INVESTIGATIONS ON GLUED STRUCTURAL TIMBER-STEEL PLATE JOINTS

UNTERSUCHUNGEN AN GEKLEBTEN HOLZ-STAHLPLATTEN-ANSCHLÜSSEN

ETUDES SUR DES ASSEMBLAGES COLLES DE BOIS ET PLAQUES EN ACIER

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SUMMARY

It is reported on a research project with glued timber-steel plate connections. An essential objective of the investigations consists in the evaluation of appropriate adhesives whereby special consideration is paid to influences of glue line thickness, elevated temperatures and long-term loading. A theoretical aspect is the geometry optimization of the joints.

In experiments so far ten different adhesives, five epoxies, four polyurethanes and a phenolic-resorcinol resin were comparatively tested with constant bond length of 150 mm in short-term compression loading at normal climate conditions. The main test variable was glue line thickness (d = 0.5, 1 and 2 mm). All "conventional" epoxies and polyurethanes showed a differently accentuated shear strength increase along with falling glue line thickness. The polyurethanes in average had a shear strength level of 4 MPa at a glue line thickness of 0.5 mm. By far the highest values, in average 6 MPa at d = 2 mm were obtained from a rubber toughened epoxy.

With respect to joint geometry optimization, finite element computations showed that tapering of the steel plates results in significant stress peak reductions as well as elongations of optimum bond lengths. Tapered plates further deliver an increase of the cross-sectional utilization factor.

Glued structural timber-steel plate joints seem feasible on the condition that temperature and long-term behaviour can be manipulated suitably.

ZUSAMMENFASSUNG

Es wird über ein Forschungsvorhaben an geklebten Holz-Stahlplatten-Verbindungen berichtet. Eine wesentliche Zielsetzung der Untersuchungen ist die Bestimmung geeigneter Klebstoffe, wobei insbesondere Einflüsse der Klebfugendicke, erhöhte Temperaturen sowie Langzeitbeanspruchung berücksichtigt werden. Ein theoretischer Schwerpunkt besteht in der Geometrie-Optimierung der Anschlüsse.

Experimentell wurden bislang zehn verschiedene Klebstoffe, fünf Epoxidharze, vier Polyurethane und ein Phenol-Resorcinharz vergleichend bei konstanter Einbindelänge von 150 mm im Kurzzeit-Druckversuch unter Normalklimabedingungen untersucht. Die wichtigste Versuchsvariable war die Leimfugendicke (d = 0.5, 1 und 2 mm). Alle "herkömmlichen" Epoxide und Polyurethane zeigten mit abnehmender Klebfugendicke einen unterschiedlich ausgeprägten Scherfestigkeitsanstieg. Die Scherfestigkeit der Polyurethane betrug im Mittel bei 0.5 mm Fugendicke rund 4 MPa. Mit Abstand die höchsten Festigkeiten von rund 6 MPa wurden mit einem Kautschuk-zähelastifiziertem Epoxid bei einer Fugendicke von 2 mm erreicht.

Im Rahmen der Anschlußgeometrie-Optimierung wurde mittels Finite-Element-Rechnungen gezeigt, daß ein Abschrägen der Stahlplatten signifikante Verringerungen von Spannungsspitzen und eine Erhöhung der optimalen Einbindelänge bewirkt. Abgeschrägte Bleche bewirken zudem eine Verringerung des Querschnittsverschwächungsgrades.

Geklebte tragende Holz-Stahlplatten-Anschlüsse scheinen machbar, vorausgesetzt, daß das Temperatur- und Langzeitverhalten hinreichend beherrschbar ist.

RESUME

Un rapport est donné sur un projet de recherche concernant des assemblages collées de bois et acier. Il est le but essentiel des études de déterminer des colles appropriées en prenant en considération les influences de l'épaisseur du joint de collage, de températures élevées ainsi que du chargement à long terme. Un aspect théorique consiste dans la meilleure géométrie des joints.

Jusqu'à présent des essais de compression à court terme ont été réalisés sur dix colles differentes, cinq résines époxyde, quatre polyuréthanes et une résine phénol-résorcine avec une longueur de collage constante de 150 mm sous des conditions climatiques normales. La variable d'essai principale était l'épaisseur du joint de collage (d = 0.5, 1 et 2 mm). Tous les époxydes et polyuréthanes "conventionnels" montraient une augmentation de la résistance au cisaillement différente avec une réduction de l'épaisseur de joint. Les polyuréthanes avaient, au moyen, une résistance au cisaillement de 4 MPa avec d = 0.5 mm. Les résistances les plus élevées d'environ 6 MPa étaient obtenues avec une époxyde-caoutchouc tenace avec une épaisseur de joint de 2 mm.

En ce qui concerne la géométrie des joints des calculs à éléments finis ont montré qu'un chanfreinage des plaques en acier cause des réductions importantes des concentrations des contraintes ainsi qu'une élongation des longueurs de collage optimum. Le chanfreinage des plaques augmente ainsi le facteur d'utilité de la section.

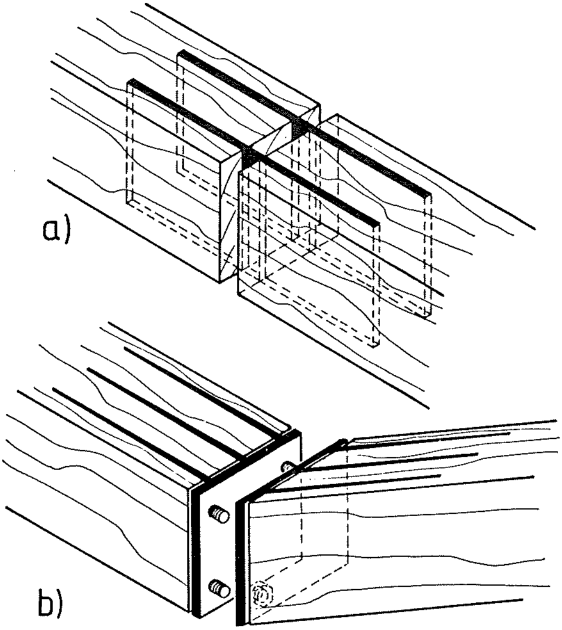
Des assemblages collés portants entre bois et plaques en acier semblent être réalisables à condition que le comportement aux températures élevées et aux sollicitations à long terme peuvent être dominés.

Key-words: Glued timber-steel plate joints, toughened epoxy, polyurethane, phenolic-resorcinol resin, glue line thickness sensitivity, optimum bond length, joint geometry optimization, steel plate taper

1. Introduction

Glued structural timber-steel connections today comprise predominantly reinforcements or anchorage systems of glulam members with steel bars.

Connections with timber glued to spacious steel plates are rare and in most countries, alike Germany, not approved by codes or building authorities. Nevertheless there have been repeated attempts in the last decades to develop such joints for some good reasons. One essential advantage of glued connections compared to joints with mechanical fasteners consists in the increased joint rigidity what can be meaningfull for wide-span plane or space trusses. Bound to the existance of appropriate adhesives such connections are easier to manufacture and can allow for a higher cross-sectional utilization factor than a joint with mechanical fasteners. Using in-lying plates (Fig. 1) what is obvious with respect to fire resistance, jointing problems with constructions in corrosive atmospheres can be reduced.



