EXPERIMENTAL INVESTIGATION OF MOLDED-IN THREADS AS A NEW SOLUTION FOR LOAD TRANSFER IN THICK-WALLED GFRP APPLICATIONS

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Abstract

The study compares the mechanical behavior of directly formed to conventionally cut threads in thick walled GFRP. Two different laminate layups were investigated: a cross-ply-laminate and a quasi-isotropic laminate, both with a thickness of approximately 12 mm, impregnated with epoxy resin. A standard metrical thread and a more coarse thread were compared, both with an outer diameter of 8 mm. Two different tests were investigated: a pullout test of the screw perpendicular to the laminate plane and a bearing-pull-through-test in the laminate plane. The quasi-static test results show a slightly increased strength of the formed threads in the bearing tests, but a slightly lower strength in the pullout tests. As a second step, the fatigue behavior of the connection was investigated. To compare the cyclic performance of the formed and cut threads in all configurations, woehler lines with a load aspect ratio of R=0.1 were determined. In nearly all tests the gradient of the woehler lines of the formed threads is much lower compared to the cut ones. So the paired woehler lines are showing a point of intersection. Starting at this point the high cycle fatigue behavior improves - up to 4 decades - when forming the threads.

1. Introduction

Background of this study is a GFRP rotor of an electric engine, used in electric drive trains in cars. Major aim is to develop a low-cost version of an existing prototype for serial production with a relatively high output of at least 50.000 units per annum. Besides the limitation of the structural deformation under operating load, the development of a proper load transfer from the metallic output shaft into the GFRP rotor was a main requirement. For serial rotor production with a high output, the direct forming of threads in the thick-walled GFRP was investigated. The direct forming of threads reduces the manufacturing costs by avoiding wear of drilling and cutting tools, although with a slight increase of tooling costs which are less relevant due to the economies of scale of high output manufacturing processes as the filament winding process. There are no studies about the mechanical behavior of the direct formed threads in thick walled GFRP. But several studies show an improvement of the mechanical behavior for flat bolts without threads [1] – [3] when formed directly instead of drilling. So in this study the mechanical behavior of directly formed threads was compared to conventionally tapped threads.

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2. Test description and program

Two different GFRP laminate layups were investigated: a cross-ply-laminate (called type B) and a quasi-isotropic laminate (called type A), both with a thickness of approximately 12 mm, impregnated with an epoxy resin. A standard metrical thread (M8) and a more coarse thread (ST8) were also compared, both with an outer diameter of 8 mm. Two different tests were investigated: a pullout test of the screw perpendicular to the laminate according to ASTM D 7332/D 7332M-07 [4] and a bearing-pull-through-test in the laminate plane according to ASTM D 5961/D 5961M-08 [5]. The test set-ups for the quasi-static tests are shown in figure 1.

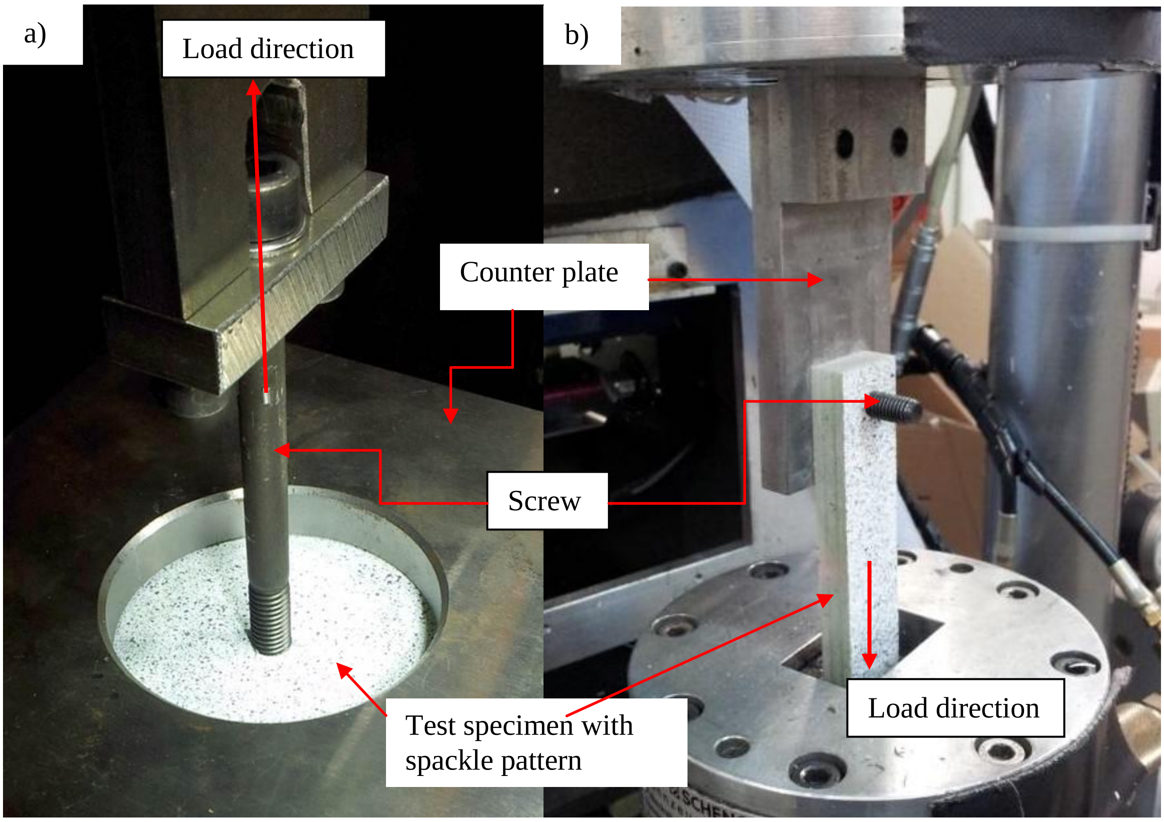

Figure 1. Test set-up for the quasi-static tests of a) pull-out strength and b) bearing strength

