Technological and constructional aspects affecting bonded joints

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Abstract: Adhesive bonding is one of many materials connecting methods. In the last ten years periods the bonding technology noted a boom almost in all industrial branches. The use of bonding technology in the engineering and repairing industry brings considerable savings. Saving in costs, in critical metallic materials and in time are reached and the decrease of the joint weight, too. Therefore the bonding technology pertains to the modern jointing methods even though it is a very old technique. The adhesive bonding technology is influenced by a number of factors which affect the adhesive bond strength. Correcting coefficients have to be considered in construction calculations too. The correcting coefficients correct the strength deviations caused by particular factors. In the paper there are published laboratory experiments results.

Keywords: bonding technology; construction; corrective coefficients; testing of adhesive bonds

The contemporary trend in individual and repairing enterprises aims at production simplicity and effectiveness. With these aspects the continuous betterment and searching for new perspective technologies are connected, which facilitate the manufacturing process. That is one of basic steps which are needed for the securing of the competition ability. One of possibilities of perspective methods introduction is the choice of suitable jointing method.

Although wide possibilities of the bonding technology applying conduce to continual betterment of adhesives, designers still do not trust in this jointing method. This distrust is rightful and it has its source in the insufficient knowledge of factors which influence the resultant strength and the service life of bonded joints. For the concrete application of bonding technology the knowledge of technological principles is necessary. They influence the qualitative characters of the final bonded joint (Sadek 1987).

Most of the principles are regarded as self-evident but on the contrary some ones are underestimated. Using the bonding technology requires care and sequence of subsequent operations.

At bonding as at other jointing methods maintaining the strength values for the whole service time is important. From the long-lasting point of view the strength properties are influenced by a number of factors. The choice of adhesive, material and constructional configuration of partial bonded components pertains to significant parameters. Next it is necessary to take in consideration the influence of operational environment and load type. Single physical and chemical influences exert complex and they have not to be omitted (Peterka 1980).

But the first step is very important, which is the joint design, so that the unsuitable load types are eliminated, e.g. spalling.

At bonded joints only one loading type very seldom occurs. Usually the combined load is found. Most often we meet with the tensile lap-shear stress. Using those joints the nonuniform stress distribution in the whole surface and in the bonded joint edges the so-called stress peak values occur (Figure 1 and 2). The non uniform stress distribution in the adhesive line is caused by the bonded materials elasticity and deformation. By moment action of pair forces the stress concentration increases in the bonded joint edges. The pair forces evoke the tensile stress. Their maximum is in the joint edges and it is the cause of spalling. In this way the crack propagation and consequently the bonded joint destruction

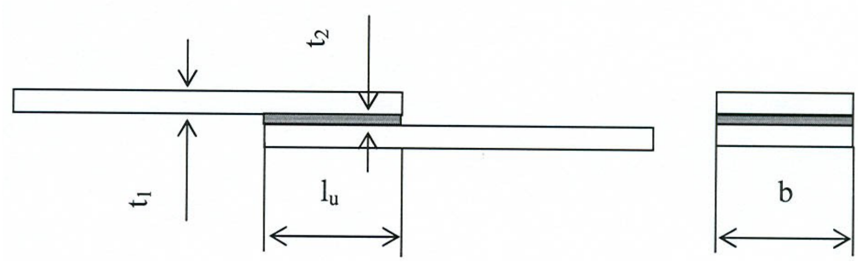

Figure 1. Lapped joint without design adaptations of spalling prevention

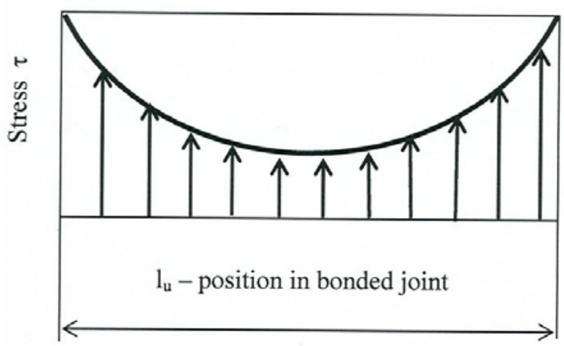

Figure 2. Shear stress distribution in the adhesive line over the lapped length

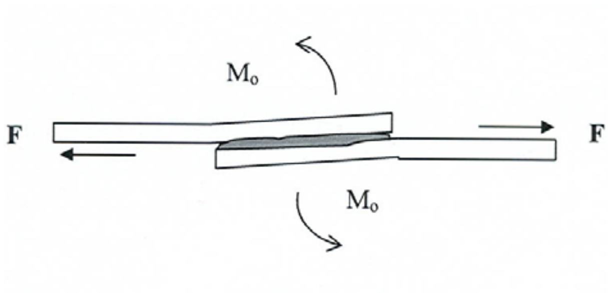

Figure 3. Deformation of the loaded bonded joint by the bending moment

occur. The spalling stress level can be decreased not only by the bonded material strength and thickness increase, but by various design adaptations, too. Then the designed joint must be adapted to the bonding technology requirements. Optimally the stress distribution must be uniform as possible (Reis 1998; Habenicht 2002).