Figs. 1a, b: Glued timber-steel plate joints
a) straight b) bent

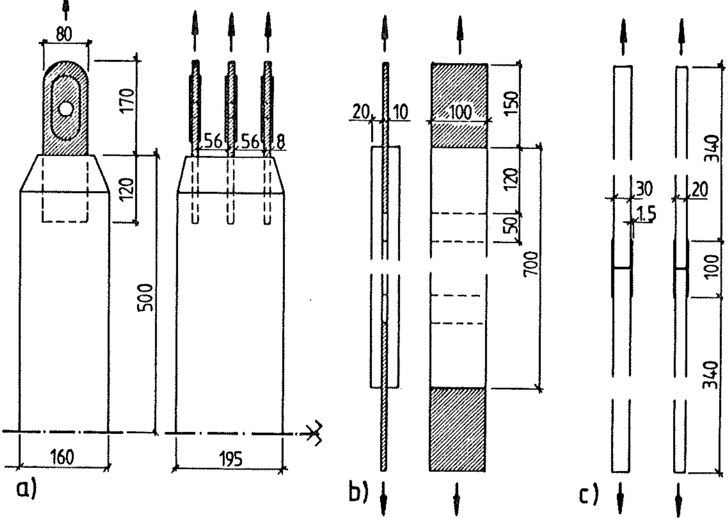
The paper reports on some investigations conducted in a current research project at the timber division of Otto-Graf-Institute on glued timber-steel plate connections. A theoretical aspect of the project is the geometry shaping of the joints. On the experimental side several different adhesives are evaluated with special consideration paid to influences of glue line thicknesses, elevated temperatures and long-term loading.

2. Literature review

The subsequent literature review shall give a rough estimation of the state-of-the-art and focusses on works conducted at EMPA in Switzerland and at Otto-Graf-Institute in Germany. For a direct comparison of cited strength values it is relevant i. a. to consider the individual bond lengths given in Figs. 2 and 3.

In 1949 at EMPA some static tension and compression tests on specimens acc. to Fig. 2a were accomplished [1], delivering mean tension and compression shear strength values of 4.1 resp. 4.8 MPa at 18 % moisture content (MC). After cold water treatment and moderate redrying to 20 % MC, compression shear strength dropped to 3.6 MPa. In this project the steel plates were not glued directly onto the laminations of the joint but were first glued to maple veneers using epoxy (Araldit).

In 1959 further static tension tests were performed at EMPA [2] with specimens acc. to Fig. 2b. The steel plates were then Araldit-bonded directly onto the spruce

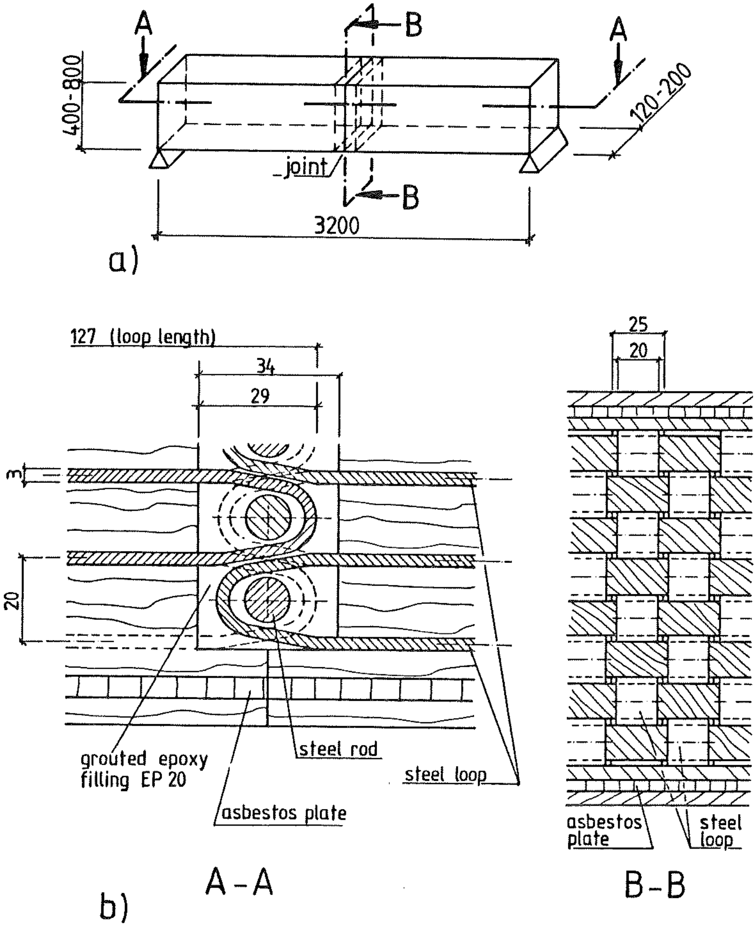


Figs. 2a - c: Specimens tested at EMPA, Switzerland and Otto-Graf-Institute
a) acc. to [1] b) acc. to [2] c) acc. to [3]

surfaces. At normal climate conditions (12 % MC) non-corroding steel "Anticorodal" and normal construction steel gave comparable tension shear strength values of 4 resp. 4.5 MPa. After water storage and reconditioning at 65 - 70 °C said strength values dropped to 45 %.

In 1964 an investigation on statically and dynamically tension loaded double lap joints acc. to Fig. 2c was conducted at Otto-Graf-Institute [3]. The testing comprised six different epoxies, three timber species, normal and toughened climate conditions. The surface preparation of the aluminium plates was done by pickling. For pine and ash adherends the mean tension shear strength values for specimens conditioned in normal climate (12 % MC) amounted to 9.6 resp. 12.2 MPa. Dynamic tension loading at 8 Hz lowered the strength values after $2 \cdot 10^6$ load cycles to 21 % of the mean static loading capacity. A pre-conditioning with changing climate conditions (20 ° to 60 °C, 25 to 95 % RH) revealed for nearly all investigated epoxies a drastic strength decrease to roughly zero, only Araldit 113 retained about 50 % of the normal climate strength values. A quite neglectable strength difference between normal and toughened climate conditions however was received with hot curing Redux (K6fl and Redux-powder). Denoted Redux consists of two components with different state of aggregate, a hot curing phenolic resin solved in organic medium and a polyvinyl resin powder. The gluing technique was alike to [1]; a 0.8 mm beech veneer was first glued to the metal surface (150 °C press temperature, 30 min press time) and second a cold phenolic-resorcinol gluing of the adherends and the veneered metal overlaps took place.

In 1985 testing of the so-called "Wiesner-Hager"system (Figs. 3) was performed at Otto-Graf-Institute [4]. Each joint end of the members to be joined is built up from a multiplicity of U-shaped steel loops of 3 mm thickness which are glued staggered into end grain slots with epoxy (EP 20). On the building site the member ends are connected so that opposite loops meet zip-like, the over-lapping is fixed by steel rods and the joint gap is filled with grouted epoxy (Fig. 3a). The described connection was tested in large scale bending members (Fig. 3b) with joints at different locations and at small specimens to determine tension anchorage strength of single glue attached loops. The outer fiber bond shear stresses (mean value along bond length as all values mentioned above) in bending specimens with joints at mid-span averaged 3.5 MPa. The latter value was very close to the mean tension shear strength of 3.6 MPa received with all small specimens.



