ADHESIVE BONDED JOINTS IN STEEL STRUCTURES

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INTRODUCTION

While classic joining techniques in steel construction have undergone advancements, fundamental problems still remain. The utilisation of structural bonding can remedy the situation, but despite having many advantages, has not been able to establish itself in civil engineering and specifically steel construction. The reason for this are doubts by engineers, architects and contractors regarding the verifiability, durability and load bearing capacity of bonded steel constructions. In order to facilitate the use of the innovative joining technique in construction, it is necessary to process bonded joints close to standardisation.

1 ADHESIVE BONDING IN CIVIL ENGINEERING

1.1 State of the art

Civil engineering, and especially steel construction, is cautious of adhesive bonding technology, justified by doubts about durability and above all by the lack of experience and design rules. Nevertheless, there is a long tradition of application of bonding in civil engineering. Mortar, which is utilized for masonry and for installing ceramic tiles, is an adhesive, and concrete can be understood as a composite of aggregates and reinforcement. The fixing of glass elements to the facade substructure with elastic silicones, is known as “structural silicon glazing” (SSG). The optical, structural and economic advantages of SSG-facades are demonstrated by the Herz-Jesu Church in Munich (*Fig. 1a*). The first bonded steel truss bridge (*Fig. 1b*) was built in the years 1955 to 1956 in Germany. The main idea of this construction was improvement of sliding resistance of pre-stressed screws.

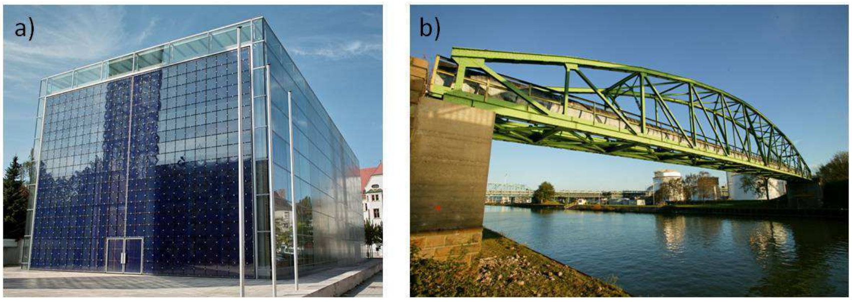

Fig. 1. a) Herz-Jesu Church in Munich [1], b) bonded steel truss (Copyright: Infracor GmbH)

To design adhesive bonded joints various standards and guidelines are available. The guideline for European technical approval for structural sealant glazing systems (ETAG 002) [2] deals with requirements and design rules for bonded joints in glass structures, but because it works with permitted values and a global safety factor, the concept is outdated and in need of revision. Current standards are based on the partial safety factor approach of Eurocode [3]. Examples of Eurocode-based design concepts are the standard for the design of aluminium structures [4] and the Eurocomp design code for the design of polymer composite structures [5]. For steel construction no Eurocode-based design concepts can be found. Due to this lack, functional and practical applications of bonding technology are still not verifiable without considerable effort. Thus, “individual approval”

or “general technical approval” is required for planning and realization of bonded joints, but since the process for these approvals is time-consuming and expensive, the ability for innovation of small and medium-sized companies is restricted.
To resolve this unsatisfying situation, a systematic approach for the development of Eurocode-based design rules for adhesive bonded joints in steel construction was investigated in a German research project (IGF-No. 16494 BG) [6]. The approach and selected results of this project are described as follow.

1.2 Adhesive bonded joints in facade structures

The application of bonding technology was investigated for two constructions of a typical steel facade. For single-storey buildings trapezoidal facades are usually employed, and the connection of the trapezoidal steel sheets with the support structure is currently done by screws. However, the adherends are weakened in their cross section by the screws. That means, that the capacity of the facade sheets is minimized, which leads to stress concentration and notches, reducing the fatigue strength in these areas. The application of adhesive technology can avoid this weakness, as shown in *Fig. 2*. Furthermore, scratches, dents and errors, which can occur during the mounting, as well as fastener heads are non-visible, assuring the self-cleaning effect of the facade. The bondlines can be completely prefabricated in a laboratory and mounted with a simple plug and screw method on the site. The connection is designed so that the dead load is compensated by the head or foot points of the facade elements.

