BONDING TECHNOLOGY IN STEEL STRUCTURES

A Summary of Research Activities at Chair of Steel and Timber Structures

Yvonne Ciupack, Hartmut Pasternak
Chair of Steel and Timber Structures, Brandenburg University of Technology, Cottbus, Germany

ABSTRACT

The bonding technology is an innovative alternative for typical joining methods in steel structures. Since more than 10 years the Chair of Steel and Timber Structures studies the potential of bonded steel joints within the scope of various research projects, which are presented in this paper. Two new application examples for façade construction are being investigated from the beginning. For these structures constructive solutions, mechanical models, design rules and testing procedures for cyclic loading were developed. The efficiency of refurbishment measures made with bonded CFRP laminates is a second research field of the chair. The future work will focus on long-term effects and cyclic loading of bonded steel joints.

INTRODUCTION

The joining technology plays an essential role in steel structures. It influences the costs of manufacturing and mounting as well as the quality of execution. The requirements on joining techniques affect the static and dynamic carrying capacity, the safety and reliability, the geometric precision as well as aesthetic and durability. The application of traditional joining methods is limited regarding the cross section reduction through drilled holes, the residual stresses through welds and the fatigue strength through notch effects together with aesthetic reasons. As an alternative to welding and screws, the bonding technology provides considerable advantages for this requirement profile.

Bonded joints are successfully used in other industries, e.g. automotive and aviation. Despite many technical developments and improved long-term resistance of adhesives, there is no noteworthy application example of adhesive bonding in structural engineering.

The Chair of Steel and Timber Structures investigates the innovative bonding technology within the scope of different research projects, some of which are presented in this paper.

DEVELOPMENT OF NEW APPLICATIONS OF BONDING TECHNOLOGY

In a first research project (Dilger *et al*. 2008) two different application examples for bonded steel joints in steel façades were developed. With these constructions a research unit was created, which still remains and has been expanded during the years at the chair. The examples of a bonded façade connection and façade reinforcement will be presented in the following.

Bonded façade connection
Trapezoidal façades are used especially for industry halls. Commonly the connection of the trapezoidal sheet with the support structure is realized with self drilling screws. Thus the cross section of structural elements is reduced in the area of the joint, which leads to a decreased load carrying capacity and stress concentration. This detail means degradation, particularly for the fatigue limit strength of the construction. This unsatisfying situation can be prevented by using bonding technology. By bonding the trapezoidal sheets to the support structure with the assistance of modified connection profiles, the cross section reduction can be avoided.
Such an alternative joining method does not only provide an advantage regarding the carrying capacity, but also improves the aesthetic of the façade view by avoiding visible fastener heads. Errors, dents or scratches, which can occur during the mounting, are avoided. Besides, an essential benefit is the preservation of the self cleaning effect of the façade through the absence of screws at the outer shell.
It is necessary to abide to the rules for bonding-suitable construction, in order to successfully establish this innovative façade joint. The connection is designed so that the complete bonding process can be realized under defined conditions in a laboratory. Thus, a specially shaped connection profile is required. Different design variants for the bonded façade connection are shown in figure 1a).

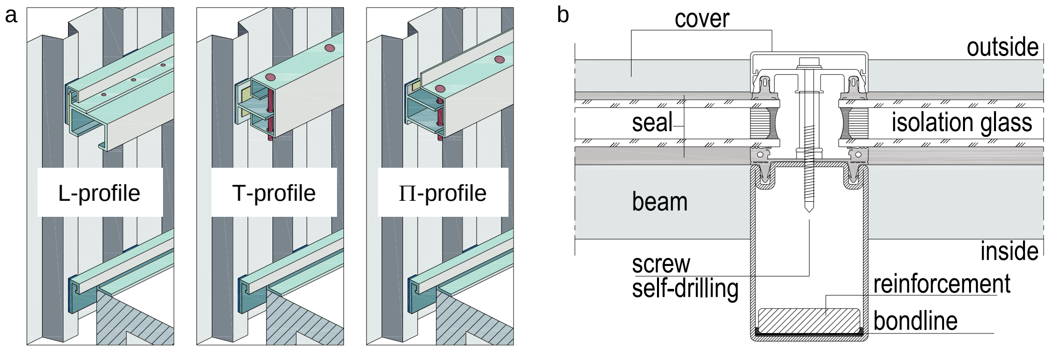

Figure 1: (a) Structures for bonded façade connections with different shape of connection profile; (b) Bonded façade reinforcement

