

The Effect of the Setting Force on the Fatigue Resistance of a Blind Rivet Nut Set in CFRP

Arne Van de Velde^{1,a*}, Jan Ivens^{2,b}, Jan Maeyens^{2,c}, Sam Coppieters^{1,d}

¹Department of Materials Engineering, KU Leuven, Ghent Technology Campus, Gebroeders De Smetstraat 1, Ghent 9000, Belgium.

²Department of Materials Engineering, KU Leuven, Campus De Nayer, J. De Nayerlaan 5, Sint-Katelijne-Waver 2860, Belgium

³Dejond NV, Terbekehofdreef 55-59, Wilrijk 2610, Antwerp, Belgium

^aarne.vandavelde@kuleuven.be; ^bjan.ivals@kuleuven.be; ^cjan_maeyens@dejond.be;

^dsam.coppieters@kuleuven.be

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Abstract. Weight reduction is often a key factor in modern mechanical design, therefore materials such as carbon fibre reinforced plastics (CFRP) are increasingly used and integrated within multi-material structures using adhesive technologies, which require high effort and are difficult to disassemble. The capability of a blind rivet nut (BRN) to join different materials without these disadvantages has created a growing industrial interest in the fastener. However, installing a BRN in CFRP laminate induces a significant stress concentration in the plate, which potentially causes damage. Given that ‘damage free’ joints are demanded by the industry, the BRN is often not considered as a suitable joining technique. In the present research, an experimental campaign is performed to investigate the fatigue resistance of a BRN joint in CFRP. It is demonstrated that the resulting compressive stress after installing a BRN can enhance the fatigue resistance of the specimen. The results increase the potential of the BRN as a fastener for CFRP.

Introduction

In industry, a Blind Rivet Nut (BRN) is a permanent mechanical fastener used in a wide variety of industrial applications to equip plate material with a threaded part. Analogous to the setting process of the more common blind rivet, the upper side of the BRN deforms plastically during the setting process in such a way that a counter head is formed on the underside of the plate. Simultaneously, the upper side of the deformation chamber expands in the radial direction creating an interference fit. The counter head together with the residual contact force after BRN installation, units the nut to the plate. Fig. 1 shows a schematic overview. Weight reduction is often a key factor in modern design, therefore materials such as carbon fibre reinforce plastic (CFRP) are increasingly used and bonded in multi-material structures. The capability of a BRN to join different materials with low effort and easy disassembly has contributed to a growing industrial interest in the fastener. However, the high contact stress between the plate and the BRN [1] might induce damage and consequently harm the mechanical strength and durability of the assembly.

Research on bolted CFRP connections reveal that an appropriate preload on the bold is beneficial for the joints structural integrity [2] [3]. Additional research confirms the positive influence of the through-thickness stress on the delamination resistance of the composite [4] [5]. However, when evaluating the BRN connection, not only the through-thickness stress but also the

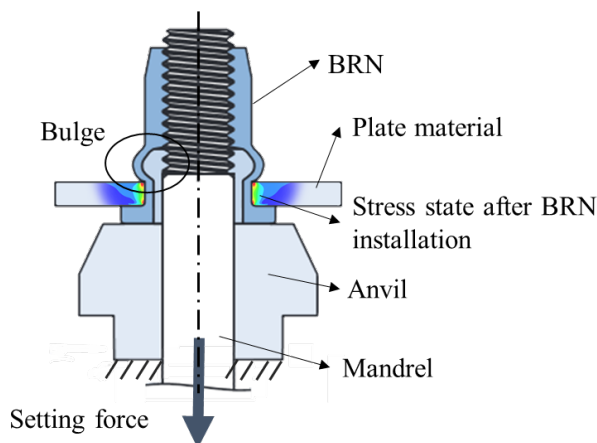


Fig. 1. Schematic cross-section of BRN setting process

detrimental circumferential tensile stress must be considered. Hassanifard et. al. [6] investigated the fatigue performance of aluminum (5083) plates using a single lap rivet-nut joint. It was concluded that the stress induced after BRN installation positively influenced the fatigue life. Walther [7] performed stepwise load increase fatigue tests on CFRP sheets with BRN joints. The loads considered were pull-out and torsion. Comparing joints with a minimum, intermediate and maximum setting force, revealed that the lowest damage accumulation could be achieved using the intermediate setting force.

