Challenging Glass 2 – Conference on Architectural and Structural Applications of Glass,
Bos, Louter, Veer (Eds.), TU Delft, May 2010.

Analysis of bonded hybrid steel-glass-beams by small scale tests

Markus Feldmann, Björn Abeln, Mascha Baitinger
RWTH Aachen University, Institute for Steel Structures, Germany,
abeln@stb.rwth-aachen.de, www.stb.rwth-aachen.de

To realize architectural attractive transparent and lightweight constructions bonded hybrid steel-glass beams have been developed, where flanges of steel and webs of glass are assembled to I-shaped profiles using adhesives. The load-bearing capacity of such beams is governed – apart from the mechanical and strength characteristics of the adherent - by ageing, temperature and creeping. By means of small scale push-out-tests the properties of different adhesive geometries, the influence of the manufacturing process and the general load carrying behaviour of bonded hybrid steel-glass-beams are shown.

Keywords: Hybrid steel-glass-beams, structural glazing, adhesive technology, small-scale-tests, structural behaviour

1. Introduction

Glass in construction plays an increasing role not only as façade cladding or windows but also as load bearing, structural element. Glass beams, glass columns or bracing façade elements are such examples, see Figure 1. To realize those architectural attractive transparent structures, bonded hybrid structures are favourable where each material according to its material properties is used in an optimised way. Hereby adhesives play a real load-bearing role.

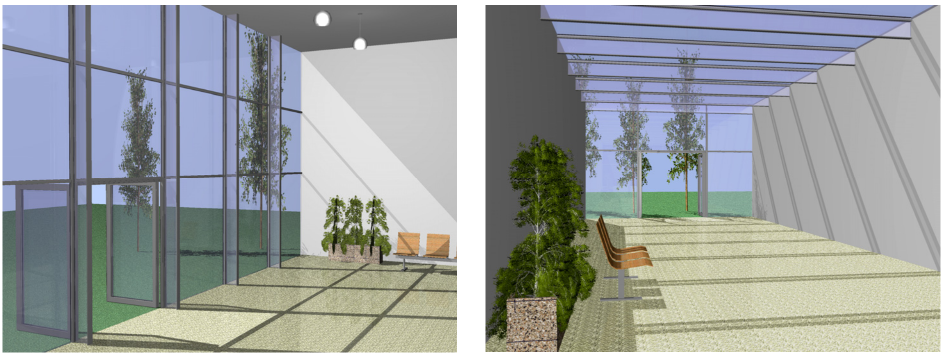


Figure 1a and b: Transparent façades and roofs using hybrid steel-glass-beams [2]

Within the scope of the European research project INNOGLAST [1] hybrid façade elements and floor girders were developed, where flanges of steel and webs of glass are assembled to I-beams using adhesive connections. This allows for a smooth load introduction into the glass panes. The shear force is carried by the glass web, whereas the bending capacity of the hybrid beam is significantly increased by slender steel flanges compared to the pure glass pane. The shear forces between steel and glass are only sustained by the adhesive between them. To maximize the exploitation of steel and glass the adhesive therefore, on the one hand has to ensure an adequate stiffness but on the other hand must be soft enough allowing for a reduction resp. redistribution of stress peaks or other constraints. However the load-bearing capacity of such beams is governed – apart from the mechanical and strength characteristics of the adherent - by ageing, temperature and creeping.

This paper introduces the advantages and disadvantages of different adhesive geometries and the influence of the manufacturing process. Adhesives with various properties are presented and the determination of the mechanical characteristic values is illustrated. By means of extensive small scale push-out-tests and accompanying FE-calculations on shear and tension specimens the general load carrying behaviour of bonded hybrid steel-glass-beams is shown.

2. General approach

The design of the adhesive joint is of vital importance for the bearing capacity of the hybrid beam. This includes the geometry of the joint as well as the detailed knowledge of the mechanical values and the durability of the adhesives. Particularly discontinuities in the boundary areas require a closer examination.

Aim of the project is to derive simple design rules for hybrid steel-glass beams, taking into consideration the common safety specification of glass thus avoiding extensive finite element calculations. An overview of detailing and testing within the project [1] can be taken from Table 1.

In the following approaches for the choice of appropriate adhesive systems are presented with respect to durability and realistic bonding geometries.

