	Hyperbolic	Hyperbolic
Internal moments	Sinusoidal	Hyperbolic	Hyperbolic

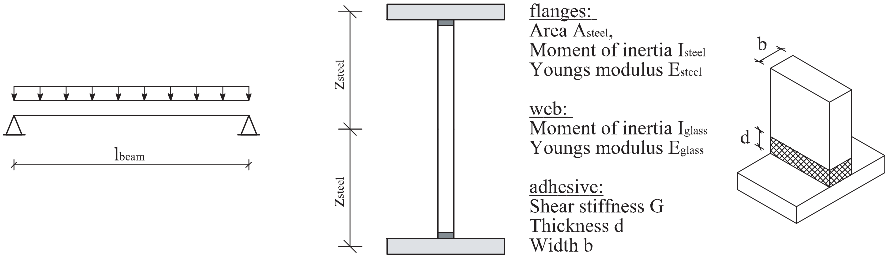


Figure 3: flexible connected simple beam with unifom load.

$$M_E = 2 \cdot M_{steel} + M_{glass} + 2 \cdot N_1 \cdot z_{s1} \tag{1}$$

$$N_{steel} = \frac{\alpha}{\gamma^2} \frac{q}{2} \left(lx - x^2 \right) \cdot \left[1 - 2 \frac{\sinh\left(\frac{\gamma l}{2}\right) - \cosh\left(\frac{\gamma l}{2} - \gamma x\right)}{\gamma^2 (lx - x^2) \cdot \cosh\left(\frac{\gamma l}{2}\right)} \right] \tag{2}$$

with $\alpha = \frac{K}{E_{steel}} \cdot \frac{z_{steel}}{2 \cdot I_{steel} + n \cdot I_{glass}}$; $\gamma^2 = \frac{1}{A_{steel}} + \frac{2 \cdot z_{steel}^2}{2 \cdot I_{steel} + n \cdot I_{glass}}$;

$n = \frac{E_{glass}}{E_{steel}}$; $K = \frac{G}{d} \cdot b$ (effective connection stiffness)

$$M_{glass} = \left(M_E - 2 \cdot N_{steel} \cdot z_s \right) \cdot \frac{n \cdot I_{glass}}{2 \cdot I_{steel} + n \cdot I_{glass}} \tag{3}$$

$$M_{steel} = \left(M_E - 2 \cdot N_{steel} \cdot z_s \right) \cdot \frac{2 \cdot I_{steel}}{2 \cdot I_{steel} + n \cdot I_{glass}} \tag{4}$$

Another easy to handle method is based on the work of Karl Möhler [2] and is known as γ-method for the design of timber structures [3]. This method considers the flexibility of the joint with an effective moment of inertia with reduced contribution of the flanges. Applying this method to a hybrid steel-glass beam yield to equation (5), see [4]. The γ-method is the exact solution for a simple beam with sinusoidal load. The sinusoidal load causes a sinusoidal distribution of normal forces along the length of the beam. According to (1) internal sinusoidal moments result und therefore a sinusoidal deflection curve, which corresponds to the external moment. Due to the congruence of the distribution of external moment, internal moments and deflection curve the structural behaviour of the whole beam can be described with the effective moment of inertia (5).

$$I_{y,eff} = I_{y,steel} + n \cdot I_{y,glass} + A_{steel} \cdot z_{s,steel}^{2} \cdot \gamma \text{ with } \gamma = \frac{1}{1 + \dfrac{\pi^{2}\, E_{steel}\, A_{steel}}{l_{beam}\, K}} \qquad (5)$$

Other systems for example the simple beam with uniform load does not behave identical. Equation (2) shows that the normal forces have an hyperbolic distribution. Thus internal moments are hyperbolic too, resulting in a hyperbolic deflection curve, which does not correspond to the external moment. Therefore the γ-method is not exact for a simple beam with uniform load. Though comparative analysis revealed that the γ-method is an adequate method for pre-design of flexible composed beams.