As there is only limited information available on the effect of the complex stress state on the structural integrity of CFRP plate material, the BRN is often approached conservatively. Therefore, the BRN is often unjustifiably avoided in assembly if a 'damage-free' result is demanded, narrowing down BRN potential applications. In the present research, the influence of installing a BRN in CFRP on the structural integrity of the plate material is experimentally investigated. Filled hole tension tests are performed using different installation forces generating different stress states within the plate. The specimens are tested to assess the static and the fatigue resistance.

Used Materials

The used laminate is composed of 18 layers unidirectional T700S carbon fiber with DT120 resin system of Delta-Tech (areal weight, 150 g/m²). T700S is a high tenacity fiber with a tensile strength of 4.9 GPa and a tensile modulus of 230 GPa. The UD layers are stacked with following lay-up: [90° / - 45° / 90° / 45° / 0° / - 45° / 90° / 45° / 90°]_{se}. The stacked prepreg is cured under vacuum in an autoclave with a compressive pressure of 4.5 bar for 90 minutes. The resulting thickness was 2.7 mm. Samples are cut with the loading direction (Fig. 2) along the lay-up orientation, further referred to as '*0° orientation*'. For those samples, the plies with transverse fiber orientation (90°) are most dominant in the lay-up. Additionally, samples are also cut perpendicular to the lay-up orientation, further referred to as '*90° orientation*'. Since the difference in dominant fiber orientation potentially causes a different damage mechanism [8], both specimens are investigated.

Test samples are machined using abrasive waterjet cutting. To avoid delamination caused by piercing the laminate, holes of 3 mm diameter are drilled prior to abrasive cutting. All holes are machined within a tolerance of $90^{+0.04}$. The tolerance is more narrow than prescribed by the BRN manufacturer to minimize the influence of the clearance between the hole and fastener on the results. The specimens are equipped with a commercially available BRN of stainless steel (AISI 304cu) with thread size M6. Three different setting forces are considered, namely 0 kN (a loose BRN), 12 kN and 15 kN. The BRN is installed on a precisely controlled tensile bench with a capacity of 20 kN equipped with dedicated tools as prescribed in previous research [9].

Testing Procedure

The dimensions of the used specimens can be seen in Fig. 2, the tests are in accordance with the MIL-HDBK-17 standard. Shortly after installing the BRN the stress in the resin will decrease due to relaxation of the polymer. The stress relaxation in the laminate is experimentally investigated. A specimen with a hole is loaded using a round punch with diameter 10 mm. The punch compressed the edge of the hole with a force of 6 kN. Keeping the position of the punch fixed whilst measuring the load, a force reduction of 20% is observed within the first 3 hours. After 48 hours, the change in force was marginal. Performing the experiment with a compression force of 15 kN, the relaxation rate is unaffected. Therefore, to minimize the influence of creep on the setting force, the BRN is set and the specimens are stored for at least 48 hours prior to testing.

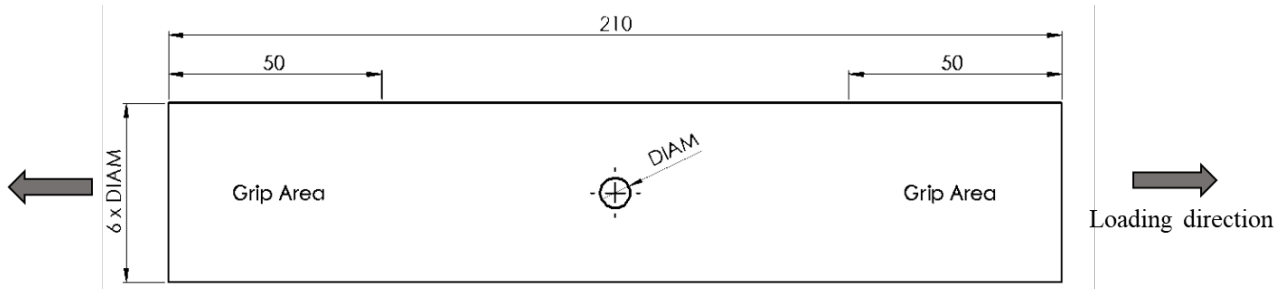


Fig. 2. Illustration of the investigated specimens with DIAM = 9 mm.

