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Development of Eurocode-based design rules for adhesive bonded joints

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ABSTRACT

Despite many advantages, adhesive bonding technology has not been able to establish in construction and specifically steel construction. The reasons 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 bonding technique in construction too, it is necessary to process bonded joints close to standardisation. The general interest of automotive manufacturing, construction, chemistry and other industries and research is highlighted by numerous experimental and analytical studies. The aspect of standardisation is of particular importance to construction engineering. While various guidelines for adhesive bonds exist, these are either not applicable to steel construction or are based on an obsolete concept. Practically relevant design concepts are based on the semi-probabilistic method of the Eurocode. In order to develop such a concept, it is necessary to calibrate analytical models by experimentation. The statistical method aims to determine partial safety and conversion factors. Therefore, a comparison of experimental results with analytical solutions is necessary. In the article, analytical models, experimental studies and statistical calibration methods are introduced.

1. Introduction

Many studies have shown that adhesive bonding technology can be successfully utilized in lightweight steel construction. The classic joining techniques in steel construction have undergone advancements, but fundamental problems and limits still remain. The use of adhesive bonding can remedy the situation. Therefore, it is necessary to continuously work on establishing innovative joining processes in the steel construction.

Civil engineering, especially steel construction is cautious of this joining technology, justified by doubts about durability and above all by the lack of design rules. Nevertheless, there is a long tradition of application of adhesive technology in civil engineering. Mortar, which is used for masonry and for installing ceramic tiles, is an adhesive. Similarly, the material concrete should be mentioned here, which can be understood as a composite of aggregates and reinforcement.

The fixing of glazing and curtain walling panels to the façade support structure with elastic silicones is known as "Structural Silicone Glazing". By this method, visually attractive structures completely encased in glass can be built. One of the most important buildings to demonstrate the functionality of structural adhesive joints is the Sacred Heart Church in Munich (Fig. 1). The essence of the impressive façade is defined by horizontal and vertical glass fins. For the transfer of loads in the rigid steel frame, the glass fins are bonded with silicone adhesives into U-shaped stainless steel profiles (Fig. 1, right). This innovative system has optical, structural and economic advantages.

Also, in steel construction there are few examples of bonding technology. In the years 1955 to 1956 the first bonded pipe and pedestrian bridge was built near Marl with a span of 56 m [2]. The basic idea was the replacement or improvement of sliding resistance of pre-stressed screws.

With recent developments in adhesive technology, material and structural lightweight construction and the growing demand for aesthetics and weight reduction, the interest in adhesive bonding noticeably increased. As an alternative to conventional welded orthotropic plates, Feldmann et al. [3] provide bonded plate elements. Meinz impressively shows in [4] a simple calculation for bonded connections of trapezoidal sheets and bonded reinforcement of hollow profiles. In Ref. [5] van Straalen shows a general procedure for the determination of design rules for overlap joints and sandwich panels. For the verification of bonded joints different design concepts can be found. An example from civil engineering is the guideline for European technical approval for structural sealant glazing systems (ETAG) [6], which provides principles and requirements for the design of bonded joints in glass structures. The proof is performed using the concept of

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permissible stresses. The permissible stresses in the bondline are to be determined based on established test methods and for defined adherend surfaces [18].

From the perspective of design concepts the approach of ETAG is out of date and in need of revision. Current design concepts are based on the partial safety factor concept of Eurocode [7]. In this concept, design values of the effect of actions (E_d) are compared with design values of the associated component or material resistance (R_d). The partial safety factors are to be determined by a suitable calibration of the analytical model or simplified estimate based on Eurocode [7] Section 4.2 (10) P, where the following information can be found: “Where a partial factor for materials or products is needed, a conservative value shall be used, unless suitable statistical information exists to assess the reliability of the value chosen”. Examples of Eurocode-based design concepts are the Eurocomp design code for the design of polymer composite structures [8] and the Standard for the design of aluminium structures [9]. The Eurocomp Design Code [8] deals with the design of polymeric materials and includes the calculation of adhesive bonding of plastics. Maximum shear and tensile stresses are defined as design relevant conditions. Only cohesive failure of the adhesive layers can be taken into account. The general design principle is based on analytical models for the adhesion between components, wherein a perfect bond between the bondline and the adherend is assumed. The mechanical properties can be taken from data sheets or experiments which are described in the corresponding manual. The Eurocomp Design Code is of particular interest because specific characteristics influence the design results, such as the source of the adhesive characteristics, the method of application and environmental conditions. This is done by forming the partial safety factor γ_M.

Due to a lack of standards for verification of bonded joints in steel construction, functional and practical applications of this joining technique are still not verifiable without considerable effort. Planning and realization of bonded constructions thus always require an “individual approval” or a “general technical

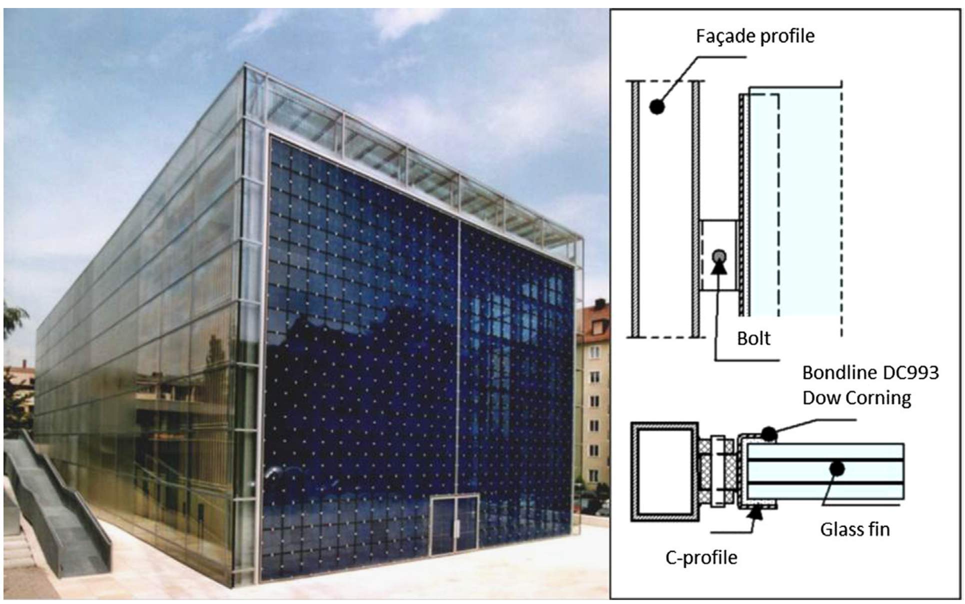

Fig. 1. Left: view Herz Jesu Church; right: detail connection vertical glass fin; [1].