Bonded façade reinforcement
The modern city panorama is defined by glass façades and slender structure components. Architects and builders demand high side view transparency, as well as segmented and wide opened façades. Therefore, transom-mullion façades are often realized.
With this construction, the wind loads are transferred from the outer shell to the mullion profiles, which induce the impacts to the transom profiles at certain points. This way, the transom profiles are stressed by bending moments and transfer the loads to the foundation.
To ensure the required side view transparency, small transom profiles need to be used, which can be arranged with high distances in-between. Thus, a reduction of the cross section dimensions, as well as decreasing of profile stiffness and carrying capacity is required simultaneously. For hollow profiles one possible solution can be found by using sections with thicker profile walls. In contrast, this kind of elements is produced with a cold forming process, which is limited to certain sheet thicknesses. The bonding technology provides an innovative and simple alternative. With the

application of an inner reinforcement (see figure 1b) the transom stiffness can be increased without changing the outer dimensions. This new compound cross section shows an increased carrying capacity compared to typical façade profiles and allows the retention of common mounting methods on site. The bonding process is conducted by means of a pneumatic method in a laboratory.

The pre-assembled profile will be connected with the mullion elements on site by use of dowel type fasteners. Such kind of façade structure provides high transom distances with slender profiles, so that the construction meets the requirement of side view transparency.

The principle of the hollow façade profile with bonded inner reinforcement is comparable to the carrying behaviour of glued laminated timber. That means, a composite section is created to increase carrying capacity and stiffness. In contrast to timber structure, the stiffness of the steel adherends is so high, that a proof of the bondline could be decisive. This fact should be considered in a design model.

DESIGN RULES FOR BONDED STEEL JOINTS

For the definition of design rules, according to the standards, mechanical models are essential for the description of the bondline behaviour. In the scope of different research activities (Dilger *et al*. 2008, Meinz 2010) two design models for the mentioned application examples were developed. The fundamental ideas of these resistance models will be presented in the following chapters.

Design of bonded façade connection

For the design of bonded façade connections an analytical model is used, based on the weakest-link-theory. The essential mode of failure can be identified by comparing the failure modes of the joint components. These are the connection profile, the bondline and the trapezoidal sheet. The resistance of the whole joint can be expressed as the smallest component resistance.

Based on the theory of elastic supported slabs, Meinz (Meinz 2010) developed a design approach for the prediction of the bondline resistance. Therefore, the joint is divided into partial models for every supporting direction. A superposition of these partial models at the end of the design procedure provides the three-dimensional system and the complex stress distribution in the bondline. The principle of the design concept is shown in figure 2.

