IN-SITU X-RAY COMPUTED TOMOGRAPHY ANALYSIS OF ADHESIVELY BONDED RIVETED LAP JOINTS

R. Füßel[1], M. Gude[1], A. Mertel[2]

[1]Institute of Lightweight Engineering and Polymer Technology, TU Dresden, Dresden, Germany
Email: rene.fuessel@tu-dresden.de, Web Page: http://www.tu-dresden.de/mw/ilk
[2]Leichtbau-Zentrum Sachsen GmbH, Dresden, Germany
Email: mertel@lzs-dd.de, Web Page: http://www.lzs-dd.de

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Abstract

Experimental investigations of an adhesively bonded riveted joint between a glass-fibre reinforced unsaturated polyester composite (GUP) and an aluminium alloy are presented in the paper. The study is focused on a novel test method, that combines destructive and non-destructive methods in a so called in-situ computed tomography (CT) analysis. The aim of the investigations is to identify different modes and locations of failure in a combined joint during quasi-static loading by simultaneous X-ray computed tomography. The combined method provides a deeper understanding of the failure and damage processes in the joining area. Different variations of a single-lap joint with varying adhesive layer thicknesses and different fasteners are examined. The in-situ CT tests are used to gain a phenomenological basis for a subsequent cross-scale modelling of the complex damage behaviour. By a combination of load and unload stages during the experiments and intermittent CT analyses, the crack initiation and the crack propagation can be detected.

1. Introduction

In the context of the limited availability of worldwide resources and the constantly increasing demand for sustainability, material and energy efficiency, lightweight design becomes increasingly important for the 21st Century. In this context, multi-material structures allow the combination of the advantageous properties of different materials. Therefore, metals in combination with fibre-reinforced plastics (FRP) offer significant benefits in terms of a targeted utilization of materials in the sense of an efficient and resource-saving lightweight construction. In manufacturing of hybrid lightweight structures a key role is attributed to the joining technology. A fundamental problem in joining of large-scaled structures, made of different materials, is the difference of thermal expansion coefficients and the resulting geometric mismatch between the adherends leading to high stresses in the adhesive layer. A promising approach to overcome these problems is the use of elastic adhesives which are able to compensate large thermally induced displacements between different adherends without a significant influence on the joint strength. Another way to improve the sustainability of adhesively bonded joints is the combination with other joining methods such as riveting, bolting or pinning. In doing so, the advantages of each type of joint can be combined in order to enhance the overall performance of the individual joint [1–3].

The failure and damage behaviour of combined joints is up to now not completely understood. Due to complex interactions between adhesives, metals, composites and fasteners, there are a lot of different modes and locations of damage, failure and post-failure. The progress made in recent years in the field of computed tomography has led to significantly improved applicability of these methods for dam-

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age analysis of fibre composites [4]. Particularly in non-transparent composites such as carbon fibre reinforced textile composites, CT allows efficient and spatially resolved detection of the characteristic damage states on the micron scale and their correlation with the degradation of the mechanical properties [5, 6]. In examinations for damage diagnosis with in-situ CT, samples can be investigated under mechanical or thermal load [7]. This allows an analysis of phenomena like fibre fracture, matrix cracks, fibre-matrix debonding or crack-closure-processes [4, 8–10].

At the Institute for Lightweight Engineering and Polymer Technology (ILK), in-situ examinations of textile-reinforced plastics were conducted and advanced testing technologies have been developed [4–6]. Specifically designed in-situ CT test rigs using a common CT-system coupled with loading devices for uniaxial and multiaxial tension/compression/torsion tests were established. In this paper, the transferability of this analysis method using combined destructive and non-destructive testing on combined joints for multi-material structures is illustrated. Therefore, different combinations of adhesive layer thicknesses and rivets were investigated and the occurring damage phenomena are analysed.

2. Typical failure modes of adhesive bonded riveted joints

Manifold failure modes with complex mode interaction can occur in adhesively bonded riveted joints. An overview of characteristic modes in case of an in-plane tensile loaded single-lap joint with respect to failure of the elastic adhesive bonding and the rivet is given schematically in figure 1. In addition to that, failures within the bonding parts are also possible, usually as a result of insufficient design of the joint. The latter type of failure is not an issue in this study.

Standard experimental test methods are applicable for determining the deformation behaviour and the failure load of such joints, but an explicit correlation between acting load and the corresponding failure mode can not be established. The presented 3D in-situ test method accounts for closing this gap.