The static tests are performed on a Zwick tensile bench with a capacity of 250 kN equipped with pneumatic wedge clamps. An extensometer is used to measure the displacement neutralizing potential slip in the clamps. Tension loading is applied until two-part failure occurred. For the three setting forces, five repetitions are used. Eq. (1) is used to calculate the filled hole tension strength. The static strength values are used to determine the fatigue loads.

$$F_{fht} = \frac{P_{max}}{W t}. \quad (1)$$

Where

- P_{max} = maximum tensile load
- W = measured width at midsection
- t = measured nominal laminate thickness

Considering the fatigue tests, specimens are axially loaded using a Zwick hydraulic fatigue bench with a capacity of 100 kN. The machine is equipped with mechanical clamps. Extra supports prevented rotation of the clamps. To improve gripping and avoid preliminary failure in the clamps, aluminum tabs are bonded onto the specimens. A sinusoidal load ($R = 0.1$) is applied with a frequency of 8 Hz. Active air cooling is directed on the BRN to enable the matrix to stay well below its glass transition temperature. The load levels are based on the 5 static tests for each load condition (i.e. 0 kN, 12 kN and 15 kN setting force).

Results and Discussion

Using a setting force of 12 kN, the bulb of the BRN is almost completely formed. It is assumed that the mandrel force is transmitted to the anvil by the bulb. Therefore, the through-thickness stress in the laminate is minimal. Nevertheless, the edge of the hole is strongly compressed. Using a setting force of 15 kN, the bulb is completely formed and the laminate is compressed between the head and the bulb of the rivet. To visualize the contact force between the BRN and the laminate, a cross-section of the joint perpendicular to the loading direction is made and inspected using SEM. Fig. 3 (a) shows a cross section of the BRN set using 12 kN setting force, it is clear that the fibers in the outer (90°) layer are locally distorted by the radial compressive force. Fiber buckling, matrix cracks and delamination between the lower three layers are observed as failure modes. When applying the 15 kN setting force, additional delamination between the 90° and 45° layers is also observed (Fig. 3 (b)). Furthermore, the laminate is significantly more compressed using 15 kN compared to 12 kN setting force. This confirms that the increase of setting force results in a higher through-thickness stress in the laminate.

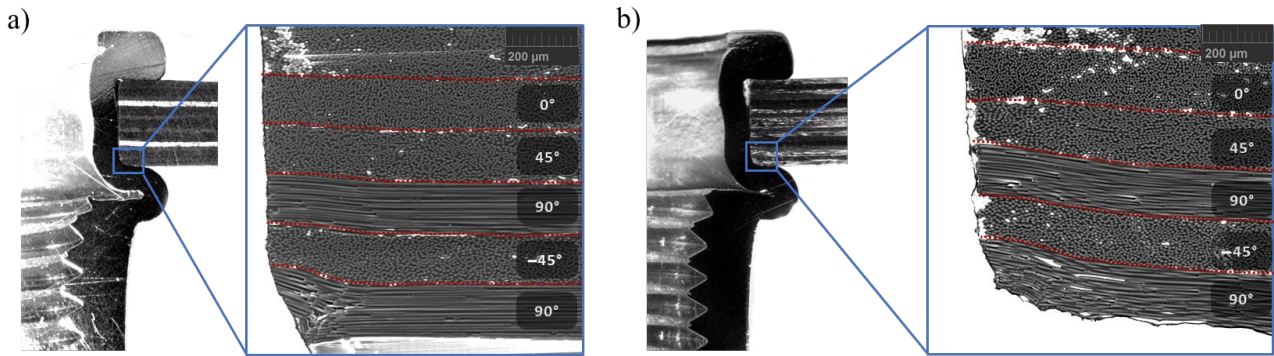


Fig. 3. (a) Cross-section analysis of the BRN set in CFRP laminate using 12 kN setting force and (b) 15 kN setting force.