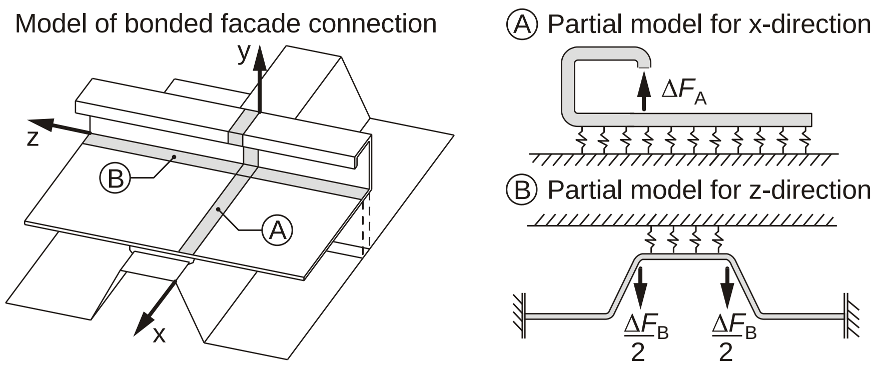

Figure 2: Model for the bonded façade connection

Design of bonded façade reinforcement

The concept for the design of bonded façade reinforcement is structured, so that the composite section is formed by the partial cross section of the reinforcement profile and the hollow profile. The first step is the proof of a quasi-rigid compound. Therefore, a dimensionless shear-effect-value is introduced and deduced from the differential equation of beam deflection and joint displacement for semi-rigid compound. If this proof has been met, a comparison of the bondline strength with the determined stresses follows. To describe the complex stress distribution in the bondline a procedure is included which is based on the theory of elastic supported slabs. This procedure is equivalent to the method for bonded façade connections. To take into account the concentrated load introductions at the joints between the transom and mullion profiles, effective lengths are determined based on numerical studies for different connection details of typical façade joints.

Model calibration

In a further project (Pasternak 2012) the presented models were calibrated aiming at the development of a general procedure of concept calibration for bonded steel joints. Basis for the calibration process is a description model for the prediction of the resistance which contains stochastic and deterministic parameters. A comparison of test result with model results is the essence of the method.

To determine characteristic material properties of a bondline based on Eurocode, so-called butt joint tests (DIN EN 15870) and shear lap tests (DIN EN 14869) were carried out. The results for tension strength (σ_k), shear strength (τ_k), Young's modulus (E_k) and shear modulus (G_k) are summarized in table 1.

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

Adhesive basis	σ_k	τ_k	E_k	G_k
MS polymer	1.31	1.32	5.64	0.54
Epoxy	38.7	29.3	3063	308.9

In a next step the investigations focused on specimen component tests for the application examples. The test setup needed to be realized so that a failure of the bondline can be observed. A general requirement is the warranty of a cohesive failure, which can be met by specific surface pre-treatments, e.g. blasting, of the steel adherends. Figure 3 shows the test setup and some results for the first application example.

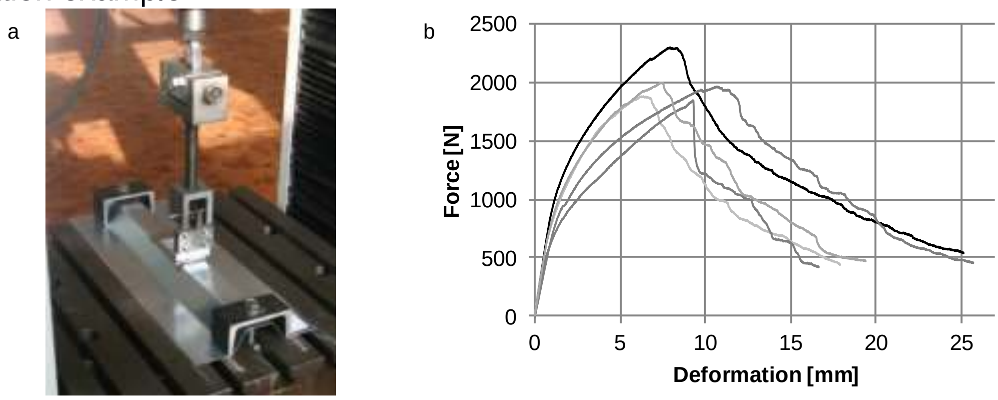

Figure 3: (a) Test setup; (b) Test results

The essential task of the bonded façade connection in the mounted state is the transformation of wind loads to the support structure of the façade. The critical wind suction loads are considered in the tests, because bondlines react more sensitive to tension loads than to compression. The specimen was modelled to be one corrugated segment of a 500 mm long trapezoidal sheet. For the bonding procedure a silane modified adhesive (MS polymer) was used, because it behaves elastic (see table 1), thus a deformability of the joint was ensured. The load introduction occurred perpendicular to the joint with a testing speed of 2 mm per minute to create a quasi-static stress state in the bondline. For all specimen tests a cohesive failure of the bondline could be achieved and the strongly non-linear behaviour was observed.

