

Numerical Investigation of the Rivet Installation in an Adhesively Bonded Joint and the Load Transfer in a Bolted/Bonded Hybrid Joint

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ABSTRACT

Hybrid (bolted/bonded) joining is becoming one of the innovative joining processes for light weight structures in the transport industry, especially in the aerospace industry where weight reduction and high joining requirements are permanent challenges. Combining the adhesive bonding with the mechanical joining -riveting for instance- can lead to an enhancement of the properties of the joint compared to the wide established riveting, as a result of a synergistic load bearing interaction between the fastener and the adhesive bondline. The influence of the rivet installation process on a hybrid joint regarding the joint stress state, the change of the bondline thickness as well as its effects on the joint performance and load transfer are some of the factors that drive the users to a better understanding of the hybrid joining process. This paper deals therefore on one hand with the numerical simulation of the rivet installation process in an adhesively bonded joint to understand the phenomena occurring during the installation process and on the other hand with the investigation of the load transfer depending on the joint parameters.

In order to simulate the rivet installation in adhesively bonded aluminium (2024-T351) adherends, two models have been developed. One for a solid rivet specified by the European standard EN6081 another for a Lockbolt specified by the standards ASNA2041/ASNA2045. The developed simulation model for the rivet installation process has been validated by comparing the simulation results with experiments regarding the qualitative change of the bondline thickness depending on the adhesive's Young's modulus and on the rivet type. The experimental rivet installation process for the validation of the simulation model takes place in a fully automated C-frame riveting machine with all-electric drilling and riveting operations aptitude. A generic numerical study to determine the effects of the adhesive's Young's modulus on the joint stress state and the effect of the rivet installation on the adhesive bondline has been carried out.

In order to determine the load transfer behaviour in a hybrid joint, a single lap joint model for the above mentioned and aluminium (2024-T351) adherends has been developed. A generic study to investigate the effect of the rivet installation and the adhesive Young's modulus on the load transfer has been carried out. To validate the simulation model for the single lap shear test, the simulation results have been compared with the experiments regarding the force displacement curves.

CITATION: Baha II, S., "Numerical investigation of the rivet installation in an adhesively bonded joint and the load transfer in a bolted/bonded hybrid joint," *SAE Int. J. Mater. Manf.* 8(1):2015, doi:10.4271/2014-01-2242.

INTRODUCTION

Hybrid (bolted/bonded) joining is becoming one of the innovative joining processes for light weight structures in the transport industry, especially in the aerospace industry where weight reduction and high joining requirements are permanent challenges. Combining the adhesive bonding with riveting can lead to an enhancement of the properties of the joint compared to adhesively bonded joints or riveted joints. Due to the increasing demands on predicting and understanding the behaviour of bonded/bolted hybrid joint, it's necessary to understand the influence of the rivet installation process in an adhesively bonded joint with regards to the joint stress state, the change of the bondline thickness as well as its effects on

the joint performance and load transfer. As experimental investigation can be very expensive and time consuming, using numerical simulation methods is a reliable alternative to conduct such investigations.

Several researches have been conducted on bonded/bolted hybrid joint. Even though generally the internal stress state after the rivet installation has an important effect on the strength of riveted joint, this seems not to have received much of the researcher's attention in literature in the case of bonding/riveting hybrid joining. As for the load transfer, several researchers have used finite element methods to study the influence of parameters like the adhesive Young's modulus, the

bondline thickness, and overlap length on the load transfer in a hybrid joint. A part of the researches about the load transfer conducted on hybrid (bonded/bolt) joints is summarized by M. Ouellet et al 2013 in [1]. In the same issue Gordon Kelly 2006 [2] and Paroissien et al., 2007 [3] [4] used finite element methods to show that about 2/3 of the applied load on a bonded/bonded hybrid joint is transferred by the bondline if using a soft adhesive. Wen S. Chan 2001 [5] used 2D and 3D finite element models to investigate the stress distribution in a single lap bonded/bolted joint. Similar works have been conducted by Vlastimil Kunc 2004 [6] and Cat-Tan-Hoang 2010 [7] using finite element methods to investigate the behavior of a hybrid joint.

