Dimensioning of the bonded lap joint

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Abstract

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Bonded joint is a complex assembly, which creation and following use is limited by a range of factors. The primary factors are the properties of the bonded material and of the adhesive. The stress distribution in the bonded joint is substantially influenced by the bonded joint geometry and by the deformation characteristics. Laboratory experiments are intent on the above mentioned influences for bonded lap joints, which are very used in practice. The geometrical parameters of bonded joints are substantial for the constructional parameters and for costs determination. At the lower lapping length the failure of the bonded joint occurs and the maximum loading capacity of the bonded material is not fully utilized. On the contrary when using the lapping length over its optimum value the failure of the bonded material occurs. At the same time the total weight of the bonded assembly increases. Therefore it is important to determine the bonded joint optimum values which secure the reliability and which do not increase the production costs.

Keywords: deformation; lapping length; epoxy adhesives; bonding technology; loading force

In single production fields the manufacturing process is different. But often one element is common, namely the joint creation. The simplicity and effectiveness of the manufacturing process are remarkable, too. With these, the continuous improvement and looking for new perspective technologies is connected, which makes the manufacturing process easier. This is one of the basic steps needed for the ability of products to compete in the global markets. One of possibilities to introduce perspective methods is the right choice of the most suitable one. It is possible to characterize three basic jointing methods, namely mechanical, chemical and heat treatment. Using the fixed bonding technology the knowledge of its technological principles is important, as they influence the qualitative properties of the final joint.

With determining of the joint type it is necessary to evaluate advantages and disadvantages of applicable technologies in comparison with other jointing methods.

One of basic jointing methods is the bonding technology, which offers indisputable advantages. The strength of bonded joints depends on adhesion and cohesion, which influence significantly the resultant joint strength. The whole complex of the adhesive and cohesive phenomenon is the result of molecules' reciprocal action. Between molecules, physical forces, chemical bonds and intermolecular forces are in use (Loctite 1998).

The first step before the tough bond creation is very important. It is the constructional arrangement of the bonded joint for the elimination of all

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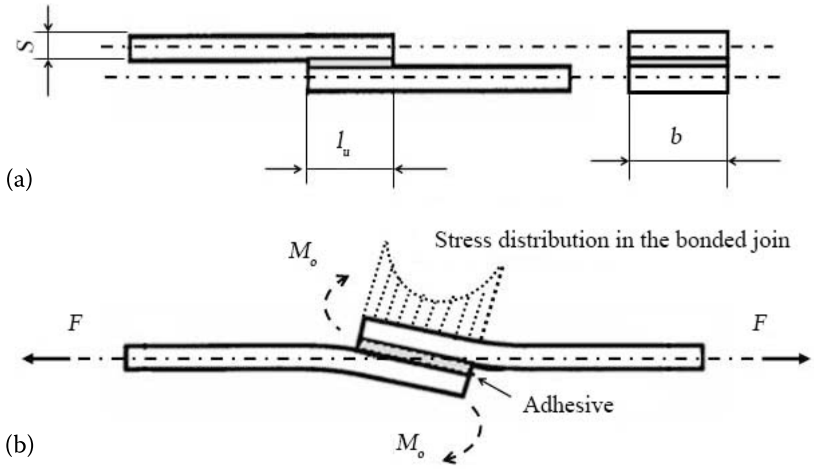

Fig. 1. Bonded lap joint: (a) unloaded joint; (b) deformation of the loaded joint by the bending moment and the stress distribution in the adhesive layer over the lapping length

unsuitable load modes, above all of peeling. The constructional arrangement is a fundamental factor at bonding of plane surfaces, which have to lap over (Fig. 1a). Bonded joints are only rarely of one loading type. Usually the combined tensile and shear stress occur. Here the non-uniform stress distribution occurs on the whole bonded surface. According to Adams et al. (1997), owing to the non-uniform deformation the different adhesive deformation occurs through adhesive layer thickness. The ends of lapping are the most deformed, where so-called stress maximum is created (Fig. 1b) (Grant et al. 2009). The approximate hyperbolic stress distribution over the total lapping length is the result. Lang and Mallick (1999) stated that the destructive causes of single lapped adhesive bond were only rarely mentioned because most of authors (e.g. Goland, Reissner, Cooper, Sawyer, Ojalvo, Renton, Vinson, Erdogen, Ratwani, Givler, Pipes) were interested in lapped adhesive bonds in which the specimen profiles had been changed constructionally in order to decrease the bending moment effect. The stress concentration increases by the bending moment action of the couple of forces (Fig. 1b) (Habenicht 2002). Grant et al. (2009) found out in their experiments that the constant bending moment occurred at the edges of lapped adhesive bond. The bending moment creates a plastic stress starting the adhesive bond failure. The non-uniform stress distribution in the adhesive layer edges, caused by the bonded materials elasticity and deformation, evokes the tensile stress at the bonded joint ends. This is the reason of peeling and in this way of the resultant strength decrease. The crack propagation and the bonded joint destruction are the result.