3. Bonding geometry

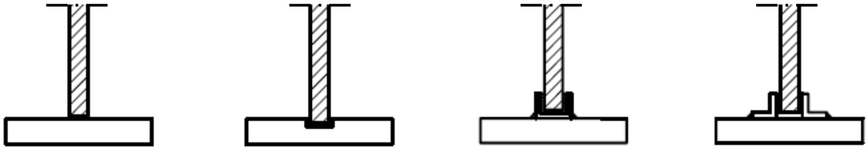
The cross-section of the hybrid beam consists of flat glass web and steel flanges (carbon steel, S235), the surfaces of which being sandblasted to cleanness Sa 2 ½ (see also [4] to this). For the small scale-test specimen the web consists of one-sheeted toughened safety glass. For the large-scale tests the web consists of laminated glass panes with PVB, made of two toughened glass sheets. Depending on the stresses, also annealed glass and heat-strengthened glass are to be investigated. To join the steel flange and glass web by adhesives all surfaces were degreased, protected with a primer, evaporated and immediately bonded.

Four different details of connection were chosen, see Figure 2:

a) **Butt splice bonding:**
   The easiest geometry with simple fabrication is butt-bonding the face of the glass-sheet directly to the steel flange. However, according to the color of the adhesive and the quality of the application visual disturbance can appear. The effective bonding surface is significantly smaller than that for the other variants.
b) **Chanel bonding in a groove:**
   Chanel bonding in a groove of the steel flanges is an attractive alternative because of the concealed adhesive surface. Furthermore it can be assembled in good quality with moderate effort. Further, the existing adhesive surface is slightly larger than in case of butt splice bonding.

Table 1: Overview of the systematic approach for the development of design rules

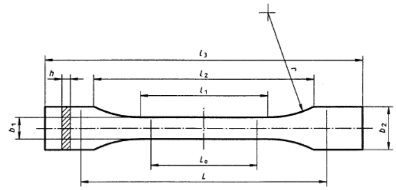
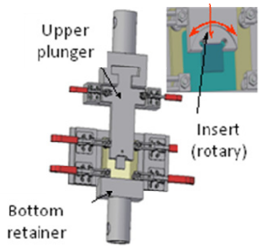
I. Design of the adhesive geometry



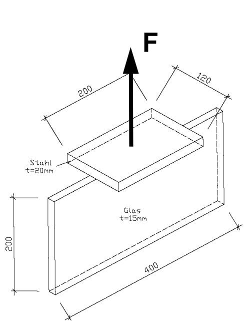
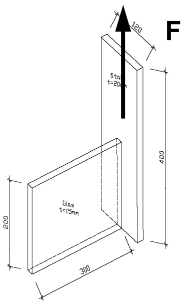
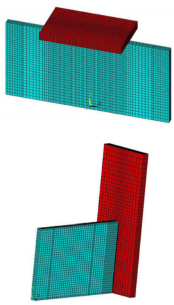
II. Derivation of basic requirements for the adhesive joint

III. Choice of adhesives

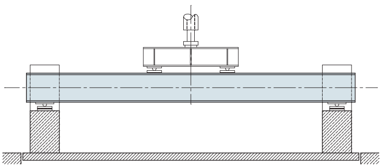
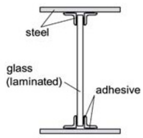
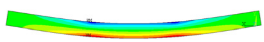
IV. Determination of mechanical values of the adhesives by means of standardized specimen

Tensile tests	Modified block shear test [3]
	

V. Determination of tensile and shear capacity by means of small scale specimen

Tensile tests	Tensile shear tests	FE-calculations
		

VI. Transfer to real structural elements

Bending tests	FE-calculations
 	

VII. Derivation of design rules

c) **Bonding with U-profiles:**
Adhesive bonding with U-profiles turns out to be less attractive depending on the choice of the U-profile. Whereas a large U-profile appears unfavourable, the use of a small profile can discreetly hide the adhesive area especially when using dark adhesives. The application process depends on the adhesive viscosity and ranges between complex, time-consuming and complicated. Also tolerance control is difficult due to fixed spacing of the channel flanges. Thus the controllability of the application quality is challenging or even impossible.

d) **Bonding with L-profiles:**
With regard to the application process bonding with L-profile means the same as bonding with U-profiles. Using L-profiles possibly increases the stiffness of the adhesive gap but appears less attractive. However compared to the U-shaped profile, tolerance control may be eased if L-profiles can variably be adapted.