This paper deals therefore on one hand with the numerical simulation of the rivet installation process in an adhesively bonded joint to understand the phenomena occurring during the installation process and on the other hand with the investigation of the load transfer depending on the joint parameters. The model for the rivet installation without the adhesive layer has been verified considering the usually referred characteristics like the geometry of the formed rivet head [10], [11] and the force-displacement progression of the squeezing process [10], [11]. After including the adhesive layer to the rivet installation model, the change of the bondline thickness after the rivet installation has been considered to complete the validation of the model for the rivet installation in an adhesively bonded joint. As for the investigation of the load transfer, the experimental approach of the force-displacement progressions during a single lap shear tensile test shall be used to validate the lap joint simulation model used to investigate the load transfer in a bonded/bolted hybrid joint.

Chapter 2 of this paper deals with the numerical investigation of the riveting process influence on the bondline stress state. Chapter 3 treated the load transfer in a bonded/bolted hybrid joint after the riveting process depending on the adhesive Young's modulus, bondline thickness, and the overlap length.

1. RIVET INSTALLATION IN AN ADHESIVELY BONDED JOINT

1.1. Rivet Installation Model

To differentiate the effect of the rivet installation from the effect of the rivet type, two simulation models of the rivet installation in an adhesively bonded joint have been developed. One model considers a solid rivet with universal head specified by the European standard EN6081KE5 and the other model considers a lockbolt specified by the standard ASNA2041/ASNA2045. Both models consist of two adherends sheets made of aluminum alloy 2024-T351 commonly used in the aircraft industry. The rivet diameter in both models is 4.8 mm, and the adherend thickness is 3 mm. During the simulation of the rivet installation, the adhesive is assumed to have already been cured. The installation process takes place in 4 steps, clamping, drilling, squeezing and unclamping. The drilling process is not considered in this paper. During the clamping

step, the upper (1) and lower adherend (2) are fixed by the upper and lower pressure foot (6+7), Figure 1 shows this exemplarily for the model with a solid rivet. The rivet is constrained by the upper die (5) for any translation in y-direction during the squeezing while the lower die (4) moves in y-direction against the rivet shank until the target squeeze force is achieved. The unclamping steps, in which all constraints and loads are removed, follow after squeezing.

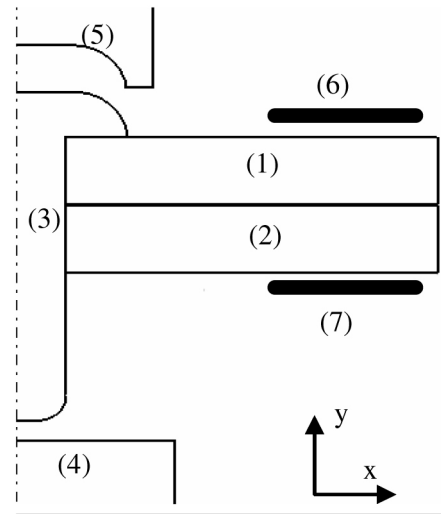


Figure 1. Riveting process configuration exemplarily for the model with a solid rivet

Two-dimensional axisymmetric models consisting of one rivet, two adherends and the installation tools are shown in Figure 2. The simulations are carried out using the FE-program ABAQUS/Explicit.

• Element type and mesh section

The riveting tools are implemented as rigid bodies. Four node elements with reduced integration have been chosen to model rivet and adherends. The mass of the critical elements, which could raise the critical time increment, was scaled once at the beginning of every simulation step to achieve a prescribed element stable time increment of 0.3 μ s. Arbitrary Lagrangian Eulerian (ALE) adaptive meshing of the collar and the pin of the solid rivet with a frequency of 10 and one remeshing sweep per increment was specified during the squeezing to optimize the element distortion. This makes it possible to maintain high mesh quality during the forming despite of high strains.

• Material model

Rivet, adherend, and adhesive materials are described by isotropic elastic-plastic behaviour. The mechanical properties of the adherend material have been obtained from the literature [12]. Data of the plastic hardening curve of the rivet and collar materials have been obtained by a compression test performed on specimens prepared from the mentioned components. The determination of this data is no topic of the current paper.

• Boundary and contact conditions

The clamping unit (6) and (7) in Figure 1 and the lower die (4) are constrained against translation in x-direction and rotation around the y-axis while the upper die is completely constrained and the adherends are unconstrained, see Figure 2. A symmetry boundary condition is applied to the rivet and to the fastener. A clamping force $f_c=3.5$ kN is applied to the pressure foot. A squeeze force f_{sq} is applied to the lower die during the squeezing step as shown in Figure 2. Its amplitude curve is smoothed at the beginning and at the end of the step. A tie constrained has been applied in the interface bondline-adherend to implement the adhesive adhesion on the adherends' contact faces.