Moreover, Grant et al. (2009) found a huge sensitivity of loaded single lapped adhesive bonds to the adhesive layer thickness. Their results gave the information that the bending moment increased with the increasing adhesive layer thickness. This decreases the adhesive bond strength secondary.

The stress level caused by the bending moment can be decreased not only by the bonded material strength and thickness increase, but by various constructional arrangements, too. Therefore the designed bonded joint must be adapted according to the bonding technology. In the bonded joint optimum design the stress distribution must be as uniform as possible. One of possibilities for reaching the optimum constructional arrangement is the bonded material thickness increase. Owing to minor deformations of the thicker bonded material the adhesive layer is less deformed. This arrangement is often economically and technically disadvantageous owing to the disproportionate weight increase. The bonded surface dimensions optimizing is the next possibility and the stress distribution does not change with the bonded joint width. This arrangement is often not possible owing to constructional reasons and at the same time the nonalignment, which causes the bending moment creation, is not eliminated. This bending moment evokes the tensile stress largely at the joint ends. The peeling forces creation is the consequence (Habenicht 2002).

Fessel et al. (2007) changed the bending moment size in their experiments thanks to the single deformation of the adhesive bonded specimen (reshaping the adhesive bonded material angle). They found out that the adhesive bond strength of "reverse bent" bonds was up to 40% higher comparing

Table 1. Chemical composition of the bonded materials (weight %)

Specimen	C	Mn	Cr	Ni	Al	Cu	Nb	Ti	Fe	Si	Mg	Zn
Steel S235J0	0.047	0.24	0.076	0.017	0.065	0.039	0.007	0.016	99.5	–	–	–
Duralumin $AlCu_4Mg$	–	0.51	0.003	0.003	93.197	5.012	–	0.013	0.304	0.35	0.571	0.014

with flat bonds. Different adhesives and materials were used for the experiments.

You et al. (2009) followed them up and found the ideal adherent deformation 7° by means of a finite element analysis in which the strength had increased by 64% comparing with the common lapped adhesive bond. The upper limit was set to 15°, in which the adhesive bond strength started to decrease.

The determination of the optimum lapping length is the suitable solution. The optimization of the lapping length does not mean only to extend and in this way to increase the bonded surface, but to determine the lower and upper limiting state. The reasons can be summarized in following criterions: the bending moment and in this way the second component of the tensile strength elimination and the bonded material mechanical properties respecting namely in the zone of the start of the plastic deformation action.

MATERIALS AND METHODS

The criteria plan of the optimum lapping length determination was the aim of the laboratory measurements. These criteria will give to the optimum load capacity the bonded joint on behalf of the tensile strength elimination. On the basis of measurements the suitable work procedure exercisable at the bonded joint design was determined.

For tests two epoxy adhesives were used:

- BISON epoxy metal (Bm) – the two-component epoxy adhesive, ratio of mixture 1:1, usable life 60 min. Thermal fastness –60°C to +100°C. It is suitable for bonding of metals, ceramics and plastics. Perfect curing occurs after 12 h. The presented orientation strength of the bonded joint is 18 MPa (Bison Epoxy Metal 2004).
- ALTECO 3-TON epoxy adhesive 30 min (A30) – the two-component epoxy adhesive with metallic filler, ratio of mixture 1:1, usable life 30 min. Thermal fastness –20°C to +120°C. It is suitable for bonding of steel, cast iron, brass, aluminium alloys, wood, glass, and plastics. Perfect curing occurs after 14 h. Orientation strength is not presented (Alteco 3-Ton Epoxy Adhesive 2008).

The evaluation was carried out according to the standard ČSN EN 1465 (1997) – determination of tensile lap-shear strength of rigid-to-rigid bonded assemblies. The tests were carried out using the steel S235J0 and the duralumin $AlCu_4Mg$ specimens. Dimensions of specimens were 100 × 25 × 1.5 mm. The chemical composition of bonded specimens, determined using the spectral analysis, is presented in Table 1. Next the measuring of the bonded material using the Vickers hardness was carried out