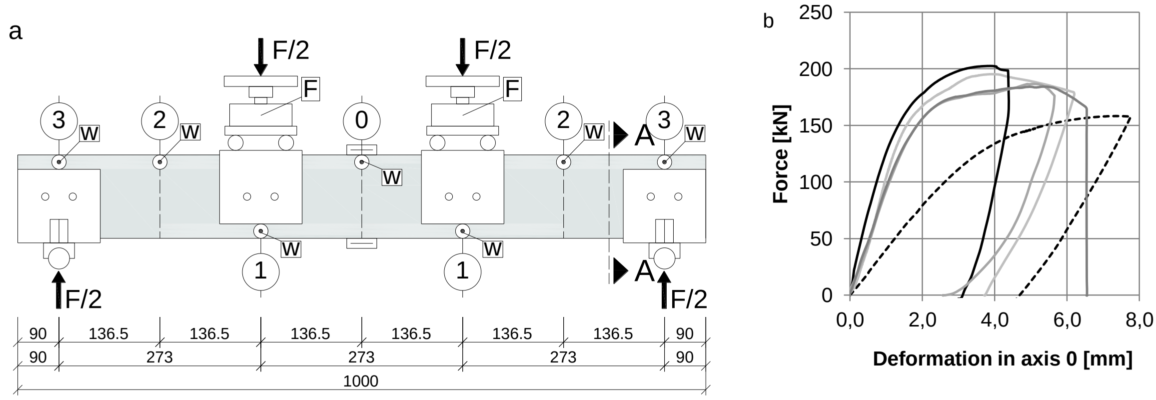

Figure 4: (a) Four point bending test; (b) Test results.

To investigate the reinforced façade profile, four point bending tests on a 1 m hollow section with inner steel reinforcement were carried out (figure 4). The compound between the adherends was made by an epoxy adhesive. Through the high stiffness of this kind of adhesive (see table 1) a quasi-rigid compound can be assumed. The real loading situation in the mounted state was modelled in tests with a load introduction into the specimens at bolted connections. A cohesive failure of the bondline due to restoring forces at the profile ends could be registered for all tests. A significant improvement of profile stiffness could be achieved compared to a reference façade transom without reinforcement (dashed line in figure 4).

Based on Eurocode (DIN 1990) the model calibration was realized in a final research step. The results are partial safety factors for the design of the mentioned application examples of bonding technology. For the bonded façade connection a factor of γ_M = 2.2 could be found and for the façade reinforcement γ_M = 1.6 , respectively.

Conversion factors

The objective of implementing conversion factors is to enhance the design model with the result that the resistance can be modified with the following equation.

$$R_d = \frac{R_k}{\gamma_M} \cdot \eta_i$$

The conversion factors η_i take into account the different influences on the value of resistance. Because the carrying and deformation behaviour of a bondline is significantly affected by the environmental temperature and the bondline thickness, the conversion factors η_t and η_m are introduced to the presented models. It is possible to describe the bondline resistance as a function of the specific influence value, based on small scale specimen tests with various temperatures and bondline thicknesses. The results of these experiments are considered in relation to reference values, which are generated from tests at normal condition (e.g. table 1). Figure 5 presents exemplary the results for the tests and the determined conversion factors at different temperatures for the MS polymer-based adhesive. A polymer specific behaviour, the decreasing of the bondline strength with increasing temperature, can be observed. Due to the fact that the conversion factors are referred to a defined limit state and thereby to a required target reliability of Eurocode, the determination of these factors is based on the design values of the resistance (see figure 5).