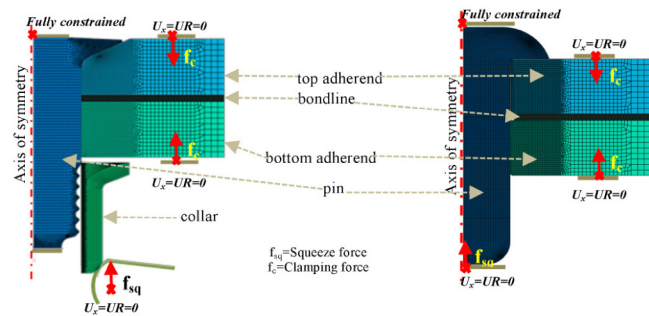


Figure 2. FE models with boundary conditions

1.2. Experimental Validation

The rivet installation model without a bondline has been previously validated using a solid rivet [8]. The force-displacement curve, the geometrical characteristics of the formed rivet head, the contact pressure between the adherends, and the strain on the adherends top side are characteristics that have been considered. The validation results are summarized in subsection 1.2.2. After including the bondline to this rivet simulation model and in an extended model with a lockbolt, the change of the bondline thickness depending on the rivet type and the adhesive Young's modulus has been qualitatively considered to complete the validation of the simulation model of the rivet installation in an adhesively bonded joint.

1.2.1. Experimental Equipment

The experiments for the verification of the simulation model for the rivet installation were performed in a fully automated C-frame riveting machine (see Figure 3) with all-electric drilling and riveting operation skills for one and two-pieces fastener like solid rivet, lockbolt stump type and Hi-Lite. All relevant process data occurred during the installation process were registered and stored by the control unit of the machine. The machine is fitted with two high-speed cameras to observe the installation process.



Figure 3. The riveting machine

1.2.2. Rivet Installation Model Without a Bondline

The rivet simulation model for a solid rivet without a bondline has been experimentally validated. The main considered validation characteristics, the force-displacement curve and the rivet formed head, are presented in this subsection.

• Force-displacement

The results of the force-displacement curves of the squeeze tool during the installation with different rivet diameters match the experiments very well, see Figure 4.

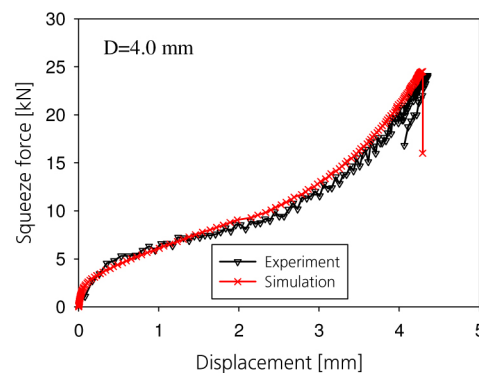


Figure 4. Force-displacement curves

• Geometrical characteristics of formed rivet head

Width and height of the formed rivet head have also been considered varying the squeeze force and the rivet diameter. The results of simulations and experiments show good agreement, see Figure 5.

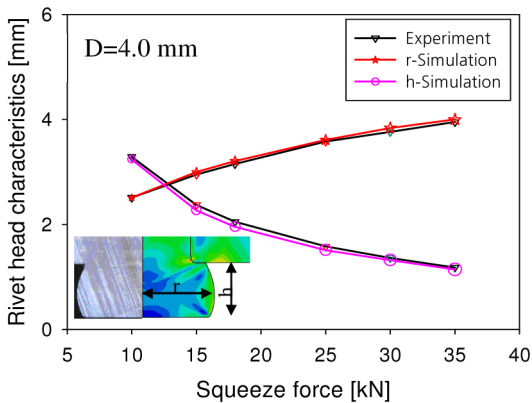


Figure 5. Rivet formed head characteristics

1.2.3. Rivet Installation Model with a Bondline

To complete the validation of the simulation model for the rivet installation in an adhesively bonded joint, a bondline has been included in the above validated model and in an extended model with a lockbolt fastener. The change of the bondline thickness after the rivet installation has been qualitatively compared with the experiment.

