# Destructive testing of adhesively bonded joints under static tensile loading

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**ABSTRACT** Several in-situ testing methods of adhesively bonded joints under static short-time tensile loading are critically analyzed in terms of experimental procedure and data evaluation. Due to its rather homogeneous stress state across the glue line, the tensile-shear test with thick single-lap specimens, according to ISO 11003-2, has become the most important test process for the determination of realistic materials parameters. This basic method, which was improved in both, the experimental part by stepped adherends and easily attachable extensometers and the evaluation procedure by numeric substrate deformation correction and test simulation based on the finite element method (FEM), is therefore demonstrated by application to several kinds of adhesives and metallic adherends. Multi-axial load decreases the strength of a joint. This effect, which is illustrated by an experimental comparison, impedes the derivation of realistic mechanical characteristics from measured force-displacement curves. It is shown by numeric modeling that tensile-shear tests with thin plate substrates according to ISO 4587, which are widely used for quick industrial quality assurance, reveal an inhomogeneous stress state, especially because of relatively large adherend deformation. Complete experimental determination of the elastic properties of bonded joints requires independent measurement of at least two characteristics. As the thick-adherend tensile-shear test directly yields the shear modulus, the tensile butt-joint test according to ISO 6922 represents the most obvious complement of the test programme. Thus, validity of analytical correction formulae proposed in literature for the derivation of realistic materials characteristics is verified by numeric simulation. Moreover, the influence of the substrate deformation is examined and a FEM correction method introduced.

KEYWORDS:

ADHESIVE PARAMETERS; DESTRUCTIVE TESTING; THICK-ADHEREND TENSILE-SHEAR TEST; THIN-ADHEREND TENSILE SHEAR TEST; TENSILE BUTT-JOINT TEST; ADHEREND DEFORMATION CORRECTION; FINITE ELEMENT STRESS ANALYSIS

## Introduction

Modern adhesive technology offers economical and efficient techniques for joining nearly all materials into complex components. Important applications in the machine-building, automotive, aviation, aerospace, electronic and bio-medical industry are, for instance, structural bonding, retaining, flange coupling and sealing, thread locking and sealing, coating and impregnation. In rolling bearing engineering, tight fitting of rings and shafts or bearings and housings as well as joining of cages and mounting of accessories and ancillary equipment are characteristic examples.

---------- Figure 1 ----------

If at all possible, adhesively bonded joints should be loaded in shear, as shown in Fig. 1 for the press fit between the outer ring of a large-size cylindrical roller bearing and the sheet metal cap, or at least in tension or compression without peel forces. Since simple destructive in situ testing methods are required for the examination of the static mechanical behavior, torsion tests (e.g. ISO 11003-1) or double-lap-joint assemblies are seldom applied and the tensile-shear test with thick (small substrate deformation) single-lap specimens, as described in ISO 11003-2, has succeeded as the most important test method for the realistic determination of shear properties of adhesive joints. For the additional measurement of tensile characteristics, the butt-joint test according to ISO 6922 suggests itself, as both methods can easily be performed using a standard universal testing machine.

## Thick-Adherend Tensile-Shear-Test

For the design of a joint, at least the elastic parameters (two out of Young's modulus E, shear modulus G, bulk modulus K and Poisson's ratio ν) and in some cases failure criteria are usually required. For the determination of the shear modulus and the failure stress and strain, the thick-adherend tensile-shear test is often applied.

*Experimental Procedure and Test Evaluation*

Deviating from the recommendation of the standard ISO 11003-2, stepped metal substrates (length 106 mm, width 25 mm, total depth 12 mm) are used. Due to increasing stiffness, these samples decrease the stress peaks at the end of the overlap area more effectively than the laminated assembly suggested by the standard. Also, such adherends are reusable, which is an important feature for industrial applications.