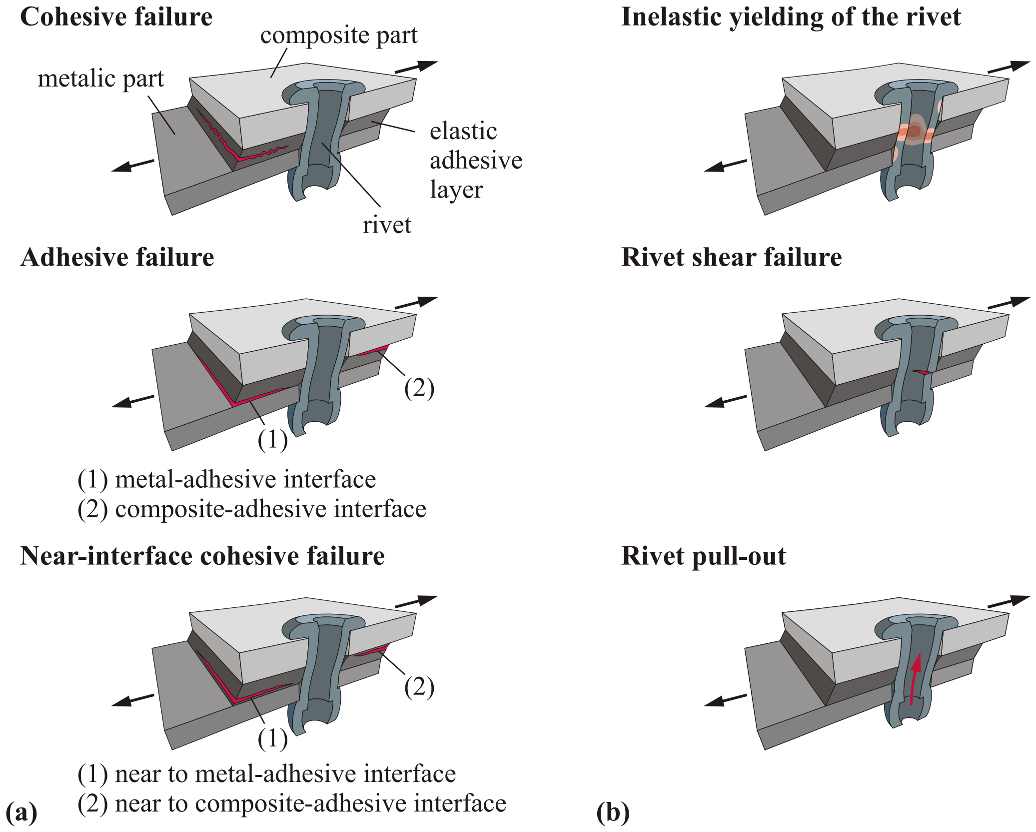

Figure 1. Typical adhesive (a) and rivet (b) failure modes of adhesively bonded riveted joints

3. Experimental method and investigated specimens

In the following section, the test method and the manufacturing of the used test specimens is described in details. In this study, single-lap shear tests are performed, using a novel in-situ CT testing machine (FCTS 160) which was developed in cooperation with Zwick/Roell (see Fig. 2a). The main advantage of this test stand is that specimens can be scanned during loading and unloading. In contrast to conventional ex-situ methods, where the unloaded specimen is scanned subsequent to loading, the crack closure effect is eliminated almost completely and the measurement of damage is improved significantly. However, a small deviation between the detected degree of damage and real amount of damage will remain because of relaxation effects of the viscoelastic adhesive before and during scanning.