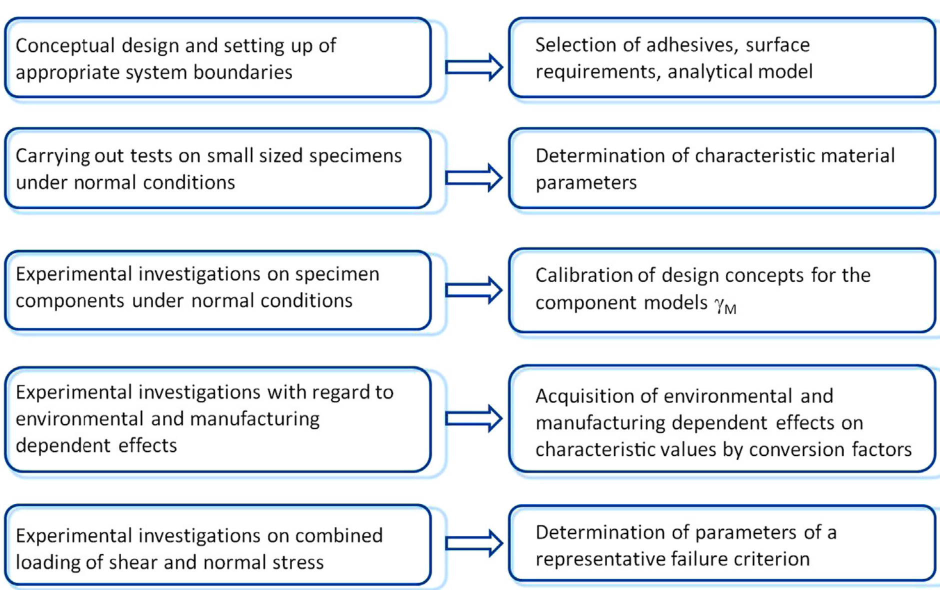

Fig. 2. Overview of the required operations.

approval", which is very complex and expensive in the absence of technical experience.

For this reason small and medium-sized companies in particular usually choose less appropriate joining techniques. Possible contracts that require bonding technology for aesthetic or other reasons are thus not executable, which remarkably limits the competitiveness and innovation of these companies. And yet because of the extensive formation of bonded joints, many potential bonding applications have such large load reserves, that even under pessimistic safety factors the load carrying capacity and suitability of the construction could easily be verified.

In a German research project (IGF-No. 16494 BG) [10], a systematic approach for Eurocode-based design of adhesive bonded joints in steel construction was investigated.

Major processing priorities can be summarized in five steps. These are shown in Fig. 2 and described in more detail below. After the conceptual design regarding the adhesive selection, the surface pre-treatment and other parameters, characteristic values of bondline properties were determined, based on experimental tests. Then, the partial safety factors were determined for two application examples. The calibration procedure is based on a comparison between the results of experimental investigations on specimen components and the results of analytical prediction models. To take into account environmental and manufacturing dependent effects, conversion factors were introduced, based on experiments and statistical investigations. The final step was the description of normal-shear-stress interaction by a representative failure criterion.

2. The concept of Eurocode

Standards play a central role in construction because they specify the requirements for the construction engineer to attain a minimal acceptable safety level. According to current standards, experimental data is encompassed in analytical models and made mathematically accessible by design values. Usually there is a single value for the resistance, the effects and the partial safety factors in the design, and consequently the result appears as a number. This also implies that the mode of thought of the design engineer is deterministic.

In the context of the Eurocode it must be proven that a component or a structure fulfils defined requirements to the carrying capacity, serviceability and durability for a planned lifetime. It must be shown that certain limits are not exceeded or undershot. In the ultimate limit state it has to be verified for a specified period that the expected effects E do not exceed the corresponding component resistance R with a certain probability. In this concept those two variables E and R are subject to stochastic fuzziness which is detected by probabilistic methods according to corresponding probability functions. Due to the complexity of this task, the evidence 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 nature of the material properties and effects and are obtained from statistical studies. For civil engineering this procedure is defined in Eurocode and for the ultimate limit state Eq. (1) applies [19].

$$Z = R - E \geq 0 \tag{1}$$

The symbol Z characterizes the limit state function, which enables the engineer to verify the capacity of structural elements. If $Z < 0$, it means that the structure fails. The probability that the limit state is reached, such that $Z = 0$, can be found by the combination of the probability functions of effect and resistance. This kind of task is solved by reliability methods. If the data is approximately normally distributed, with the introduction of a reliability index β as the ratio of the mean to the standard deviation of the limit state function Z, the simple relationship can be found in Eq. (2).

$$P(E > R) = \Phi(-\beta) \tag{2}$$

Φ herein is the distribution function of the standard normal distribution. In the semi-probabilistic approach of the Eurocode, a weighting of influences is carried out by α-values (Eqs. (3) and (4)).

$$P(E > E_d) = \Phi(-\alpha_E \beta) \tag{3}$$

$$P(R < R_d) = \Phi(\alpha_R \beta) \tag{4}$$

The β-values are declared in the Eurocode depending on the service life. The weighting factors α are results of a first-order reliability analysis and set to $\alpha_E = -0.7$ and $\alpha_R = 0.8$ according to Ref. [7].