When the lapped joint without adaptations is stressed (Figure 1), the force does not act in the plane of the adhesive line and when the force F increases the deformation of bonded materials (adherends) occur. At calculation it would be necessary to take the bending moment M_o in consideration (Figure 3), too (Kříž & Vávra 1994; LOCTITE 1998).

Theoretical calculation of the tensile lap-shear strength taking the bending moment in consideration presents the Eq. (1). The Eq. (2) presents the bending moment calculation and the Eq. (3) the modulus of resistance calculation (Herák *et al.* 2005).

$$\tau_{THEOR} = \frac{F}{bl_u} + \frac{M_0}{W} \tag{1}$$

where:

τ_{THEOR} – theoretical shear strength of the bonded joint (MPa)
F – acting force (N)
b – bonded adherend width (mm)
l_u – adherend lapping length (mm)
M_0 – bending moment (Nmm)
W – modulus of resistance for rectangular section (mm^3)

$$M_0 = \frac{F\,(t_1 + t_2)}{2} \tag{2}$$

where:

M_0 – bending moment (Nmm)
F – acting force (N)
t_1 – thickness of bonded adherend (mm)
t_2 – adhesive thickness (mm)

$$W = \frac{l_u^2 \times b}{6} \tag{3}$$

where:

W – modulus of resistance for rectangular section (mm^3)
l_u – adherend lapping length (mm)
b – bonded adherend width (mm)

Further the design engineer must suitably simulate the influences of various environment conditions and the acting stress distribution in the bonded joint.

For calculations it is very important to take corrective coefficients in consideration, which correct the strength deviations caused by individual factors. The corrective coefficients k_n should include information about bonded material, adhesive layer thickness, bonded surface preparation, bonded surface size, stress type and environment influence (temperature, moisture content etc.), which is the substantial part. The curing influence on the bonded joint strength for a certain declared time should be the integral part of the calculation.

From this enumeration it follows the necessity of the corrective coefficients k_n determination on the basis of laboratory measurements and calculations. The coefficients make the calculation of the joint real strength possible. Therefore it is important to modify the theoretical calculation and to add the corrective coefficients (4).

$$\tau_{REAL} = \tau_{THEOR} \sum_{i=1}^{n} k_n \tag{4}$$

where:

τ_{REAL} – real strength (MPa)

τ_{THEOR} – theoretical shear strength of the bonded joint (MPa)

k_n – corrective coefficients

As above mentioned a number of factors exists, which influence the bonded joint strength. In this paper only the environment temperature influence on the bonded joint changes is presented. On the basis of tests the possible deviation of the corrective coefficients for various adhesives can be determined. 4 two-component epoxy adhesives are judged. The aim of this experiment is to determine the different action of the used adhesives in dependence on the environment temperature.

MATERIAL AND METHODS

The experimental appraisal of environment temperature influence on the resultant bonded joint strength is the test substance, when destructive tests were carried out at various temperatures. On the basis of results the corrective coefficients were determined, which take the temperature influence on the resultant strength into consideration. Tests were carried out according to ČSN EN 1465 (1997). Using this standard the tensile lap-shear strength of rigid-to-rigid bonded assemblies is determined. The shape and dimensions of steel and duralumin specimens are presented in Figure 4.

The tests were carried out using the specimens from steel 11 373 and the specimens from duralumin $AlCu_4Mg$. The specimens in the size of strips were cut from the sheet panel of 1 × 2 m dimensions. For bonding the two-component epoxy adhesives were used. The ratio of mixture was 1:1 (Table 1).

The surface of bonded specimens was mechanically worked. The optimum preparation was determined on the basis of laboratory tests. But at first the optimal thickness of the adhesive layer was determined. The optimal values of adhesive layer thickness and of the optimum surface preparation were used for the influence determination of the environment temperature.

After obtained values evaluation the tests were carried out. As the environment temperatures were chosen following temperatures: –50°C, –25°C, 0°C, 25°C, 60°C and 90°C. Minus temperature was reached using the refrigerator, lower temperature (–50°C) using the liquid nitrogen diluted for required temperature reaching by industrial spirit. Positive temperature values were reached using the drier KBC G-100/250 (Figure 5) where the bonded specimens were placed. To these temperatures the tested assemblies were exposed for 24 hours.