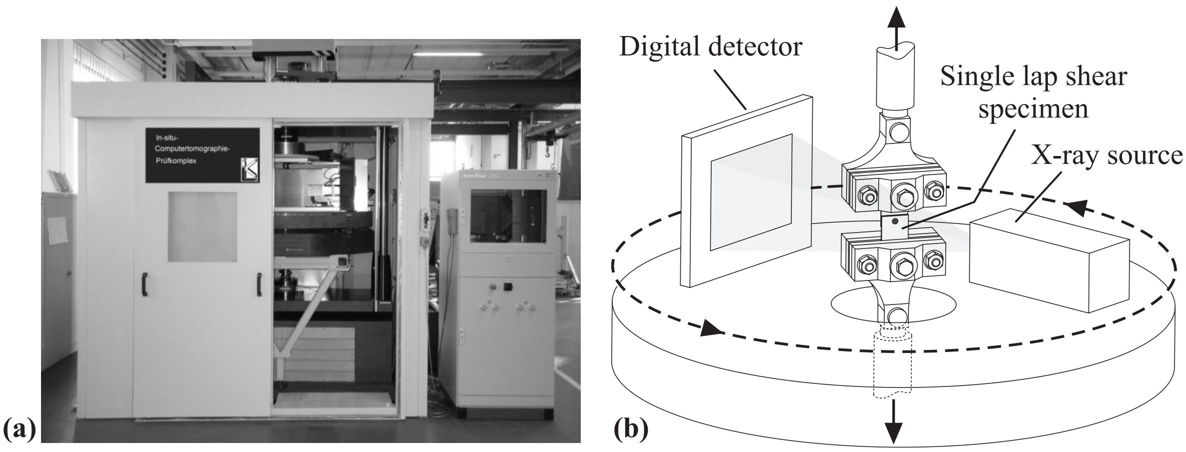

Figure 2. In-situ CT machine (a) and schematic illustration of the in-situ shear test set-up (b)

The used experimental set-up is shown schematically in figure 2b. During the scanning phase, a massive circular support base, with an X-ray source (160 kV) mounted on the one side and a digital X-ray detector (3200 x 2300; 14-bit pixels) on the opposite side, is rotating around the tensile test set-up. The resolution of the scans depends on the distances between X-ray source, specimen and target. When capturing the whole region of overlap, a maximum resolution of about 20 micrometres is achieved.

In order to detect different modes of damage and failure as well as crack-closure phenomena, the test sequences were performed as a combination of different load and unload stages, intermitted by multiple CT analyses (Fig. 3). Load was applied stepwise by uniform motion complying with quasi-static condition up to total failure of the joint. Taking into account the time dependent mechanical behaviour of the elastic adhesive each scan process starts after a short relaxation phase, when a quasi state of equilibrium is reached.

In the presented study, single-lap shear specimens (Fig. 4) according to DVS/EFB 3480-1were used to investigate the progressive failure behaviour of combined adhesively bonded riveted joints. The adherends of the multi-material joint are aluminium on the one hand (thickness 2.0 mm) and unsaturated polyester with glass-fibre reinforcement on the other hand (thickness 3.2 mm). The textile reinforcement of the GUP composite consists of an inner stack of chopped strand mat plies which is covered by a single woven fabric outer ply respectively.

After abrasive blast cleaning of the adherend bonding surfaces, the aluminium surface was pre-coated with the two-component primer system BETAPRIME$^{\text{TM}}$ 1707. Aluminium sheets and GUP parts were bonded using the two component polyurethane adhesive BETAFORCE$^{\text{TM}}$ 2850. By means of a special bonding tool (Fig. 4a, 4b) adhesive layer thickness can be adjusted exactly on the intended value in steps of 0.1 mm. The viscous adhesive was applied in form of a trapezoidal bead with tapering to the top. The adhesive layer thickness was varied in a range from 1 to 4 mm. The second manufacturing step includes

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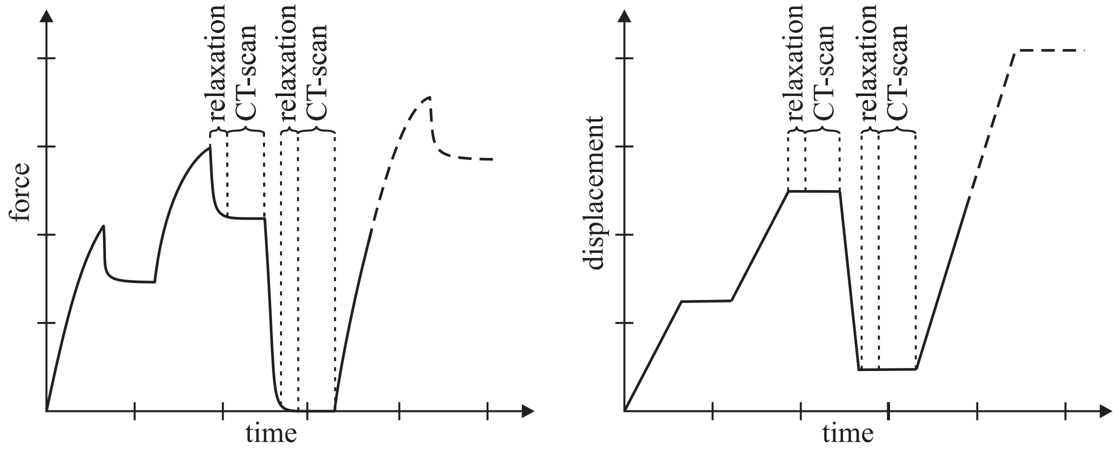