The quantities R and E from Eq. (1) are subject to many dependencies and their expression is affected by randomness. Due to their stochastic nature, in the context of design, the arithmetical values of these parameters are applied with partial safety factors. Thus, resistance parameters are divided by a partial safety factor γ_R. This captures simplifications and inaccuracies in the mechanical models and the variability of material properties due to their natural scattering and manufacturing inaccuracies. The partial safety factor γ_E incorporates the influence of the main and accompanying action effects. These correlations are shown in Fig. 3 for the example of the relevant Eurocode. Thus results a verification based on Eq. (5).

$$E_k \times \gamma_E \leq R_k / \gamma_M \tag{5}$$

It can be seen that so-called design values are developed with the arithmetic operation in Eq. (5). These values are identified by the index d. Fig. 3 demonstrates that the characteristic values of R and E are taken into account with their statistical distributions. The nature and form of the statistical density functions $f_E(e)$ and $f_R(r)$ are essentially determined by the basic variables that quantify the influences on resistances and effects. It should be noted that independence between impact and resistance is assumed in Eurocode [7]. Thus, the effects are considered to be known and regulated in Eurocode 1 [11].

Furthermore, it is assumed that all basic variables are log normally distributed. For the calibration of concepts and the determination of characteristic material parameters such assumptions are of central significance.

2.1. Statistically significant determination of material properties

In order to estimate partial safety factors, analytical models are to be used, which enable the prediction of bondline behaviour with reasonable accuracy. Various calculation models are useful, ranging from continuum mechanics approaches to cohesive zone models. A typical engineering approach to describe the adhesive layer is a model with spring elements (Fig. 4). In this model, only a cohesive failure of the bondline is considered. The connection is divided into different components (adherends, bondline). The failure modes for each component can be treated separately.

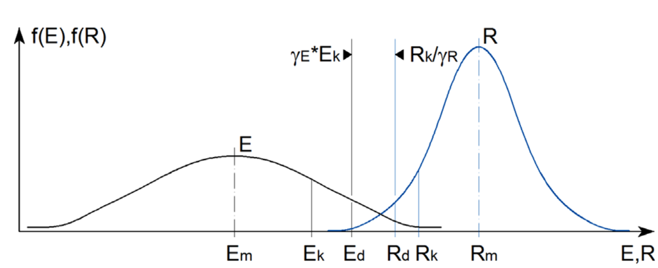

Fig. 3. Principle of design concept of Eurocode.

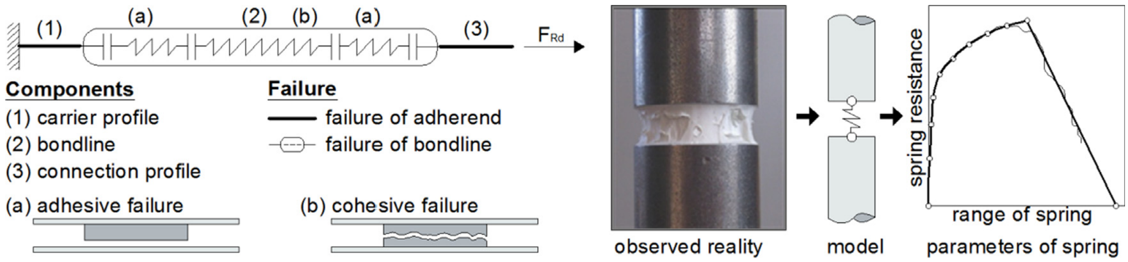

Fig. 4. Component-spring-model [4].

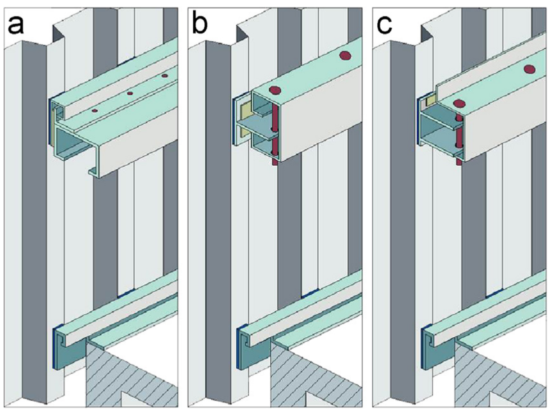

Fig. 5. Structures for bonded façade connections with different shape of connection profile, (a) L-profile, (b) T-profile, (c) Pi-profile [4].

The connection is designed according to the principle of the weakest link theory. The design rules for steel adherends are defined in Eurocode 3 [12]. Thus, the following studies focus on the adhesive layer.

To verify the resistance of a bonded joint, the knowledge of characteristic material properties of the bondline is essential. For typical materials, which include steel, information on essential characteristics is given in standards. The material parameters provide an appropriate basis for the design to be consistent with standards and must be guaranteed in practice. For bondlines, there is no such information available in standards.

Characteristic material properties of an adhesive layer are essential in order to verify its sustainability, serviceability and durability. The main task consists on the experimental determination of these relevant values. Because of the good applicability to analytical calculation approaches and because of the more realistic illustration of the real conditions in the adhesive layer, material properties are to be determined exclusively on specimens having well-defined surface properties, i.e. in so-called in-situ samples. Therefore, characteristics such as the transverse elongation disability on rigid adherends and fringe effects are considered. For this reason, experimental studies on butt joint specimens according to DIN EN 15870 [13] and lap shear joints according to DIN EN 14869-2 [14] were performed (hereinafter called small specimen tests). Stiffness properties are indicated as mean values according to Ref. [7]. However, parameters of strength values are expressed by the 5% fractile.

For the statistical calibration of design concepts, the knowledge of relevant material parameters is of fundamental significance. The results of small specimen tests provide the basis for the application of the semi-probabilistic method of Ref. [7]. In the experimental evaluation, knowledge of distribution functions and their parameters should be utilized.