Table 2 summarizes the different alternatives including the advantages and disadvantages.

Table 2: Advantages and disadvantages of the different joining details

	Adhesive surface	Producibility	Appearance	Controllability
Butt splice bonding	+	+ + +	+ +	+ + +
Chanel bonding in a groove	+ +	+ +	+ + +	+ +
Bonding with U-profiles	+ + +	+	+	+
Bonding with L-profiles	+ + +	+	+	+

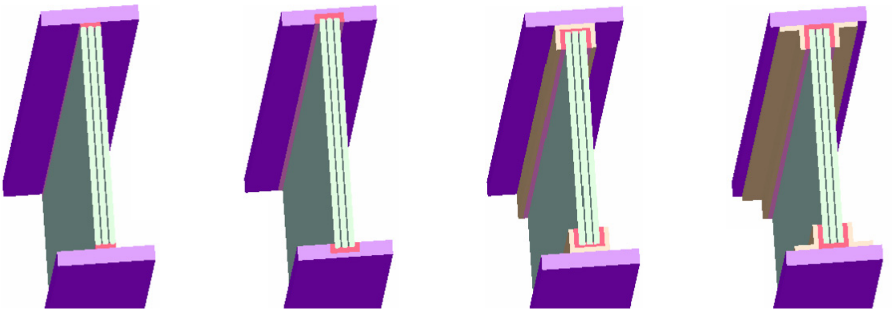


Figure 2: Four joining details of the bonded connection

4. Choice of adhesives

In addition to the required mechanical and durability properties the choice of adhesives is significantly governed by manufacturing issues, e.g. flow characteristics and curing mechanism, application behaviour, specific working conditions and tolerances. Furthermore the adhesive must meet the following structural demands:

- Transfer of longitudinal shear forces
- Reduction of stress peaks
- Compensation of temperature strains
- Compensation of manufacturing tolerances

Depending on the selected joining geometry, see Figure 2, the adhesives have to be chosen appropriate to avoid trapped air or bubbles while filling the gap. It has also to be ensured that environmental impacts as UV radiation or outdoor exposure do not cause a relevant loss of adhesion or reduction of strength and that the adhesive can cure completely, especially in case of one component or UV-curing adhesives. Furthermore the compatibility with PVB foil or screen print must be checked (particularly necessary for adhesives susceptible to ageing). Last but not least the thickness of each adhesive has to be specified such way that the longitudinal shear force is carried in an optimal way.

Against this background applicable structural adhesives were selected for which the structural behaviour and working properties as well as the adhesion and durability properties were examined. After close discussions with most of the adhesive producers, only associated adhesive-primer-systems indentified by the producers were used to avoid additional disturbing parameters (like applicability and compatibility of the primer or surface treatment). Beyond that the choice of adhesives was made with regard to potential inside and outside application, which means that adhesives should withstand weathering, UV-radiation, cleaning agents and temperature changes without a relevant change of their mechanical properties or even loss of their bearing capacity. Not all of those four joining geometries are well suited for each adhesive, thus the advantages and disadvantages, considering Table 2, must be checked for each application. Besides the required bonding length the ensurance of a high workmanship and optical criteria are of particular importance.

Having a wide range of possible adhesive systems applicable for hybrid steel-glass-beams seven cold-hardening, preferable two-component adhesives were selected, see Table 3: a high strength two-component epoxy resin with high temperature resistance (K01), four two-component polyurethanes of different strength classes (K02, K03, K05, K06), one UV-curing acrylate (K04) and as a reference a two-component silicone, which is generally used for structural glazing aspects in civil engineering (K07).

Table 3: Properties of the selected adhesives (tension and shear strength are 5% fractiles)

Adhesive	**K01**	**K02**	**K03**	**K04**	**K05**	**K06**	**K07**
Type	Epoxy resin	Poly-urethan	Poly-urethan	Acrylate	Poly-urethan	Poly-urethan	Silicone
Components	2	2	2	1	2	2	2
Pot life [Min.]	90	10	90	UV-curing	15	30	10
Tension strength [MPa]	27,3	9,6	8,0	9,4	4,2	6,3	0,9
Shear strength on glass [MPa]	18,6	12,9	2,7	15,1	6,7	3,7	1,4
Sliding at break [-]	0,2	0,4	0,03	1,6	3,6	2,4	2,5

The adhesives were selected in such a way, that very stiff systems with high elastic modulus and high strength as well as hyper-elastic systems with small stiffness and low strength were included into the research. Generally excluded were those adhesives, that show a short processing time or pot life, a minor temperature resistance, a very low viscosity or which curing mechanism seemed to be inappropriate for the existing application, e.g. hot setting systems or humidity cross-linking one-component systems.