To pre-design an optimised beam, parametric studies were carried out with the γ-method. Figure 4a presents the influence of the adhesive shear modulus for beams with dimensions presented in 4.1. In general high carrying capacity is reached with stiff adhesives, because the contribution of flanges increases. When flanges reach the yield strength an increase of the connection stiffness does not have significant influence on carrying capacity. The length of the beam also influences the structural behaviour, see Figure 4 b. A large span leads to a higher efficiency. Flanges of beams with low and medium connection stiffness do not reach the yield strength, because glass web fails. Therefore flanges should be small, to design a beam with full utilisation of the cross section.

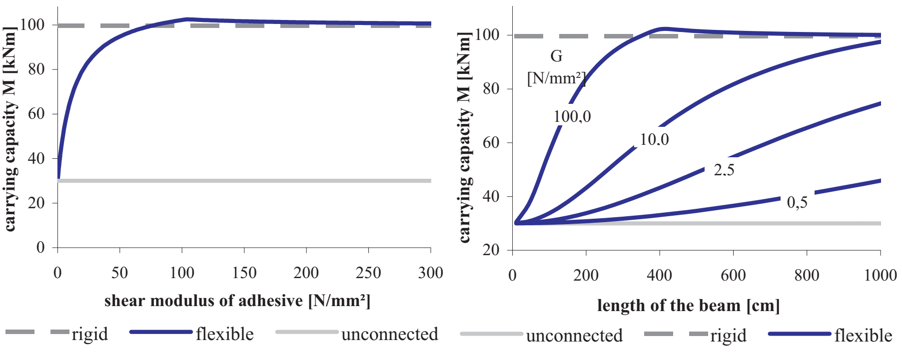


Figure 4 a and b: influence of beam length and adhesive stiffness on carrying capacity.

3.2. Choice of adhesives

Multiple types of adhesives are available for bonded connections for structural applications. Within the research project INNOGLAST numerous small scale tests were carried out at the Institute for Steel Structures at RWTH Aachen to find appropriate adhesives for hybrid beams. Results are presented in the article "*Analysis of bonded hybrid steel-glass-beams by small scale tests"* [6]. The collection of adhesives of RWTH Aachen considered mechanical and durability properties as well as manufacturing issues.

For the production of large scale test specimen presented in this paper three adhesives were chosen, which fitted best structural and manufacturing requirements:

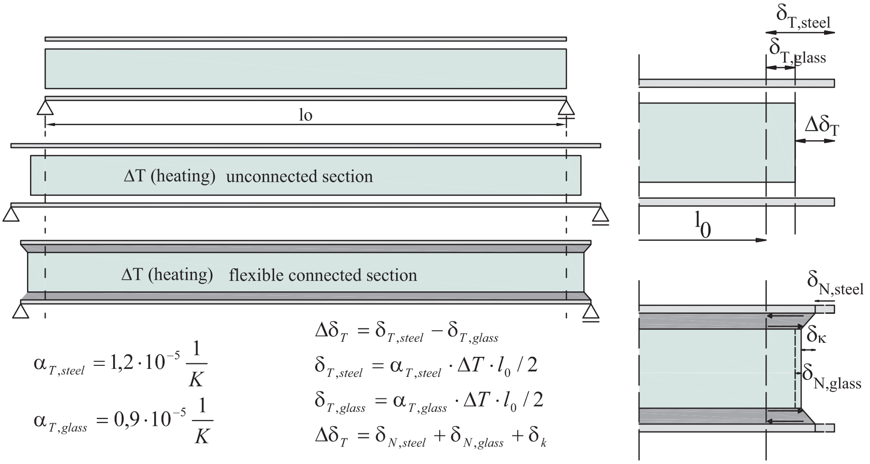
- K07: a two component silicone generally used for structural glazing applications
- K05: a two component polyurethane with higher stiffness than silicone and good ageing behaviour
- K01: a stiff and high strength two-component epoxy resin

Properties of the selected adhesives are presented in Table 2. These adhesives cover a wide range of mechanical properties.