Based on Eurocode, the characteristic value of a material is expressed by Eq. (6). It is shown that the characteristic property X_k depends on the mean value m_X and the standard deviation s_X of a data base. k_n is a fractile factor and defined in Eurocode [7].

$$X_k = m_X - k_n \times s_X \tag{6}$$

As a result the design value of the resistance of the bondline can be described by the characteristic value R_k, a partial safety factor γ_M and various conversion factors.

$$R_d = (R_d/\gamma_M) \times \eta_t \times \eta_m \times \eta_i \tag{7}$$

The approach in Eq. (7) was proposed by van Straalen [5]. The identified conversion factors η_t and η_m in Eq. (7) capture effects from environmental conditions and variation of bondline thickness. The consideration of additional effects is possible by introducing new conversion factors η_i.

3. Investigations of specimen components

3.1. Façade connection

Trapezoidal façades are primarily used for industrial hall constructions. After the construction of the steel skeleton as the primary support structure, a substructure made of lightweight steel sections is usually mounted, which is used for connection with the trapezoidal profiles. Currently the construction industry provides screws as a non-positive connection method. However, this joining technique produces disadvantages. Thus, the adherends are weakened in their cross section by the screws. This minimizes their capacity and leads to stress concentrations and notches. This is a weak point for the limit state of durability, because the fatigue strength is reduced in these areas. The mentioned weaknesses can be avoided by application of adhesive technology (Fig. 5).

Furthermore, the connection of a trapezoidal sheet on the post-beam-construction by structural adhesive bonding has the advantages that dents, scratches, errors or fastener heads are not visible. That means that the self-cleaning effect of the whole façade is assured. Moreover the bondlines can be completely prefabricated in a laboratory and the connection can be assembled with a simple plug and screw method. Specially moulded lightweight steel profiles are required, which are connected by bonding with the trapezoidal profile in the workshop. Thus an attachment to the building envelope is realized by mechanical fasteners on the site. In this way, non-reproducible bonds are avoided. The connection concepts are designed so that the dead load is compensated by the head or foot points of the façade elements (Fig. 5). Permanent static loads of the bondline due to self-weight are avoided.

The connection was investigated experimentally (Fig. 6), in order determine the adhesive-dependent load and deformation behaviour. For this, the adhesives Körapop 225-2K and SikaFast 5241 were used. Körapop 225-2K is a solvent-free, elastic, two-component adhesive with good resistance to humidity and weathering. SikaFast 5241 is a fast curing, elasticized two-component adhesive system based on acrylate. In the uncured state, SikaFast 5241 is a pasty material that can be easily and precisely applied.

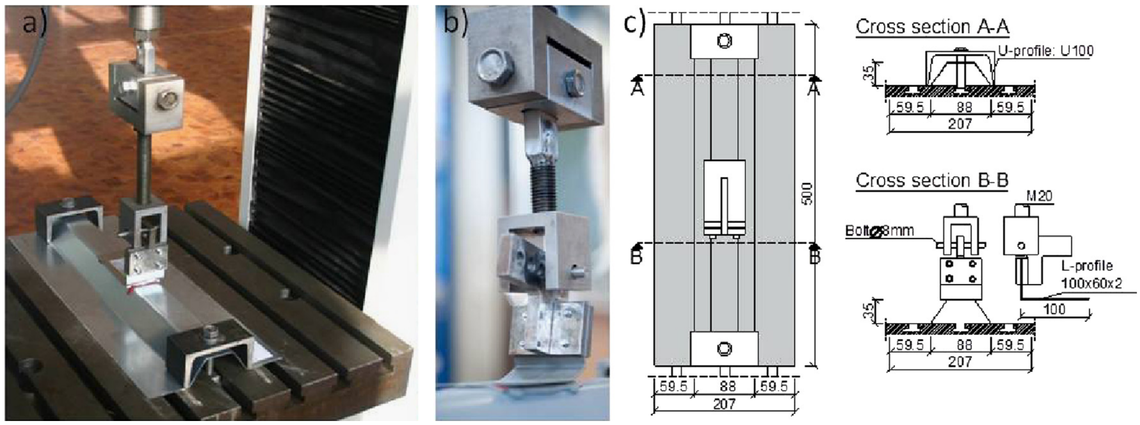

Fig. 6. (a) Test setup: façade connection, (b) detail: L-profile, (c) technical drawing: dimension in mm.

It is particularly suitable for large components. The bondline thickness was chosen to be 2 mm. For all experiments the geometry of the connection profile was simplified as an L-hook. The corresponding analytical model allows a consideration of further variants.

A strip coated trapezoidal profile was used. The thickness of the trapezoidal profile was 1.0 mm and of the connection profile 2.0 mm. The belt width of the profile rib, on which the attachment profile is mounted, was 40 mm. The length of the adhesive layer was chosen to be 100 mm.

Before joining the steel parts, the adherends needed to be appropriately prepared. The strip coated surfaces of the trapezoid profile were cleaned with acetone. The steel surface of the connection profile was first blasted with rounded cut wire and subsequently also cleaned with acetone. Through the mechanical pretreatment by blasting, the adherends were not only freed from the oxide and contamination layer, but also the wettability was improved. By this pre-treatment surface qualities were reached that complied to the requirements Sa 2½ according to [15]. The blast-cleaning grade Sa 2½ characterises a very thorough blast-cleaning and is defined in DIN EN ISO 8501-1 [15] with the requirement that "the surface shall be free from visible oil, grease and dirt, and from mill scale, rust, paint coatings and foreign matter. Any remaining traces of contamination shall show only as slight stains in the form of spots or stripes." Before the experiments were conducted, the samples were stored for seven days at normal climatic conditions (20 °C, 65% rel. humidity).