For the sake of completeness, it must be noted that for the BRN's installed with a setting force of 12 kN some of the formed bulbs were remarkably non-axisymmetric. Since the installation process is in essence a buckling phenomenon, the shape of the bulb is highly sensitive to geometrical imperfections in the cylindrical deformation chamber. Fig. 4 (a) shows an example of such a non-axisymmetric bulb. The smaller bulb visible on the left side potentially induces a local stress peak on the edge of the hole. The position of the expected stress peak could be taken into account in order to reduce possible deviation in the results. However, since the aim of the present research is to investigate the performance of the laminate influenced by the stress induced after installing a BRN in general, the inconsistent shape is ignored for reasons of simplicity. Further loading the BRN with a setting force of 15 kN, the shape becomes consistently more axisymmetric (Fig. 4 (b)).

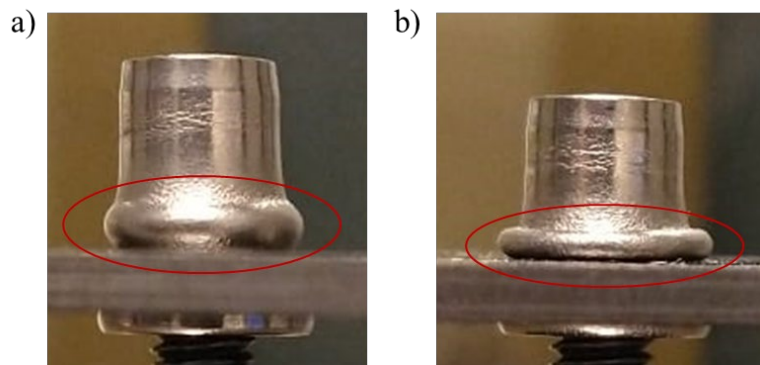


Fig. 4. Non – axisymmetric formed BRN using (a) 12 kN setting force and (b) 15 kN setting force.

Fig. 5 (a) shows the measured tensile curve of a '0° specimen' with a loose BRN (0 kN). The curve can be divided in two linear parts with a different slope. Most likely, the 90° plies will gradually degrade first caused by matrix cracking. As the load is redistributed over the remaining plies, the 45° plies will also suffer from matrix cracking and fail subsequently. Since the 0° plies are responsible for approximately 60 % of the stiffness of the laminate, the change in slope (around 1% strain) indicates that all off-axis plies are degraded and the load is mainly carried by the two 0° plies up to final failure of the laminate.

In Fig. 5 (b), the results of all static tests are visualized. It can be seen that the average ultimate filled hole tensile strength is hardly influenced by installing the BRN. Near the hole, the laminate suffers from interlaminar shear and normal stresses promoting delamination. It is assumed that the severity of the local stress state is reduced by the compressive stress between the bulb and the head of the BRN. Additionally, the tensile stress at failure of the off-axis plies is also plotted. The point at which the slope of the curve changes is determined at the intersection of the fitted straight lines. Installing the BRN with a setting force of 12 kN, the results show a higher scatter. However, the mean value is not influenced. Further loading the BRN using a setting force of 15 kN, the stress at which

the off-axis plies fail dropped. It is assumed that matrix cracking is advanced by the high stress induced after installing the BRN.