Table 1. Characteristics of used adhesives (FIRM MATERIALS)

Adhesive – (used designation)	Suitable bonded materials	Curing time	Heat resistance
Bison metal (Bm)	metals, aluminums alloys, ceramics, wood and plastics	12 h	–60 to +100°C
Alteco 30 min (A30)		14 h	–20 to +120°C
Uhu 2 min (U2)		5 min	–60 to +80°C
Uhu 5 min (U5)		30 min	–60 to +80°C

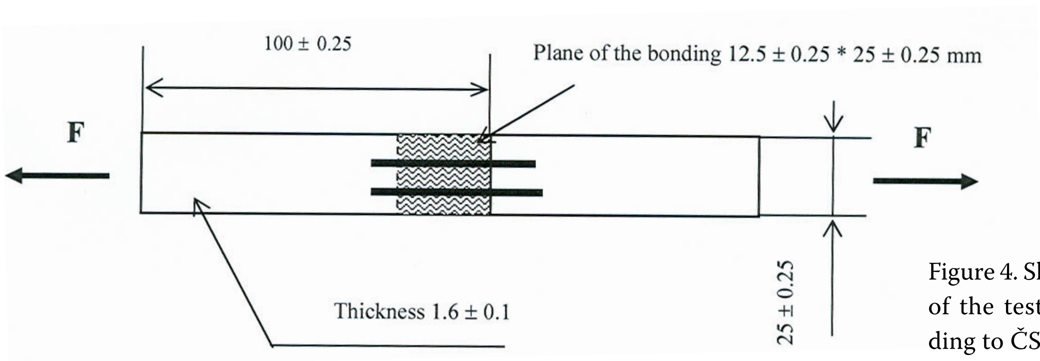

Figure 4. Shape and dimensions of the tested assembly according to ČSN EN 1465 (1997)

Figure 5. Drier KBC G-100/250

Tests were carried out using so-called "warm destructive testing" (that means that the tests were carried out after heating/cooling down the specimens to stated temperature –50°C, –25°C, 0°C, 25°C, 60°C and 90°C). The specimens of required temperature (increased or decreased) were tested using the universal tensile-strength testing machine ZDM 5. The temperature of fixed specimens was measured using the contact thermometer Therm 2220-13. When the required temperature was reached the destructive test was carried out according to ČSN EN 1465 (1997). After the bonded joint rupture the maximum force was read, the lapped surface was measured, the rupture type according to ISO 10365 was determined and the bonded joint strength τ was calculated according to ČSN EN 1465 (1997) (5).

$$\tau = \frac{F}{S} \qquad (5)$$

where:
τ – shear strength (MPa)
F – maximum force (N)
S – lapped surface (mm^2)

Next the coefficient of variation was calculated (6). It was used for the determination of the strength values fluctuation related to the change of the environment temperature of single sets (Macháček & Majer 1981).

$$v = \frac{s_0}{\bar{x}} \times 100 \qquad (6)$$

where:
υ – coefficient of variation (%)
s_0 – standard deviation (MPa)
$\bar{x}$ – arithmetic mean (MPa)

Test results

On the basis of the laboratory tests it was necessary to determine the optimal adhesive layer thickness, which was used in next tests. Following adhesive layer thicknesses were judged: 0.06 mm, 0.11 mm, 0.16 mm, 0.22 mm, 0.29 mm and 0.38 mm. Each adhesive layer thickness was secured by use of two distance wires of demanded diameter, which were sandwiched in the bonded joint. On the basis of tests the optimal surface preparation was determined. The results are presented in Table 2 (Müller *et al.* 2006). The results show that the optimum values keeping is important.

Next factor which influences significantly the bonded joint strength is the bonded surface prepa-

Table 2. Determination of the adhesive layer optimum thickness (all specimens were mechanically treated by blasting using the synthetical corundum of grain 24, R_a 2.85 μm)

Adhesive layer thickness (mm)	Adhesive designation			
	Bm	A30	U2	U5
	(MPa) – determined using steel specimens			
0.06	17.14	14.41	4.94	6.28
0.11	**18.03**	12.14	6.82	9.17
0.16	17.87	11.54	**6.92**	7.71
0.22	17.16	**14.45**	4.03	**10.20**
0.29	16.39	13.33	3.23	7.69
0.38	15.89	11.53	2.46	7.07

Figure 6. Surface roughness measuring of bonded specimens

ration. Therefore the suitable mechanical preparation of bonded steel and duralumin specimens was selected. The bonded surface was mechanically treated by blasting using the synthetical corundum of grain 24 (fraction size 710–850 μm) and by grinding using the abrasive cloth of 40, 100, 150, 240, 320, 400 and 500 grit. The mechanically prepared surface was evaluated using the surface roughness measuring by means of the Mitutoyo SURFTEST – 301 profilograph (Figure 6). The test results are presented in Table 3 (Müller *et al.* 2006). Values in Table 3 were reached by using the adhesive layer optimum thickness for each adhesive: Bm – 0.11 mm, A30 – 0.22 mm, U2 – 0.16 mm, U5 – 0.22 mm.