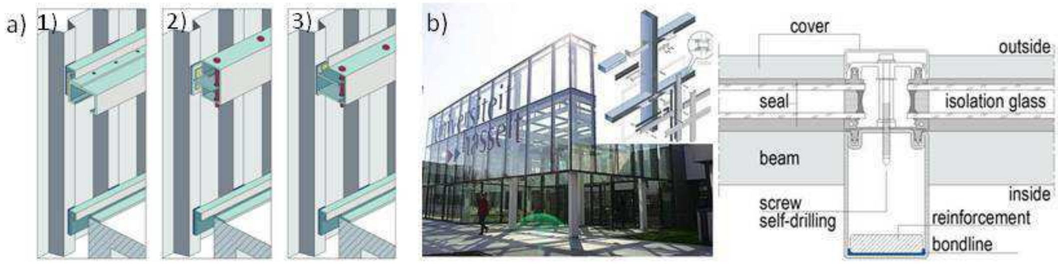

Fig. 2. a) Structures for bonded facade connections with different shape of connection profile 1) L-profile, 2) T-profile, 3) Pi-Profile; b) post and beam facade with bonded facade reinforcement [11]

Major requirements by architects and developers are an increased side view transparency, structured and transparent facades. To obtain these objectives a minimization of outer dimensions of the structural facade elements is necessary. Bonding technology can solve this problem. A section with increased stiffness and high carrying capacity can be created by an inner reinforcement of the hollow profile made of sheet metal steel and a bondline (*Fig. 2*). Thus, the facade posts can be deployed in larger distances, which leads to the desired side view transparency. The bonding of the inner reinforcement in *Fig. 2* is an additional process step, so familiar principles and processes of mounting facade posts do not need to be changed. Since the reinforcement is applied facing away from the facade, even self-drilling screws for attaching the cover panels can still be used.

2 INVESTIGATIONS OF ADHESIVE BONDED JOINTS

2.1 Determination of material properties

Characteristic material properties are essential in order to verify the sustainability, serviceability and durability of constructions. For steel adherends material parameters are defined in Eurocode 3 [7]. Nevertheless, for bondlines such information is missing in current standards and needs to be determined experimentally. For this purpose, experimental studies on butt joint specimens according to DIN EN 15870 [8] and lap shear joints according to DIN EN 14869-2 [9] were performed. In *Fig. 3* the geometry and loading situation of these in-situ specimens are shown.

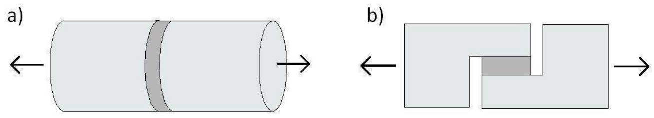

Fig. 3. a) Butt joint test; b) Lap shear test

According to [3] stiffness properties are indicated as means values and strength parameters are expressed as 5% fractile. The results of the experimental investigations for three adhesives are summarized in *Table 1*. Herein, E^*_k is a special elastic modulus determined at one-third of the ultimate strength. σ_k and τ_k are the bond strength and lap shear strength. The shear modulus G_k of the bondline was determined by lap shear joints. Logarithmic normal distribution function is assumed for all test results in *Table 1*.

Table 1. Characteristic material properties of different adhesives [N/mm²]

Adhesive	E^*_k	σ_k	G_k	τ_k
Körapop 225-2K	5,641	1,320	0,540	1,319
SikaFast 5241	525,3	6,456	10,41	3,904
DP 490	3063	38,67	3018,9	29,28

Körapop 225-2K is an elastic, two-component adhesive with good resistance to humidity and weathering. It shows a strongly non-linear elastic behaviour with small strength and stiffness values. SikaFast 5241 is a fast curing, elasticized two-component adhesive system based on acrylate. The adhesive named DP 490 is a thixotropic, gap filling two component epoxy with a stiffer and more brittle carrying behaviour.