---------- Figure 2 ----------

All tests are performed on a tensile testing machine (Zwick Z 010) with an appropriate load cell of 10 kN and a constant machine speed of 0.5 mm/min, as recommended by the standard. This way, the strain rate-sensitive mechanical behavior of polymers is better taken into consideration than with a continuously increasing force with time [1]. The load is applied without additional torque over the drilled holes in the samples, as shown schematically in Figs. 2 and 3. A mobile furnace (Noeske-Kaeser) was able to be attached to heat the specimens. All tests, with the number of specimens for each series being greater than the three repetitions required by the standard, are carried out up to the fracture of the glued sample. Displacement measurement was performed across the adhesive layer using two extensometers with strain gauges (Instron, measuring accuracy about 2 μm). These devices were attached on both sides of the sample to three reference points directly at the overlap zone, as schematically illustrated in Figs. 2 and 3. This measuring method ensures a minimum contribution of the substrate deformation to the total displacement.

The measuring principle is explained in detail by means of Fig. 3 [2]: the applied force F causes a total displacement d of the metal pin C, relative to the drilled holes A and B (both diameters 1 mm), to which the extensometer with reference length $t_e$ is attached. From the recorded force versus displacement curve, the shear stress-shear strain diagram, $\tau = \tau(\gamma)$, is determined as follows:

$$\tau = \frac{F}{A}, \quad \gamma = \arctan\frac{d - d_s}{t_a} \tag{1}$$

Here, A and $t_a$ denote the glue surface area (300 mm$^2$) and the adhesive thickness, respectively. If the $\tau$–$\gamma$ curve reveals a linear increase for small strains, Hooke's law can be applied:

$$\tau = G \times \gamma \tag{2}$$

Thus, the shear modulus G of the joint can be obtained from the slope of the initially linear part of the $\tau$–$\gamma$ diagram.

---------- Figure 3 ----------

Although the total displacement of the joint is measured across the polymer layer from one metal part to the other over a short reference distance (cf., Figs. 2, 3), derivation of the desired adhesive displacement $d_a = d - d_s$, however, requires determination of the deformation of the substrates (1 and 2), $d_s = d_{s1} + d_{s2}$, at least if high-strength adhesives are applied. The reliability of this adherend deformation correction depends upon appropriately attached extensometers [3]. It can be best performed by the numerical simulation of the linear elastic deformation of a dummy sample [2,4], as the high measuring accuracy (<< 1 µm) necessary for corresponding reference tests, which are proposed in the ISO 11003-2 version of 1993, is not reached by standard extensometers and the simplified analytical method, suggested in the revised standard version of 2001, yields wrong results [5]. The authors recommend finite element (FE) computation. In order to improve its accuracy, the whole sample geometry is meshed using solid elements with quadratic shape functions. The three-dimensional mesh consisted of 1920 elements with 13865 nodes. For steel and aluminum samples, the FE simulation provides linear relationships between the adherend deformation $d_s$ and the applied tensile force F as shown in Fig. 4.

*Selected Results*

The applicability of the simulation-aided thick-adherend tensile-shear test with the improved measuring technique as described above is demonstrated with the example of an anaerobic adhesive (30 µm bond gap) using steel samples (structural steel S235). Fig. 5 reveals both, typical force-displacement curves and the derived shear stress-strain diagrams. Note that the bond strength is characterized by the maximum shear stress with the corresponding shear strain as a measure of the ductility of the joint. Test evaluation also permits examination of the dependence of the obtained mechanical characteristics on temperature and adhesive thickness [2,4].

---------- Figure 4 ----------

Fig. 6 shows the applied method for the determination of the shear modulus G on a sample tested at room temperature. The shape of these curves in the range of large shear strains has been discussed elsewhere [6]. The observed strengthening could result from viscoelastic effects.

---------- Figure 5 ----------

*Advanced Numerical Test Evaluation*

A FE test simulation based on linear elastic materials behavior is applied to calculate Young's modulus E using the experimentally determined shear modulus G as input [2,4]. By iterating Poisson's ratio ($0 < \nu < 0.5$), the measured displacement can be approximated as a function of the applied load. In order to avoid high computing time and time for modeling of the thin bond gaps, the adhesive layer is described by a fine two-dimensional mesh, using 40 by 320 plate elements with linear shape functions. As a slight crossover onto larger elements is necessary outside of the adhesive layer (in the metal part), the whole model includes 43911 nodes. The relative displacement of those nodes at the same level as the reference points of the extensometer (cf. Figs. 2, 3) is calculated to simulate the measured deformation. The FE computation converges quite well after a few iteration loops.