Figs. 3a, b: "Wiesner-Hager" glued joint system
a) joint scheme b) tested joined members

In 1989 the most recent wood-steel plate jointing project at Otto-Graf-Institute was finished where besides other aspects a comparative study on epoxy and polyurethane was performed [5].

3. Computational work

3.1 Analytical approach

For an axially loaded joint comparable to Fig. 1a some essentials of the mechanical behaviour can be studied in a qualitative manner by solutions given in [6]. With respect to symmetry the joint can be replaced approximately by a lap joint configuration acc. to Figs. 4 as no end grain load transfer at location $x = 0$ has to be considered. It is further assumed that no bending occurs as well the adherends and the adhesive shall be isotropic and behave strictly linear elastic. The shear stress distribution along bond length is then given by

$$f_{xy} = \overline{f_{xy}} \, \frac{\sqrt{\frac{\Delta}{\omega}}}{\sinh \sqrt{\Delta\,\omega}} \left\{ (\omega - 1) \cosh\left(\sqrt{\Delta\,\omega} \, \frac{x}{\ell} \right) + \cosh\left(\sqrt{\Delta\,\omega} \left[1 - \frac{x}{\ell} \right] \right) \right\} \qquad (1)$$

with

$$\Delta = \frac{G\,\ell^2}{E_2 s_2 d} , \quad \omega = \frac{E_1 s_1 + E_2 s_2}{E_1 s_1} , \quad \overline{f_{xy}} = \frac{F}{\ell \cdot b} = \frac{F'}{\ell} . \qquad (2a - c)$$

E_i, s_i are Youngs' moduli and depths of both adherends, the values G, d denote shear modulus resp. depth of adhesive layer and ℓ is bond length. $F' = F/b$ is applied load per unit joint width and $\overline{f_{xy}}$ the mean shear stress in the glue line.

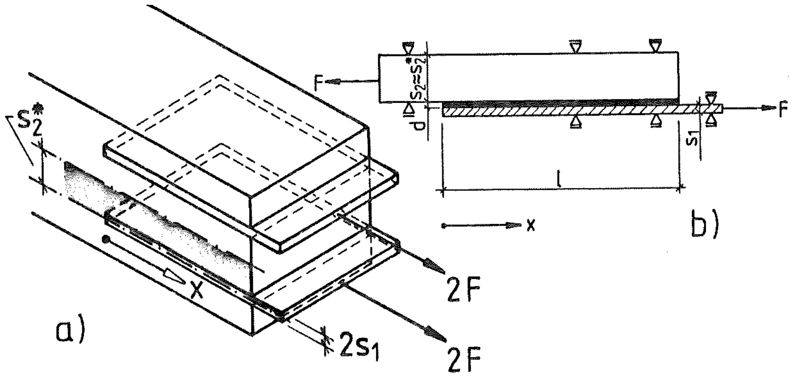
It can be seen from Eq. (1) that except for $\omega = 2$, meaning symmetric conditions $E_1 s_1 = E_2 s_2$, the shear distribution becomes increasingly unsymmetric to half bond length when the difference of the adherend stiffnesses, denoted by ω, increases. For $E_1 s_1 > E_2 s_2$ and hence $1 < \omega < 2$ the maximum shear stress occurs at $x = 0$, being

$$\max f_{xy} = F'\rho \left\{ \frac{\omega - 1}{\sinh(\ell\omega\rho)} + \coth(\ell\omega\rho) \right\} \tag{3a}$$

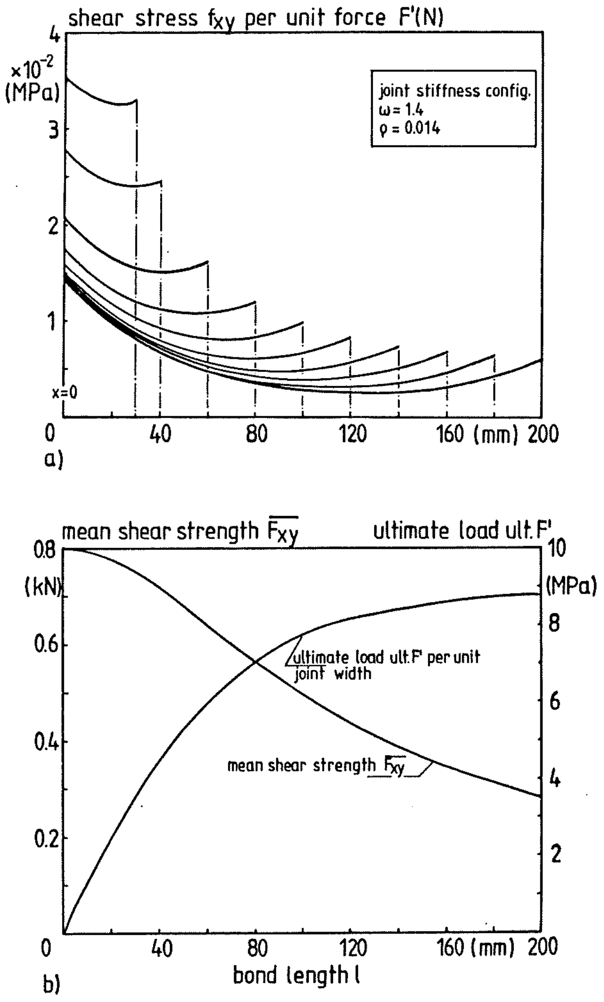
with

$$\rho = \sqrt{\frac{G}{E_2 s_2 d\,\omega}} \;. \tag{3b}$$

Eqs. (3) enable some conclusions how bond length, adherend and glue line stiffnesses affect the maximum shear value. It can be seen that the expression in the curved brackets decreases with increasing bond length and tends to the limit value 1, i. e. from a certain value of bond length (termed optimum bond length) onwards the maximum shear stress remains constant for unchanged loading F'. Based on the definitely crude assessment that joint failure occurs when $\max f_{xy}$ equals the adhesive shear strength $F_{v,glue}$ Eqs. (3) deliver an experimentally well known relationship of $ult.F'$ and mean shear strength $\overline{F_{xy}} = ult.F'/\ell$ versus bond length. Figs. 5a, b depict the above for a random joint stiffness configuration which could be a timber-steel plate connection $(\omega = 1.4,\ \rho = 0.014)$. Fig. 5a shows the bond line shear stress distribution for different bond lengths, i. a. revealing the degressive decrease of $\max f_{xy}$ at $x = 0$ (and alike at $x = \ell$). Fig. 5b gives the theoretical joint load capacity $ult.F'$ and mean shear strength $\overline{F_{xy}}$ depending on bond length; the ultimate values are based on $\max f_{xy}$ in Fig. 5a and result from the equality condition $\max f_{xy} = F_{v,glue} = 10$ MPa .