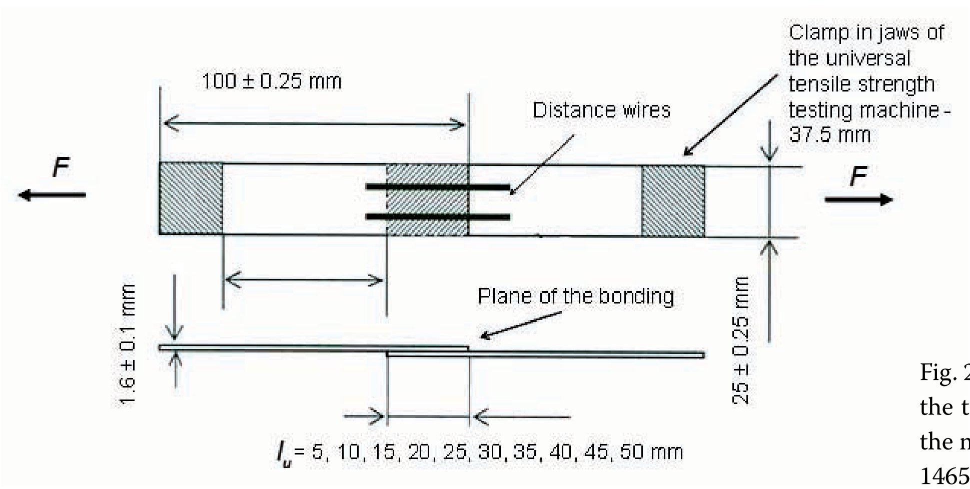

Fig. 2. Shape and dimensions of the test specimen according to the modified standard ČSN EN 1465 (1997)

at the load of 147 N. The hardness mean value was HV_{15} = 100 for steel and HV_{15} = 130 for duralumin.

For the bonded joint upper limit load capacity determination the yield point *Re* (proof limit $Rp_{0.2}$) according to ČSN EN 10002–1 (2002) was determined. The matter is the elastic zone of very low deformations. The elastic deformation is facilitated by the relatively small atoms movement around the equilibrium position in the crystal lattice and then it nearly minimizes the adhesive deformations in the joint. When this limit is exceeded the plastic deformation occurs and influences the origin of peeling. In the zone of plastic deformation the bonded joint dimensioning is unsuitable. The yield point of steel specimens was measured *Re* = 240 MPa, of duralumin specimens $Rp_{0.2}$ = 300 MPa. The next measuring targeted the maximum lapping length determination, thus the reduction with regard to the cross section of bonded material was decisive. From these values the limit lapping length for the maximum loading force of steel specimens 9,000 N and of duralumin specimens 11,250 N was calculated.

For the bonded surface preparation the mechanical method of blasting by the use of synthetic corundum F24 was used. The adhesive layer thickness was secured by the insertion of two distance wires placed parallel to the acting force. Using the adhesive Bm, A30 the adhesive layer thickness was of 0.11 mm. According to previous tests this thickness proved the optimum.

The length and the width of the tested specimens were used according to the standard. The lapping was not made according to the standard, but it was graded in dimensions of 5 mm. At the first bonded series the lapping length was of 5 mm, at the last it was 50 mm (Fig. 2).

Then the specimens were bonded. The number of tested assemblies of each series was determined according to the standard demands. The bonded assemblies were left in the laboratory for the time which was needed for curing under the temperature of 22 ± 2°C. The tensile-strength test was carried out using the universal tensile-strength testing machine.

After the bonded joint destruction the maximum force was read, the lapping surface was measured, the failure type according to ISO 10365 was determined and according to the standard ČSN EN 1465 (1997) the bonded joint strength was calculated Eq. (1).

$$\tau = \frac{F}{b \times l_u} \quad (1)$$

where:

τ – tensile shear strength (MPa)

F – maximum force (N)

b – lapping width (mm)

l_u – lapping length (mm)

At the bonded joint loading without special constructional adaptations (Figs. 1 and 2) it is necessary to regard for the bending moment which evokes the tensile strength, too. For the reduced strength σ_{red} calculation, it is possible to use hypothesis for maximum normal stress. The reduced strength σ_{red} calculation with regard to the bending moment is presented in the Eq. (2). In the Eq. (3) the partial calculation of the bending moment and in the Eq. (4) of the section modulus is presented.

$$\sigma_{red} = \sqrt{\sigma_o^2 + 4 \times \tau^2} = \sqrt{\left(\frac{M_o}{W_o}\right)^2 + 4 \times \left(\frac{F}{b \times l_u}\right)^2} \quad (2)$$

where:

σ_{red} – reduced strength of the bonded joint (MPa)

σ_o – bending strength (MPa)

τ – tensile shear strength (MPa)

M_o – bending moment (N.mm)

W_o – section modulus in bending for the rectangular section (mm^3)

F – loading force (N)

b – lapping width (mm)

l_u – lapping length (mm)

$$M_o = \frac{F \times \left(\frac{s_1}{2} + t_{ad} + \frac{s_2}{2}\right)}{2} \quad (3)$$

where:

M_o – bending moment (N.mm)