Table 2: Properties of adhesives for large scale tests (average values)

Adhesive	K01	K05	K07
Young´s modulus [N/mm²]	1283	9	1,8
Shear modulus [N/mm²]	> 100	~ 3	0,5 - 0,7

3.3. Risk of temperature failure



$$\alpha_{T,steel} = 1{,}2 \cdot 10^{-5}\,\frac{1}{K}$$

$$\alpha_{T,glass} = 0{,}9 \cdot 10^{-5}\,\frac{1}{K}$$

$$\Delta\delta_T = \delta_{T,steel} - \delta_{T,glass}$$

$$\delta_{T,steel} = \alpha_{T,steel} \cdot \Delta T \cdot l_0 / 2$$

$$\delta_{T,glass} = \alpha_{T,glass} \cdot \Delta T \cdot l_0 / 2$$

$$\Delta\delta_T = \delta_{N,steel} + \delta_{N,glass} + \delta_k$$

Figure 5: displacement of hybrid steel glass beam at heating

Analytical investigations presented in 3.1 had the result, that the application of stiff adhesives is suggested to reach high load carrying capacity. Thus, it was investigated if temperature influence will lead to failure of the beam due to different thermal expansion coefficients of steel and glass. Figure 5 presents the mutual interaction of steel and glass. Rigid connection between steel and glass leads to maximum stresses. The corresponding internal forces at the glass web can be calculated by equation (6). These analytical considerations were confirmed by finite element calculations with the result that even at high connection stiffness no failure of steel flange, glass web or bonded connection could be predicted. Thus, also adhesives with high stiffness were chosen for further investigations.

$$N_{glass} = \frac{\Delta\delta_T}{\frac{1}{2}\frac{l_0}{E_{glass}A_{glass}} + \frac{1}{4}\frac{l_0}{E_{steel}A_{steel}}} \tag{6}$$

4. Bending tests

4.1. Test set-up and test specimen

During the research project INNOGLAST [1] large scale tests were carried out to investigate the structural behaviour of hybrid steel-glass beams. The test series presented in this paper was carried out with test specimen with identical dimensions but connected with different adhesives (see 3.2). Therefore bending tests are suitable for the evaluation of the influence of different shear stiffnesses of the connection. Test results can be compared directly due to identical dimensions.

The test set up was a 4-point-bending test according to Figure 6. Tests should reveal structural behaviour of beam without instabilities, due to lateral torsional buckling. Therefore fork bearings were provided at the end of the beam. Due to the high slenderness of the test beams an additional lateral support was provided at midspan.

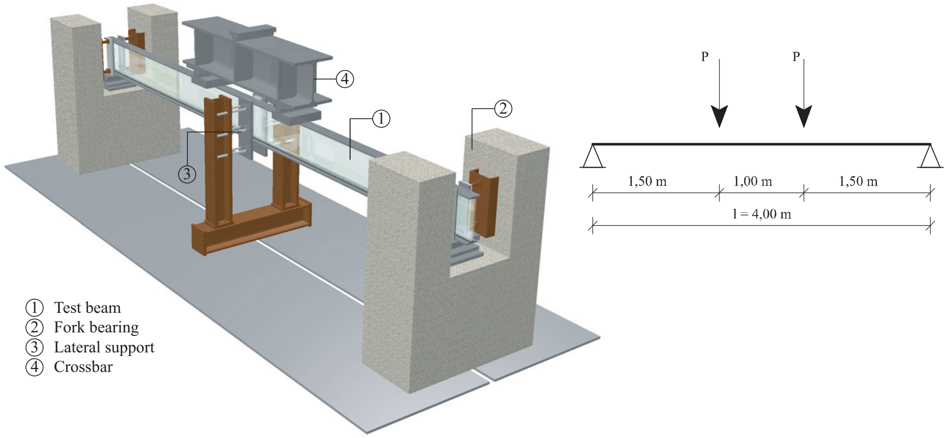


Figure 6: test set-up

Configuration of test series is presented in Table 3. Glass webs were made of laminated toughened glass made of two panes to provide the possibility of measure strains at both panes. All flanges were made of steel S 235, except test specimen TS 3. Due to the high shear stiffness of the epoxy resin, it was expected that the yield strength of flanges would be reached during the tests. To enhance the expected load carrying capacity of this test specimen steel S 355 with higher yield strength was used.