a) force-time-graph b) displacement-time-graph

Figure 3. Schematic illustration of a test sequence of an in-situ shear test

riveting. A single aluminium blind rivet with a head diameter of 9.5 mm and a shaft diameter of 5.0 mm was set in the middle of the overlap area after drilling. The clamp length of the rivet matches to the total thickness of the specimen in the region of overlap. The rivet head is placed on the composite side whereas the closing head is placed on the aluminium side.

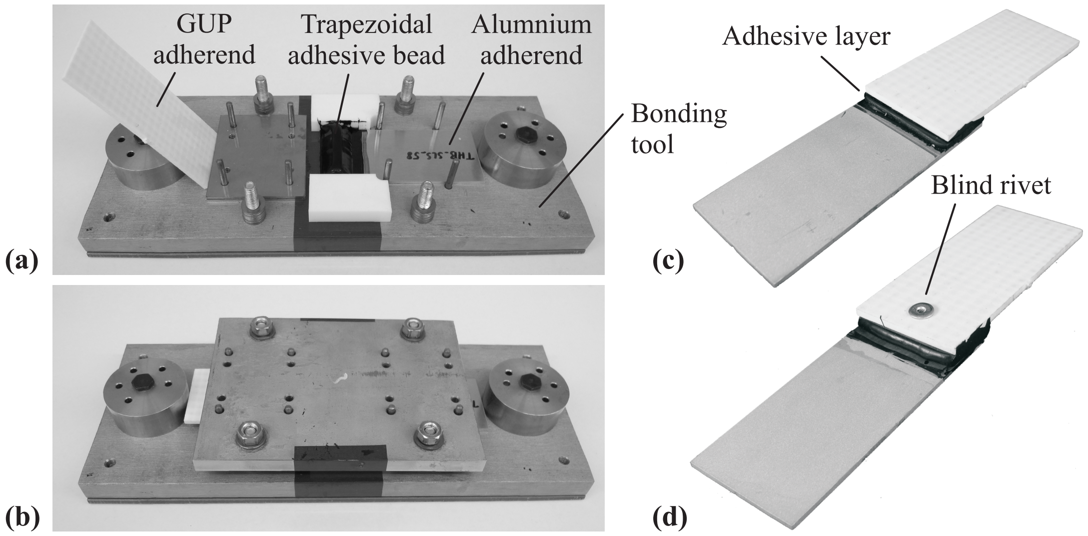

Figure 4. Manufacture of single-lap shear specimen: (a) adherends with applied adhesive bead, (b) closed bonding tool, (c) bonded specimen after curing, (d) completely bonded riveted specimen

4. Experimental results and discussion

Figure 5 shows exemplarily a test cycle of an adhesively bonded riveted hybrid joint with different load and unload stages and the related CT analyses, marked by the stage number. The scanning frequency was increased just before initial failure occured up to total failure of the joint.

After carrying out the experiments, a complex 3D failure analysis was performed, using the obtained tomograms. For this purpose, the area reserved to the region of overlap was extracted and the individual adherends, the rivet and the adhesive layer were separated into different regions of interest (ROI). Subsequently, the progressive failure analysis was based on the entrapped air and the corresponding grey

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values. The entrapped air volumina were highlighted in red color for a clear 3D-visualisation.