F – loading force (N)

s_1 – thickness of the first bonded material (mm)

s_2 – thickness of the second bonded material (mm)

t_{ad} – adhesive layer thickness (mm)

$$W_o = \frac{b \times l_u^2}{6} \quad (4)$$

where:

W_o – section modulus in bending for the rectangular section (mm^3)

l_u – lapping length (mm)

b – lapping width (mm)

By the introducing of the Eqs. (3), (4) in Eq. (2) it is possible to write Eq. (5):

$$\sigma_{red} = F \times \sqrt{\frac{9 \times \left(\frac{s_1}{2} + t_{ad} + \frac{s_2}{2}\right)^2}{b^2 \times l_u^4} + \frac{4}{b^2 \times l_u^2}} \quad (5)$$

According to the Mohr and Guess's state of stress theory the reduced tensile strength σ_{red}, it is possible to transform in the reduced shear strength τ_{red} Eq. (6) (Marghitu 2001).

$$\tau_{red} = 0.5 \times \sigma_{red} \quad (6)$$

Using the coefficient k of the reduced strength τ_{red} and the shear strength τ Eq. (7) it is possible to numerically evaluate and graphically determine the partial components of the tensile and shear stresses related to the fixed length of the lapping.

$$k = \frac{\tau_{red}}{\tau} \quad (7)$$

where:

k – coefficient of the reduced shear stress (–)

τ – tensile shear strength (MPa)

τ_{red} – reduced shear strength (MPa)

For the telling capability of the previous relation determined according to Eq. (7) it is possible to calculate the relative length coefficient Eq. (8). By the comparison of the relations Eqs. (7) and (8), not only the length, but also the width of the lapping is considered. By the use of the relation Eq. (8) it is possible to vary not only the lapping length, but the width, too. At the same time it is possible to eliminate the negative action of bending moment, respectively the tensile stress.

$$\lambda_p = \frac{l_u}{b} \quad (8)$$

where:

λ_p – relative length coefficient (–)

l_u – lapping length (mm)

b – lapping width (mm)

RESULTS AND DISCUSSION

The bonded joints were prepared according to the above mentioned specifications and destructively tested. The test factors were the destructive force and the lapping surface. These two values were used for the strength calculation based on the Eqs. (1) and (5). It was necessary to transform the values from the Eq. (5) according to the Eq. (6). The loading force and the calculated values from the Eqs. (1) and (6) were plotted. The course of the tensile shear strength and the reduced shear strength related to the lapping length are expressed by the connecting line of the 2nd degree polynomial trend, which corresponds best to the correlation field of the measured values. The relation between the loading force and the lapping length is expressed by the connecting line of the 3rd degree polynomial trend, too.

For the correct evaluation of the relationships the closeness coefficient was calculated using the correlation analysis. The value of correlation function R^2 can be from 0 to 1. The higher value corresponds to the higher declaring capacity. The course of the above mentioned relations was described by the equations, too.

Fig. 3 presents the results of values measured and calculated for the adhesive (Bm). The bonded specimens were made from the steel S235J0. The upper limit of the loading force at the bonded joint yield point is 9,000 N. If this value is exceeded the plastic deformation of the bonded material occurs. In the interface adhesive – bonded material expressive deformations occur, which conduces to the absorbed loading force lowering. This statement is based also on the following measured loading forced reduction. After reaching of l_u = 40 mm (λ_p = 1.6) the loading force reduction occurs.

The fracture area between the adhesive (Bm) and the bonded material (steel) was evaluated as the cohesive failure.

The Eq. (9) describes the relation between the destruction force and the lapping length l_u as showed in Fig. 3. The correlation function R^2, Eq. (10), is presented, too.

$$F_{\text{Bm – steel}} = -0{,}1434 \times l_u^3 + 7.8297 \times l_u^2 + 101.45 \times l_u + 1976.5 \quad (9)$$

$$R^2_{F\,\text{Bm – steel}} = 0.9533 \quad (10)$$

The Eq. (11) describes the relation between the reduced shear strength τ_{red} and the lapping length l_u as showed in Fig. 3. The correlation function R^2, Eq. (12), is presented, too.

$$\tau_{\text{Bm}\,red\,\text{– steel}} = 2.6124 \times l_u^2 - 11.15 \times l_u + 19.692 \quad (11)$$

$$R^2_{\text{Bm}\,\tau\,red\,\text{– steel}} = 0.8495 \quad (12)$$

The Eq. (13) describes the relation between the tensile shear strength τ and the lapping length l_u as

