ADHESIVELY BONDED FAÇADE JOINT UNDER CYCLIC SERVICE LOADING

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***Abstract**: This paper presents briefly obtained results of ongoing research project on the determination of the durability and estimation of the lifetime of adhesively bonded steel-steel joints under cyclic loading. The fluctuating service conditions are represented by the loading models of the façade connections. They consist of, apart from the self-weight of the outer shell, wind and temperature cycles. The time course of the façade temperature is determined by means of a structural physics balance equation, and the relevant limiting temperatures for Germany are determined statistically (-20°C and +80°C). The method for simulation of the wind stress, based on computer generation of stochastic stress-time function according to limited measured data, is presented. The important part of the project is the selection of suitable adhesives for steel construction. The decisive criteria for the selection are mechanical properties of the adhesives and the adhesion properties of the steel surfaces. As the result of the investigation, three different adhesive systems are selected (acrylate system and epoxy-based system, as well as a polyurethane-based adhesive).*
***Key words**: Steel joints, cyclic loading, fatigue, lifetime, temperature, wind, structural adhesives.*

1. Introduction

Application of adhesive bonding technology is an innovative and progressive alternative to the traditional joining methods in structural steel (screws and welding). However, there are examples of structural use of adhesive bonding in civil engineering in the past, e.g. the bridge over the Lippe channel in Marl, built in 1955 and still in use without any major intervention [1]. The potential of adhesively bonded steel connections has already been investigated at BTU in the scope of two research projects [2,3] and in the PhD dissertation [4]. The ongoing research project [5] continues the research on bonding technology in steel construction. Since the research project deals with cyclic loading of glued façades, the relevant aspects are effects of temperature and wind load, which are transmitted through the structure of the exterior façade.

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2. Joint components

Due to the fact that the bondline geometry significantly affects the connection behavior under stress, all studies relate to specific connection geometry. Geometry used in the scope of this project was optimized in [4]. The aim of the optimization was to avoid stress concentrations, as well as achieve the maximum load capacity. This results in the connection geometry (T-connection), which has nearly uniformly distributed tensile stress in the bondline - see Figure 1b) and 1c).

2.1. Structural configuration

Figure 1 shows the studied structure, which is most commonly known as mullion and transom façade. The supporting structure is formed from the mullion and transom profiles. For assembling the façade structure, a T-profile was adhesively bonded to a trapezoidal sheet and fastened with a bolt to a transom profile. The transfer of the dead load is realized by the transom profile with closed cross-section positioned in the center and connected directly, without adhesively bonded T-profile. Through this type of fastening all manufacturing errors and tolerances can be compensated and the influence of the temperature deformation of the trapezoidal sheet on the adhesive bondline can be eliminated. Also, in this way adhesive can be applied in workshop which is of great importance due to the fact that gluing implies that all elements stay in the same position during the whole curing process.

