TESTING OF THE STRENGTH OF AN ALTERNATIVE MANUFACTURING METHOD FOR BOLTED JOINTS USED IN A GFRP-ROTOR OF AN AXIAL-FLUX ELEKTRIC MOTOR FOR SERIAL PRODUCTION IN AUTOMOTIVE

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Abstract

The strength of two different manufacturing types of threads in two types of thick-walled GFRP laminates is tested. The strength of molded-in threads is compared to conventionally cut threads. This is done with a quasi-isotropic and a cross-ply laminate. Test procedures are axial pull-out of a screw and bearing behavior. In most cases the strength is equal. Differences are measured in two tests. First the strength of the molded-in thread of the cross-ply laminate at pull-out is lower. On the other hand the same laminate has a higher strength in bearing test.

1. Introduction

The electrification of drivetrains in personal and commercial vehicles can provide a significant reduction of the emission of climate changing gases. One of the main challenges of electrical or electrically supported drivetrains is the relatively high system weight, next to the storage of the energy. The project “GroAx”, funded by the German Federal Ministry of Education and Research, has been started to develop the electrical engine Dynax® 60i made by Compact Dynamics GmbH, Starnberg, Germany, for large scale production. The Dynax® 60i is a transversal flux electrical engine on a level of an evaluation model. With a voltage of 42 to 58 V it reaches a torque of approximately 75 Nm and a power of 25 kW, with a weight of only 14 kg. One of the work packages of the project is the development of a thick walled GFRP rotor. In the actual Dynax® 60i it is made using preform resin transfer molding, a fabrication method too expensive for large scale production. So the rotor should be fabricated using wet filament winding technology. Several structural requirements must be considered, especially the stiffness of the rotor, but also the transmission of the torque between the GFRP rotor and the attached steel drive shaft over the product lifetime. The examination of two alternatives of this attached is the content of this study. In the Dynax® 60i the attachment is realized by a bolted connection with screws with inserts glued into drilled holes in the GFRP-rotor (see figure 1). This type of coupling is well established, but requires many process steps: The rotor has to be mounted into a drilling machine and the holes must be drilled, causing wear of the tool due to the high abrasive effects of the GFRP. After drilling, the inserts need to be glued into the holes.

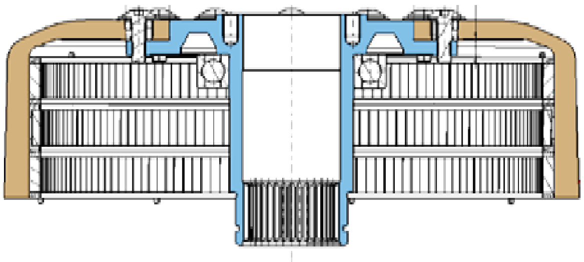

Figure 1. Cut through the GFRP-rotor (light brown) and the drive shaft (blue) using a screwed joint

In the GroAx-Project, the fabrication of the rotor was changed to the wet filament winding technology. Comparable to pressure vessels, two rotors were wound simultaneously on one tool, after curing of the matrix the structure is cut in two separate rotors. To obtain a high fiber volume content in the area of the turning zones, contour-discs were pressed on the non-cured structure (see figure 2).

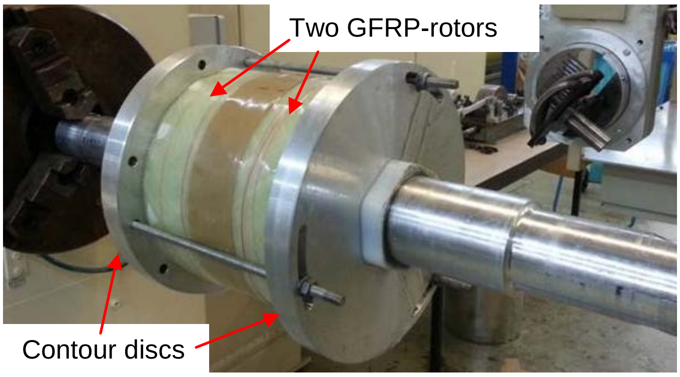

Figure 2. Two wet filament winded GFRP-rotors with the contour-discs on the ends to increase the fiber volume content