Figs. 4a, b: Approximative joint idealization



Figs. 5a, b: Shear stress distributions f_{xy} and hereof deduced ultimate loads ult.F' resp. mean shear strengths $\overline{F_{xy}}$ for different bond lengths

a) f_{xy} b) ult.F' and $\overline{F_{xy}}$

For a given adherend stiffness configuration Eqs. (3) tell that $\max f_{xy}$ can be lowered and inversely $\mathrm{ult.}F'$ increased by reducing the slip resistance **G/d** of the adhesive layer. This theoretical conclusion of an increase of $\mathrm{ult.}F'$ with decreasing **G** and especially with increasing glue line thickness **d** is however experimentally stated only within very narrow limits. Beyond a certain value of **d** in most cases a distinct strength decrease can be observed; acc. to [7] the optimum glue line thickness is in the range of 0.05 to maximally 0.2 mm.

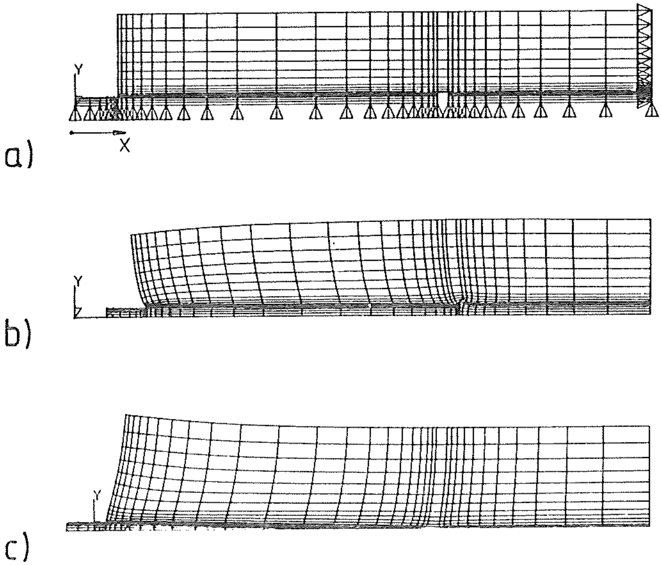
For more thorough investigations on how different geometry and stiffness parameters affect joint behaviour or ultimately for a joint optimization the literature known analytical solutions are too coarse and a numerical approach is necessary.

3.2 Numerical solutions

3.2.1 Model and relevant stress distributions

Fig. 6a shows a finite element mesh and the boundary conditions for a joint with one centrically bonded steel plate where due to symmetry only half of the joint is idealized. The assumed constitutive properties for the orthotropic wood stud and the isotropic adhesive were $E_x = 11$ GPa, $E_y = 0.3$ GPa, $G_{xy} =$ GPa, $\nu_{yx} = \nu_{xy}\, E_x/E_y = 0.4$ resp. $E = 3.36$ GPa, $\nu = 0.4$. The glue line layer was discretizised by two layers of elements. The computations up to now were elastic, however plasticity of the adhesive will be included when some experiments (see chap. 4.4) have revealed more of the actual nonlinear glue line behaviour. Fig. 6b shows the deformed structure (deformation enlarged) of the joint loaded in compression and Fig. 6c gives the deformation appearance of a similar joint in tension loading. The steel plate in the latter figure however is tapered what is discussed below in more detail.

Figs. 7 give some important stress distributions along bond length in a joint acc. to Fig. 6a. Figs. 7a, b illustrate the axial normal stresses of the steel plate in its center plane (A-A) resp. the axial wood normal stresses in two planes, i. e. in the adhesive-wood interface (C-C) and at 0.7 mm off-set from there (D-D). Figs. 7c, d depict the wood and adhesive layer shear stresses in the adhesive-wood interface (C-C) resp. in the center plane of the glue line (B-B). Figs. 6e, f give for both latter planes the wood and adhesive stresses perpendicular to the joint axis.

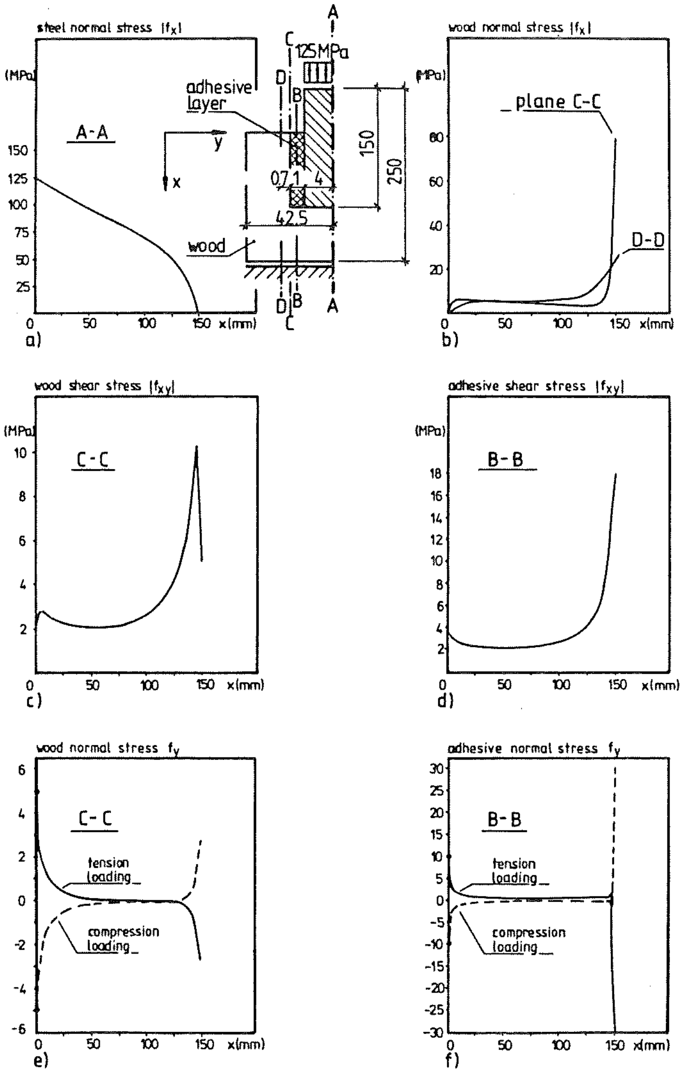


Figs. 6a - c: Finite element idealization of single steel plate joint

a) undeformed geometry
b) deformed structure in compression loading (disp. enlarged)
c) deformed structure with tapered steel plate in tension loading (disp. enlarged)

3.2.2 Effect of steel plate taper

For realization of highest possible joint efficiency the fracture co-determining shear stress maximum has to be lowest possible for distinct bond lengths and second the optimum bond length must be as long as possible. Both objectives can be met by tapering the plates towards the inner bond length end. By means of a continuous decrease of the plate stiffness a significant reduction of the stress peak causing strain differences of the adherends is received. An alike approach is made in [8] where for attachment of wooden wind turbine blades (16 m length) to the hub, conical steel studs were bonded in the blade roots.