5. Determination of the mechanical characteristic values of the selected adhesives

The following approach has been chosen to determine the mechanical values of the selected adhesives:

- Accelerated ageing of shear specimen using the immersion test
- Tension tests of dumbbell specimen and determination of the Young´s modulus, the tension strength and the Poisson´s ratio according to DIN EN 527
- Shear tests of unaged and aged modified block shear specimen (see Table 1), determination of the shear stress-sliding-behaviour according to DIN EN ISO 13445
- Determination of the temperature behaviour and the glass transition temperature by Dynamic Mechanical Analysis (DMA)

In Figure 3 the shear strengths derived from modified block shear tests are shown exemplarily for the unaged situation and after six weeks water bath storing (immersion test) with declaration of the failure criteria (CF: cohesive fracture, AF: adhesive fracture).

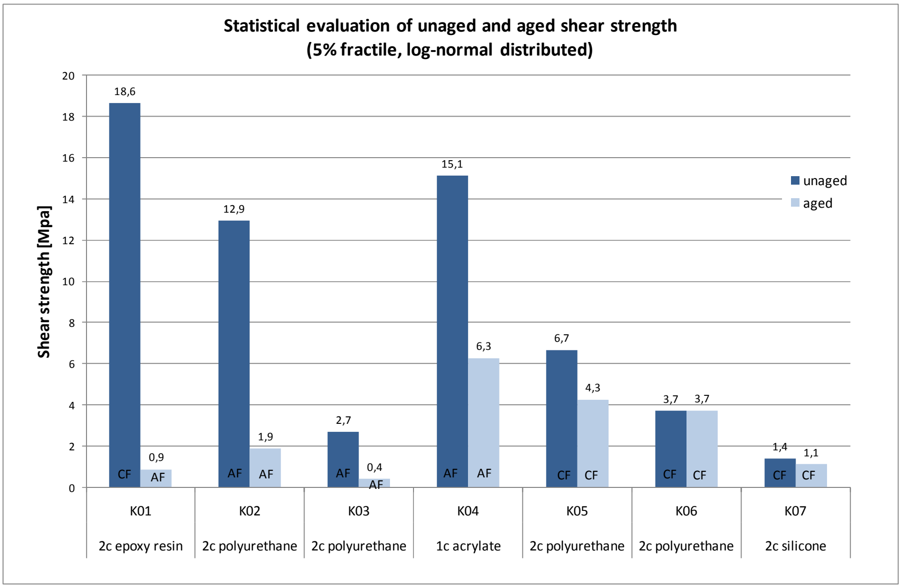


Figure 3: Decrease of shear strength after water bath storing

Comparing a two-component silicone (K07) usually applied for structural glazing issues with an effective two-component polyurethane (K05 or K06), it becomes apparent (see Figure 4) that modern adhesive systems are available by now which are equal or even better than standardized silicones concerning stiffness, strength and elongation at break – in particular for aged situation, too. Thus for structural glazing application new alternatives arises with respect to transmission of load and design of adhesive joints. On the other hand silicones offer still bearing reserves, because the current normative design of silicone joints [5] is based on very conservative partial safety factors, having not been experimentally verified on a big scale.