Table 3: Test matrix of full scale tests.

Test specimen	Adhesive	Web	Flanges	Failure Load
Pure glass fin		Laminated safety glass 2x 12 x 250 mm		40 kN (calculated)
TS 1	Polyurethane K05 3 mm	Laminated safety glass 2x 12 x 250 mm	80 x 10 mm S235	72,1 kN
TS 3	Epoxy resin K01 3 mm	Laminated safety glass 2x 12 x 250 mm	80 x 10 mm S355	126,55 kN
TS 4	Silicone K07 3 mm	Laminated safety glass 2x 12 x 250 mm	80 x 10 mm S235	52,80 kN

4.2. Test results and evaluation

Evaluations of test results were carried out using analytical methods. Adjusting the method of Pischl [5] to a beam composed of different materials and a structural system presented in Figure 7 equations (7) and (8) resulted. Distribution of internal moments can be calculated according to (3) and (4). This method was used for the evaluation of test results assumed a linear behaviour of adhesive.

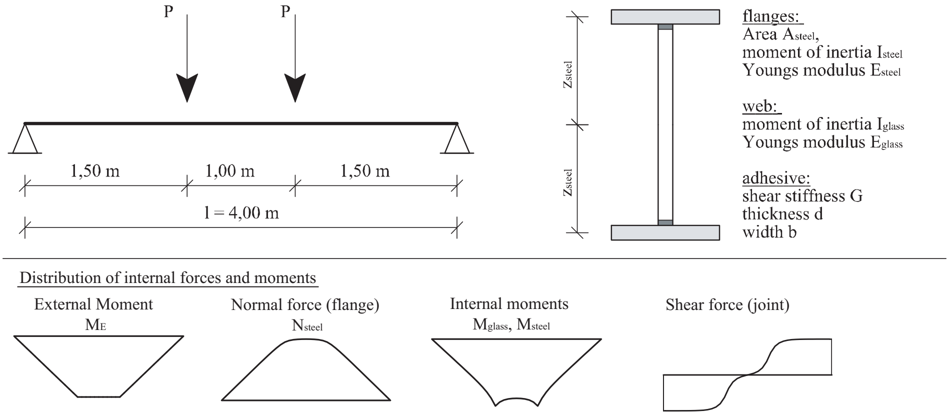


Figure 7: structural system and distribution of internal forces.

$$N_{steel} = \frac{\alpha}{\gamma^2} Pl \cdot \left[\frac{3}{8} - \frac{\sinh^2\left(\frac{3}{8}\gamma l\right) - \sinh\left(\frac{3}{8}\gamma l\right) \cdot \sinh\left(\frac{5}{8}\gamma l\right)}{\gamma l \cdot \sinh(\gamma l)} \right] \quad \text{(load introduction) (7)}$$

$$N_{steel} = \frac{\alpha}{\gamma^2} Pl \cdot \left[\frac{3}{16} - \frac{\sinh\left(\frac{3}{8}\gamma l\right) \cdot \sinh\left(\frac{1}{2}\gamma l\right)}{\gamma l \cdot \sinh(\gamma l)} \right] \text{ (at midspan)} \tag{8}$$

Due to different connection stiffnesses carrying capacity of the three test specimen was significantly different (see Table 3). Calculated load capacity of the glass fin without flanges was 40 kN assuming a glass strength of 120 N/mm². In comparison test specimen TS 4 reached an increased carrying capacity of 132% (52,7 kN). Stress distribution of the section at midspan showed, that flanges had only little contribution on the load carrying capacity, due to low stiffness of silicone, see Figure 8. There is still an increase of 32% because glass strength was higher than expected. TS 1 was made with polyurethane, which offers a higher stiffness than silicone. This resulted in better carrying capacity due to higher contribution of flanges, see Figure 9. Therefore a carrying capacity of 180% compared to a glass fin was reached. Glass strength was higher than expected as well. Maximum carrying capacity was reached by TS 3 with a joint made of epoxy resin, which had high stiffness. The stiff connection resulted in high contribution of flanges, so flanges were well utilised and nearly reached the yield strength, see Figure 13. Therefore the carrying capacity of the glass fin was enhanced to 126,55 kN (316%).