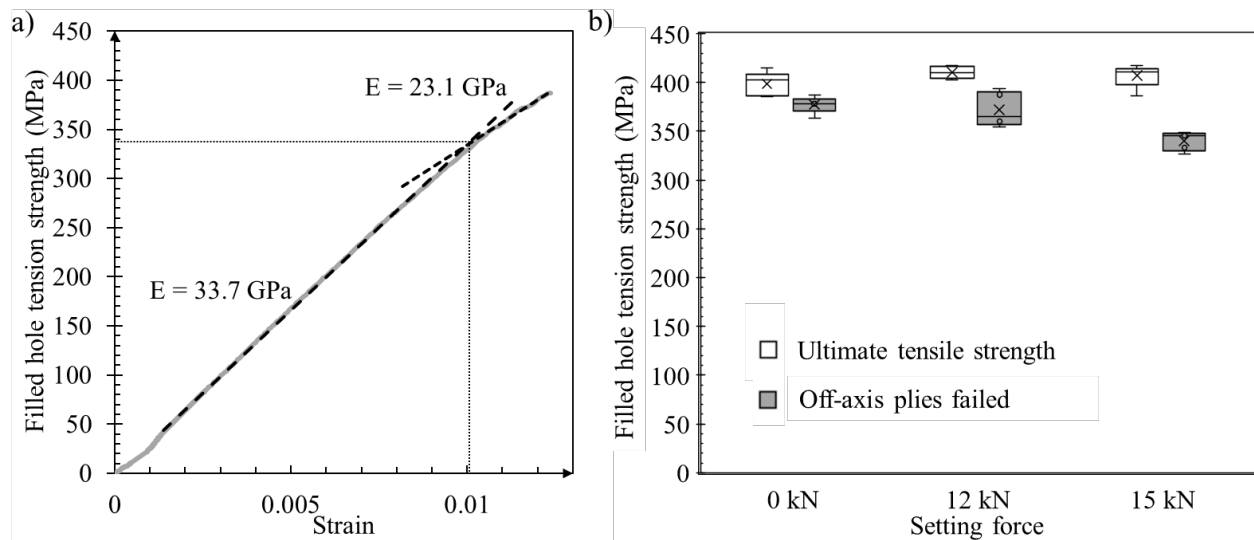


Fig. 5. Stress – strain diagram of a 0° filled hole tension test with loose BRN (a) and summary of the obtained strength values (b).

All fatigue tests on the ' 0° specimen' showed similar degradation before complete failure. During the test, clear delamination and debonding of the matrix and fiber is observed. Fig. 6 (a) shows the fatigue life for each load level. Using a load of 220 MPa (55% $F_{fht, 0kN}$), the specimens for all three configurations resisted 5M cycles. Using a load of 340 MPa (85% $F_{fht, 0kN}$), the deviation of the obtained life is excessively high, indicating that the specimens are tested too close to the static regime. Therefore, only the results for stress values between the range of 240 MPa and 320 MPa are used to fit the required SN curves.