With these discs an alternative fabrication of the bolted joining can be realized. Sharpened screws can be used to form a thread into the non-cured laminate. The discs can guide and position the screws for molding-in the threads, where the holes are formed and not drilled. The increased strength of bolts (without threads) of molded-in holes compared to drilled holes was shown in several studies [1, 2]. In molded-in holes the fibers are not cut, but laid around the hole, thereby adjusting the load paths, allowing transferring the forces parallel to the fiber. With the given thick-walled GFRP it seems also possible to mold-in complete treads into the laminate instead of plain holes. This can be an advantage when a screw nut cannot be used, e.g. due to space restriction or restrained accessibility, and a coupling partner made of metallic material with a thread cannot be used. The aim of the study is to test the performance of molded-in thread compared to cut thread in thick-walled GFRP.

2. Preparation of the thick walled GFRP-specimens

For the strength comparison of the cut and molded-in threads, flat GFRP-sheets with 16 layers were produced. The unidirectional e-glass-fiber S14EU910-00950-01300-499000 by Saertex is used. For the stabilization of the fiber mats in every layer a low percentage of the fiber is oriented perpendicular to the main orientation. The fibers density is 2.6 g/cm³, the modulus is 73,000 MPa and the tensional strength is 2,200 MPa [3]. The epoxy resin Huntsman Araldite® LY 1564/ Aradur® 3487 is used as matrix. The tension strength is about 80 MPa and the modulus of 3,100 MPa [4]. Two different layups are investigated, one quasi-isotropic layup $[0_2/+45/-45/90_2/+45/-45]_s$, named Type A, and a cross ply laminate $[0_6/90_2]_s$, named

Type B. The laminate was impregnated using the Vacuum Assisted Resin Infusion process (VARI). The laminate was placed on metallic tool plates. For the molded-in threads the tool plates have threads for the placement of the screws for the forming of the treads into the laminate. In these threads of the tool sharpened screws sized M8 were driven through the dry fibers. After the forming, other, not sharpened screws with form release agent, are installed into the laminate. The not sharpened screw is necessary to prevent damage of the vacuum film used as cover in the VARI-process. To achieve a good consolidation in the area of the screw, washers and a flat nut are used (see figure 3). This is only of concern when manufacturing the test plates, with a metallic tool on both sides, as it will be used in the GroAx filament winding production process, these washers and nuts are not necessary.

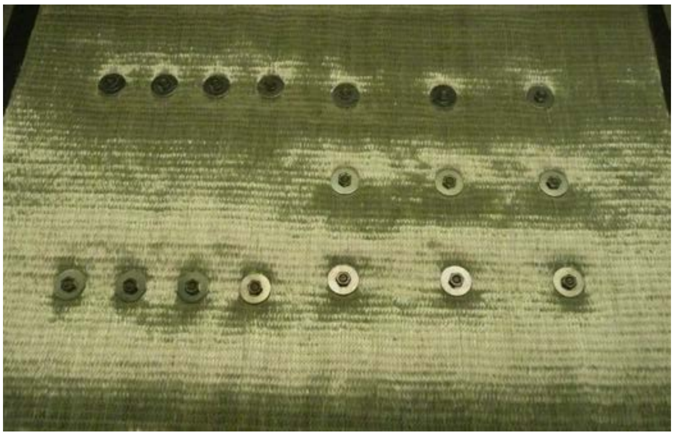

Figure 3. Stapled GFRP-laminate with formed threads before the impregnation process

The cut threads were manufactured with a new carbide drill and a new tapper. New tools are used to reduce the damage caused by the mechanical processing [5, 6, 7]. The sheets have a thickness of 11.7 mm after completing the curing process.

3. Pull-out and bearing tests

To compare the strength of the molded-in and the cut thread, two types of test procedures were carried out. In one procedure the screw was pulled out of the thread axially (a), in the other, the thread was tested with regard to its bearing strength in a single lap-shear tension test (b) (see figure 4). The specimens are prepared with speckle pattern, which is used for optical measurement of deformation to correlate it with future finite element simulations.