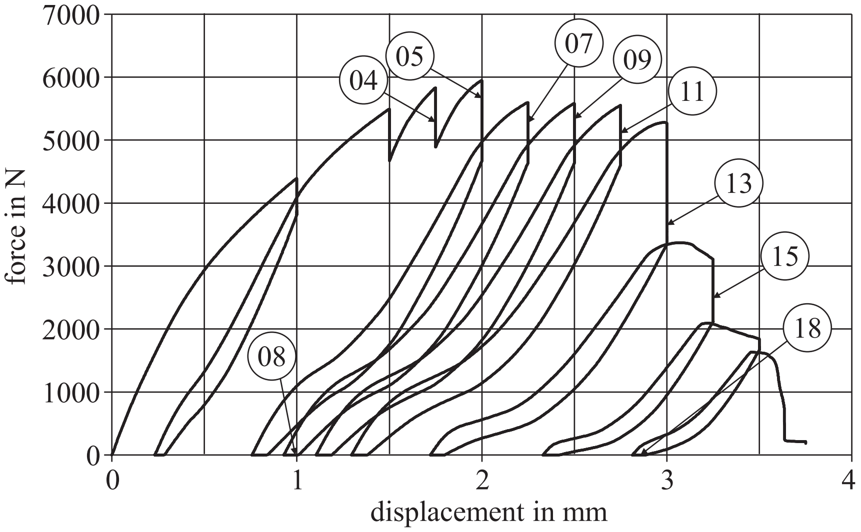

Figure 5. Force-displacement-graph of an in-situ tested specimen with numbers of CT-scans

The reconstruction of the load and unload stages and the subsequent separation into multiple ROI enables the analysis of the phenomena occurring in the overlap region. One distinctive effect was the closing of existent cracks during unloading of the specimens. This phenomena is illustrated in figure 6. The clearly visible open crack (Fig. 6 left) closes almost completely during unloading of the specimen and thus, the crack is not detectable by usual inspection methods. Therefore, in an ex-situ CT analysis the amount of damage in the joining zone is clearly underestimated. This shows the indispensability of combined destructive/non-destructive testing methods for a detailed damage analysis.

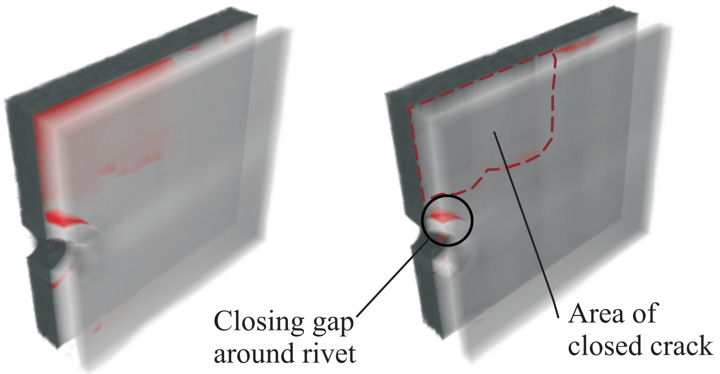

Figure 6. Detectable damage in the joining zone during a load stage and the subsequent unload stage

Another advantage of the novel test method, developed here, is the possibility of a detailed 3D-analysis of the inelastic deformation of the joint, caused by damage of the adhesive bonding as well as plastic yielding of the rivet at different stages of the loading. In figure 7, a comparison of longitudinal cross sections of the overlap region, at different unload stages are shown. With respect to the initial CT scan of the joint (Fig. 7a) the image of stage ⑧ shows the plastic deformation of the rivet after maximum loading of the specimen. The subsequent rivet shear failure, in accordance to Fig.1, can clearly be seen in Fig. 7c.

The major benefit of the presented method comes into effect when a continuous series of CT scans is analysed. Here it is possible to track the progress of damage up to total failure. As an example, figure 8

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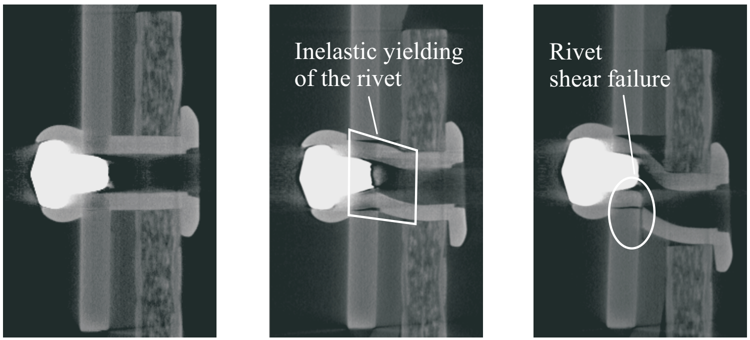

a) Initial stage before test
b) Unload stage (08) after max. load
c) Unload stage (18) after rivet failure

Figure 7. Longitudinal cross section of the joining zone during different unload stages

illustrates a series of 3D CT images of the half-section of the overlap region, in accordance to the stages in Fig. 5. A clear detection of crack initiation and the subsequent crack propagation is possible. The image sequence shows the initiation of a near-interface cohesive crack at the upper edge of the overlap region (04), which progresses to the center of the joint (07). Subsequently, the crack is evolving to a through thickness cohesive crack at the upper half of the joint (08). In the following, the crack progresses as near-interface cohesive failure around the rivet. After the failure of the adhesive (15) the total failure of the joint is caused by rivet shear failure (18).