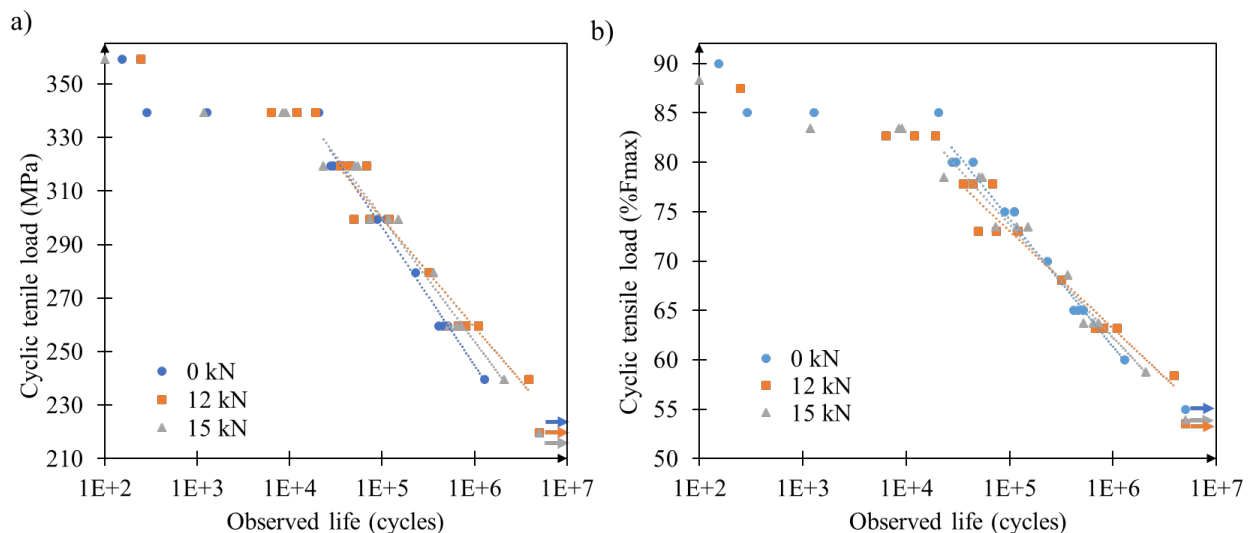


Fig. 6. Obtained SN-curves using (a) absolute load levels and (b) relative load levels.

Comparing the obtained SN-curves (Fig. 6 (a)) for the loose BRN (0 kN) and the BRN installed with a setting force of 12 kN, an improved slope of approximately 21 % can be calculated. Increasing the setting force to 15 kN only improves the slope with 10 %. To take the improvement of the static tensile force into account, the SN curves are also constructed defining the load relative to the ultimate tensile force. The result is shown in Fig. 6 (b). It can be seen that the upward shift of the SN – curves disappeared, however, the improvement in the slopes of the curves is very similar.

A setting force of 12 kN and 15 kN yield a slope improvement of 23% and 11%, respectively. Currently, it is assumed that loading the specimen with the loose BRN promotes delamination at the edge of the hole by the interlaminar shear stress. Starting near the hole, the laminate degrades until

failure. Installing the BRN at 12 kN seemed to restrain the free edges and the through-thickness stress reduces local damage risks. Most likely, further increasing the setting force will excessively load the resin thereby accelerating the degradation again. The latter hypothesis will be studied in future research. Considering the variation on the experimental values, it is safe to conclude that after installing a BRN in the CFRP laminate, the fatigue life is not detrimentally influenced despite the stress and damage induced near the hole.

Fig. 7 (a) shows the measured tensile curve of a ' 90° specimen' with a loose BRN (0 kN). The curve is almost perfectly linear up to failure. Calculating the stiffness of the laminate according to the classic laminate theory, a theoretical value of 71.1 GPa is predicted. The good agreement between the calculated values and the fitted slopes indicate that the hole in the plate will only marginally influence the stiffness of the laminate. In Fig. 7 (b), the results of all static tests are visualized. It can be seen that the average ultimate filled hole tensile strength is influenced after installing the BRN. Using 12 kN setting force, the average is reduced by 10%. Further increasing the setting force to 15 kN results in a total reduction of the filled hole tensile strength by 17.8%. It is assumed that the damage in the outer layers with the fibers oriented in the loading direction is responsible for the observed reduction.

Fatigue tests on ' 90° specimens' showed that when using 70% of $F_{fht, 0kN}$, the specimens resisted 5M cycles. Analyzing the dynamic stiffness, a drop can be observed at the start of the test followed by a limited decrease. The drop indicates fast accumulation of matrix cracking in the off-axis plies. Subsequently, the load will be redistributed over the 90° plies where matrix cracking and interface failure will gradually develop. Repeating the tests on ' 90° specimens' using a setting force of 12 kN, similar gradual damage development could be observed.

Increasing the fatigue load to 80% of $F_{fht, 0kN}$, fast failure and run-outs are obtained. The latter indicates that the 80% of $F_{fht, 0kN}$ fatigue load is chosen close to the static strength of the specimen. Consequently, the ' 90° specimen' show fiber breakage and almost no degradation. The latter complicates obtaining valid SN - curves. Therefore, the influence of the BRN installed in the ' 90° specimen' is determined based on the unambiguous static test results.