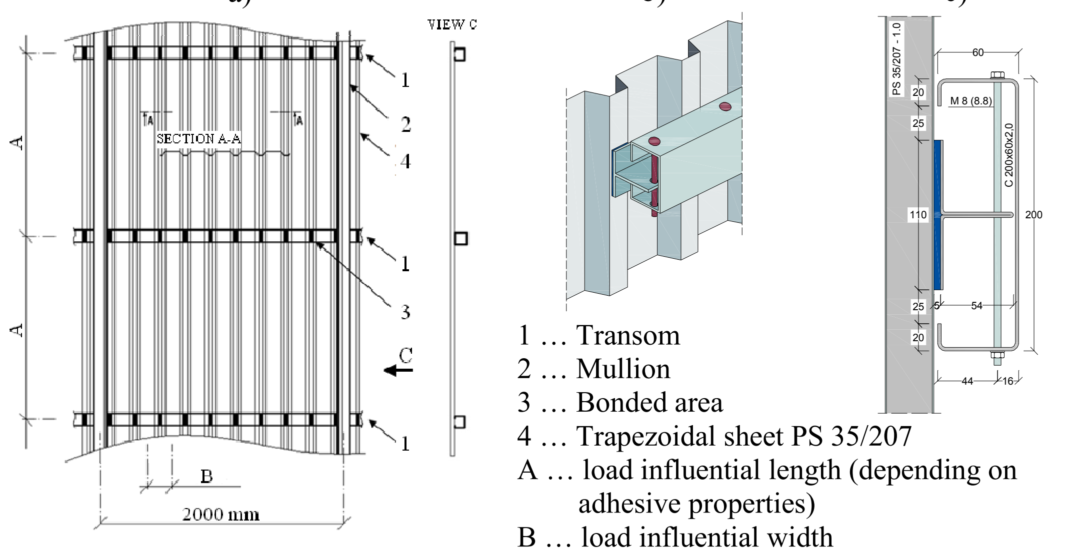


Fig. 1. Façade with adhesively bonded connections: a) technical view; b) schematic figure; c) cross section normal to the longitudinal axis

3. Temperature actions on the outer façade component

Temperature of the façade was calculated using the equation (1.1). The aim of the calculation is determination of the extreme temperatures for a period of 50 years (required for the static analysis) and of the time course of temperature load. The obtained values are given in Figure 2a). Extreme temperatures from the simulation confirm the temperature range from -20 °C to 80°C, defined in German codes [6], and are in agreement with Eurocode 1 [7]. Parameters that were considered in this analysis are shown in Figure 2b).

$$\alpha * I = (h_c - h_r) * (\vartheta_F - \vartheta_L) + \frac{1}{R_T}(\vartheta_F - \vartheta_i) + C * d * (\vartheta_{F(t)} - \vartheta_{F(t-1)}) , \qquad (1.1)$$

Where:

α: absorption coefficient

h_c: heat transmission coefficient by convection

ϑ_F: façade temperature

ϑ_i: inside air temperature

C: heat capacity of steel

I: solar radiation intensity

h_r: heat transmission coefficient by radiation

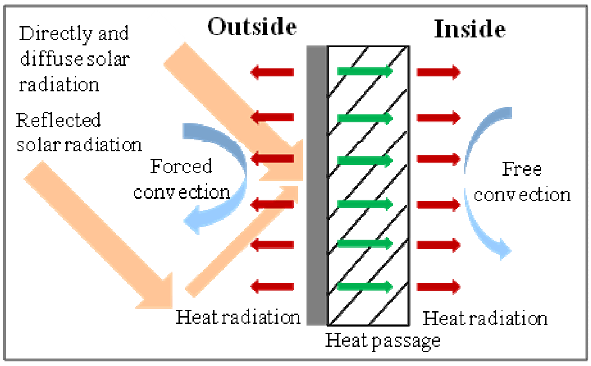
ϑ_F: outside air temperature

R_T: thermal transfer resistance

d: thickness of the trapezoidal sheet

City	Maximum [°C]	Minimum [°C]
Berlin	77.91	-18.52
Bremen	76.32	-16.12
Dresden	78.46	-18.33
Düsseldorf	76.48	-15.43
Erfurt	78.25	**-19.52**
Hamburg	76.00	-16.45
Hannover	76.82	-16.77
Karlsruhe	**80.34**	-16.56
Kiel	73.52	-16.67
Magdeburg	78.35	-17.48
Mainz	78.41	-14.98
München	79.13	-18.73
Potsdam	78.03	-17.10
Saarbrücken	78.16	-16.02
Stuttgart	79.33	-17.21
Wiesbaden	78.01	-16.15

a)



b)

Fig. 2. Temperature values and influencing parameters: a) temperature values obtained by the equation (1.1); b) the façade temperature influencing parameters.

The temperature analysis was performed on an hourly basis, since the hourly values provide a suitable loading cycle, which is shown on Figure 3. In order to fulfill all code requirements, the negative temperatures in two coldest months are adopted directly [6] (dashed line in Figure 3). The curve defines the temperature variation during a "model day" every month. The "model day" was determined by taking into account the largest and smallest calculated façade temperatures in each month. During the experimental investigation, a "model day" will be repeated the number of times equal to the number of days in the month.

