Analytic adherend deformation correction in the new ISO 11003-2 standard: Should it really be applied?

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ABSTRACT For reliable determination of mechanical characteristics of adhesively bonded joints used e.g. as input data for computer-aided design of complex components, the thick-adherend tensile-shear test according to ISO 11003-2 is the most important material testing method. Although the total displacement of the joint is measured across the polymer layer directly in the overlap zone in order to minimize the influence of the stepped adherends, the substrate deformation must be taken into account within the framework of the evaluation of the shear modulus and the maximum shear strain, at least when high-strength adhesives are applied. In the standard ISO 11003-2 version of 1993, it was prescribed to perform the substrate deformation correction by means of testing a one-piece reference specimen. The authors, however, pointed to the excessive demands on the measuring accuracy of the extensometers connected with this technique in industrial practice and alternatively proposed a numerical deformation analysis of a dummy specimen. This idea of a mathematical correction was included in the revised ISO 11003-2 version of 2001 but in the simplified form of an analytical method based on Hooke's law of elasticity for small strains. In the present work, it is shown that both calculation techniques yield considerably discordant results. As experimental assessment would require high-precision distance determination (e.g. laser extensometer), finite element analyses of the deformation behavior of the bonded joint are performed in order to estimate the accuracy of the obtained substrate deformation corrections. These simulations reveal that the numerical correction technique based on the finite element deformation modeling of the reference specimen leads to considerably more realistic results.

KEYWORDS:

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

1. Introduction

For quality assurance and the determination of reliable input data for computer-aided design of complex adhesively bonded components, the thick-adherend tensile-shear test according to ISO 11003-2 is the most important material testing method. Although the total displacement of the joint is measured across the polymer layer directly in the overlap zone in order to minimize the influence of the stepped adherends, the substrate deformation must be taken into account within the framework of the evaluation of the shear modulus and the maximum shear strain at least when high-strength adhesives are applied.

In the standard ISO 11003-2 version of 1993 [1], it was prescribed to perform the substrate deformation correction by means of testing a one-piece reference specimen. The authors, however, pointed to the excessive demands on the measuring accuracy of the extensometers connected with this technique in industrial practice and alternatively proposed a numerical deformation analysis of a dummy specimen [2]. The idea of a mathematical correction was included in the revised ISO 11003-2 version of 2001 [3] but in the simplified form of an analytical method based on Hooke's law of elasticity for small strains [4]. In the present paper, it is shown that both calculation techniques yield considerably discordant results. As experimental assessment would require high-precision distance determination (e.g. laser extensometer), finite element analyses of the deformation behavior of the bonded joint are performed in order to estimate the accuracy of the obtained substrate deformation corrections. These simulations reveal that the numerical correction technique based on the finite element deformation modeling of the reference specimen leads to more realistic results.

2. Evaluation of the thick-adherend tensile-shear test

The measuring and evaluation principle is explained in detail in Fig. 1.

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

The applied force F causes a total displacement d of the metal pin C of the extensometer relative to the drilled holes A and B, to which the displacement transducer is attached. The measured displacement d is the sum of the displacement of the adhesive d_a and the contribution of the adherends d_s:

$$d = d_a + d_s = d_a + d_{s1} + d_{s2}. \tag{1}$$

From the recorded force versus displacement data, the average shear stress τ and the average shear strain γ are given by Eq. (2) and (3):

$$\tau = F / A_a, \tag{2}$$

$$\gamma = \arctan \frac{d - d_s}{t_a}. \tag{3}$$

Here, A_a stands for the glue surface area and t_a denotes the adhesive thickness. In the calculation according to Eq. (3), the substrate deformation d_s must be taken into account. In the following sections, we will compare two different mathematical correction methods. If the shear stress-strain diagram of the joint, derived from Eq. (2) and (3), reveals an initial linear increase, Hooke's law valid for small strains can be assumed. With ε_{ij} and σ_{ij} being the strain and stress tensors, the following Eq. (4) describes the response of a linear-elastic isotropic material to an applied load:

$$\varepsilon_{ij} = \frac{1}{2G}\sigma_{ij} - \frac{\nu}{2G(1+\nu)}\delta_{ij}\sigma_{kk}. \tag{4}$$

Here, ν denotes Poisson's ratio of the adhesive and δ_{ij} is the Kronecker tensor. In the case of a pure plane shear stress state, the shear modulus of the adhesive, G, results from Eq. (4),

$$G = \tau / \gamma \tag{5}$$

and can be determined from the slope of the linear part of the τ-γ diagram. I should be noted here that Eq. (5) holds also for a complex state of stress with superimposed normal stresses.