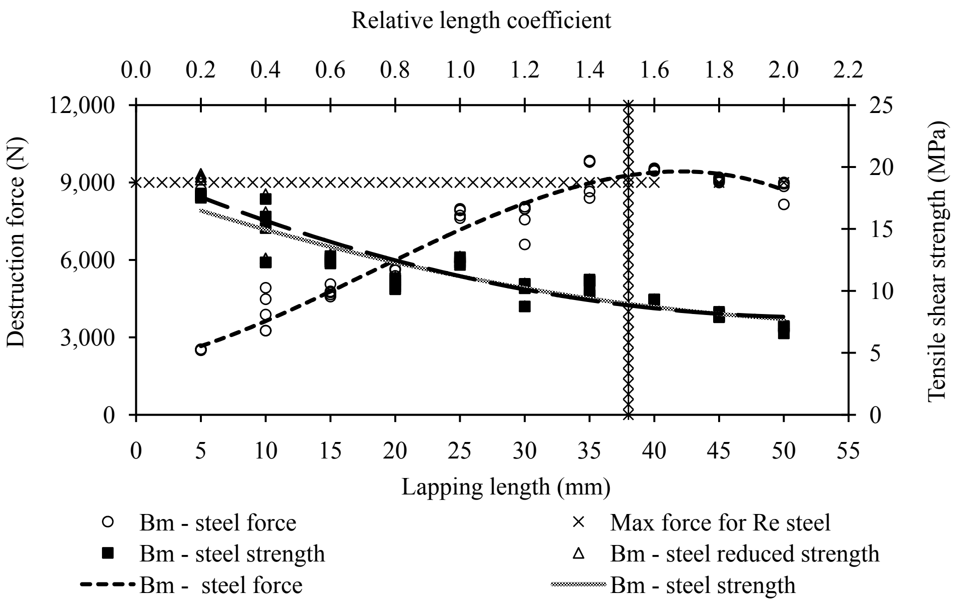

Fig. 3. Influence of the lapping length on the destruction force and on the adhesive strength Bm – steel

showed in Fig. 3. The correlation function R^2, Eq. (14), is presented, too.

$$\tau_{Bm-steel} = 1.7569 \times l_u^2 - 8.7232 \times l_u + 18.154 \quad (13)$$

$$R^2_{Bm\ \tau-steel} = 0.8488 \quad (14)$$

Fig. 4 presents the test results of values measured and calculated for the adhesive (A30) at bonding steel.

The upper limit of the loading force of the yield point 9,000 N was not reached. After exceeding the lapping length of 35 mm (λ_p=1.4) only the minimum variation of the loading force occurred. Between 35 and 50 mm lapping length the mean destructive force of 8,002 ± 137 N was measured. But after reaching of l_u = 40 mm (λ_p = 1.6) a decrease in the destructive force occurred.

The joint destruction between the adhesive (A30) and the bonded material (steel) was evaluated as the cohesive failure.

The Eq. (15) describes the relation between the destructive force F and the lapping length l_u as showed in Fig. 4. The correlation function R^2, Eq. (16), is presented, too.

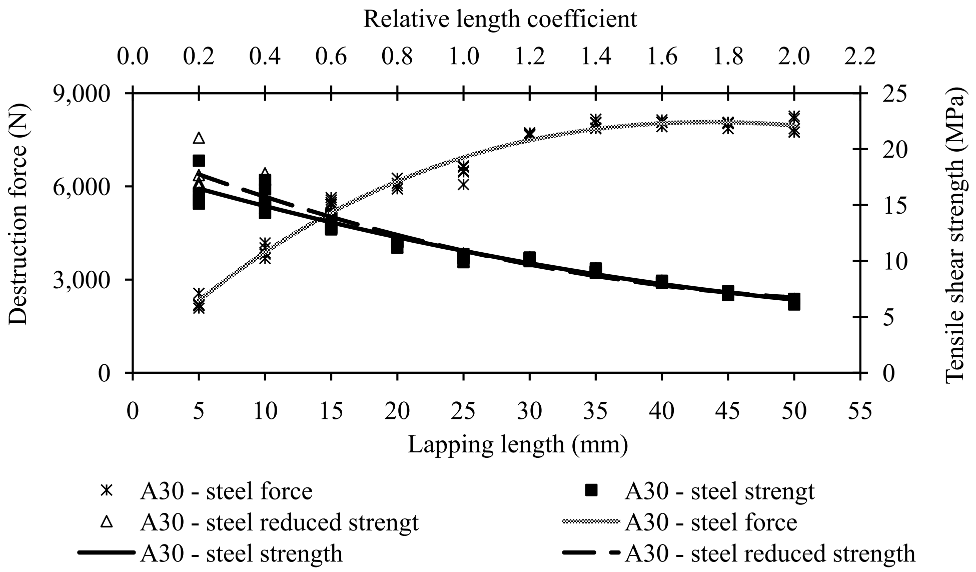

Fig. 4. Influence of the lapping length on the destructive force and on the adhesive bond strength A30 – steel