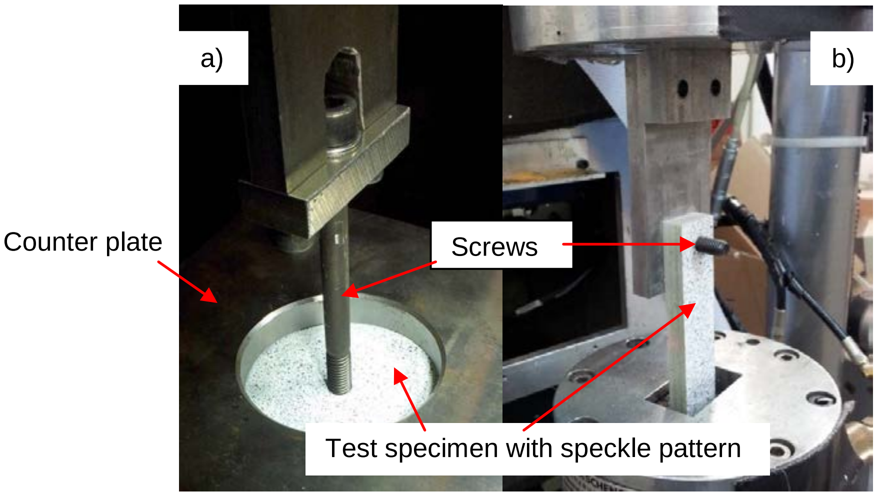

Figure 4 a) and b). Test procedures for threads strength: a) pull-out, b) bearing

The single lap-shear tension test is based on the standard ASTM D5961/D5961M-08. However, the distance between the edge of the test specimen and the center line of the screw is 1.5 instead of 3 times the screw-diameter, as required by the standard. This was necessary because the application of screws M8 with property class 12.9 would not have been strong enough to withstand the shear stress. Consequently, the distance was reduced to 12 mm (see figure 5a).

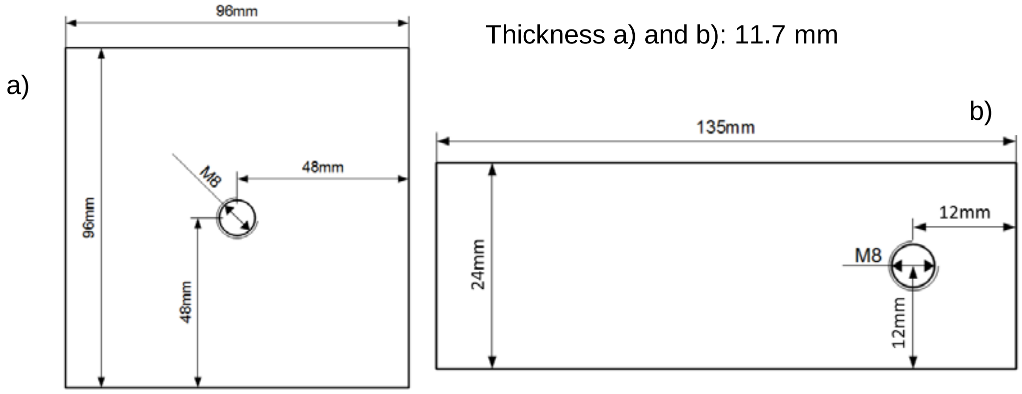

Figure 5 a) and b). Dimensions of the test specimens: a) pull-out test, b) bearing test

The test specimens were installed on a cranked steel plate and the screws were tightened using a torque of 25 Nm. This low torque was used to avoid damages of the laminate which can be caused by the axial load and to avoid that higher loads are transferred by the frictional contact pressure between the two sheets. The reason for this procedure is that it can be expected that the contact pressure will decrease to a relatively low level due to the setting effect of the GFRP and that the loads will only be transferred by bearing. The testing speed was 2 mm/min. Test device was a hydraulic INSTRON PSA 100.