Figs. 7a - f: Stress distributions in selected planes of single steel plate joint

Fig. 8 shows the effect of differently linear tapered steel plates on the shear stress distribution for a similar specimen configuration as given in Fig. 7a, only bond length increased to 200 mm. It can be seen how the maximum shear stress and the ratio of maximum to mean stress drops with increasing slope $\tan\alpha$ i. e. how we get an increasingly smoothed stress distribution along bond length. At a slope of $\tan\alpha = 1/50$ what means zero tip width in this configuration the maximum shear stress is only 40 % of the value of the untapered plate. Experimentally the ultimate load of course will not show the inverse factor of 2.5 but there should be a substantial increase.

Fig. 9 shows exemplary how optimum bond length can be increased thoroughly compared to an untapered plate. In the given example all dimensions are as in Fig. 7a only bond length and plate taper were accordingly altered. For the untapered plate the optimum bond length is roughly 150 mm (a prolongation in the range of 150 - 200 mm results only in very poor increases of ult. $F' \sim 1/\max f_{xy}$). Compared thereto the stronger tapered plates with $\tan\alpha > 1/150$ show an optimum bond length of well beyond 200 mm.

The third major advantage of using tapered plates apart from stress peak reduction and enlargement of optimum bond length lies in the possibility of increasing the net to gross area ratio of the jointed wooden member significantly. For practice with respect to saw blade thicknesses net area ratios of 0.9 - 0.95 are realistic. This, in case the plates and glue lines can transfer the loading would be a definitely higher joint efficiency than received with mechanical fasteners where due to slots and fastener holes good ratios are in the range of 2/3.

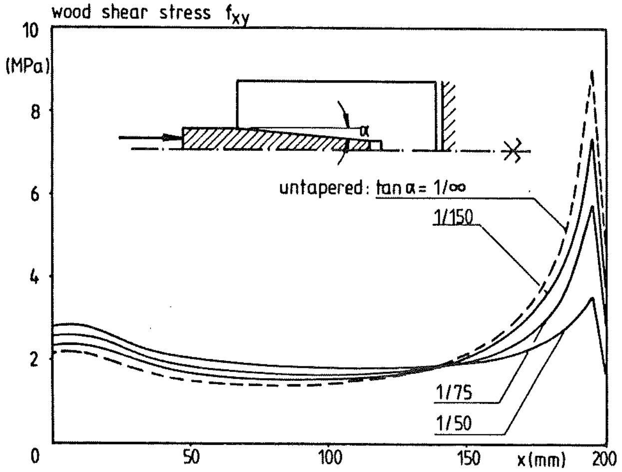


Fig. 8: Effect of differently tapered steel plates on shear stress distribution of single steel plate joint

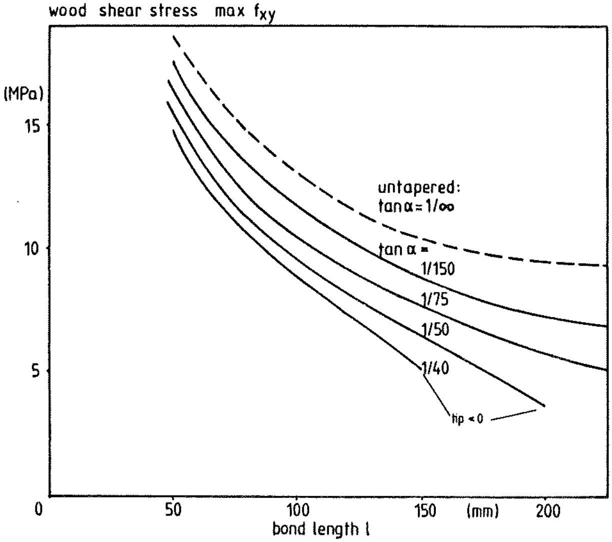


Fig. 9: Maximum wood shear stress depending on bond length and steel plate taper of single steel plate joint

4. Experimental investigations

4.1 Objective

The main objective of the experimental part of the project is the evaluation of adhesives appropriate for wood-steel plate connections. Suitable adhesives should be rather indifferent against increased glue line thicknesses and show an acceptable strength resp. stiffness loss at both, elevated temperatures up to 70 °C and long-term loading. It should be mentioned here, that Otto-Graf-Institute is Germany's sole material testing institute authorized by the Institute of Bautechnik (Ifbt) in Berlin to approve or certify adhesives for structural timber gluing.

4.2 Adhesives

The testing comprised in total five different epoxies, four polyurethanes and one adhesive of the phenolic-resorcinol type. Some remarks on the used adhesives are given hereinafter.

4.2.1 Epoxies

Until today only one epoxy is certified for structural wood gluing in Germany, and exclusively for wood to wood applications along with repair and upgrading actions. It was apparent to incorporate that adhesive (here termed EP1) known for good adhesion to wood as well as for excellent long-term and gap-filling behaviour. Epoxies EP2a, EP2b were specially composed for this project. Both adhesives belong to the class of toughened epoxies which contain a certain amount of rubber particles in the normal epoxy matrix giving the normally brittle epoxy a more ductile behaviour. Furthermore the rubber particles do absorb strain energy, when hit by the tip of a developing crack, thus restraining the crack propagation. EP2b contains a lesser amount of rubber particles than EP2a. Adhesive EP3 is a filled epoxy grout approved for gluing dowels into concrete and brickwork. EP4 is known for excellent behaviour between steel and concrete and successfully used for bonded steel reinforcements of cracked or underdesigned concrete structures. The cited epoxies differ strongly in pot lifes (5 to 35 min), open assembly times (5 to 40 min) and curing times (15 min to 24 hours).

4.2.2 Polyurethanes

By end of this year the first polyurethane adhesive will be certified in Germany for usage in structural wood to wood bonding, i. e. for glulam. As there is little experience on the long-term behaviour of polyurethanes in this type of application said certification will include an intermediate span limit of 6 meters (here termed PU4). Polyurethane PU1 is another one-component adhesive of comparable handling characteristics as PU4, yet of another producer and not certified now. PU2 was included representing the two-component type of polyurethanes curing with an amino-hardener. PU3 is a quasi two-component polyurethane, i. e. a one-component adhesive which has to be applied in combination with a special adherend dependant primer. This adhesive possesses an extreme indifference to very thick glue lines up to more than 10 mm and thus is used widely where both, sealing and gluing effects are of alike interest.

4.2.3 Phenolic-resorcinol adhesive

Only one adhesive of the polycondensation type of adhesives (PR1) was chosen and this mostly to give further evidence that urea-, amino- or phenolic-resorcinol-formaldehydes are by no means appropriate for bonding larger steel areas to wood what was already shown in [5] for glue line thicknesses of nominally 0.25 resp. 0.5 mm. Here it was intended to prove an even increased unsuitability for larger glue line thicknesses and that this holds true even when a fairly recently certified PR is taken which is well suitable for glue line thicknesses up to 2 mm in wood to wood applications.

The problem of steel gluing with polycondensation adhesives results from the distinct shrinkage of the adhesive what, when restraint in thicker glue lines or/and by far stiffer adherends results in delaminating eigenstresses.