The determined adhesive layer optimal thickness and the optimal mechanical preparation of the bonded surface was utilized in next tests with a view to the environment temperature influence on the strength values change of the bonded joint.

Behaviour of the function was best described by the non-linear regression function of second degree. The function type was derived from the correlation field, which was formed by the cross points of the dependent and independent variables, then by the bonded

Table 3. Determination of optimal surface mechanical preparation of bonded specimens (in MPa)

Bonded surface preparation	Steel				Duralumin			
	Bm	A30	U2	U5	Bm	A30	U2	U5
Abrasive cloth 40	18.95	13.86	5.99	7.62	13.52	12.75	2.88	4.27
Abrasive cloth 100	**19.33**	14.15	6.16	7.31	15.19	**13.43**	2.86	**4.57**
Abrasive cloth 150	17.81	15.78	5.04	6.74	18.04	12.64	**3.46**	4.18
Abrasive cloth 240	16.84	16.48	3.74	4.96	**18.70**	12.85	3.11	3.62
Abrasive cloth 320	16.36	**16.68**	4.41	5.78	18.69	11.57	3.19	3.23
Abrasive cloth 400	17.02	16.37	2.94	5.11	16.79	10.58	2.96	2.60
Abrasive cloth 500	17.00	15.95	2.84	5.69	18.45	11.11	2.18	1.86
Blasted F24	18.03	14.45	**6.92**	**10.20**	15.97	13.36	2.61	4.19

Table 4. Functional equations and determination index

Adhesive designation	Functional equation	Determination index $I^2_{\tau x}$
Adherend: steel		
Bm	$\tau = -0.0008T^2 - 0.0437T + 18.713$	0.922
A30	$\tau = -0.0008T^2 - 0.0061T + 14.006$	0.835
U2	$\tau = -0.0002T^2 - 0.0383T + 8.5436$	0.954
U5	$\tau = -0.0005T^2 - 0.0234T + 9.5187$	0.850
Adherend: duralumin		
Bm	$\tau = -0.0012T^2 - 0.018T + 14.013$	0.750
A30	$\tau = -0.001T^2 + 0.026T + 10.297$	0.730
U2	$\tau = -0.0004T^2 + 0.0092T + 3.0721$	0.735
U5	$\tau = -0.0006T^2 + 0.0196T + 3.4951$	0.751

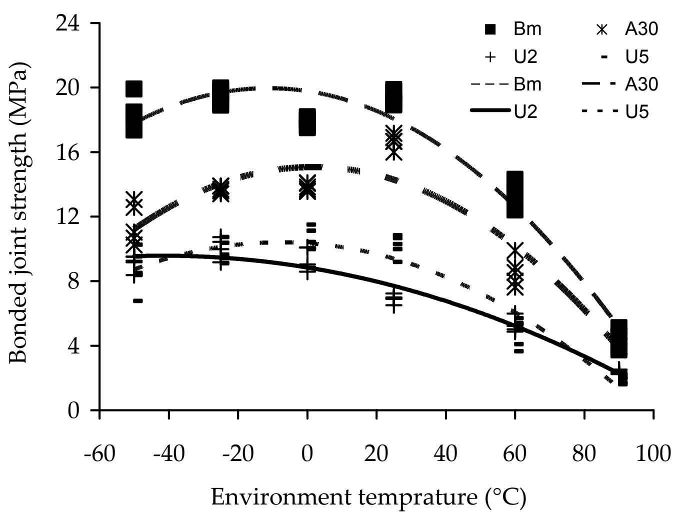

Figure 7. Relation between bonded joint strength and environment temperature – steel adherends

joint strength and the environment temperature. Figure 7 shows the relation between bonded joint strength and environment temperature using steel adherends, Figure 8 using duralumin adherends.

By interlining of correlation field points we get the function equations of the environment temperature (T) influence on the bonded joint strength (τ) at the "warm destructive testing" (Table 4). The strength-temperature curve is expressed by the function equation. The determination index indicates the closeness of the relation.