The general effects on the trapezoid profile façade in the mounted state result from wind, temperature and dead load. The constructions that are investigated not only avoid a permanent static load by dead load, but also allow strains by temperature gradients, so that the adhesive layer only performs as a load conductor for wind. This effect acts perpendicular to the connection and thus to normal and peel stresses in the bondline. Special consideration is given to wind suction, because this leads to critical tension and normal stresses in the bondline.

The experimental assembly was chosen so that a failure of the bondline would occur, and the actual conditions in the mounted state were well represented. Thus the tensile loading was performed perpendicular to the connection of the trapezoidal profile and conducted into the middle of the connection profile through a plug and screw connection. The rib ends of the trapezoidal profile were braced against the table of the testing machine, and the longitudinal edges remained non-supported. To avoid constraints in the system through horizontal effects, the load conduction into the connecting piece was realized by an approximately 20 cm long pendulum rod. This construction allowed deformations to develop freely.

The experiments were conducted displacement-controlled.

The joints bonded with Körapop 225-2K all failed by a cohesive failure of the bondline. The adhesive allowed large deformations and failed in a very ductile manner, which is positive in regard to the principle of advance notice of failure. Furthermore, non-linear behaviour of Körapop 225-2K was observed.

Specimen components that were bonded with SikaFast 5241 exhibited a stiffer deformation behaviour, but also a lower ultimate load. The specimen failed by special cohesive failure at the surface of the connection profile. The behaviour of the specimen components up to failure can be seen as nearly linear, which can be useful for the integration of the system into a simple material law.

3.2. *Façade reinforcement*

Major requirements by architects and developers are an increased side view transparency, high quality mostly transparent and structured façades, which are mainly used for public and representative buildings. In many cases, a post and beam façade is used (Fig. 7). To obtain the desired effect, it is necessary for the primary supporting structure to disappear into the background. That means that a minimization of the outer dimensions of the structural elements must be achieved, while at the same time increasing the stiffness. This could be achieved through thicker hollow sections, but because typical façade hollow profiles are produced by cold forming, the maximum profile wall thickness is limited. Bonding technology can solve this problem. An inner reinforcement of the hollow façade profile made of sheet metal steel and a bondline create a new composite section with increased stiffness and carrying capacity. As a result, the posts can be deployed in larger distances, which leads to the required increased side view transparency.

The advantages of the presented system with inner reinforcement are mainly that the bonding is simply one additional process step, without changing the familiar principles and processes. This makes the application of the solution especially probable. First of all, the typical cold formed strip coated hollow profiles with 2.5 mm wall thickness can still be used as posts. Furthermore, the steel reinforcement does not interfere with the usual plug and screw system. Even self-drilling screws for attaching the cover panels can still be used, since the reinforcement is applied facing away from the façade. The main advantage of the reinforced façade profile opposed to a usual hollow profile is the lower slenderness ratio of the webs. Thus a buckling of the webs under compression is avoided.

To evaluate the adhesive-dependent load and deformation behaviour of the composite section, to different adhesives were examined: SikaFast 5241 and the stiffer and more brittle epoxy DP 490. The latter is a thixotropic, gap filling two component epoxy

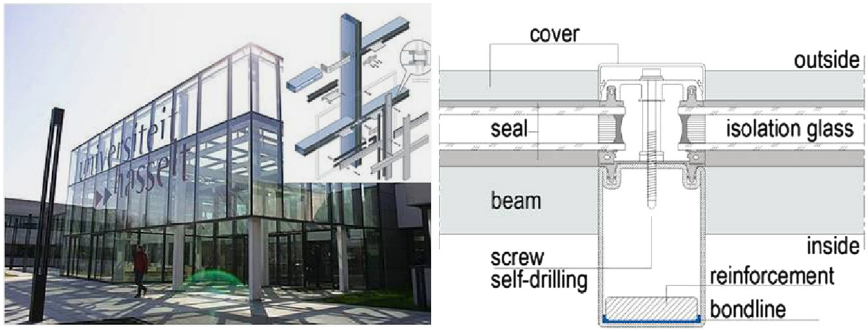

Fig. 7. Left: post and beam façade; Right: bonded façade reinforcement.

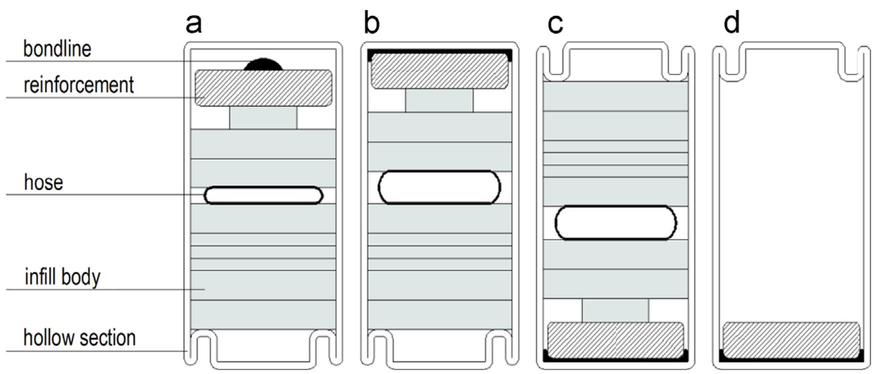

Fig. 8. Pneumatic method for bonding the reinforcement, (a) filling of the profile with infill bodies, hose and reinforcement, (b) application of an inner hose pressure of 3 bar, (c) the profile is turned over after handling time, (d) reinforced façade profile [4].

adhesive with particularly good application characteristics. It is designed for use where toughness and high strength are required. The bondline thickness was chosen to be 0.2 mm.

In order to induce a failure of the bondline, pilot tests and analytical examinations were carried out, and the profile length set to 1 m. A typical strip coated façade profile from “RP Technik” was chosen for the hollow section. The profile was 60 mm wide and 181.5 mm high with a wall thickness of 2.5 mm. A sheet metal steel (width: 50 mm; height: 20 mm), which had been previously blasted with rounded cut wire, was bonded inside as reinforcement.