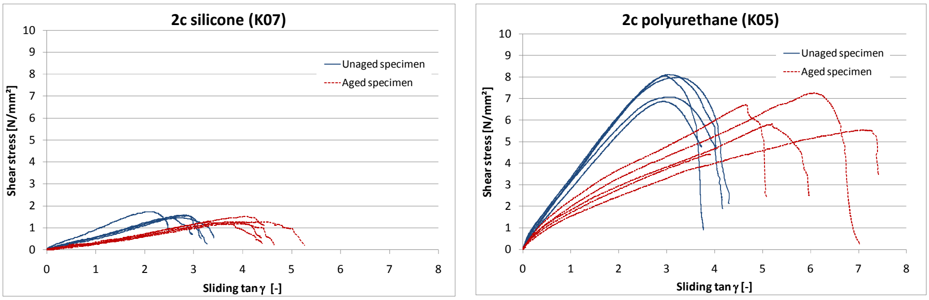


Figure 4: Comparison of the shear stress – sliding behaviour before (blue) and after (red dashed) ageing of a traditional two-component silicone (K07) and a effective two-component polyurethane (K05)

6. Determination of the structural behaviour by small scale load tests

To derive reliable design methods small scale load carrying tests were performed. Both tension and shear tests were envisaged, since depending on the real loading of a structure different bearing mechanisms (tension, shear or mixed) are activated in the adhesive joint.

This approach allows that the experimental results for the adhesives themselves (modified block shear tests and dumbbell tension tests) can be transferred to small scale construction elements, so-called push out specimen, to derive influence factors. Based on these small scale test the influence of the adhesive system, the adhesive geometry and the kind of loading on the load bearing behaviour of the bonded steel-glass-element can be separated.

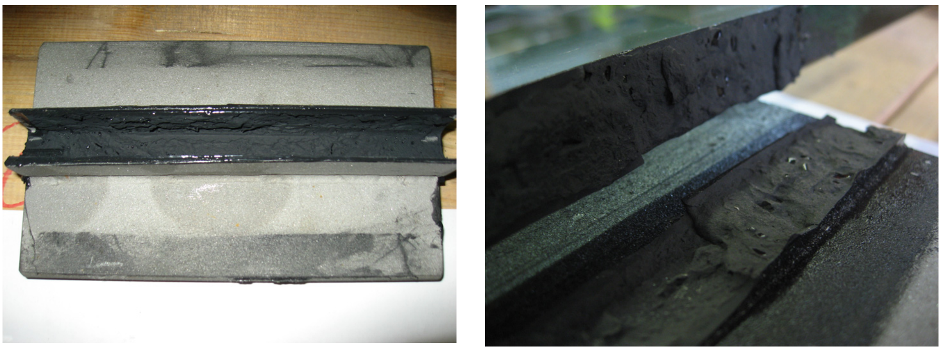


Figure 5a and b: Cohasive fracture pattern of a U-bonded specimen with a two-component silicone (left, K07) and of a chanel-bonded one with a two-component polyurethane (right, K05)

The testing matrix comprises the four joining geometries presented above using all seven adhesives (K01 to K07) that have been selected. Because of the multitude of varying parameters all in all more than 70 push out test were performed.

In Figure 5a and b representative fracture patterns after the performed push out tests are shown. Both the silicone (K07) and most of the polyurethanes (here K05) used revealed

predominant cohesive fracture or cohesive fracture near the boundary layer of the adhesive, infrequently also failure of the primer layer occurred.
Although the results of the push out tests are still object of ongoing research it can be stated already that the use of adhesive systems with medium stiffness is advantageous compared to the application of silicones. Figure 6a and b exemplarily show the development of the tension stress and shear stress curves from load tests on small scale push out specimen. The specimen were either subjected to tension or shear loading (for test setup see Table 1, V) using a two-component silicone (K07) and a two-component polyurethane (K05). It becomes visible that the specimen using polyurethane bonded joints feature higher carrying capacity with remarkable ductility compared to the silicone. Irrespective of the action effect (Figure 6a: shear, Figure 6b: tension) the bearing load of each of the adhesives ranges on the same level.

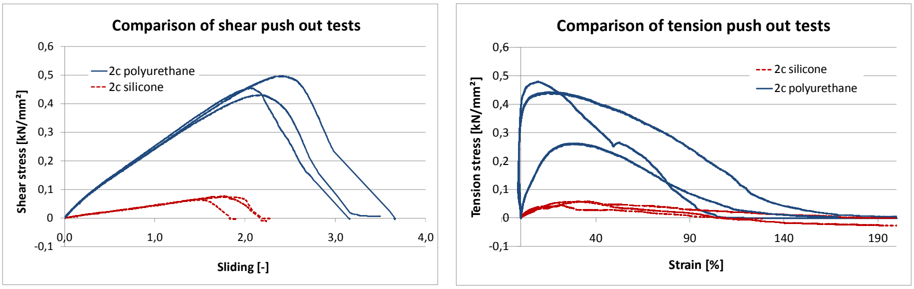


Figure 6a and b: Comparison of shear (left) and tension tests (right) on push out specimen bonded with a two-component silicone (red dashed, K07) and a two-component polyurethane (blue, K05)

In contrast high strength epoxy resins offer substantially higher ultimate loads, but their brittleness and therefore behaviour after breakage are limiting the application. Therefore, according to the current state of research, the use of stiff epoxy resin adhesives in combination with glass is innovative, but has to be designed carefully particularly because of stress peaks.