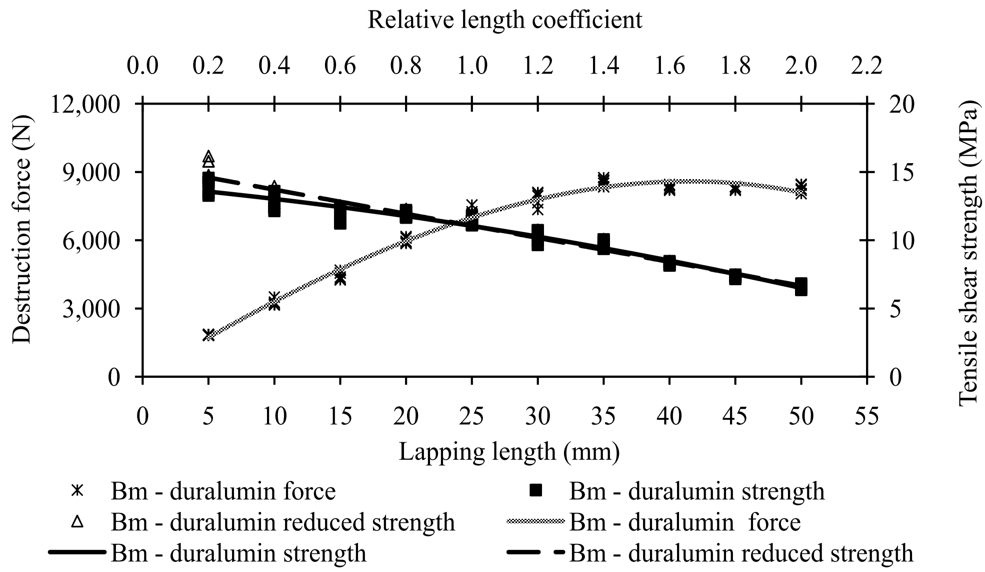

Fig. 5. Influence of the lapping length on the destructive force and on the adhesive bond strength Bm – duralumin

$$F_{A30-steel} = 0.0293 \times l_u^3 - 6.5462 \times l_u^2 + 404.3 \times l_u + 463.33 \quad (15)$$

$$R^2_{F\,A30-steel} = 0.9826 \quad (16)$$

The Eq. (17) describes the relation between the reduced shear strength τ_{red} and the lapping length l_u as showed in Fig. 4. The correlation function R^2, Eq. (18), is presented, too.

$$\tau_{A30\,red-steel} = 2.4221 \times l_u^2 - 11.44 \times l_u + 19.926 \quad (17)$$

$$R^2_{A30\,\tau\,red-steel} = 0.9543 \quad (18)$$

The Eq. (19) describes the relation between the tensile shear strength τ and the lapping length l_u as showed in Fig. 4. The correlation function R^2, Eq. (20), is presented, too.

$$\tau_{A30-steel} = 1.4437 \times l_u^2 - 8.6947 \times l_u + 18.152 \quad (19)$$

$$R^2_{A30\,\tau-steel} = 0.9516 \quad (20)$$

When duralumin was bonded using the adhesives (Bm) and (A30), the conventional yield point $Rp_{0.2}$ (converted with regard to the bonded material cross section to the conventional yield point of 11,250 N)

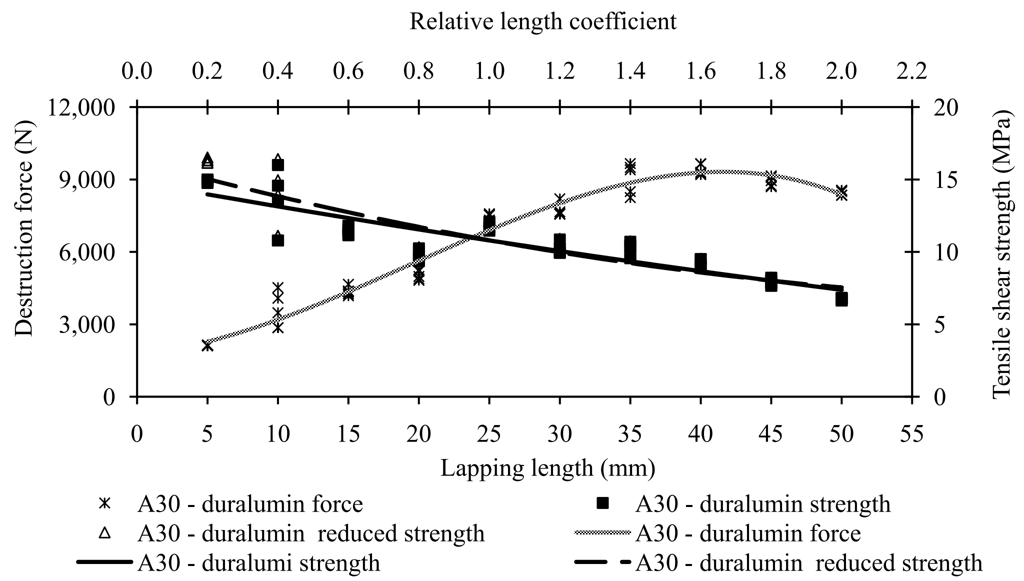

Fig. 6. Influence of the lapping length on the destructive force and on the adhesive bond strength A30 – duralumin