The dimensions of the hollow profile and of the reinforcement of the sample specimen had to be designed so that a failure of the bondline would occur. For this reason, all other components and their modes of failure had to be considered. It must be pointed out that in reality installation lengths of the profile $L > 1$ m are to be expected. This means that one of the other failure criteria can become dominant, especially regarding the shear load in the bondline, which decreases in longer profiles. Experiments with shorter profiles are thus on the safe side concerning statements about the bondline carrying capacity, if the compound effect can be guaranteed.

To produce the bonding, a pneumatic method was utilized. In this procedure, the hollow section is first cleaned on the inside. The blasted sheet metal steel (satisfying the requirements Sa 2½ according to Ref. [15]) was also cleaned. Subsequently the façade profile was filled with infill bodies of rigid PVC foam in addition to a reinforced hose. Still outside the hollow profile the adhesive beading was applied to the reinforcement, and the bondline thickness of 0.2 mm was set by adding glass beads. Afterwards, the reinforcement was carefully inserted into the pre-assembled hollow profile, and a hose pressure of approximately 3 bar applied. After reaching the handling time, the bonded composite section was carefully rotated, infill bodies and hose removed and the sheet metal steel ends secured against lifting. The specimen components produced in this manner were stored for 7 days at normal climate (20 °C, 65% rel. humidity) before conducting the experiments. The presented pneumatic method is summarized in Fig. 8.

The role of the described specimen components in their mounted state, apart from bearing the façade dead loads, is to conduct the wind loads out of the building hull, while the connected beams of the façade construction transmit these effects into the profile at certain points. Due to the actual load transmission, the four-point bending test was ideal for conducting tests on the girders. For this reason the composite section was examined regarding the carrying and deformation behaviour of the joint using the test setup in Fig. 9. Here the test setup was chosen to be symmetrical and the load application occurred in the third points. The loads were transmitted into the profile via a fourfold shear bolted connection, so that an early failure of the system by buckling of the webs was prevented. This type of connection reflects the practical connection situations very well and is also an easily calculable type of load transmission. The support and application points were designed so that horizontal deformation and rotation could occur tension-free. Welded elements in the supports prevented the girder from tilting and thus guaranteed positional stability. A continuous measurement of loads, deformations and strains allow a comprehensive study of the structural and deformation behaviour of the reinforced façade profile. The experiment was conducted displacement-controlled with a test speed of 2.5 mm/min, so that the load conditions could be seen as quasi-static.

The evaluation of the experiment shows that those reinforcements bonded with SikaFast 5241 failed through a special cohesive failure in the bondline at the hollow section surface. The adhesive allowed greater deformations and failed in a more ductile manner than those bonded with DP490, which is positive in regard to an advance notice of failure. 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.

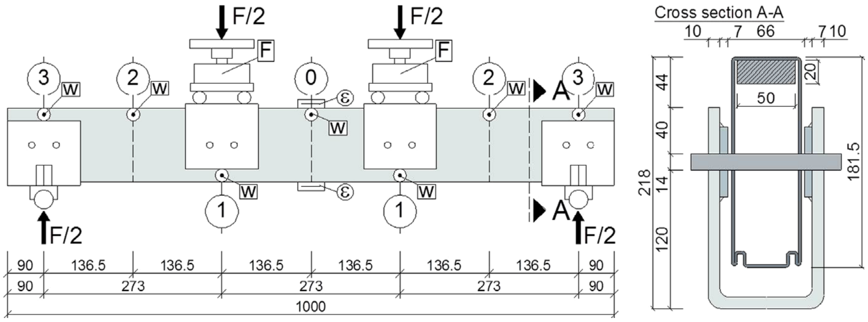

Fig. 9. Test setup: façade reinforcement, dimension in mm.

Independent of the chosen adhesive, the behaviour of the specimen components "bonded façade reinforcement" can be described as approximately linear until failure, which can be useful for simple manual calculations.

4. Calibration of design rules

4.1. General remarks

The statistical calibration was conducted based on experimental results for the specimen components. The starting point of the statistical examinations were analytical models based on the theory of elastically supported slabs.

By means of the experimental results of the butt joint tests, shear lap tests and specimen component tests, the parameters for the statistical functions normal distribution, log normal distribution and Weibull distribution were estimated, using various methods. The utilized distribution types were estimated by various point estimate methods and subsequently checked by a goodness of fit test (Anderson–Darling test).

It was determined that the tensile strength, lap shear strength, the ultimate load of the specimen components as well as all other basic variables could be accurately represented by a normal distribution, and partially also by a log normal distribution. For all basic variables and the results of the 1:1 experiments statistical outlier tests (Dixon *r*-test) [16] were conducted on a 95% significance level. The requirement for a nearly normal distributed dataset is thereby fulfilled for all parameters. In each case, it was examined whether the smallest or largest result of the test series represented statistical outliers and if these must be removed from the basic set.

When a statistical outlier was detected using Dixon's *r*-statistics, it was discarded and a new sample was formed. Because by this process the parameters of the distribution functions and their suitability to describe the stochastic character changes, the methods parameter estimation and goodness of fit test had to be repeated. Apart from the analysis of the experimental results by statistic tests, the consistency of the dataset had to be verified based on the defined population.