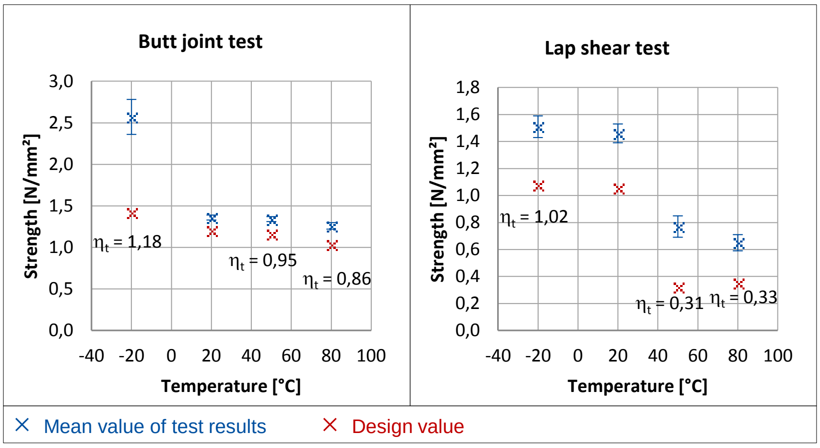

Figure 5: Conversion factors for a MS polymer adhesive

LONG-TERM BEHAVIOUR OF BONDED STEEL JOINTS

The presented investigations focused on quasi-static load situations and short-term loading. But it is known that the bondline strength can be reduced by long-term influences and cyclic loading. That is why ongoing research projects at the chair aim at taking into account such effects.

Cyclic loading

The objective of an ongoing research project is to carry out cyclic test procedures for the presented application of the bonded façade connection, taking into account long-term effects (Pasternak *et al.* 2016). In a first step, representative load functions for the test sequences were deduced from actual measured wind speed and air temperature data from various weather stations. The main procedure of the project was presented at Metnet seminar 2015 (Ciupack *et al*. 2015).
In order to describe the general behaviour of bonded joints under cyclic loading, some investigations on small scale specimens and the façade connection were carried out under constant amplitudes. The stress ratio was chosen with a value of 0.1, which means a varying but permanent tensile loading for the bondline. To prevent heating of the adhesive due to mechanical load, the tests were carried out with a frequency of 5 Hz. If $2 \cdot 10^6$ load cycles are reached and no damage is detected, the value of the load is assigned within the fatigue strength. The results of these examinations for a polyurethane adhesive are shown in figure 6.
All specimens failed with a cohesive failure of the bondline. The notch sensitivity (k) is calculated with a value of 6.19 for the butt joint tests and of 6.74 for the façade connection. The threshold of the load, which the joint can withstand permanently (fatigue limit S_k), is evaluated with a value of 3.3 kN for the small scale specimen and of 1.3 kN for the specimen component.