7. FE calculations

Especially viscoelastic adhesives have a strong dependence on their yield or rather fracture behaviour and the hydrostatic state of stress. This means that the yield point and the breaking limit can vary with the predominant hydrostatic stress. Beyond that there is a correlation to the strain rate and temperature [6]. Up to now modern finite element programs do not comprise this fact properly so that the stress strain behaviour of viscoelastic adhesives can not be modelled easily.
Aim of the research within this project is to model the adhesive behaviour using existing material models, but already starting approaches target on modelling the adhesive behaviour more exactly with commercial finite element programs by adapting the material laws for civil engineering issues (e.g. proposal [7]).
Figure 7 exemplarily shows finite element results of a push out specimen using a two-component polyurethane (K03) under tensile load. Although the load is introduced smoothly, the corners of the adhesive joints form local discontinuities where significant stress peaks appear. This fact could also be observed in the experimental load tests.

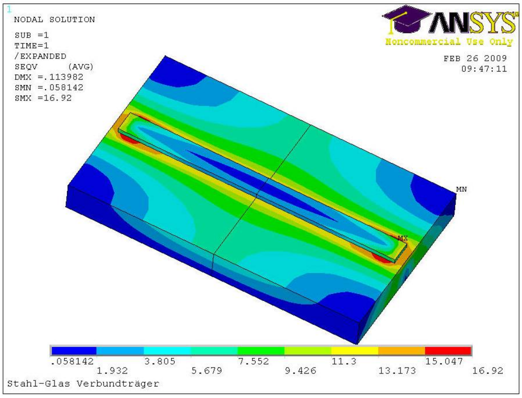


Figure 7: FE modelling of a push out test subjected to tension loading bonded with a two-component polyurethane – stress peaks at the local discontinuities in the corner regions of the joint

8. Summary and future prospects

The intention of the research carried out within the current project INNOGLAST [1] is to develop design rules for the dimensioning of hybrid steel-glass beams as façade elements or floor girders on the basis of existing preliminary work [8] - [12]. The project contains both small scale tests and large scale tests (see also [13] to this) and especially focuses on the adhesive joint und its geometry, which primarily rules the bearing capacity of the hybrid cross section. For this reason adequate adhesives were analyzed systematically, including the detailed determination of mechanical characteristic values, and were finally applied to four realistic joining geometries of small scale specimen. The results point out the great potential of structural adhesive systems comparing strength, stiffness, workability and durability to silicones. Ongoing in-depth studies enclosing analytical and numerical calculations are part of current research and large scale tests are in progress. The approach is listed in Table 1.

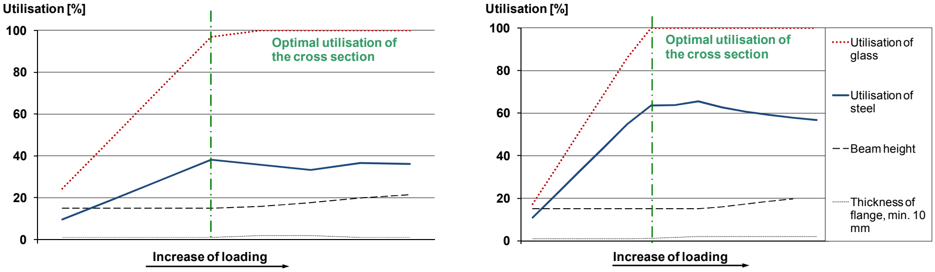


Figure 8a and b: Utilisation of steel and glass for constant cross sections and different shear stiffnesses of the adhesive (left G=5 MPa, right G=20 MPa)

The results of the adhesive tests demonstrate in particular that modern polyurethane, which are so far rarely used for structural glazing aspects, possess a high load bearing potential going along with satisfying elasticity and ductility. However for applications in civil engineering and especially for structural glazing issues the durability, e.g. resistance against UV-radiation, must be checked specific to the product with adequate testing methods.