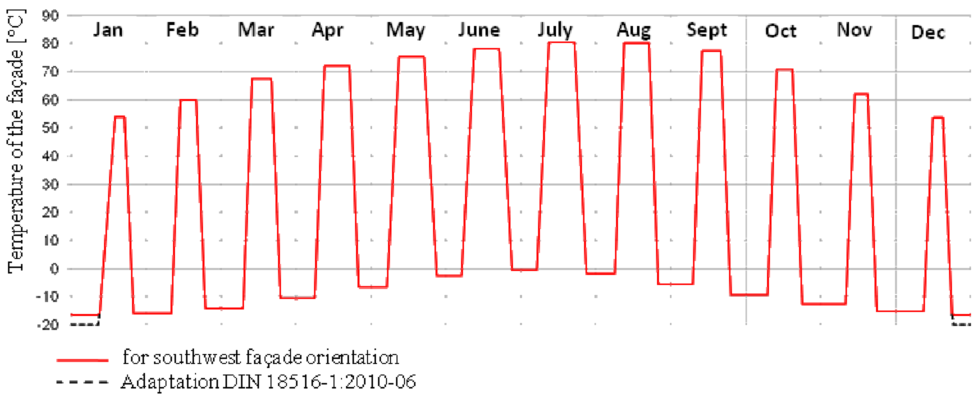


Fig. 3. Statistically determined temperature load cycle (Germany)

4. Wind actions on the outer façade component

Determination of the wind load history of façade compounds is a difficult task, because it is influenced by the vortex shedding frequency. Energy spectrum of the free wind flow is defined by the frequencies of the gusts that give a substantial contribution to the energy spectrum. This scale ends at 0.2 Hz [8]. The shedding frequency of vortices for the unsteady flow can be analytically expressed by Strouhals-number and in the project it is assumed to be 0.3 Hz[2]. In this context, the sampling frequency of the wind speed measurement is chosen to be 1Hz, which is sufficiently conservative. According to [9] the façade motion induced load can be neglected because of the minimal dynamic system response. It was also determined that the natural frequency of the pattern façade system is greater than 15 Hz (depending on the adhesive strength and transom spacing), so there was no danger of resonant behavior.

Whole procedure of the measured wind speed to cycle count is shown in Table 1. The transition of the wind speed at the local wind pressure on surfaces was done strictly according to [10].

Table 1. The wind data processing

<table>
<tr><th>Measured wind speed[3]</th><th>Step 1</th><th>Step 2</th><th>Step 3</th></tr>
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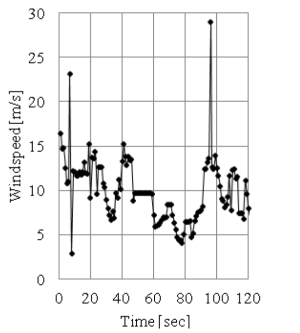
<td>
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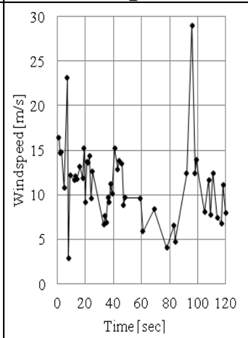
<td>
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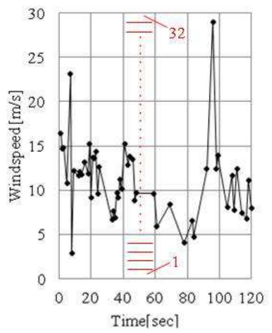
<td>
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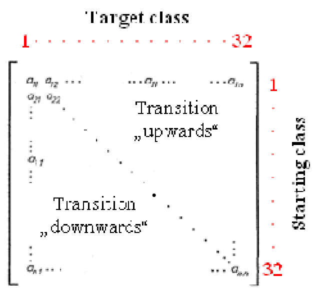
<td>
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<tr><th>Step 4</th><th>Step 5</th><td rowspan="2" colspan="2">Step 1: Separation of the turning points
Step 2: Division of the range of values into classes
Step 3: Counting according to the method of transition matrix (Markov-Matrix)
• One class comprises wind speed interval of 0.92 m/s</td></tr>
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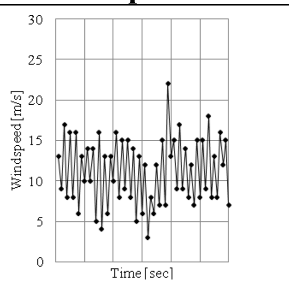
<td>
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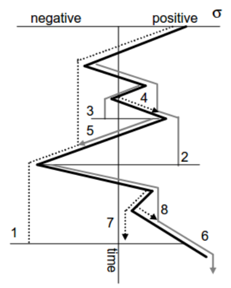
<td>
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Step 4: Digital generation of stochastic stress-time functions.