4.3 Steel plates and surface preparation

The tests were performed with two types of steel, with common construction steel ST 37-2, mat. no. 1.0037, DIN 17100 and with non-corroding CrNiMo construction steel, mat. no. 1.4571, DIN 17440. For surface preparation of the steel plates various pickling methods would be best technically but seemed inadequate for building practice. As second best alternative sand blasting was chosen. About 75 % of specimens of part I tests were blasted with "Edelkorund" of grain size 0.1 - 0.25 mm following recommendations in [9]. Degreasing in this case was only done shortly before gluing. In an attempt to reduce adhesion failure occurances in the steel-adhesive interface, grain material and size was then changed to "Normalkorund" K 0.5 - 1 mm (DIN 8201, part 1). The realized surface quality was Sa 3 and the plates were degreased twice, before sand blasting and immediately before bonding.

4.4 Testing scheme

As it was impossible to conduct all tests with the entity of selected adhesives the investigations were separated into two parts. In part I from the total of 10 adhesives four were selected for part II comprising more comprehensive tests.

4.4.1 Part I

The main test variable was glue line thickness with three discrete values: 0.5, 1 and 2 mm. For achievement of the required thicknesses, headless nails with relevant diameters (length 10 mm) were bonded to the corners of the glued steel plate surfaces. All tests were performed with specimens of constant size (Figs. 10 to 12) after long-term conditioning in 20 °C / 65 % RH. The wood material was glulam from spruce laminations of 32 mm thickness. The steel plates were oriented normal to the width of specimens' four laminations. When cutting the specimens to exact length an end slice for density measurements was taken to allow for mean density adjustments in the final test evaluation. The specimen densities ranged from 380 - 440 kg/m^3 at 12 % MC. The chosen bond length of 150 mm equalled roughly the theoretical linear elastic optimum bond length (chap. 3.2.2). The second reason for the choice of that fairly long bond length was to provide a high ratio $\mathbf{\max f_{xy}/\overline{f_{xy}}}$ thus enabling non-brittle adhesives to develop a marked plastic strength increase. Of each specimen configuration mostly five samples were tested in deformation controlled loading (cross-head speed 1 mm/min).

The glue line slip was measured at half bond length as relative displacement of a screw-fixed transducer at mid-thickness of the steel plate against two opposite reference points mounted on the wood stud closely to the glue line layer. The fixation of the wood reference points was first achieved by means of small screws with a clearing in between of throughout 18 mm (method A). In order to minimize the additional slip portion resulting from the included wood layer the measuring set-up was slightly changed in the further course of the investigations. The outer

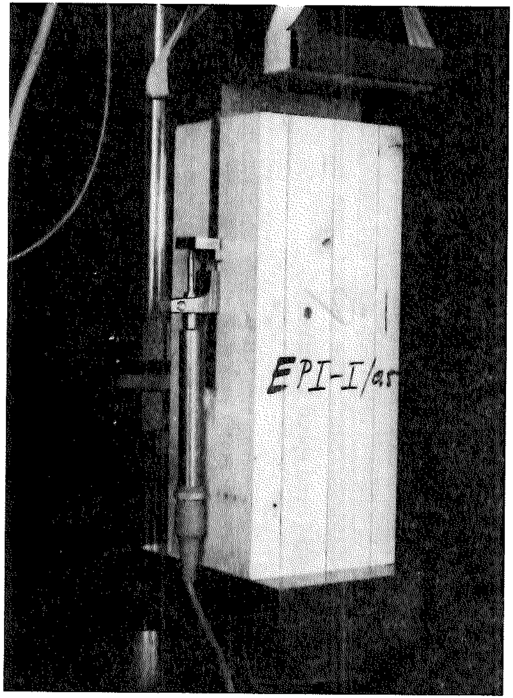


Fig. 10: Compression test set-up

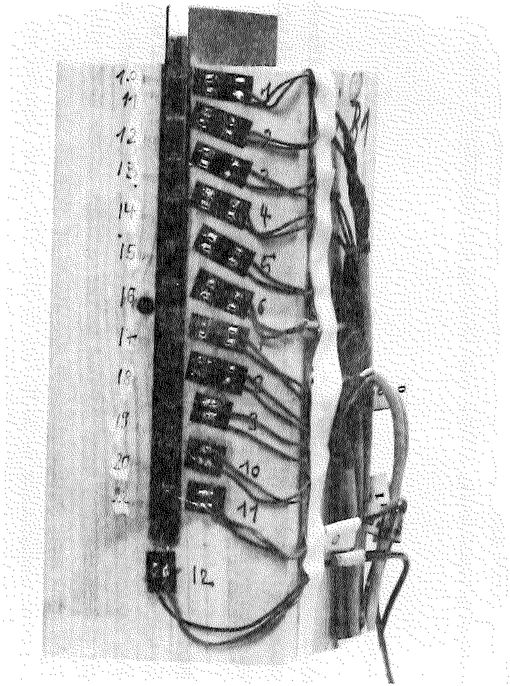


Fig. 11: Compression specimen with applied strain gauges

reference points ($5 \times 5\ mm^2$) were then bonded to the specimen with a constant offset of 0.5 mm from the glue line rim (method B). Both measurements give qualitative similar curves but due to the additional wood layer slip they can't be taken as a basis for determination of the adhesive shear modulus. This aspect requires a more sophisticated instrumentation and can be pursued either purely experimentally or in a mixed experimental-computational approach. The latter one consists of measuring the steel plate strain (stress) distribution (Fig. 11) which then is iteratively approximized numerically by appropriate G-modulus variation.

4.4.2 Part II

In the second part of the testing just started short-term tension and compression tests at normal and elevated temperatures (20, 40, 70 °C) along with long-term tension tests (10^4 hours) at a stress level of $\overline{f_{xy}} = 0.9 MPa$ are conducted. The test variable glue line thickness is maintained in all part II tests.

4.5 Results of testing part I

4.5.1 Load slip and fracture behaviour

Fig. 12 shows the typical load slip curves registered in the testings (measuring method B), here in case of 0.5 mm glue line thickness; for 1 and 2 mm thickness the curves are similar but of lower slope. Three types of deformation and fracture appearances can be stated.

First we have a group of very stiff adhesives which nearly up to brittle fracture behave linear elastic. Adhesives of this type are the phenolic-resorcinol glue PR1, all epoxies with exception of the toughened EP2b (i. e. EP1, EP3, EP4) and the amino-cured polyurethane PU2. The failure slips at half bond length of this group of adhesives depending on ultimate load and adhesive type were in the range of 0.0025 to 0.04 mm for 0.5 mm glue line thickness and reached maximally 0.2 mm with glue lines of 2 mm thickness.