Based on the sandwich theory the cross sections can be optimized by extensive analytical calculation. Therefore the overall height of the beam as well as the steel cross-section and the shear stiffness of the adhesive as leading parameters were varied for increasing loads, resulting in economic hybrid beams with a high utilisation of the cross section (see Figure 8a and b). By establishing simple design tables based on relations like Figure 8 further extensive finite element calculations may be avoided in the future.

9. Acknowledgements

The research project „*Development of innovative steel-glass-structures in respect to structural and architectural design (INNOGLAST)*“ is funded by the Research Fund for Coal and Steel (RFCS, No RFCS-CT-2007-00036). The following partners were involved in the project:

- Institute for Steel Structures, RWTH Aachen University, Germany
- Institute of Steel Construction, Dortmund University of Technology, Germany
- The Steel Construction Institute, United Kingdom
- Faculty of Civil Engineering, Czech Technical University in Prague, Czech Republic
- Centre Scientifique et Technique du Bâtiment, France

Sincere thanks are given to the European Commission, particularly to the Steel Technical Group TSG 8, and to the research partners for the good cooperation.

10. References

[1] Feldmann, M.; Ungermann, D.; Abeln, B.; Baitinger, M.; Preckwinkel, E.; et al., *Development of innovative steel-glass-structures in respect to structural and architectural design (INNOGLAST)*, RFCS Research Project No RFCS-CT-2007-00036, 2007-2010.

[2] Baitinger, M.; Abeln, B.; Preckwinkel; et. al., *Mid-term technical implementation report*, Technical report N° 3, RFCS Research Project No RFCS-CT-2007-00036, 2009.

[3] Geiß, P.L.; Wagner, A.; Luhn, R., *Verbesserung der Alterungsbeständigkeit von Glasklebungen durch prozessintegrierte umweltverträgliche Oberflächenbehandlungsverfahren (Proglazing)*, AiF Projekt Nr. 14.776 BG/1, 2006-2008.

[4] Feldmann, M.; Geiß, P.L.; Dilger, K.; Pasternak, H.; Ummenhofer, T., *Neue Konstruktionen durch Einsatz von Klebverbindungen im Stahlbau*, AiF-ZUTECH Projekt Nr. 169 ZBG/1

[5] EOTA (European Organisation for Technical Approvals), *ETAG No.2 Guideline for European Technical Approval for Structural Sealant Glazing Systems*, Brüssel, 1998.

[6] Schlimmer, M.; Matzenmiller, A.; et al., Methodenentwicklung zur Berechnung höherfester Stahlklebverbindungen des Fahrzeugbaus unter Crashbelastung, FOSTA P 676, Düsseldorf, 2008.

[7] Bucak, Ö.; Feldmann, M.; Geiß, P.L., *Lastabtragende Klebverbindungen im konstruktiven Ingenieurbau (LAKKI)*, AiF Projekt Nr. N073060/08.

[8] Völling, B., *Analytische Berechnung von Sandwichtragwerken mit Hilfe von Eigenspannungslösungen*, Diss. RWTH Aachen, 2007.

[9] Wellershoff, F., *Nutzung der Verglasung zur Aussteifung von Gebäuden*, Diss. RWTH Aachen, 2006.

[10] Bucak Ö.; Hagl A.; Held B.; Bues M., *Geklebte Verbindungen im konstruktiven Ingenieurbau*, AiF Projekt Nr. 17040255, 2007.

[11] Sedlacek, G.; Feldmann, M.; Naumes, J.; Wellershoff, F., *Development of optimum hybrid steel-glass-beams in respect to structural and architectural criteria*, Aachen, 2005.

[12] Geiß, P.L.; Kötter, M.P.; Bucak, Ö.; Bues, M., *Teiltransparente tragende Verbundbauteile aus Stahl und Glas (3TVB),* AiF Projekt Nr. 15058N, 2006-2008.

[13] Ungermann, D., Preckwinkel, E., *Structural behavior of hybrid steel-glass beams*, Proceedings of the Conference on Architectural and Structural Applications of Glass (Challenging Glass 2), Delft, Netherlands, 2010.