3. Adherend deformation correction using Hooke's law

In the standard ISO 11003-2 version of 2001 [3], a simple method based on Hooke's law is recommended for the determination of the substrate deformation d_s. Assuming a uniform state of pure shear stress (cf. Fig. 2) in the region of the adherends that is spanned by the extensometer, the substrate deformation d_s results from

$$d_s = \tan \gamma_s \cdot t_s = \tan \gamma_s \cdot (t_e - t_a) \approx \gamma_s \cdot (t_e - t_a), \qquad (6)$$

where γ_s denotes the shear strain of the substrate und t_e is the extensometer pin separation.

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

Application of Hooke's law gives the final formula for the calculation of the substrate deformation d_s,

$$d_s = \frac{\tau_s \cdot (t_e - t_a)}{G_s} = \frac{F \cdot (t_e - t_a)}{A_a \cdot G_s}, \qquad (7)$$

where G_s stands for the shear modulus of the adherend and τ_s is the average shear stress in the adherend in the region spanned by the extensometer. It is also possible to extend Eq. (7) to adherends made of different materials (index 1 and 2). Assuming the same reference length $t_s/2$, one can obtain

$$d_s = \frac{1}{2} \cdot \left(\frac{\tau_s}{G_{s1}} + \frac{\tau_s}{G_{s2}} \right) \cdot t_s = \frac{1}{2} \cdot \frac{t_e - t_a}{A_a} \left(\frac{1}{G_{s1}} + \frac{1}{G_{s2}} \right) \cdot F. \qquad (8)$$

According to standard ISO 11003-2 version of 2001 [3], the assumption is made that the average shear stress τ_s in the adherend region spanned by the extensometer is equal to the average shear stress τ in the adhesive (τ_s=F/A_a).

4. Adherend deformation correction using the finite element method

The simple adherend deformation correction recommended in [3] is based on the assumption that the shear stress τ_s of the adherends is equal to the shear stress τ in the adhesive. In a previous paper, the authors proposed a numerical computation of the adherend deformation using the finite element method [2]. This approach - based on a dummy specimen - is independent of the above mentioned assumption. To numerically calculate the deformation behavior of this reference sample (single piece specimen of the same geometry without bonding), only a coarse finite element mesh was necessary.

However, to compare this correction method with the behavior of a bonded joint, a more detailed finite element modeling of the joint including a thin glue layer is required. Assigning the elastic characteristics of the adherend material and subsequently of the adhesive, which were also assumed to be constant, to the thin interphase, the behavior of the dummy specimen and of the bonded joint is obtained, respectively. The geometry with the boundary conditions and some details of the finite element mesh are shown in Fig. 3.

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

Since a detailed finite element mesh is necessary to model the thin glue layer, only a two-dimensional mesh could be generated using elements with linear shape functions in order to obtain a system of equations possible to solve on a standard personal computer. However, special elements with reduced integration using an assumed strain formulation written in natural coordinates which insures good representation of the shear strains in the element were used. Thus the well-known phenomenon of shear-locking is avoided. The final mesh density is shown in Fig. 4.

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

It should be noted here that comparison of the results for the substrate deformation with the coarse three-dimensional finite element mesh in [2] reveals no significant difference.

5. Results

The results for the substrate deformation d_s caused by an applied load F are summarized in Fig. 5. It can be seen that the FE results for a two-dimensional plane strain state (rather in the middle) and a two-dimensional plane stress state (rather at the surface) are close together, but differ quite strongly from the results obtained by the simple correction method based on Hooke's law. The figure shows also that the adherend deformation increases with decreasing stiffness of the adherends. Furthermore, it was investigated in the case of the correction based on Hooke's law whether the adhesive thickness t_a influence the results obtained by Eq. (7). For the considered example, the calculations based on $t_s = t_e - t_a = 3$ mm and $t_s = 3.03$ mm reveal practically the same results.

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

The FE simulation provided the following *linear* relationships between the adherend deformation d_s and the applied load F (calculated up to 1500 N)

$$d_s = c_1 + c_2 \cdot F, \tag{9}$$

where the parameters c_1 and c_2 are summarized in Tab. 1 for common engineering materials.

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

The stress state for the single piece specimen (dummy specimen) is shown in Fig. 6 for the plane stress and plane strain state. It can be seen that a quite complex stress state is acting. Tensile and compressive normal stresses are superimposed to a strongly varying shear stress τ_{xy}.

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

To investigate the effect of the different correction methods on schematic shear stress-strain diagrams, tensile tests of bonded joints (material data of the steel adherends: E = 210 GPa, ν = 0.3) were simulated. The material data of the adhesives - Young's modulus E, shear modulus G and Poisson's ratio ν - is summarized in Tab. 2.