Table 5 presents the corrective coefficient values which must be taken in consideration when elevated or reduced temperature threatens. The corrective coefficient values are related to the laboratory temperature of 25°C.

In Table 5 the corrective coefficient values for individual adhesives are presented. From results

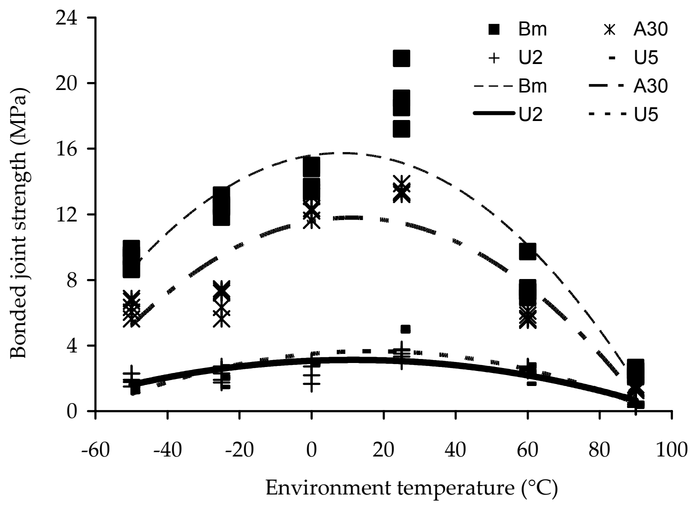

Figure 8. Relation between bonded joint strength and environment temperature – duralumin adherends

Table 5. Corrective coefficient values in dependence on the environment temperature change

Temperature (°C)	Steel				Duralumin			
	Bm	A30	U2	U5	Bm	A30	U2	U5
–50	0.95	0.69	1.33	0.85	0.49	0.47	0.56	0.32
–25	1.01	0.82	1.61	1.00	0.67	0.51	0.65	0.45
0	0.92	0.83	1.35	1.04	0.75	0.93	0.73	0.65
25	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
60	0.70	0.51	0.76	0.47	0.41	0.43	0.75	0.52
90	0.23	0.26	0.34	0.19	0.13	0.11	0.10	0.09

presented in Table 5 the influence of the bonded material is perceptible, too. This influence is above all caused by different mechanical and physical properties of individual materials.

CONCLUSION

Bonded joints are often subjected to various temperatures of environment. The temperature fluctuation can be up to several tens of degrees. The bonded joint stress at elevated or reduced temperatures can be critical. Therefore the elimination of as much as possible detrimental factors is important. One of ways is the choice of a temperature resistant adhesive. The second possibility is to take the strength decrease in calculations. The third and optimal possibility is the combination of both above mentioned ways.

On the basis of preliminary laboratory tests the corrective coefficients were determined which are advantageous to be taken into account. With regard to the paper extent only one basic factor is presented. For the effective use of bonding technology in the concrete application the determination of all corrective coefficients would be suitable. These corrective coefficients should be included in the resultant stress calculation.

Bonding steel adherends in a cold environment (minus temperatures) the expressive strength decrease did not occur. But the increased temperatures (plus values) cause the very unfavorable influence on the resultant strength.

Bonding duralumin specimens the significant strength decrease occurs at minus as well at plus temperatures. Owing to temperature the significant strength decrease occurred at a relatively high temperature resistance of used adhesives, too.

The presented corrective coefficient values are related to measured environment temperature values. For determination of another temperature values either the graphical representation or the function equation can be utilized.

The corrective coefficients modify the theoretical reached bonded joint strength according to the defined temperature. At the present geometry of a bonded joint the premature destruction could occur.

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Abstrakt

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Jednou z mnoha metod spojování materiálů je technologie lepení. V posledních desetiletích zaznamenala technologie lepení rozmach téměř ve všech odvětvích průmyslu. Zavedení technologie lepení do výrobního nebo opravárenského průmyslu přináší značné úspory. Dosahuje se úspor jak finančních, tak i deficitních kovových materiálů, času a rovněž se zmenšuje hmotnost celého spoje. Z těchto důvodů se technologie lepení řadí mezi moderní způsoby spojování, i když je ve skutečnosti technikou velmi starou. Technologie lepení je ovlivněna řadou faktorů mající vliv na pevnost lepeného spoje. Při konstrukčních výpočtech je rovněž důležité zohlednit opravné koeficienty. Opravné koeficienty korigují pevnostní výchylky způsobené jednotlivými faktory. V příspěvku jsou publikovány výsledky laboratorních experimentů.

Klíčová slova: technologie lepení; konstrukce; opravné koeficienty; laboratorní experimenty lepených spojů

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