A second group consisting of polyurethanes PU1, PU4 and epoxy EP2b shows a differently accentuated, initially elastic than soon nonlinear plastic behaviour. The

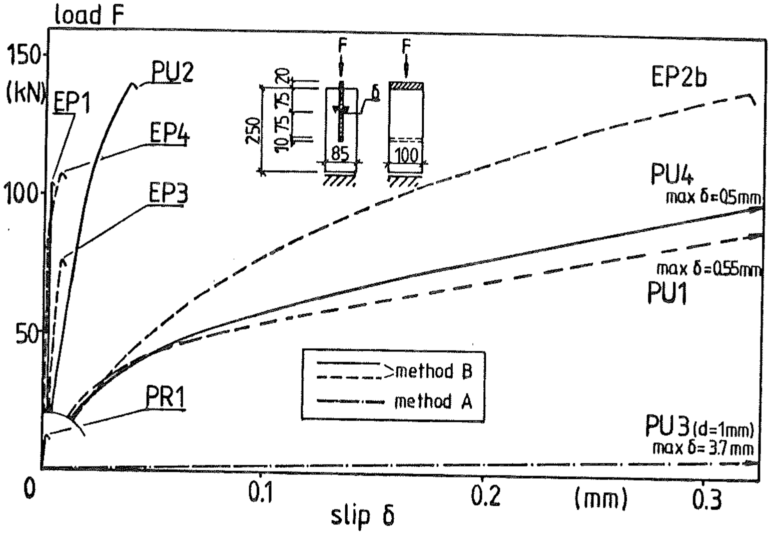


Fig. 12: Typical load slip curves of specimens bonded with different adhesives

slips at ultimate loads are roughly one magnitude higher compared to those of the brittle adhesives with relative lowest stiffnesses. Alike the first group the experiment gets unstable at ultimate load.

A third deformation resp. fracture characteristic is revealed by polyurethane PU3. This adhesive first shows a linear behaviour nearly until maximum load at enormous slips (3 to 8 mm, measuring method A) and then, after a short yielding plateau stable strain softening nearly until zero loading is received. In no test with PU3 an actual fracture of the bond was received at slips up to 10 mm and after unloading the deformations recovered to a large extent.

4.5.2 Fracture surfaces

Four distinct types of fracture planes were received, i. e. adhesive failures in the steel plate-adhesive interface (Fig. 13a), cohesive failures within the adhesive layer (Figs. 14a, b), wood failure in the adhesive-wood interface and complete wood failures (Fig. 13b). Most adhesives showed at lower glue line thicknesses transitions between two distinct fracture types.

Complete adhesive failures in the steel-adhesive interface occured with the phenolic-resorcinol resin PR1 throughout all glue line thicknesses, and with most epoxies (except EP2b) however only at thicker glue lines. At glue line thicknesses of 0.5 mm said epoxies then showed mixed, differently articulated, steel adhesion resp. wood failures.

Predominant cohesive failures were received with all polyurethanes (except PU3 which did not fracture at imposed displacements) at glue line thicknesses of 1 and 2 mm whereby some differentiations can be made. The one-component polyurethanes PU1, PU4 showed a mid-layer fracture surface including a lot of foam-like bubbles (Fig. 14a). Compared thereto fracture planes of the amino-cured polyurethane PU2 had the characteristic outlook given in Fig. 14b, showing that the cohesive fracture occurs very close to the adhesive-timber interface. At 0.5 mm glue line thickness all polyurethanes had mixed cohesive and wood failures. Then the cohesive fracture surfaces were of alike appearance on wood and steel adherends and similar to those shown in Fig. 14b on the wooden parts (half bond length downwards), i. e. without including foam-like bubbles.

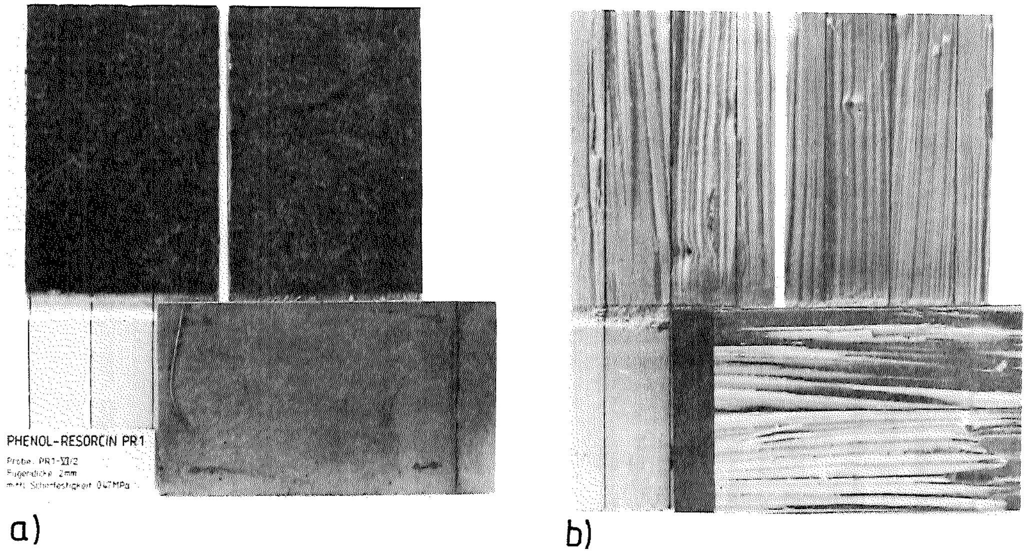
Throughout complete wood failures with fracture surfaces as in Fig. 13b were received with epoxy EP2b at very high strength levels.

4.5.3 Compression shear strength values

Table 1 contains the compression shear strength values (means and coef. of var.) of all adhesive-glue line thickness configurations tested so far. Figs. 15 give a graphic representation of the table values.

The polyurethanes except the exotic PU3 show a distinct strength increase with falling glue line thickness most pronounced below 1 mm (Fig. 15a). This strength trend goes along with the mentioned loss of foam-like character of the adhesive with dropping glue line thickness. The same effect of increasing strength values along with falling glue line thickness is also valid for the epoxies EP1, EP4, however, the increase below 1 mm is less marked compared to the polyurethanes. Alike glue line thickness sensitivity of strength values was stated in wood to wood bondings with PU4 and EP1.

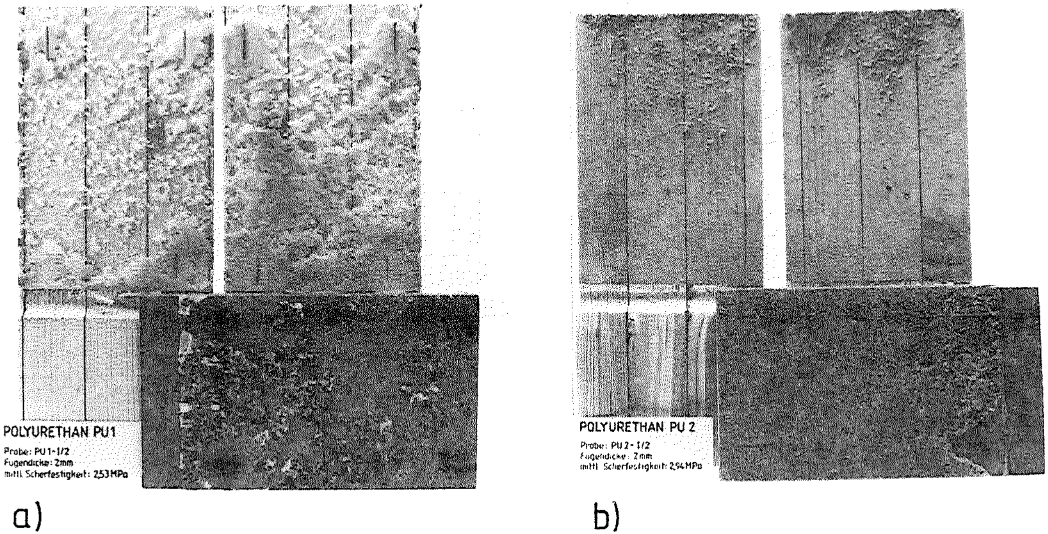
In contrary to aforementioned tendencies, the filled epoxy grout EP3 revealed a nearly absolute indifference against glue line thickness variations. Finally the rubber



