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Measurement of epoxy film adhesive properties in torsion and tension using tubular butt joints

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ABSTRACT

With the increasing amount of composite materials used for aircraft structures, structural bonding and bonded repairs are needed. However, a huge challenge is the availability of reliable material properties for the adhesives. A common approach for determining the material properties is to use adhesively bonded tubular butt joint specimens, tested in a biaxial testing system. In order to determine stress-strain curves of the adhesive systems local strain or deformation measurements needs to be performed. But because of the small bondline thickness of an e.g. epoxy film adhesive, the resulting deformations are very small. Within this study, two different strain measurement techniques are used. First a high resolution digital image correlation (DIC) system. Second capacitive sensors combined in a manner, which allows the decoupled measuring of axial and torsional movements. Both methods and results are compared and discussed. Both have their advantages and the ability to measure the small deformations.

1. Introduction

With the increasing amount of composite materials used for civil aircraft structures, joining and repair methods suitable for composite structures are necessary. Possible methods are structural bonding and bonded repairs. However, a huge challenge is the availability of reliable material properties for the adhesives [1–3]. Since the preferred loading of adhesively bonded joints is to be stressed in shear the main interest is to characterize the adhesives shear stress - shear strain behaviour. For high strength structural adhesives systems within the ISO standard 11003-2 single lap joint specimen geometry for shear tests is proposed (Thick Adherends Shear Test, TAST). Due to the short overlap length and the thick adherends the stress concentrations at the overlap ends and the influence to the shear strength are quite small, but still present at the TAST specimen [3]. Alternative specimen geometry for the determination of the adhesives shear stress - shear strain behaviour is an adhesively bonded tubular butt joint following ISO 11003-1. When joining two tubular adherends with the same geometry in terms of inner and outer diameter by means of adhesive butt-wise together, in the intermediate circular ring shaped bondline shear stresses can be introduced by torques acting around the longitudinal axis of the specimen. Due to the circumferential bondline a continuously load flux alongside the bondline is guaranteed so that no stress concentrations occur [3,4]. This enables this specimen type to determine the adhesives shear behaviour very accurate especially in terms of yielding and strength. However, therefore some requirements need to be fulfilled which will be discussed below [5]. In addition the bondline can be stressed not only in shear but also in tension by introducing axial forces in the tubular butt joint specimen [4,6]. By varying the relationship of torque and axial loading arbitrary multiaxial stress states can be generated in the bondline. These results are needed e.g. for the Mahnken-Schlimmer model [7] and for the design of bonded repairs on aircraft primary structures were curved surfaces induce through-thickness stresses as well as shear stresses in the adhesive [8]. By now, for bonded repairs and structural bonded CFRP aircraft structures mostly epoxy film adhesives with a high stiffness and strength and less plasticity are used. Within this study the Henkel Hysol EA9695 AERO 0.05NW film adhesive (Henkel AG&Co., Düsseldorf, Germany) is used. The epoxy film adhesive has a typical cured thickness of 50 to 100 µm. The small thickness and the elevated curing temperature of 130 °C cause manufacturing issues. Thus the tubes are bonded with a new joining device, allowing a pressured and aligned curing in an oven [9]. The thin adhesive between the two bonded adherends means that the occurring deformations for torsion as well as in tension are very small. Furthermore the bonded tubular butt joint configuration allows a multiaxial loading of the specimen type. In order to separate the torsional and axial displacements of the adherends a decoupled measuring of each displacement vector during testing is necessary.

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Within this study, two different strain measurement techniques are analyzed and compared. The first is a high resolution digital image correlation (DIC) system. DIC measuring has the advantage of measuring a complete strain field in each direction within the measurement area. The second method relies on contactless working capacitive sensors, combined in a manner, which allows the decoupled measuring of relative axial and torsional movements of the bonded adherends. This method is easy to use and online applicable also to fatigue testing. But it gives only global displacement information. Both methods and results are compared and discussed.

2. Material and methods

2.1. Improved manufacturing of tubular butt joints

As already mentioned above for a multiaxial adhesive characterisation the use of bonded tubular butt joints, under variable torsion and tension loads, is an expedient approach. Important for the quality of the determined material values is the coaxial alignment of the bonded tubes. Also the bondline has to be free of voids and air inclusion. In previous work [5] Wölper investigated the effects of coaxial and angle deviations for the results of material characteristics using FEA. Slight deviations have a strong negative impact to the results. Particularly for thin film-adhesives with elevated curing temperatures, the change of viscosity of the adhesive and the thermal expansion of the tubes must be considered. Previous investigations regarding the manufacturing of the specimens showed shortfalls in joining and curing them [10]. Due to voids, deviations or poorly-bonded tubes, no reliable results could be achieved yet. Therefore, a new joining-device is developed. To bond the specimen both tubes have a separate male and female PTFE core which expands during the increase of temperature in the cure process to the inner diameter of the tubes. Due to an integrated loose fit bearing of the cores, a perfectly coaxial alignment of the tubes is ensured. The separation of the core movement also allows to press the bondline by applying weights on top of the tubes. The constant pressure persists over the whole curing process [9]. The results show well joined tubular specimens without a significant angular and lateral deviation of the adherends. The thickness of the bondline can be adjusted by the weights and is constant over the whole diameter. The new joining-device enables the testing of high quality bonded tubular butt joints to determine the material values of thin elevated-temperature-cured film-adhesive.