---------- Figure 6 ----------

As an example of the outcome of the FE test simulation, Fig. 7 presents the derived temperature curve of Young's modulus and the corresponding G–T input data.

---------- Figure 7 ----------

**Thin-Adherend Tensile-Shear Test**

In many practical cases, for instance quality control by measuring bond strengths, the simpler static thin-adherend tensile-shear test in accordance with ISO 4587 is widely used. In order to realistically assess data derived from these two most important destructive test methods of adhesive technology, it is expedient to compare the stresses acting along the glue line and the resulting failure stress. This is done by a linear elastic FE calculation of the stress distributions and an experimental determination of bond strengths at room temperature (296 K). As a concrete example, S235 substrates and an anaerobic adhesive are chosen. The mechanical characteristics of the adherends and the adhesive are $E = 210$ GPa, $G = 80.769$ GPa, $\nu = 0.3$ and $E = 14.96$ MPa, $G = 4.99$ MPa, $\nu = 0.499$, respectively.

### *FE Modeling*

Again, the commercial FE code MSC.Marc is used. With the glue length $l_a = 12$ mm and the specimen width of 25 mm, the glue surface area A amounts to 300 $mm^2$ in both cases. The thickness of the adhesive layer (bond gap) equals 30 μm, which is typical of anaerobic products. The essential difference between both types of test joints is the substrate thickness: the numbers of nodes and elements are 49,581 and 49,018 (thick adherends: 12 mm) and 56,847 and 55,676 (thin adherends: 1.6 mm), respectively. The utilized element type No. 114 is a four-node isoparametric arbitrary quadrilateral written for plane stress applications using reduced integration. This element employs an assumed strain formulation developed in natural coordinates, which ensures good representation of the shear strains within the element. Note that the applied plane stress state corresponds to the situation prevailing in the region near the surface, where the joint actually fails. A point load of 100 N is applied, resulting in an average shear stress for each calculation of $\tau_{ave} = 1/3$ MPa.

### *Results and Discussion*

The computed stress curves are normalized with respect to the mean shear stress, $\tau_{ave}$. The origin of coordinates is placed in the center of the adhesive layer with the y axis directed towards the applied force and the x axis defined perpendicular to the glue area (A). For all calculated stress components, the edge raise in the case of the joined thin substrates is much higher if compared with thick adherends. Fig. 8 reveals that the shear stress is nearly constant across the bond line: even for the thin steel plates, the arising build-up of stress in the rim zone is not particularly pronounced. On the other hand, Figs. 9 and 10 show that the distance distributions of the tensile stresses, especially $\sigma_x$, reveal a large increase in the edge region of the joint, $x \rightarrow \pm \frac{1}{2} l_a$. However, for the thick adherends, due to the lowered influence of differential straining in these substrates, a rather uniform stress state is formed as indispensable prerequisite for the derivation of realistic mechanical characteristics. Here, the normalized tensile stresses in the middle of the adhesive layer ($x \approx 0$) approximately reach zero, whereas for the thin plate specimens, marked compression occurs there.

The result of the static single-lap tensile-shear tests with thick and thin adherends according to ISO 11003-2 with stepped substrates and ISO 4587 are shown in Fig. 11. In agreement with the FE simulation, the measured fracture strength of the adhesively bonded thick substrates is more than two times higher than the one of the glued thin adherends. This test comparison indicates that adherend thickness considerably influences the effect of differential straining in the substrate and thus the uniformity of the stress state. For the thick adherends, a much more homogeneous stress distribution across the bond line exists, whereas the thin plane sheet assembly reveals high stress increase (particularly tensile component $\sigma_x$) at the edge of the joint and compression in the middle region. Data obtained from the ISO 4587 test has very limited connection to the desired intrinsic adhesive parameters. As this study clearly emphasizes, realistic shear characteristics, necessary for engineering joint design, can only be determined by applying the ISO 11003-2 thick-adherend test.