Figs. 13a, b: Typical fracture planes of different adhesives

a) phenolic-resorcinol adhesive PR1 (d = 2 mm)

b) epoxy EP2b (d = 1 mm)

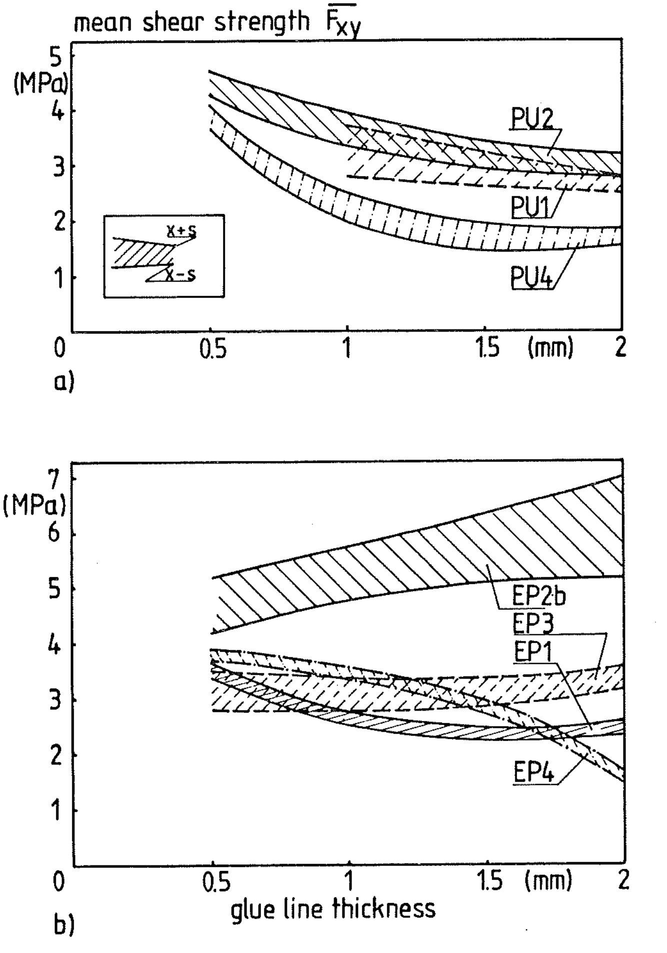


Figs. 14a, b: Typical fracture planes of different adhesives
a) polyurethane PU1 (d = 2 mm)
b) polyurethane PU2 (d = 2 mm)

glue line thickness d	compression shear strength values $\overline{F_{xy}}$ [MPa]										
	polyurethanes				epoxies				"unconventional" polyaddition adhesives		phenolic-resorcinol formaldehyde
(mm)	PU1	PU2	PU4	Σ PU_i/3	EP1	EP3	EP4	Σ EPi/3	polyurethane PU3	epoxy EP2b	
0.5	--	4.59 $^{(4)}$ (6 %)	3.84 $^{(5)}$ (5 %)	4.22	3.51 $^{(7)}$ (9 %)	3.11 (11 %)	3.80 (2 %)	3.47	--	4.72 $^{(3)}$ (12 %)	--
1.0	3.08 (20 %)	3.65 $^{(6)}$ (9 %)	2.26 (12 %)	3.00	2.64 (10 %)	3.05 (12 %)	3.50 (--)	3.07	2.18 (22 %)	5.24 $^{(2)}$ (10 %)	1.11 (50 %)
2.0	2.64 (6 %)	3.02 (6 %)	1.75 (8 %)	2.47	2.48 (8 %)	3.36 (5 %)	1.63 (--)	2.49	2.71 (14 %)	6.18 $^{(1)}$ (13 %)	0.58 (38 %)

Table 1: Mean compression shear strength values $\overline{F_{xy}}$ [MPa] along bond length (150 mm) of several adhesives for different glue line thicknesses. Test set-up acc. to Figs. 11, 12; nominally 5 specimens per glue line thickness - adhesive configuration.

(... %) ≙ coefficient of variation; (--) ≙ only 1 or 2 specimens; $^{(i)}$ ≙ ranking of values: $^{(1)}$ ≙ highest, ...



Figs. 15a, b: Mean compression strength values depending on glue line thickness
a) polyurethanes b) epoxies

toughened epoxy EP2b showed a significant strength increase along with rising glue line thickness thus solely confirming the conclusions acc. to Eqs. (1), (3).

The averaged strengths of "normal" epoxies (EP1, EP3, EP4) and polyurethanes (PU1, PU2, PU4) have comparable magnitude of roughly 2.5 and 3 MPa at glue line thicknesses of 2 resp. 1 mm. These strength levels seem rather low for practical applications as further allowances have to be made for long-term behaviour and elevated temperatures. At a glue line thickness of 0.5 mm the polyurethanes in average lie well higher than the epoxies and the strength level of about 4 MPa becomes interesting. The highest values, however, at a surprising strength level were received with the toughened epoxy EP2b. The mean values at glue line thicknesses of 0.5, 1 and 2 mm amounted to 4.7, 5.2 resp. 6.2 MPa. With respect to phenolic-resorcinol resins table 1 confirms definitely that these are by no means appropriate for timber-steel plate gluing. In some cases the received strength values were almost zero due to delaminations occured during curing and conditioning in 20 °C/65 % RH.

The test results revealed no significant influence of the different steel types used. However there are strong indications that sand blasting with larger grain sizes and twofold degreasing results in superior strength values.

5. Conclusions

Efficiency of glued timber-steel plate joints apart from timber quality and manufacturing performance depends on three essential aspects, i. e. geometry shaping of joint components, steel surface preparation and on strength, stiffness resp. reliability of adhesives.

Tapering of the connecting steel plates theoretically has a strong influence on increased joint strength through reduction of stress peaks and elongation of optimum bond length. There is indication that sand-blasting with grain sizes of 0.5 - 1 mm applied to pre-degreased metal surfaces and a second degreasing before gluing is superior to usage of smaller sand-blast grain sizes and sole degreasing before gluing. With respect to adhesives it looks promising to use either polyurethanes with glue line thicknesses lesser than 0.5 mm or toughened epoxies which showed surprising strength most pronounced at glue line thicknesses of 2 mm. Appropriate fillers of the resins can provide a distinguished insensitiveness against glue line thickness variations.

Glued structural timber-steel plate joints seem feasible on the condition that temperature and long-term behaviour can be manipulated suitably.

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