4.2. Façade connection

Starting point of the calibration procedure, which follows, is the juxtaposition of theoretical results of the analytical model with the experimental results. For this purpose the model [4,17] must be reconditioned accordingly, in order to obtain information on the expected normal stresses in the bondline (Eq. (8)).

$$\sigma_{k,i} = F_{\max,i} \times \frac{f_\sigma(\xi)}{L_0} \times \frac{f_B}{B_0} \tag{8}$$

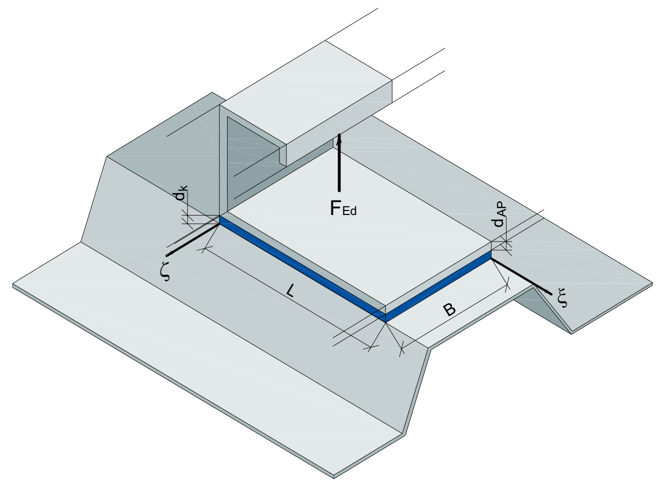

Fig. 10. Façade connection.

here the results of the specimen component experiments on the bonded façade connection must be inserted for $F_{\max,i}$ while L_0 and B_0 are system-specific values and refer to the length and width of the joint in Fig. 10, respectively. In the longitudinal direction of the bondline, the plate bending stiffness of the connection profile is to be considered, and in the breadth that of the trapezoidal profile. Through the system specific measurements the stochastic character of the E-modules (Young's modulus) of the adherents and the joint is included in the model. The form function $f_\sigma(\xi)$ captures the qualitative normal stress distribution in the bondline based on the theory of elastically supported slabs. For the user, the function is presented graphically, so to determine the normal stress the values can simply be read. The load applied during the experiment causes an influential stress concentration in the load application point, at $\xi = 0$. Thus the form function at this point must be evaluated during the model calibration. The initial equation (Eq. (8)) forms the basis of the comparison between theoretical and experimental results. Inserting the experimental results of the specimen component $F_{\max,i}$ yields the maximum normal stress $\sigma_{k,i}$. The juxtaposition of these values with those of the butt joint test whilst considering the characteristic value of the tensile strength is the purpose of the concept calibration.

$$F_{\max,i} = \begin{bmatrix} 1848.75 \\ 1878.00 \\ 1974.50 \\ 1995.75 \\ 2306.00 \end{bmatrix} N \quad \sigma_{k,i} = \begin{bmatrix} 2.892 \\ 2.938 \\ 3.089 \\ 3.122 \\ 3.607 \end{bmatrix} \frac{N}{\mathrm{mm}^2}$$

The calibration resulted in a partial safety factor for the specimen component "bonded façade connection" of 2.16.

4.3. Façade reinforcement

Similar to the procedure for the bonded façade connection, the analytical model [4,17] was prepared to state the normal stress in the bondline.

$$\sigma_{k,i} = \frac{F_{\max,i} \times f_{starr}}{b_{eff,\sigma} \times L_{eff}} \tag{9}$$

here the results of the specimen component tests on the bonded façade reinforcements are to be inserted for $F_{\max,i}$, while f_{starr} is a dimensionless parameter that incorporates the existing composite properties.

Furthermore, the basic Eq. (9) contains the value of an effective length L_{eff}, which incorporates areas of discontinuity by the connection situation, and an effective width $b_{eff,\sigma}$, determined by Eq. (10).

$$b_{eff,\sigma} = \frac{b_0}{f_\sigma(\xi)} \tag{10}$$

At this point, the analytical model for the bonded façade connection is resorted. Also, based on the theory of elastically supported slabs a form function $f_\sigma(\xi)$ can be evaluated at the relevant position and considered for the concept calibration. The hollow profile is defined as a plate in the joint area.

The presented system of equations forms the scaffolding for the comparison of theoretical and experimental results.

$$F_{\max,i} = \begin{bmatrix} 179.4 \\ 181.9 \\ 188.1 \\ 192.8 \end{bmatrix} kN \ \sigma_{k,i} = \begin{bmatrix} 56.21 \\ 57.00 \\ 58.94 \\ 60.41 \end{bmatrix} \frac{N}{mm^2}$$

The calibration resulted in a partial safety factor of the specimen component "bonded façade reinforcement" is 1.56.

4.4. Determination of conversion factors

In a subsequent step, the conversion factors for the coverage of environmental dependent influences η_t and manufacturing effects η_m must be determined.

For the employed adhesives, η_t-values are determined for different exposures by small specimens and specimen component tests. Because the reference components are from façade structures, the effects of exposure temperature are of particular interest. For this reason, the examinations focus exclusively on temperature effects from $-20\,^\circ C$ to $+80\,^\circ C$.

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.

For the statistical conceptions, it is assumed that the effects remain constant and the resistance is shown as dependent on the environmental condition or bondline thickness, see Eq. (11).

$$R = f(T) \text{ or } R = f(d_k) \tag{11}$$

herein, T is the temperature and d_k indicates the bondline thickness. The entire period of the variables is divided into p regions (Fig. 11). The length of each region is chosen so that the influence on the resistance in this region remains small. As a conservative simplification, only the resistance value at the end of such a region is considered. The distribution function of resistance must be formulated depending on the variables (T, d_k).

To determine the conversion factors and the probability of failure, probabilistic conceptions with respect to possible probability functions are employed. A conservative simplification is to divide the reference range in one period and to determine the resistance at its end. If the distribution functions of resistance depending on environmental conditions are known, the design value at the end of the period $R_d(T_p)$ or $R_d(d_{k,p})$ can be calculated. The conversion factor is then given by Eq. (12).