2.2 Experimental investigations of specimen components

The application examples from *Fig. 2* were investigated experimentally, in order to determine the adhesive-dependent load and deformation behaviour.

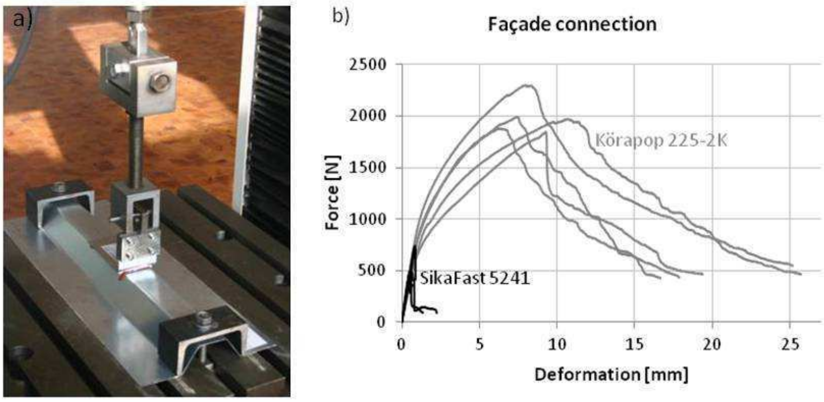

Fig. 4. a) Test setup; b) Test results

For the facade connection a strip coated trapezoidal profile with a thickness of 1 mm was used. The connection profile was simplified to an L-hook with a thickness of 2 mm. The bondline thickness was chosen to be 2 mm and the surface to be bonded to be 40x100 mm. The surfaces were cleaned with acetone. In addition, the surface of the connection profile was blasted with rounded cut wire. In the mounted state of the trapezoidal profile, the general effect results from wind loads, which act perpendicular to the connection and thus lead to normal and peel stresses in the bondline. The experimental set up (*Fig. 4*) led to a bondline failure and accurately represented the actual conditions in the mounted state of a bonded facade connection. The rib ends of the trapezoidal profile were braced against the table of the testing machine, and the longitudinal edges remained non-supported. The tests were conducted displacement-controlled.

All joints bonded with Körapop 225-2K failed with a cohesive failure in the bondline and behaved strongly non-linear. Large deformations and a very ductile behaviour are possible with this kind of

adhesive, which is positive in regard to advance notice of failure. However, SikaFast 5241 bonded specimen components exhibit a stiffer deformation behaviour but a lower ultimate load. It failed by special cohesive failure (cohesive failure closed to the substrate). Up to this failure mode, the specimen behaved linear, which can be useful for the integration into a simple material law.
In order to evaluate the structural behaviour of the facade reinforcement, specific experimental investigations were carried out. A typical hollow section with a width of 60 mm, height of 181.5 mm and a wall thickness of 2.5 mm was chosen. To induce a bondline failure during the tests, pilot tests and analytical examinations were carried out, and the profile length was set to 1 m. The sheet metal steel (width: 50 mm; height: 20 mm) was blasted with rounded cut wire and bonded inside the hollow section as a reinforcement. Due to the actual load transmission, the four-point bending test (*Fig. 5*) was ideal for conducting tests on the girders. This kind of connection reflects the practical situations very well. The support and application points were designed so that horizontal deformation and rotation could occur tension-free.