The axial pull out test was carried out according to ASTM D7332. The values given in figure 5b show the dimensions of the test specimens with a M8 thread. The diameter of the counter plate hole (cf. fig. 4) was 63 mm. The testing speed was 1mm/min. Test device was a Schenck Hydropuls with a MTS flex test 100 control.

Both test procedures were carried out with at least 6 specimens of both laminate types A and B with cut and molded-in threads. Table 1 shows the testing program with 8 test series.

Test series	Test	Type of thread	Type of laminate
1	Pull-out	molded-in	A
2			B
3		cut	A
4			B
5	Bearing	molded-in	A
6			B
7		cut	A
8			B

Table 1. Testing program for pull-out and bearing tests

4. Results of the tests

4.1. Comparison of the pull-out strength

Except of the beginning, both laminate types show significantly different behaviors when the screw is pulled out of the laminate (see figure 6 and 7). At the beginning the force level of both test types increases relatively linear, then it reaches some kind of plateau where the load level stays constant for a longer bolt head displacement. With the conventionally cut threads (red lines) of both laminate types, the maximum force is generally reached by the end of the plateau. However, with the molded-in threads the maximum force can be detected at the beginning of the plateau.

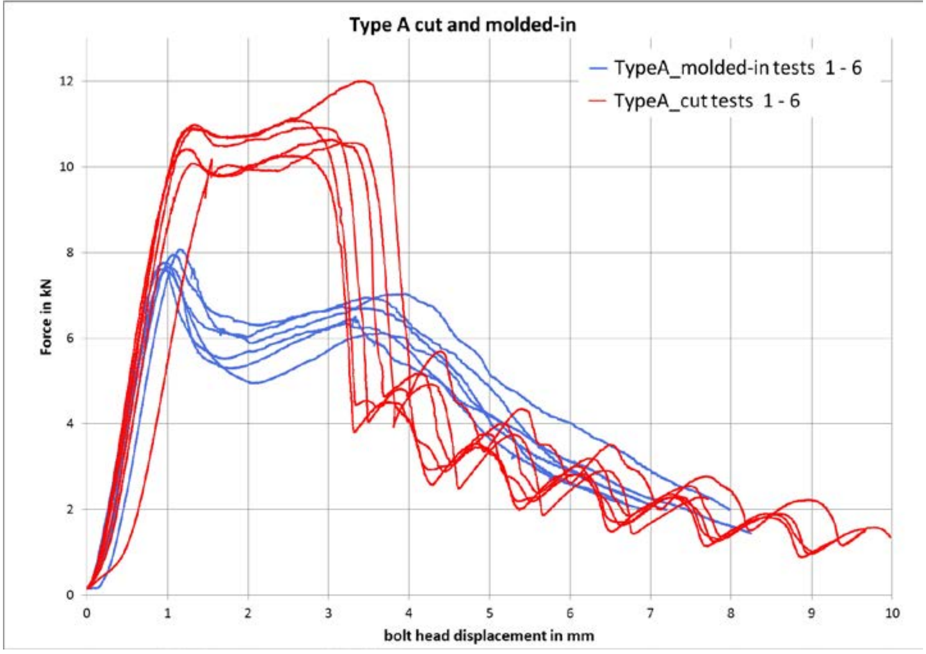

Figure 6. Force-bolt head displacement-graph of the pull-out test with quasi-isotropic laminate (Type A)