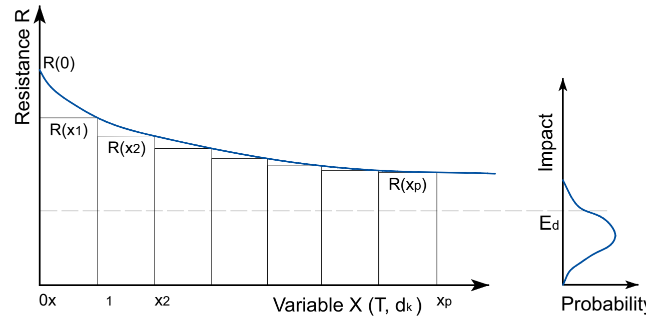

Fig. 11. Procedure of determination of conversion factors.

$$\eta_t = \frac{R_d(T_p)}{R_d(T_0)} \quad \text{or} \quad \eta_m = \frac{R_d(d_{k,p})}{R_d(d_{k,0})} \tag{12}$$

The results of the experimental and statistical investigations for three adhesives are summarized for temperature dependent effects in Table 1 and for the influences of bondline thickness in Table 2.

It is shown that 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 some adhesives at high temperatures and different bondline thicknesses the conversion factors are declared for ranges.

5. Discussion

To be able to conduct a concept calibration according to current standards in civil engineering, the requirements of the reliability method and the Eurocode must be guaranteed. For evaluation and interpretation of the experimental results it is necessary to define a population to be examined. During the course of the statistical calibration, results that are consistent in their failure criteria, expansion rate, maximum strain and prevention of transverse strain can be used. The examination of the requirements of consistency already clearly shows the problem of converting findings from small specimen tests to specimen components. Under load the bondline behaves anisotropic. Different states of transverse strain, stress distributions and expansion rates are found in the experiments. Whilst elastic adhesives tend more towards lateral contraction, structural adhesives show a much lower transverse contraction. In the scope of the research three adhesive layers with different propensity of lateral contraction were studied. Jointly calibrating these in a single concept poses a major problem of consistency.

Even the temperature influence on the structural behaviour is dependent on the type of specimen and the experimental boundary conditions. This is caused by a hydrostatic stress condition in the bondline of the specimen components. Such a stress condition could not be produced by the small specimens. The effects of temperature influences on the structural and deformation behaviour could not be transferred between the different experiments.

The various discontinuities in the experiments have different influences on the results of the statistical calibration, which must be regarded, respectively. But during application of the semi probabilistic method according to Ref. [7], the discontinuous results are jointly considered and transferred from the small specimen to the specimen component.

Furthermore, in the simplified material model, the depiction of the bondline as springs, the energy-elastic behaviour of adhesives

Table 1
Conversion factors for environmental dependent effects.

η_t	Körapop 225-2K		SikaFast 5241		DP490	
	$-20\,°C \le T \le 25\,°C$	$T > 25\,°C$	$-20\,°C \le T \le 25\,°C$	$T > 25\,°C$	$-20\,°C \le T \le 50\,°C$	$T > 50\,°C$
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 2
Conversion factors for manufacturing dependent effects.

η_m	Körapop 225-2K	SikaFast 5241	DP490	
	$2\ mm \le d_k \le 5\ mm$	$2\ mm \le d_k \le 5\ mm$	$0.2\ mm \le d_k \le 0.5\ mm$	$0.5\ mm < d_k \le 2\ mm$
Shear	0.25	0.15	0.51	0.12
Tension		0.76		

cannot be taken into account. The analytical model is based on the principle of verification on stress level. The occurring stresses in the bondline are dependent on the parameters of the population (e.g. expansion rate, transverse contraction) and constitute the effects. These are juxtaposed to the bondline resistances, which are obtained as 5%-fractile of the strength parameters from the small specimen tests. It can be seen that the resistances themselves are dependent on the boundary conditions, such as expansion rate and states of lateral contraction. The assumption of statistical independence between effects and resistance, which is necessary for applying the semi probabilistic concept according to Eurocode, does not apply in this case.

To be able to develop a universal rule for the calibration of bonded joints, the problem of consistency must be focused on. As such, the introduction of expansion rate regulated experiments is recommended, as well as introducing energy-based material models for the bondline. Through a sufficiently accurate description of the bondline by thermo-physical means, the foundation for the assessment of the energy-elastic and entropy-elastic behaviour of adhesives can be formed. Furthermore, by an additional implementation of the value time, creep effects, temperature influences as well as chemical and mechanical ageing could be considered. Even though this leads to a complex physical model in the baseline, by providing "master curves" and design aids, the demand by civil engineers of closed and simple models can be met. With the assistance of such a material model the description of alternative design levels is appropriate. Instead of the typical proof level of ultimate stresses, proofs in the ultimate limit state as well as serviceability limit state, based on maximum expansion rates, deformations and energy states in the bondline are recommended.

All results obtained which are discussed in this report apply only to a single, quasi-static loading up to failure of the bondline. The developed coefficients (partial safety factors and conversion factors) apply to the described experiments, parameters and boundary conditions. Time- and environmental dependent influences are simplified. For example the description of a structural behaviour of adhesive bondlines with preliminary damage or considering creep is not possible with the parameters determined. However, the model is simple in its fundamentals and can be extended accordingly.

6. Conclusions

For two specific use-cases of bonding in civil engineering, the presented procedure resulted in standards-compliant analytical models. Partial safety factors and conversion factors were determined based on the limit state concept of Eurocode. The partial safety factors consider natural scattering of bondline parameters, model inaccuracies and a permitted safety level, while the conversion factors take into account environmental and manufacturing dependent effects. These factors reduce the design value of the resistance and describe the resistance as a decreasing function in relation to the influences temperature and bondline thickness.

With the scientific and technical result of the presented procedure, two Eurocode-based calibrated bonded steel constructions are available. The application of the partial safety factor concept and other key methods in the design of bonded joints are thus further consolidated. Especially in the area of steel structures, it is to be expected that the acceptance of use of the joining process "bonding" will continuously increase, and so with a growing number of functional and calculable applications, the general interest in producing standards as a basis for analysis and design of adhesive joints in steel is expected to rise.

Since the developed methodology can be used for the development and market introduction of further applications of bonding technology in construction, the effort for the introduction of innovative products 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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