2.2. Measuring principle

Within this section the principle of the two different strain measurement techniques are explained. First the high resolution digital image correlation (DIC) system, second the contactless biaxial measuring high resolution extensometer.

2.2.1. High resolution digital image correlation (DIC) system

The first measurement technique investigated within this study is the digital image correlation (DIC). Here the ARAMIS 12M System from GOM GmbH, Braunschweig, Germany is used. As described in previous work [11], it is possible to measure very fine displacements with the right system setup. The DIC measuring has the advantage of measuring a complete strain field in each direction within the measurement area.

2.2.1.1. Parameters. Based on previous work [11] the following setup is used for the undertaken testing. A 3D setup was chosen as there is an out of plane movement of each measuring point during torsional testing. The camera distance and angle is set up for a measurement volume of 24 × 30 mm, which results in an area of 0.16 mm × 0.16 mm for one facet. Using 100 mm lenses, a small aperture and strong light enables a sufficient depth of focus. One more crucial factor for a good measurement is the speckle pattern. Therefore a combination of white titanium dioxide and black iron oxide powder which is dispersed in ethanol and applied with an air brush system was used. In order to calculate the time-depended strain values during a quasi-static test a high frame rate is necessary.

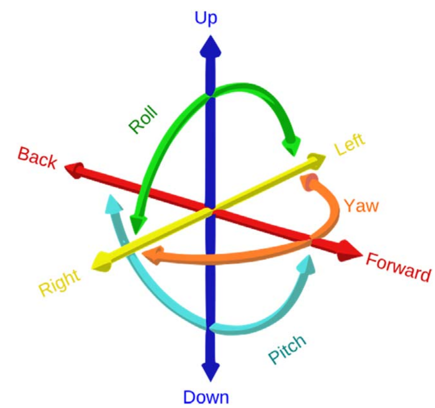

Fig. 1. 6DoF [public domain].

2.2.1.2. Post processing. To gain the necessary data to calculate the material deformation from the DIC measurement several steps are necessary. The evaluation approach within this study is based on local coordinate systems in both adherend tubes. Between this coordinate system the six degrees of freedom (6DoF), see Fig. 1, can be calculated. In here only the up and down movement, which is the axial strain, and the yaw angle for the torsional stain are of interest. Especially the roll and pitch angle should be zero, as a movement in this direction would mean a misaligned testing setup.

Each coordinate system is based on a fitting cylinder over the adherend surface next to the bondline, on a plane normal to the cylinder direction and on a fitting point in the center of the surface, see Fig. 2.

The coordinate system generation based on the fitting elements has the advantage that single facet errors are not critical for the result, but the bigger the fitting area the more adherend strain is cumulated within each fitting point. Furthermore the created local coordinate systems are exactly localised in the middle of the tube and have the right orientation, as shown in Fig. 3, independently of a misaligned camera setup. Without correct referenced coordinate system, the distinction in axial and torsional strain ratios is not possible. The advantage with the calculation of the 6DoF between both local coordinate systems is that the resulting torsional angle and the axial displacement are directly measured on the specimen surface. As shown in Fig. 3 there are two cylinders within each adherend, one next to the bondline and another in some distance to the bondline. This enables to calculate the adherend strains in each tube. Furthermore the axial distance between the supporting fitting points is measured. With both, the adherend deformations can be calculated for each load step. The measured deformation over the adhesive is corrected to obtain the pure adhesive strain.

2.2.2. Contactless biaxial measuring high resolution extensometer

The second measuring method within this study is a contactless biaxial extensometer. Since a main requirement when testing adhesively bonded tubular butt joint specimens under biaxial loading conditions is to measure precisely the expected very small relative displacements (typically in the range of microns). Therefore an appropriate measuring system with a sufficient resolution and accuracy has to be chosen. Another crucial requirement is to reliably decompose the displacement vector of a biaxially loaded, tubular butt joint specimen into its orthogonal components in axial and tangential directions. A third requirement aims at the specification that the measurement shall be performed without significant time delay, such that the test procedure may be controlled based on local displacement data. Furthermore, test data may be obtained in real time in fatigue