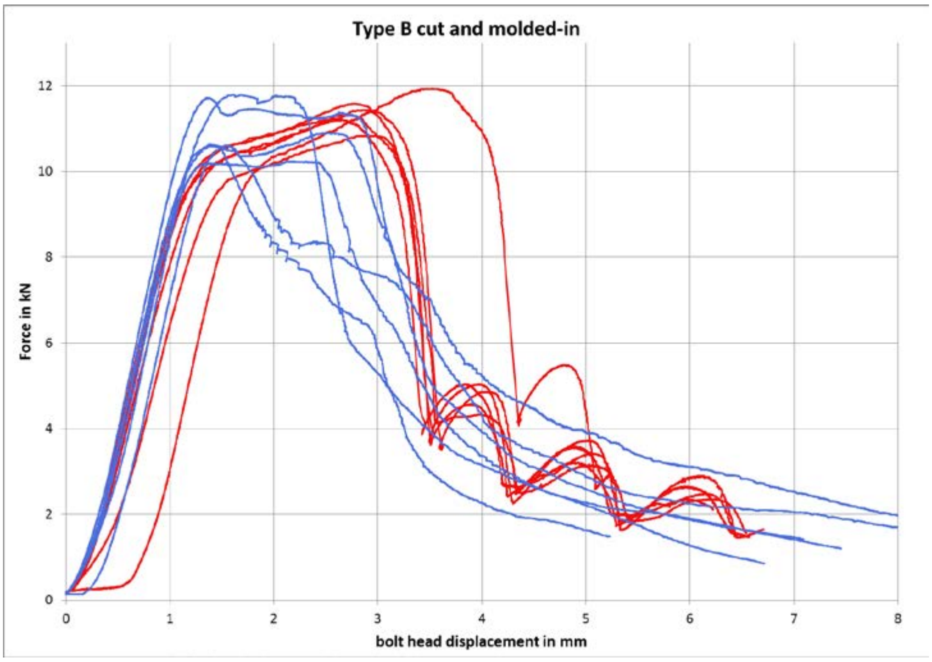

Figure 7. Force-bolt head displacement-graph of the pull-out test with cross-ply laminate (Type B)

Observations of the test suggest that the first failure of the laminates is a delamination of the layers. The delamination leads to a degradation of the laminate stiffness which causes the plateau. At the end of the plateau the force decreases rapidly for both types of laminates, which results from the actual pulling out of the screw threads out of the laminate. The behaviors of both thread types differ significantly when pulling out the screw after the delamination. In the cut threads the laminate slips through the threads, which is why an altering in- and decrease of the force level can be observed (see figure 6 and 7).
This behavior cannot be noticed with the molded-in threads. In this case, the thread is sheared-off which can be concluded from the residues that were found on the screw thread (see figure 8).

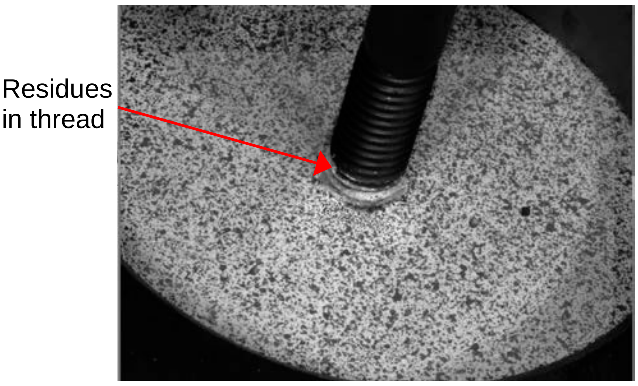

Figure 8. Residues in the thread of the screw containing sheared-off GFRP

A comparison of the maximum forces as an equivalent measure for the strength of the connection shows that there are only small differences between the two types of threads of the cross-ply laminate types B. The mean value of the maximum force of the molded-in threads lies with 11.07 kN and a standard deviation of 0.6 kN on the same level as the cut thread with a mean value 11.37 kN and a standard deviation of 0.34 kN. A significant difference can be observed with the quasi-isotropic laminate type A. In this case, the mean value of the molded-in threads is only 7.78 kN with a standard deviation of 0.18 kN. The cut threads show a mean value of 10.95 kN with a standard deviation of 0.53 kN. The low maximum forces of the molded-in threads are presumably caused by the fact, that most of the fibers are not reaching the ground of the threads. Thereby a significant area of the shear surface is not reinforced by fibers.

4.2. Comparison of the bearing strength

For small loads, the force-distance-diagrams of the bearing tests show a visibly diverging behavior (see figures 9 and 10). Some curves are showing in the beginning a strong increase of distance nearly without an increase of force. This can be explained by the fact that at first the force was transferred by contact pressure. Yet, both sheets start sliding under even low force and the test of the bearing force starts.