---------- Figure 8 ----------

---------- Figure 9 ----------

---------- Figure 10 ----------

---------- Figure 11 ----------

## Tensile Butt-Joint Test

From the measuring results of the thick-adherend tensile-shear test, Young's modulus can be derived using FE simulation. However, complete experimental in situ determination of the elastic properties of bonded joints requires independent measurement of at least two characteristics. As the thick-adherend tensile-shear test directly yields the shear modulus, the tensile butt-joint test according to ISO 6922, which is illustrated in Fig. 12, represents the most obvious complement of the test programme.

---------- Figure 12 ----------

Substrate deformation correction can again be performed by means of a FE computation of the elastic deformation of a one-piece sample, as described above. For steel and aluminum specimens, the calculated $d_s$–F curves are summarized in Fig. 13.

---------- Figure 13 ----------

Due to the multi-axial stress state with stiffening of the adhesive by radial substrate constraints, however, interpretation of the test results is more difficult than in the case of the thick-adherend tensile-shear test. In literature, the following analytical correction formulae for the derivation of realistic materials characteristics are proposed [7]:

$$E = \frac{(1+\nu)(1-2\nu\nu}{1-\nu} \times E_{test} \;, \quad \nu = \frac{E_{test} - 2G}{2E_{test} - 2G} \tag{3}$$

To investigate the validity of Eq. (3) and to point out the influence of the adherend deformation correction in the axial tension test, the deformation behavior of an axi-symmetric sample was simulated by means of the finite element method. The linear elastic behavior of two steel butt joints of 25 mm diameter and 25 mm length glued due a 30 μm adhesive layer was evaluated. Figure 14 shows that the calculation of the apparent Young's modulus based on the pure deformation of the glue layer yields a quite different result than the evaluation of the two ends of the butt joints. Both displacements were referred on the initial glue thickness of 30 μm. However, the deformation of the steel butt joints yields to significant undervaluation of Young's modulus. This evaluation is the maximum error that can appear if the adherend deformation is neglected. In practical use, the pin separation of an extensometer will be smaller than the length of both butt joints so that the error will be decreased. Table 1 summarizes the errors and proofs the high accuracy of the correction formula (3).

---------- Table 1 ----------

---------- Figure 14 ----------

**Conclusion**

The most important in-situ testing methods of adhesively bonded joints under static short-time tensile loading, i.e. thick- and thin-adherend tensile-shear test and tensile butt-joint test, are discussed in terms of experimental procedure and data evaluation. Realistic mechanical characteristics can best be determined by means of the thick-adherend tensile-shear test with stepped substrates. Thus, this technique is presented in detail. It is shown that numerical test simulations improve and enlarge data evaluation.

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Captions for Illustrations:

Figure 1: Adhesively bonded press fit between a bearing outer ring and a sheet metal cap.

Figure 2: Bonded stepped samples and application of the extensometers.

Figure 3: Schematic representation of the adhesively bonded test sample.

Figure 4: Numerical adherend deformation correction for steel and aluminum substrates.

Figure 5: F–d and resulting $\tau$–$\gamma$ diagrams for steel samples and an anaerobic sealant ($t_a$=30 µm).

Figure 6: Substrate deformation correction (steel) and determination of the shear modulus G (296 K).

Figure 7: Temperature dependence of the shear modulus (input) and Young's modulus (calculated).

Figure 8: Comparison of the shear stress-distance curves of thick and thin adherends.

Figure 9: Comparison of the tensile stress $\sigma_x$ of thick and thin adherends.

Figure 10: Comparison of the tensile stress $\sigma_y$ of thick and thin adherends.

Figure 11: Comparison of the test results according to ISO 4587 and ISO 11003-2.

Figure 12: Bonded samples and application of extensometers.

Figure 13: Numerical adherend deformation correction for steel and aluminum substrates.

Figure 14: Influence of strain evaluation in the axial tension test on Young’s modulus.

| | $E_{test}$ in MPa | E in MPa | Error in % |
|---|---|---|---|
| Glue layer | 79.03 | 22.81 | 0.4 |
| Entire specimen | 48.90 | 14.11 | 38.38 |

Table 1: Evaluation of Young's modulus for different gauge lengths