• Change of the bondline thickness after the rivet installation in an adhesively bonded joint

To bring out the effect of the rivet installation on the bondline thickness, the adhesive Young's modulus was varied as follows; 350 MPa, 750MPa, 1500MPa, 3000MPa, and 6000 MPa. in the rivet simulation model with a solid rivet and a lockbolt. The change of the bondline thickness have been evaluated at three points (left=L, Middle=M, and right=R) as presented in Figure 6 after the simulation.

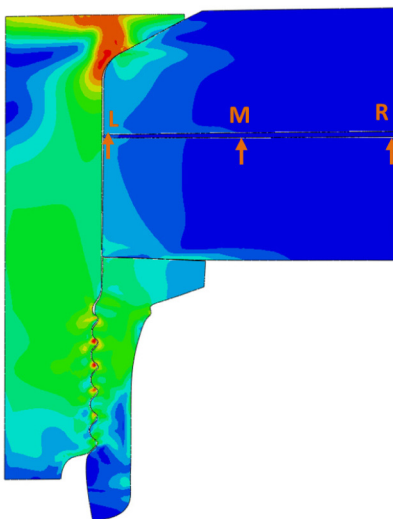


Figure 6. Evaluation points for the change of the bondline thickness

The obtained results are presented in Figure 7. The rivet installation seems to have much influence on the bondline thickness in a bonded/bolted hybrid joint when an adhesive with a low Young's modulus is used, especially at the evaluation point "L". The obtained results also reveal that the Lockbolt fastener more affects the bondline thickness compared to the solid rivet.

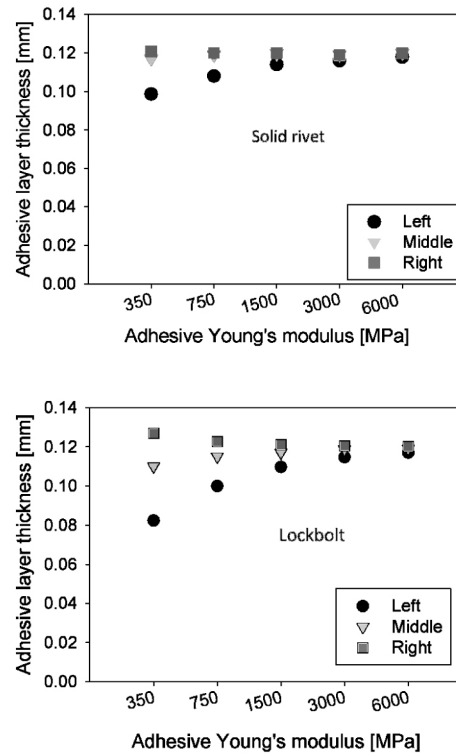


Figure 7. Change of the bondline thickness after the simulation of the rivet installation

As for the experimental consideration of the effect of the rivet installation on the bondline thickness, two extremely different adhesives in terms of the stiffness were used; the structural adhesive Hysol-EA9394 and the rubber-like adhesive Terostat MS9399 with Young's modulus of about 4200 MPa. and 1.5 MPa. respectively. The effect of the riveting process was observed at the red marked area as presented in Figure 8. A detailed view of the effect of the rivet installation on the bondline is presented in Figure 9. The experimental observed effect of the rivet installation on the bondline thickness qualitatively well confirms the simulation results.

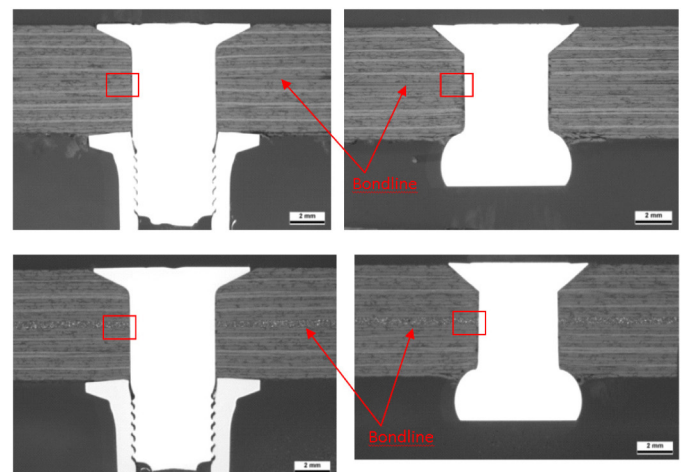


Figure 8. Evaluation area for the change of the bondline thickness after the rivet installation test