Hybrid test beams were designed so that the carrying capacity of the beam was defined by the bending carrying capacity of the glass web. Regarding the distribution of moments inside the glass web (Figure 7) crack initiation was expected at the lower, tensioned edge of the glass pane at load introduction points. Fracture pattern of test specimen TS 1 and TS 4 revealed initial cracks near the expected position. Position of crack initialisation of test beam TS 3 was not identified definitely. There was adhesive fracture near the bearing but it could not be checked if this was the cause of damage or a collateral damage. Glass stress at load introduction points did not reach the assumed glass strength (see Figure 13). Therefore further investigation is necessary to check if failure was caused by adhesive fracture or possibly by stress peak due to high adhesive stiffness.

Figure 14 presents the load carrying capacity of the test specimen compared to the analytical solution. There was a good accordance of test results and analytical solutions. For further investigations it is suggested to test promising adhesives with medium stiffness (marked grey).

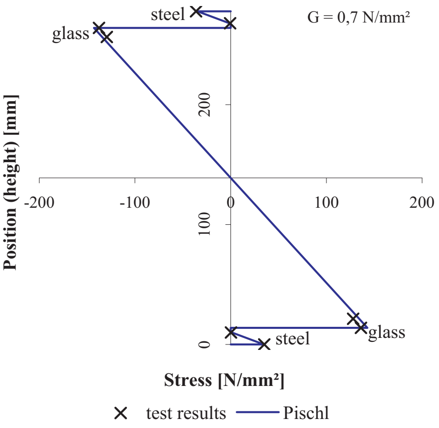


Figure 8: Stress at midspan, TS 4

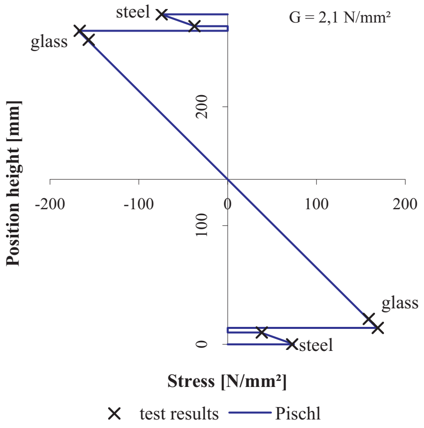


Figure 9: Stress at midspan, TS 1

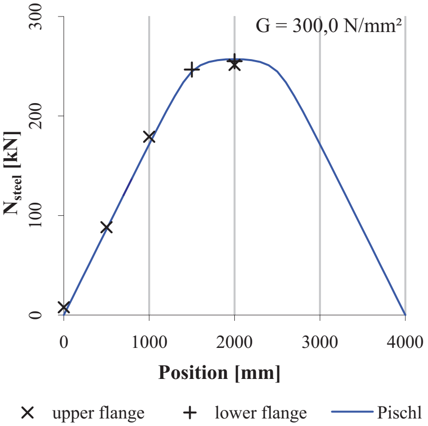


Figure 10: Normal force at flange, TS 3

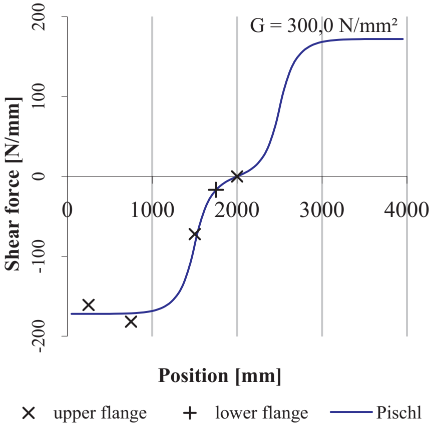


Figure 11: Shear force at bonded joint, TS 3

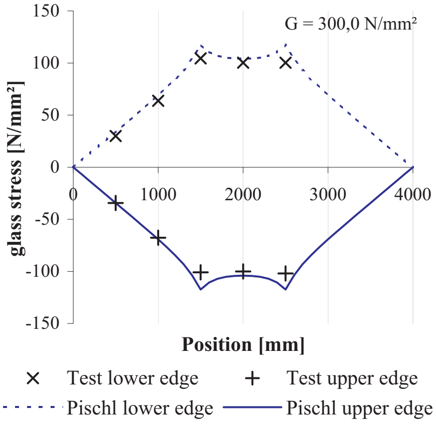


Figure 12: Glass stress, TS 3

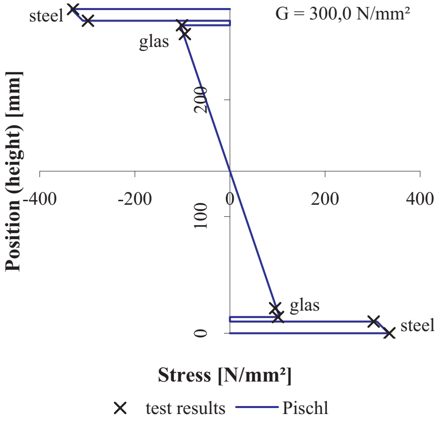


Figure 13: Stress at midspan, TS 3

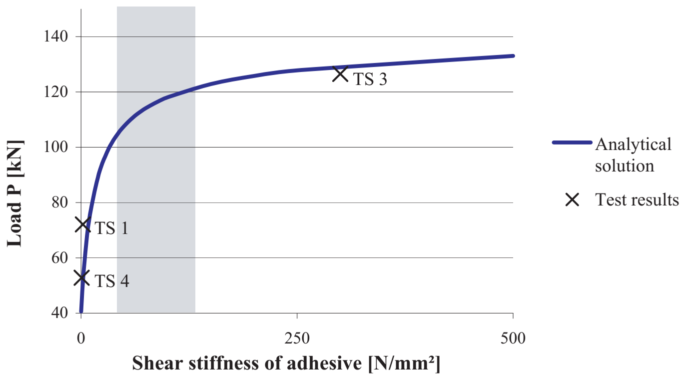


Figure 14: Load carrying capacity of bending tests

5. Conclusion and prospects