- It is possible to produce different functional sequences from the same transition matrix [11]. At present, the computer program for generating a Markov sequence of peaks is being checked for compatibility.

Step 5: Rainflow cycle counting method.

- The generated function is further processed by rainflow counting method which gives the number of cycles of corresponding amplitude for the whole range of amplitudes. In Table 2 the result of rainflow counting for a speed range (12.88 to 14.72 m/s) is given.

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[2] Value obtained for 10 m wide quadratic building, and wind speed 25 m/s (average wind speed for wind zone II)

[3] Scope of the data: January – December 2014, Source: KIT, Institut für Meteorologie und Klimaforschung: http://imkbemu.physik.uni-karlsruhe.de/~fzkmast/

Table 2. Rainflow cycle counting method – Example for 10 min sequence

Range [m/s]		Cycle	Ave	Max	Ave	Min	Max
From	To	Counts	Amp.	Amp.	Mean	Valley	Peak
12.88	14.72	7	6.9	7.36	14.98	6.44	23

The procedure described in Table 1 allows the exact description of the load history based on limited measurement data. This fact is of particular importance for the subsequent proposal of the design concept.

5. Selection of suitable adhesives and properties of selected adhesives

The experimental investigation on three types of adhesives was done at the Institute of Joining and Welding, University Braunschweig. The static strengths of these adhesive systems are given in Table 3. The selection was done based on mechanical properties of the adhesive system and adhesion properties of the steel surfaces. For the selection of the adhesive system it is important that the glass transition temperature should be as high as possible.

Since the bondline is loaded purely by normal stress, adhesive properties are obtained by performing but-joint tests [12]. In order to describe the influence of adhesive layer thickness on the tensile strength and the modulus of elasticity of the adhesive joint, these tests were conducted with four different adhesive layer thicknesses and two temperatures (Table 4).

Table 3. Results of tests on small scale samples at room temperature

Adhesive		Characteristic [MPa]	Adhesive layer thickness [mm]			
Basis	Product		0.3	1.0	3.0	5.0
Acrylate	Lord 410	$\sigma_{d,A}$[4]	25.44	24.57	20.05	20.29
		E[5]	129 277	90 583	28 269	16 159
Polyurethane	Körapur 842/20	$\sigma_{d,A}$[4]	11.94	11.72	7.26	4.09
		E[5]	110 763	23 171	7 296	1 988
Epoxy	SikaPower 477 R	$\sigma_{d,A}$[4]	35.91	36.62	31.25	23.63
		E[5]	159 953	96 513	45 594	25 227

Table 4. Results of tests on small scale samples at 80°C temperature

Adhesive		Characteristic [MPa]	Adhesive layer thickness [mm]			
Basis	Product		0.3	1.0	3.0	5.0
Acrylate	Lord 410	$\sigma_{d,A}$[4]	X	8.64	X	X
		E[5]	X	35 561	X	X
Polyurethane	Körapur 842/20	$\sigma_{d,A}$[4]	X	2.68	X	X
		E[5]	X	4 891	X	X
Epoxy	SikaPower 477 R	$\sigma_{d,A}$[4]	X	24.04	X	X
		E[5]	X	72 122	X	X

Note: X … currently not available

Failure mode observed (according to [14]) in all test series was cohesive to special cohesive.

[4] 5 % fractile from five samples
[5] Mean value from five samples – Bilinear idealization by [13]

Conclusion and future work

As already mentioned, the publication relates to the current state of the ongoing research project. The geometry was defined together with the properties of façade structure. Suitable adhesives were chosen in collaboration with the adhesive manufacturer. Their mechanical properties are determined. Based on the statistics, the temperature-time function was determined as well as the scientifically-based concept of wind-stress function.

The future scientific work will consist of experimental investigation on small scale specimens using the cyclic loading defined in the previous work under constant as well as variable amplitudes.

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