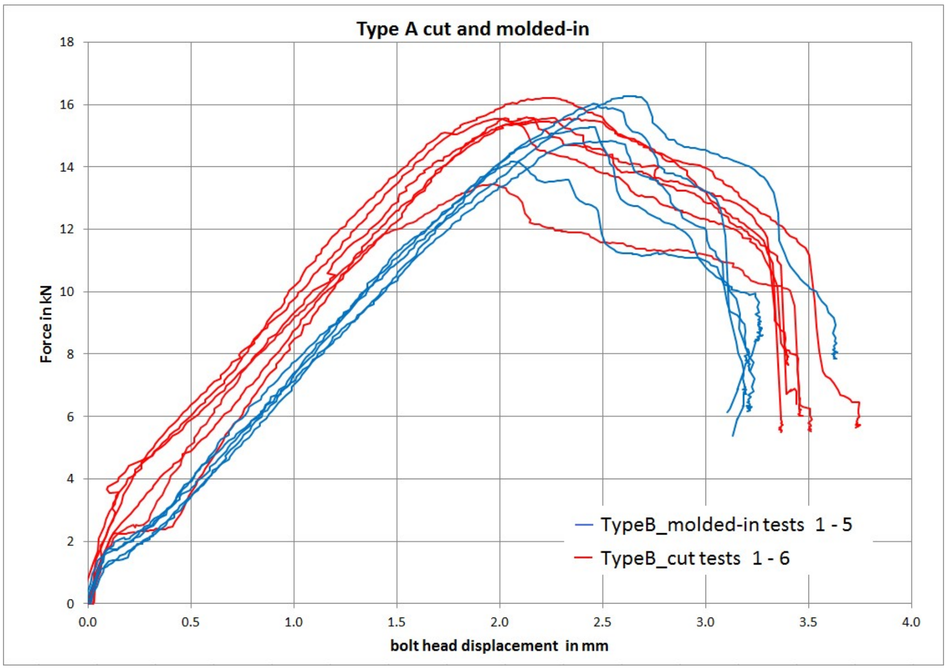

Figure 9. Force-bolt head displacement-graph of the bearing test with quasi-isotropic laminate (Type A)

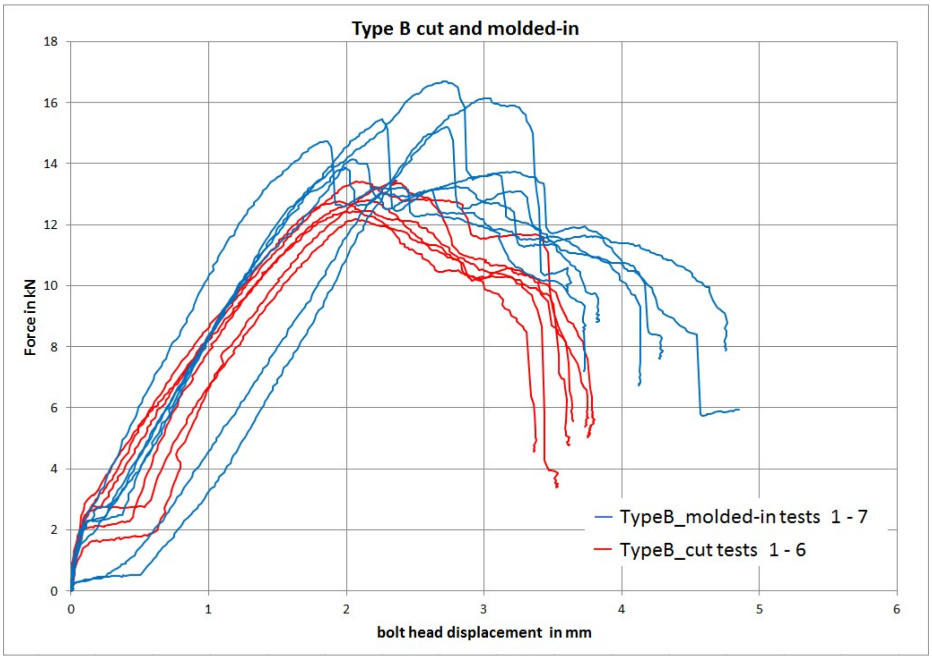

Figure 10. Force-bolt head displacement-graph of the bearing test with cross-ply laminate (Type B)