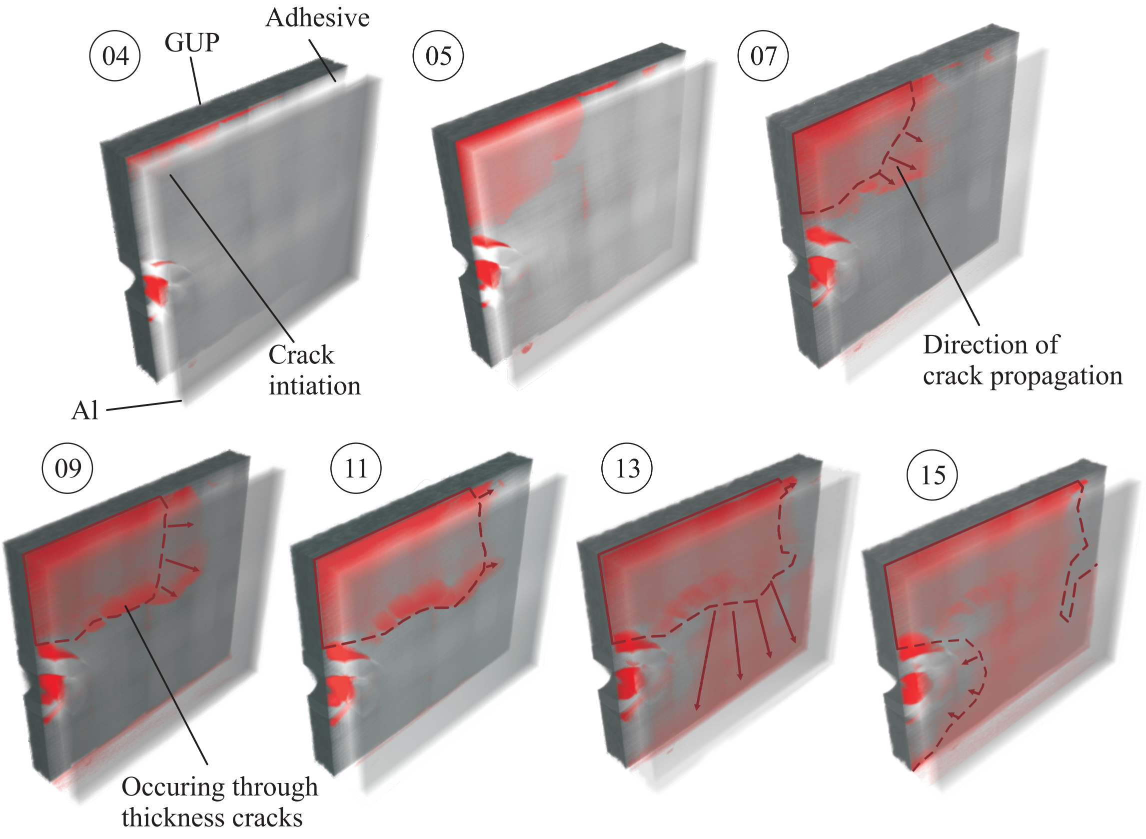

Figure 8. Section of the joining zone with areas of damage (indication according to Fig. 5)

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5. Conclusion

The combined use of destructive and non-destructive testing methods in in-situ CT analyses makes it feasible to analyse the complex progressive failure behaviour of adhesively bonded riveted joints. In detail, the initial failure of the joint with information about mode and location, as well as the progress of damage can be determined in correlation to the acting load. Hence, this new method of damage analysis is an excellent tool for the development of phenomenological based deformation and failure approaches. Further studies will focus on a targeted induction of specific failure modes, like adhesive failure caused by kissing bonds. By a separated consideration of different damage phenomena and a detailed study of the interaction of the failure modes, a comprehensive knowledge for a deeper understanding of the deformation and failure behaviour of combined joints can be achieved.

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