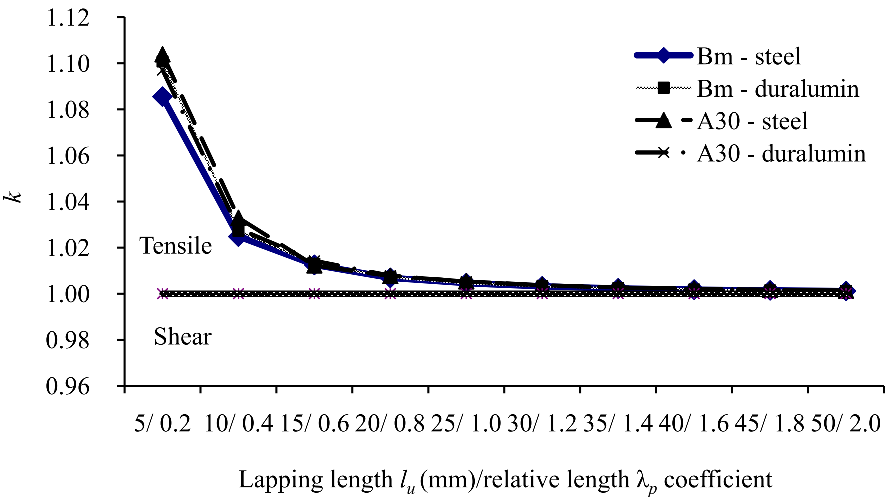

Fig. 7. Influence of the lapping length l_u and the relative length coefficient λ_p on the coefficient k of the reduced strength τ_{red} and on the shear strength τ

was not exceeded. Fig. 5 presents the results of duralumin joints bonded using the adhesive (Bm).

After exceeding the lapping length of 35 mm (λ_p = 1.6) only the minimum variation of the destructive force occurred. Between the lapping length of 35 and 50 mm the mean loading force of 8367 ± 165 N was measured. But after reaching l_u = 40 mm (λ_p = 1.6) lapping length, a mild decrease of destructive force occurred.

The joint destruction between the adhesive (Bm) and the bonded material (duralumin) was evaluated as the cohesive failure.

The Eq. (21) describes the relation between the destructive force F and the lapping length l_u as it is showed in Fig. 5. The correlation function R^2, Eq. (22), is presented, too.

$$F_{\text{Bm – duralumin}} = -0.0356 \times l_u^3 - 2.0329 \times l_u^2 + 352.27 \times l_u + 19.667 \quad (21)$$

$$R^2_{F\,\text{Bm – duralumin}} = 0.9893 \quad (22)$$

The Eq. (23) describes the relation between the reduced shear strength τ_{red} and the lapping length l_u as it is showed in Fig. 5. The correlation function R^2, Eq. (24), is presented, too.

$$\tau_{\text{Bm } red \text{ – duralumin}} = 0.0188 \times l_u^2 - 4.444 \times l_u + 15.482 \quad (23)$$

$$R^2_{\text{Bm } \tau\, red \text{ – duralumin}} = 0.9480 \quad (24)$$

The Eq. (25) describes the relation between the tensile shear strength τ and the lapping length l_u as it is showed in Fig. 5. The correlation function R^2, Eq. (26), is presented, too.

$$\tau_{\text{Bm – duralumin}} = -0.7776 \times l_u^2 - 2.21 \times l_u + 14.037 \quad (25)$$

$$R^2_{\text{Bm } \tau \text{ – duralumin}} = 0.9612 \quad (26)$$

In Fig. 6 the results of duralumin joints bonded using the adhesive (A30) are presented. After exceeding the lapping length of 35 mm (λ_p = 1.4) the variation decrease of the destructive force (8,966 ± 466 N) occurred. The deviation was higher compared to the results presented in Figs. 3, 4, 5. The higher destructive force variation compared to other foregoing results was above all caused by the higher scattering of measurements (6.4%) at l_u = 35 mm (λ_p = 1.4). The mean variation of other series (l_u = 5–50 mm) was 2.7%. After reaching of l_u = 40 mm (λ_p = 1.6) the expressive decrease of destructive force occurred.

The joint destruction between the adhesive (A30) and the bonded material (duralumin) was evaluated as the combined adhesive and cohesive failure.