A predominantly linear force-distance-development follows, decreasing shortly before reaching the maximum force level. By reaching the maximum force, a delamination of the layers occurs comparable to the pull-out tests (see figure 11). The occurring maximum forces with laminate type A are almost equal in both types of threads. The mean value of the maximum force of the cut threads lies with 15.36 kN and a standard deviation of 0.81 kN on the same level as the cut thread with a mean value 15.69 kN and a slightly higher standard deviation of 1.09 kN. As well, a significant difference can be observed with the cross-ply laminate type B, but the other way around. The mean value of the molded-in threads is 15.19 kN, the cut threads show a mean value of only 12.83 kN. But the standard deviation of the molded-in one is 0.94 kN, remarkably more than 0.43 kN of the cut one.

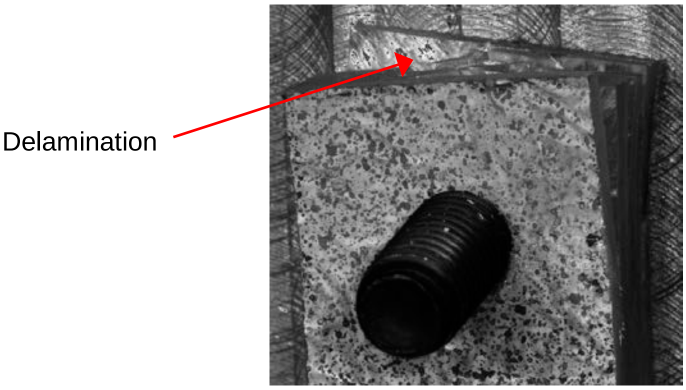

Figure 11. Delamination of the specimen during bearing test

5. Conclusions

Threads molded into a dry, thick-walled GFRP-laminate show a significantly different behaviour under axial load or bearing compared to conventionally cut threads. Especially the force-distance-development differs in some segments clearly. The maximum forces occurring with the destructive load of the coupling show significant differences between the two laminate types. In the pull-out-test with quasi-isotropic laminate a difference cannot be observed, with the cross-ply laminate, the molded-in thread reaches a lower strength level compared to the cut thread. At the bearing test both threads show equal results with the quasi-isotropic laminate, whereas the molded-in thread of the cross-ply laminate reaches a higher strength level compared to the cut thread. The aim of further examinations is to research into the underlying reasons for the effects that have been measured in the shown experiments.

Regards

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References

[1] M. Durante and A. Langella. Bearing Behaviour of Drilled and Molded-in holes. *Applied Composite Materials*, 16:297-306, 2009.
[2] A. Langella and M. Durante. Comparison of Tensile Strength of Composite Material Elements with Drilled and Molded-in holes. *Applied Composite Materials*,15:227-239, 2008.
[3] Datasheet, download at “http://saertex.de/fileadmin/user_upload/PDFs_etc/Standards /9592_E.pdf on 12 March 2014
[4] Datasheet, download at “http://www.swiss-composite.ch/pdf/t-Araldite-LY1564-Aradur3486-3487-e.pdf” on 12 March 2014.
[5] I. Singh and N. Bhatnagar. Drilling-induced damage in uni-directional glass fiber reinforced plastic (UD-GFRP) composite laminates. *The International Journal of Advanced Manufacturing Technology*, 27: 877-882, 2006.
[6] E. Persson, I. Eriksson and L. Zackrisson. Effects of hole machining defects on strength and fatigue life of composite laminates. *Composites Part A: Applied Science and Manufacturing*, 28:141–151, 1997.
[7] R. Teti. Machining of Composite Materials. *CIRP Annals - Manufacturing Technology*, 51:611–634, 2002.