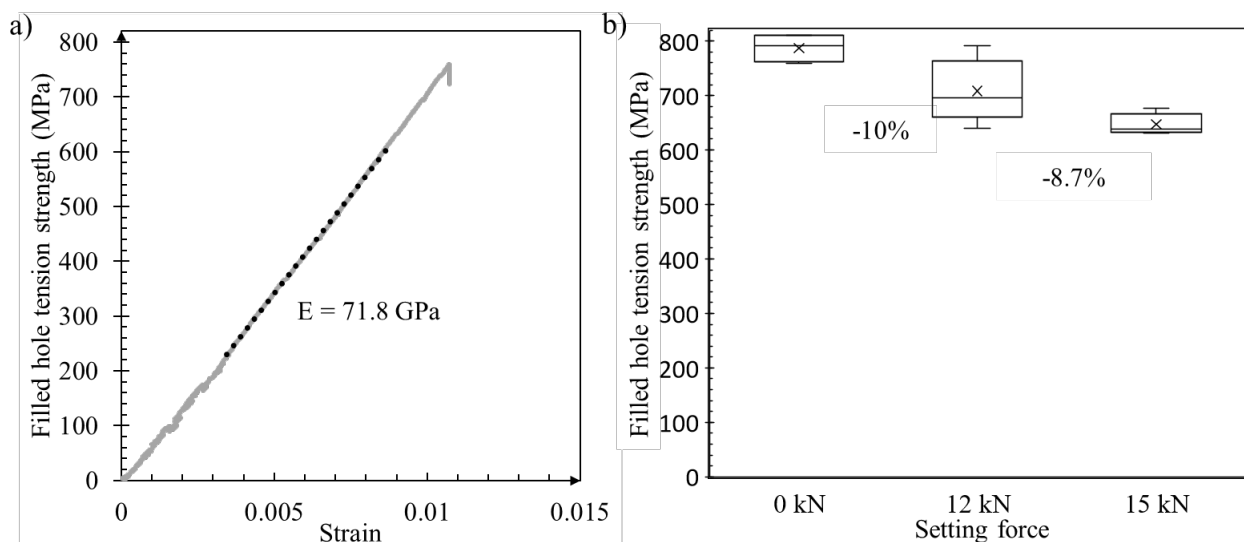


Fig. 7. Stress – strain diagram of a 90° filled hole tension test with loose BRN (a) and summary of the obtained strength values (b).

Summary

The influence of installing a BRN in CFRP on the integrity of the plate material is experimentally investigated. Using SEM, the damage induced by setting a BRN is visualized for two different setting forces. Filled hole tension tests are performed to compare different installation forces and associated stress state in the plate. In the selected lay-up, the amount of UD-layers in the longitudinal orientation

and transverse orientation was notably different. The difference is used to investigate different failure modes depending on the loading direction of the laminate.

- When loading the laminate in the ' 0° orientation' (transverse fibers are dominant), it is shown that the quasi-static strength is hardly influenced after installing the BRN. It is hypothesized that the through-thickness stress reduces the severity of the local stress state, thus reducing local damage risks and counteracts the possible detrimental effect of the damage. Executing fatigue tests for this laminate orientation showed that the fatigue resistance of the specimens improved after installing the BRN. The difference in slope of the SN – curves obtained with different setting forces suggests that an optimum setting force can be found. This finding will be further studied.
- When loading the laminate in the ' 90° orientation' (longitudinal fibers are dominant), the quasi-static test indicated that the strength is reduced after installing the BRN. Here it is assumed that the damage in the outer layers, where the fibers are oriented in the loading direction, is responsible for the observed strength reduction. Since the specimens with and without BRN showed almost no difference in degradation while fatigue testing, no SN – curves are obtained.

The results suggest that the influence of the fastener in CFRP depends on the lay-up and the applied installation force. Future research will embark on the stress state in the plate material and corresponding damage evolution. The ultimate goal of this research is to provide the necessary insight to select the optimal process parameters when installing the fastener in a laminate. Finally, it should be noted that the observed damage in this paper is moderately low. The aim of future work is to establishing the maximum tolerable damage level.

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