---------- Table 2 ----------

The displacements d were evaluated on the level of the extensometer pins t_e. Furthermore, Fig. 7 shows the results without substrate deformation correction and the result for a bonded joint including the glue layer (reference solution: FE bonded joint). In the case of the reference solution, only the pure displacement of the adhesive, d_a, was used to calculate the shear strain according to Eq. (3).

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

It can be seen in Fig. 7 that the FE substrate deformation correction is much closer to the reference solution than the result obtained by the simple calculation based on Hooke's law. The deviation is due to different force fluxes in a specimen with and without bonded joint. Thus, one can conclude that the assumption of the correction method, recommended in the revised ISO 11003-2 version of 2001 [3], is not justified. Furthermore, it can be seen that the adherend deformation correction is of great importance in the case of adhesives with higher stiffness.

6. Discussion and conclusions

For industrial routine testing, calibrating curves for standard specimen geometries and usual adherend materials (e.g. steel and cast iron, aluminum alloys, brass) obtained by finite element calculations are an elegant way to provide more realistic results from this most important basic test method in adhesive technology. Further FE evaluations of the stress state in the region of the adherend that is spanned by the extensometer ($y = 0$; $-t_e/2 \le x \le t_e/2$; cf. Fig. 1 and 3) may result in an improved analytical formula for the correction of the substrate deformation. Figure 8 shows the stress state along the bond line where $-l_a/2 \le y \le l_a/2$ and $x = 0$ holds. The stress distribution is exemplarily investigated for steel adherends and the adhesive number 3 according to Tab. 2 for the plane strain and plain stress case.

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

It can be seen in Fig. 8 that the stress state along the bond line is not a pure shear stress state. Only for two points, the normal stresses vanish and a state of pure shear stress is obtained. Otherwise, a normal stress state is superimposed to the shear stress so that an area element is strained in tension or compression. Thus, a complex and altering stress state prevails in the bond line. The variations of the normal stresses are quite higher than the one of the shear stresses. The plane strain and plane stress case result in no significant difference concerning the shear stress distribution whereas the stress maxima of the normal stresses are considerably more marked in the case of the plane strain case. Comparison of the stress distribution for the glued specimen (cf. Fig. 8) and the single piece specimen (cf. Fig. 6) indicates that the stress distribution is quite different in both cases. However, the deformation correction based on the single piece specimen yields better results than the simple correction based on Hooke's law.

Acknowledgments

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Captions for Illustrations:

Figure 1: Schematic representation of the bonded test specimen.

Figure 2: Uniform state of pure plane shear stress.

Figure 3: Two-dimensional mesh (details) and boundary conditions.

Figure 4: Mesh density.

Figure 5: Results and comparison of the substrate deformation correction techniques.

Figure 6: Stress distribution along bond line for plane strain and stress case, dummy specimen.

Figure 7: Influence of the different correction methods on shear stress-strain diagrams.

Figure 8: Stress distribution along bond line for plane strain and stress case.

Adherends	Case	c_1 in µm	c_2 in µm/N
Steel-Steel	Plane stress	$3.8019\ 10^{-7}$	$8.7796\ 10^{-4}$
	Plane strain	$8.1956\ 10^{-8}$	$8.0018\ 10^{-4}$
Al-Al	Plane stress	$-1.2262\ 10^{-7}$	$2.5269\ 10^{-3}$
	Plane strain	$-2.1415\ 10^{-7}$	$2.2392\ 10^{-3}$
Al-Steel	Plane stress	$-5.7902\ 10^{-8}$	$1.5168\ 10^{-3}$
	Plane strain	$-5.2878\ 10^{-7}$	$1.3630\ 10^{-3}$
Cu	Plane stress	$-1.4135\ 10^{-7}$	$1.5052\ 10^{-3}$
	Plane strain	$-2.6801\ 10^{-7}$	$1.3287\ 10^{-3}$
Mg	Plane stress	$9.0088\ 10^{-7}$	$4.0961\ 10^{-3}$
	Plane strain	$-2.0351\ 10^{-7}$	$3.7801\ 10^{-3}$
Ti	Plane stress	$5.5688\ 10^{-7}$	$1.6768\ 10^{-3}$
	Plane strain	$6.1095\ 10^{-7}$	$1.4969\ 10^{-3}$

Table 1: Parameters c_1 and c_2 for adherend deformation correction according to Eq. (9).

Adhesive	*E* in MPa	*G* in MPa	ν -
1	14.96	4.99	0.499
2	229.046	79.28	0.4445
3	443.132	159.4	0.39

Table 2: Elastic constants of the adhesives