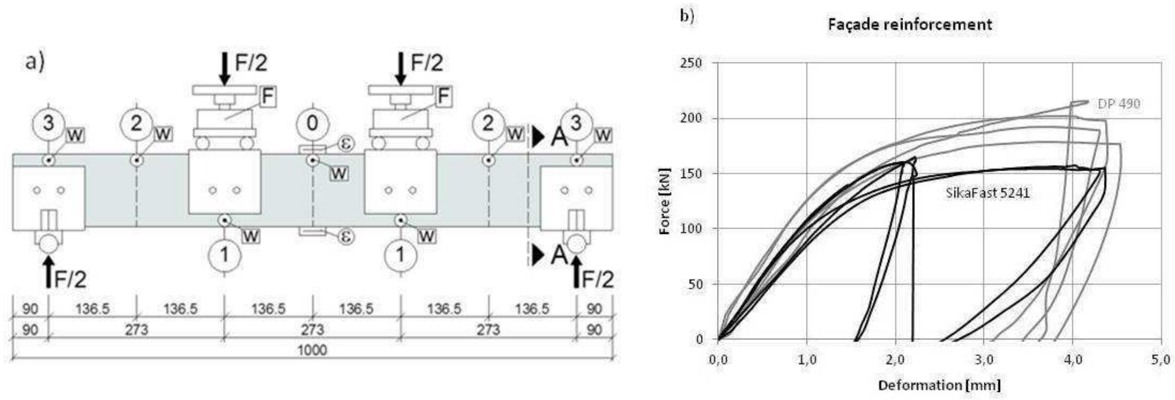

Fig. 5. a) Test setup; b) Test results

The evaluation of the experiment shows that those reinforcements bonded with SikaFast 5241 failed through a special cohesive failure. The adhesive allowed greater deformations and failed in a more ductile manner than those bonded with DP490. The specimen components bonded with DP490 displayed slightly larger ultimate loads. Characteristic for the reinforcements produced with the epoxy resin based adhesive is the distinct levelling of the ultimate load, which develops with the bondline failure. The specimen components failed by cohesive failure.

3 CALIBRATION OF DESIGN RULES

3.1 Eurocode Concept

In the context of the Eurocode it must be proven that a structure fulfils defined requirements to the carrying capacity, serviceability and durability for a planned lifetime. That means for the ultimate limit state that the expected effects E do not exceed the corresponding component resistance R with a certain probability. The two variables E and R are subject to stochastic nature which can be detected by probabilistic studies. Due to the complexity of this task, the proof in the design practice should be carried out with partial safety factors for the effect and resistance side. The partial safety factors capture the stochastic fuzziness of material properties and effects and are obtained through statistical methods. For civil engineering the design procedure in *Eq. (1)* is realized with design values.

$$E_d = E_k \cdot \gamma_F \leq \frac{R_k}{\gamma_M} = R_d \quad (1)$$

In order to estimate partial safety factors, analytical models are to be used, which enable the prediction of bondline behaviour with reasonable accuracy. A typical engineering approach to describe the adhesive layer is a model with spring elements (*Fig. 6*). In this model, the connection is divided into different components (adherends, bondline) and only a cohesive failure of the bondline is considered. Thus, the failure modes for each component can be treated separately. The connection is designed according to the principle of the weakest link theory. In Eurocode 3 [7] the design rules and material properties for steel adherends are defined. Thus, the following studies focus on the adhesive layer.

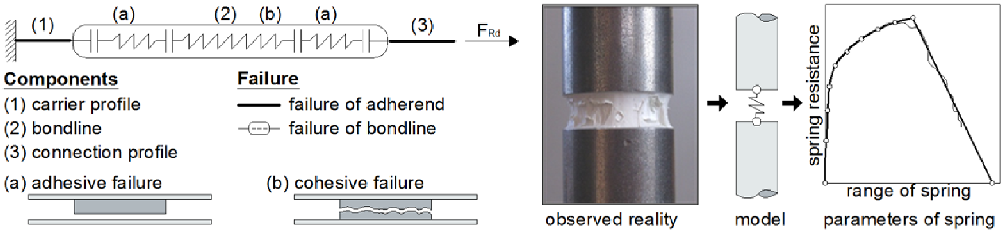

Fig. 6. Component-spring model

Based on known characteristic material properties, the design value of the resistance of a bondline can be expressed by *Eq. (2)*.

$$R_d = \frac{R_k}{\gamma_M} \cdot \eta_t \cdot \eta_m \cdot \eta_i \tag{2}$$

The approach in *Eq. (2)* was proposed by van Straalen [10] and defines a material dependent partial safety factor and different conversion factors η to capture effects from environmental conditions η_t and variation of bondline thickness η_m. Additional effects, e.g. UV-radiation, can be considered by the introduction of new conversion factors η_i.