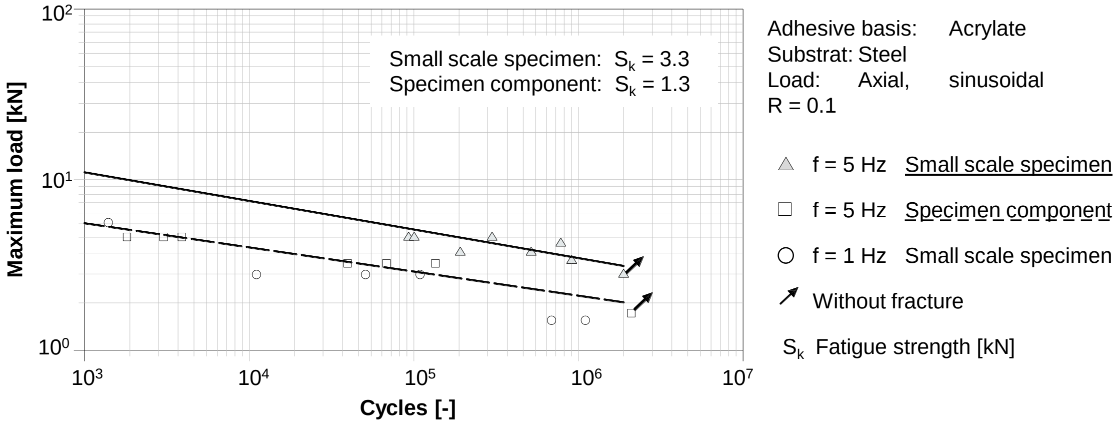

Figure 6: Comparison of test results of cyclic tests

Additional pre-investigations showed a dependency of the bondline strength on the testing frequency (circular symbols in figure 6) for small scale specimens. The lower the frequency, the smaller the fatigue limit strength. Based on these experiments it can be concluded that the real wind load sequences (low frequency and small amplitudes) mean higher fatigue damage than observed in the standard experiments. The future work of the Chair will focus on the possibilities of modelling the actually amplitude collective and frequencies as well as methods to reduce testing time of cyclic tests.

Creep behaviour

If the trapezoidal façade is used as structural or stabilizing construction element, the bonded connection is loaded by wind loads and dead loads simultaneously. Such long-term impacts lead to creep effects in the bondline.

To study the general creep behaviour of bondlines shear creep tests at overlapped steel plates bonded with a structural epoxy adhesive were carried out (Sahellie *et al*. 2015). The testing time totalled to 110 days and the testing condition to air temperature of 20 °C ± 2 °C, relative humidity of 65% ± 4%, respectively. The objective was to estimate the bondline strength for defined a lifetime. Therefore, two model for viscoelastic materials were used, Findley's and Burger's models.

The test results showed that the shear creep behaviour is dependent on the magnitude of the applied stress. Moreover, it was found that Findley’s model fits better to the data for shorter lifetime periods in general. But longer lifetime of adhesives should be predicted by Burger's model. Findley's model, which indicated huge relative errors, is not useful for predicting long lifetimes due to the unlimited retardation spectrum of that model (Feng *et al*. 2005).

REINFORCEMENT OF STEEL STRUCTURE WITH BONDED CFRP LAMINATES

General investigation

An innovative alternative to typical reinforcement measurements of steel structure, e.g. welding or screwing of additional steel sheets, could be created by bonding of CFRP (carbon fibre reinforced polymer) laminates to the steel members. In the scope of an initial research project (Pasternak *et al*. 2015) applicability and efficiency of steel-CFRP-composites were studied. The main objectives were the testing based

and analytical demonstration of the potential, as well as the development of recommendations for utilization of bonded CFRP reinforcements in steel structure.
Different influences of parameters, e.g. bondline thickness, joint length and surface pre-treatment of adherends, were studied at double lap shear joints. Moreover, aging tests were performed at shear lap specimens, which were outsourced at various temperatures and climate conditions. The corrosion resistance was determined by means of salt spray tests.