The Eq. (27) describes the relation between the destructive force and the lapping length l_u as showed in Fig. 6. The correlation function R^2, Eq. (28), is presented, too.

$$F_{\text{A30 – duralumin}} = -0.1773 \times l_u^3 + 10.359 \times l_u^2 + 57.696 \times l_u + 1{,}755.7 \quad (27)$$

$$R^2_{F\,\text{A30 – duralumin}} = 0.9679 \quad (28)$$

The Eq. (29) describes the relation between the reduced shear strength τ_{red} and the lapping length l_u as showed in Fig. 6. The correlation function R^2, Eq. (30), is presented, too.

$$\tau_{\text{A30 red – duralumin}} = 1.128 \times l_u^2 - 6.6403 \times l_u + 16.315 \quad (29)$$

$$R^2_{A30\ \tau\ red\ –\ duralumin} = 0.7979 \quad (30)$$

The Eq. (31) describes the relation between the tensile shear strength τ and the lapping length l_u as showed in Fig. 6. The correlation function R^2, Eq. (32), is presented, too.

$$\tau_{A30\ –\ duralumin} = -0.3152 \times l_u^2 - 4.3587 \times l_u + 14.835 \quad (31)$$

$$R^2_{A30\ \tau\ –\ duralumin} = 0.7874 \quad (32)$$

The results of coefficient *k* with respect to the reduced strength τ_{red} calculated according to the Eq. (7) are presented in Fig. 7. It is the connecting line graph, where the arithmetic mean values of the partial lapping lengths l_u are plotted. The mentioned values make possible the determination of the tensile and shear strength components action related to the concrete lapping length of the bonded joint.

From the comparison (Fig. 7) the almost identical course of individual connecting lines is evident regardless of the material and adhesive types.

Graphical representation of the coefficient *k* presents a part of influence of the shear and tensile stresses at single lapping lengths l_u. At the values $k > 1$ of the joint the combination of the shear and tensile stresses is in action. The tensile stress action may influence the bending moment and in this way the peeling forces are associated.

At the *k* coefficient near to 1 the bending moment and in this way the probability of the peeling force acts are insignificant. The expressive deformation influenced by the bending moment occurred at the lapping length l_u of 5 mm (λ_p = 0.2). At the constructional design of the lap joints it is necessary to eliminate the influence of bending moment.

From the foregoing results presented in Figs. 3–6 it is evident that at the lapping length l_u of 35 mm the maximum destruction force is reached. At this lapping length the values of coefficient *k* are in average of 1.0025 and the influence of the bending moment is insignificant.

CONCLUSION

By the optimum overlapping design not only the loading capacity of bonded joint increases, but also the costs decrease, which are invested in the unjustifiedly overdimensioned bonded joint surface. At the design of the one-side lapped bonded joints it is important to have regard to following criterions:

- the bonded material maximum loading capacity utilization by reaching of the force near the yield point,
- the adhesive maximum loading capacity utilization,
- tensile stress elimination,
- utilization of shear stress type, when the bonded joints compared with other stress types (tension, peeling, their combination) reach in total higher loading force values.

From the experiments the optimum value of bonded joints overlapping followed, namely l_u = 35 mm (λ_p = 1.4). At this length an increase in the minimum loading capacity occurred. The influence of the bending moment decreased and in this way the influence of peeling forces, too. The adhesive layer deformation was distributed in the sufficiently large surface. For the design it is necessary to regard for the total geometric shape, not only for the lapping length l_u, but for the bonded joint width (*b*), too. This problem is solved by the introduction of the bonded surface optimum value in form of the relative length coefficient λ_p Eq. (8). By the introduction of the optimum value of λ_p = 1.4, determined for both bonded materials and both adhesives, in the Eq. (8) it is possible to calculate the dependent variable using the known independent variable – l_u or *b*, which is given by the constructional design.

At calculations the destruction force is specified and in this way the maximum allowable stress is determined. It is possible to calculate the bonded surface dimensioning approximately according to the Eq. (33), (34) under presumption that the limiting yield point is not exceeded. If overranged, the plastic deformation would occur, which would conduce to various inaccessible deformations of shape and dimensions. At bonded joints the excessive peeling occurs, too. The Eq. (33) results from the modification of Eq. (8) with introducing in Eq. (1).

$$\tau = \frac{F_e}{b^2 \times 1.4} \quad (33)$$

$$\tau = \frac{1.4 \times F_e}{l_u^2} \quad (34)$$

where:

τ – tensile shear strength (according to ČSN EN 1465) (MPa)

F_e (or $F_{0.2}$) – force at the (conventional) yield point of the bonded material (N)

l_u – lapping length (mm)

b – lapping width (mm)

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