Aim of the presented project INNOGLAST [1] is to develop applicable hybrid steel-glass beams and to provide design rules for dimensioning. Characteristics of bonded connections were investigated in detail at RWTH Aachen (see [6]). Within ongoing investigations at TU Dortmund structural behaviour of hybrid beams without instabilities is investigated:

The carrying capacity of glass fins can be enhanced significantly by adding steel flanges with a linear bonding. Economic hybrid beams with good utilisation of all section members are reached with small ratio of steel area to glass area. In addition carrying capacity of glass panes limits the carrying capacity of the whole beam. Thus, glass with high carrying capacity is suggested. Structural behaviour of hybrid steel-glass beams significantly depends on the stiffness of the connection. Best carrying capacities are reached with high stiffness. Further investigations will follow to check if adhesives with high stiffness are suitable or will lead to an early failure of the glass due to stress peaks.

Presented analytical methods provide accurate results, even for non linear adhesives. Therefore analytical methods can be used for the design of economic beams with high utilisation of all components.

Further investigations on hybrid steel glass beams will be carried out by all research partners of the ongoing project INNOGLAST with focus on

- robustness,
- stability (lateral torsional buckling) and
- design

for a fully developed steel-glass beam.

6. Acknowledgment

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- Institute of Steel Construction, Technische Universität Dortmund, Germany
- The Steel Construction Institute, United Kingdom
- Faculty of Civil Engineering, Czech Technical University in Prague, CzechRepublic
- Centre Scientifique et Technique du Bâtiment, France

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