Starting point of the concept calibration is the juxtaposition of theoretical results of the analytical model with experimental results. For both specimen components, the analytical models [11] are based on the component-spring approach (*Fig. 6*) and the structural behaviour of the bondline is described by the theory of elastically supported slabs. The calibration resulted in a partial safety factor for the specimen component "bonded facade connection" of 2.16 and for "bonded facade reinforcement" of 1.56.

3.2 Conversion factors

In order to take environmental dependent influences and manufacturing effects into account, so-called conversion factors were determined in a subsequent step, indicating the repetition of the described tests under variation of certain boundary conditions.

Table 2. Conversion factors for environmental dependent effects

η_t	Körapop 225-2K		SikaFast 5241		DP 490	
	$-20° \leq T \leq 25$ °C	$25°C < T \leq 80°C$	$-20° \leq T \leq 25$ °C	$25°C < T \leq 80°C$	$-20° \leq T \leq 50$ °C	$50°C < T \leq 80°C$
Shear	0.83	0.12	0.55	0.05	0.64	0.18
Tension	1.00	0.76	1.00	0.07	0.47	0.28

Table 3. Conversion factors for manufacturing dependent effects

η_m	Körapop 225-2K	SikaFast 5241	DP 490	
	$2mm \leq d_k \leq 5mm$	$2mm \leq d_k \leq 5mm$	$0{,}2mm \leq d_k \leq 0{,}5mm$	$0{,}5mm < d_k \leq 2mm$
Shear	0.25	0.15	0.51	0.12
Tension	0.76			

For the employed adhesives, η_t-values are determined for different temperature (T) effects from -20 ° C to +80 ° C.

Similar to η_t, studies are conducted regarding the influence of manufacturing-related effects on the strength and stiffness properties of the considered bondlines. For this purpose, the small specimen experiments are repeated by varying the bondline thickness (d_k).

For the statistical conceptions, it is assumed that the effects remain constant and the resistance is shown as being dependent on boundary conditions. To determine the conversion factors and the probability of failure, probabilistic conceptions with respect to possible probability functions are employed. The distribution function of resistance must be formulated depending on the variables (T, d_k). A conservative simplification is to calibrate the conversion factors at the smallest value for the design value of the resistance $R_d(T_p)$ or $R_d(d_{k,p})$ (*Eq. (3)*).

$$\eta_t = \frac{R_d(T_p)}{R_d(T_0)} \quad \text{or} \quad \eta_m = \frac{R_d(d_{k,p})}{R_d(d_{k,0})} \tag{3}$$

The results for the conversion factors are summarized in *Table 2* for temperature dependent effects and in *Table 3* for the influences of bondline thickness.

The investigated effects depend on the type of loading. Consequently different conversion factors for normal and shear stresses inside the bondline are recommended. Due to strong decrease of the material parameters of some adhesives at high temperatures and different bondline thicknesses, the conversion factors are declared for ranges.

4 CONCLUSION

With the scientific and technical result of the presented procedure, two Eurocode-based calibrated bonded steel constructions are available. Especially in steel structures, it is to be expected that the acceptance of use of the joining technology will continuously increase. With a growing number of functional and calculable applications, the general interest in developing standards as a basis for analysis and design of adhesive joints in steel is expected to rise.

For the introduction of alternative innovative bonded steel joints, the effort is limited to the development of engineering-models, planning and construction design. General technical approvals or individual approvals can be achieved more easily, thus sustainably increasing the innovative capacity of small and medium-sized enterprises.

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