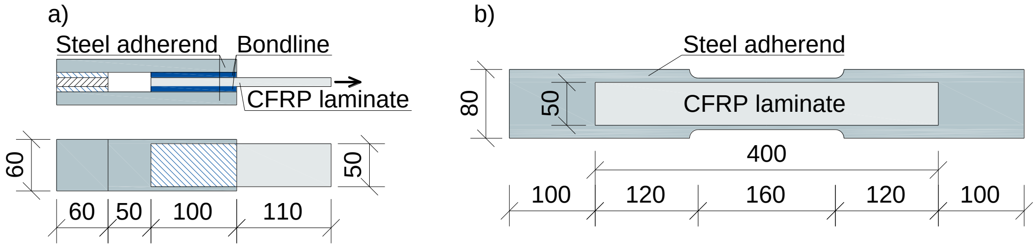

Figure 7: (a) Double steel-CFRP laminate-assemblies; (b) dumbbell specimen

These investigations were carried out within tensile shear tests at bonded double steel-CFRP laminate-assemblies based on DIN EN 1465 (see figure 7a). It was shown that the carrying capacity of the specimens can be increased by increasing the joint length up to 100 mm. From this specific joint length, no essential improvement of bondline strength was possible. For all tests an adhesive failure at the laminates surface was observed, which can be explained by the characteristic of the employed adhesives, commonly used for the bonding of CFRP laminates to concrete. Thus, the adhesive is designed for adherends with lower strengths than steel members. Taking into account aging effects, the specimens were tested for climate change conditions based on DIN EN ISO 9142 with single dependency (temperature) and double dependency (temperature and humidity). Depending on the kind of adhesive, degradation effects but also post-curing effects were observed.
The described experiments were repeated for 8 mm thick dumbbell specimens (see figure 7b) loaded by tension. Supplementary to the mentioned influences, the arrangement of the CFRP reinforcement was investigated, single-sided and double-sided. Some results are presented in figure 8. The efficiency of this reinforcing measurement is shown in the diagram, because the resistance of the double reinforced specimen is 38% higher than that of the reference.

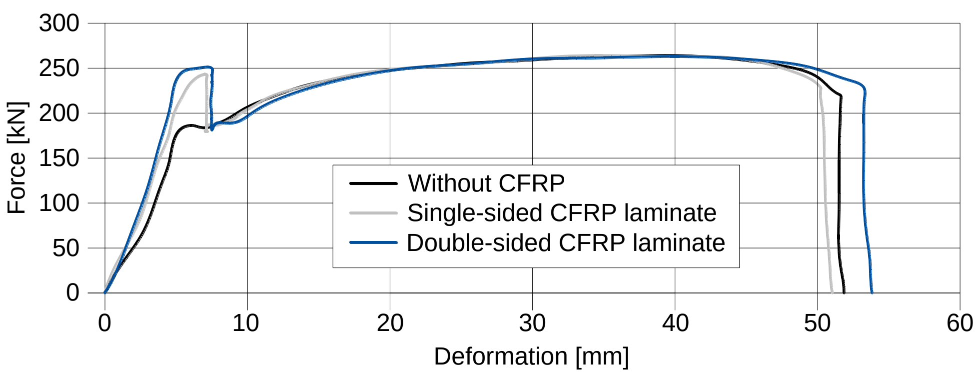

Figure 8: Diagramm CFK

Refurbishment of fatigued stressed steel members

An ongoing research project (Ummenhofer *et al*. 2016) deals with the refurbishment of steel structure with bonded CFRP laminates. The main idea is to substitute common refurbishment measures, e.g. welded steel sheets, with this innovative rehabilitation method. On the one hand, the possibility of refurbishment of cracked welds will be investigated. And on the other hand, the efficiency of bonded CFRP laminates or sheets for the reduction and the avoidance of crack growth will be studied.
Thereby, different application dependent retrofitting measurements will be developed and tested in for cyclic loaded specimens. The focus is on long-term effects, e.g. the decreasing of pre-stressing of CFRP sheets through the creep behaviour of a bondline. The development of a suitable testing methodology is planned for the characterizing of the carrying and deformation behaviour of CFRP reinforced steel construction, aiming the establishment of this new refurbishment procedure.

CONCLUSIONS AND FUTURE WORK

Bonding technology is more than just an alternative joining method for steel structures, which can be shown by various applications and research projects in different fields. Despite many advantages of bonded joints, the civil engineering and especially steel construction community is reluctant in embracing this innovative technique. Often it is justified by doubts about the durability and a lack of experience. Interpreting such doubts as open questions and challenges creates the possibility and the potential for exceptional innovations. The general interest in developing standards as a basis for analysis and design of adhesive joints in steel is expected to rise with a growing number of functional and calculable applications.
The future work for the presented application examples for façade structures focuses on experimental investigations under variable amplitudes and the creation of a scientific based guideline for the design of bonded steel joints. 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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