The dimensions of the specimens are 135 x 24 mm for the bearing-tests and 96 x 96 mm for the pullout tests. For glass fiber material S14EU910 00950 01300 499000 by SAERTEX is used, for the epoxy resin system Araldite® LY 1564 SP / Aradur® 3487 by Huntsman is chosen. The quasi-isotropic lay-up type A is $[0_2/+45/-45/90_2/+45/-45]_s$, the cross-ply lay-up type B is $[0_6/90_2]_s$.
All the combinations of the test set-ups, the kind of thread, the laminate lay-up and the kind of manufacturing (cut or formed) leads to 16 different test series. An overview is given in table 1. For the quasi-static tests at least 6 specimens for each series were tested. Test speed was 2 mm/min. The strain was measured with a three dimensional digital image correlation system, for this the specimens were prepared with a stochastic speckle pattern (ref. Fig. 1).
Additional to the quasi-static tests, cyclic tests were carried out. To compare the fatigue behavior of the formed and cut specimens, woehler lines were determined. The material specifications and setup were the same like for the quasi-static tests, only the bearing test was modified to double lap shear instead of single lap shear, because with single lap shear in the fatigue test the screw itself and not the laminate is the weakest part in the set-up. With double lap shear in the screw the load is reduced and the fracture occurs in the laminate. The cyclic tests were done with a load aspect ratio of R=0.1 at a frequency of 5 Hz. The load was chosen to reach three supporting points for the woehler lines at

approximately 10^4, 10^5 and 10^6 cycles. Also 16 tests series were measured, with the same parameter variation as used in the quasi-static tests.

Table 1. Test program for quasi-static and fatigue tests

test	*thread*	*manufacturing method*	*Laminate type*
pullout	M8	cut	A
			B
		formed	A
			B
	ST8	cut	A
			B
		formed	A
			B
bearing	M8	cut	A
			B
		formed	A
			B
	ST8	cut	A
			B
		formed	A
			B

3. Test results

The quasi static test results show differences in fracture behavior, but in general very good strength and stiffness behavior compared to conventionally cut threads in thick-walled GFRP. Figure 2 shows the results of the strength. In the pullout tests (left) in three of the four series the conventional cut threads archived a higher strength as the formed ones. These formed ones reached only 71 to 74 % of the strength of the cut ones. Only at the cross-ply laminate with the metrical screw the formed thread reach slight improvement. The results of the bearing tests are in opposite direction. In three series the formed tread reached a higher mean value of the strength of 102 to 118 % of the cut ones. But here the quasi-isotropic layup with the coarse thread shows a different behavior. It reached only 90 % of the strength of the cut one. For more detailed information about the quasi-static test results of the metric thread see [6].

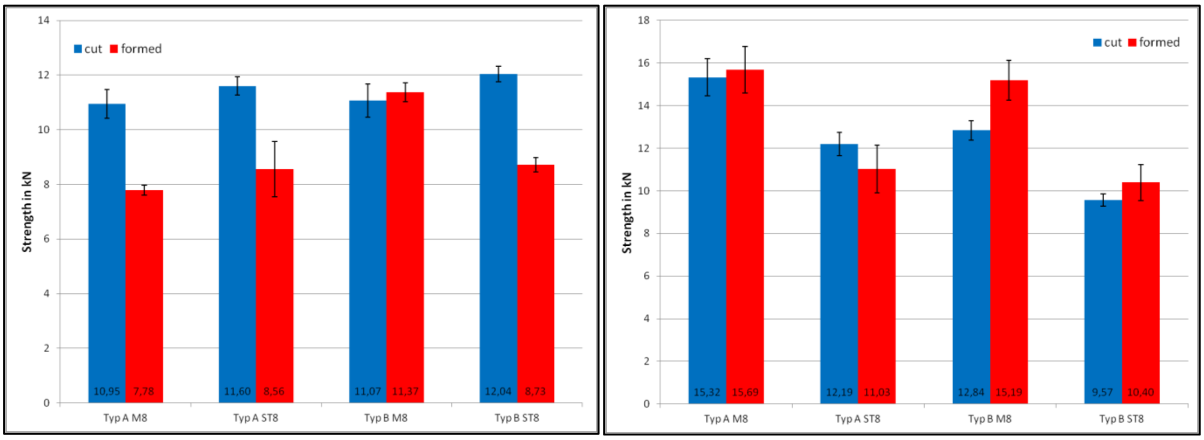

Figure 2. Results of the quasi-static pull-out test (left) and bearing tests (right)

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The reason for the inhomogeneous results could be a strong correlation to the quality of manufacturing. Due to the manual process the variation of the results seems very high. This conclusion is supported by the results of the cyclic pullout tests of the laminate type A as shown in figure 3. The specimens for each woehler line are prepared out of two different GFRP plates. Most of the lines show a relatively low spreading within the 5 results per load step. An exceptional case is the result of the metric threads in the laminate type A. In figure 3 the results of this case are separated into the two plates the specimens were cut out. Within the two plates the spreading of the results is also very low, but the plate 2 shows very low cycle numbers, but on the other hand plate 1 reached in lower load levels the best results of all type A woehler lines.

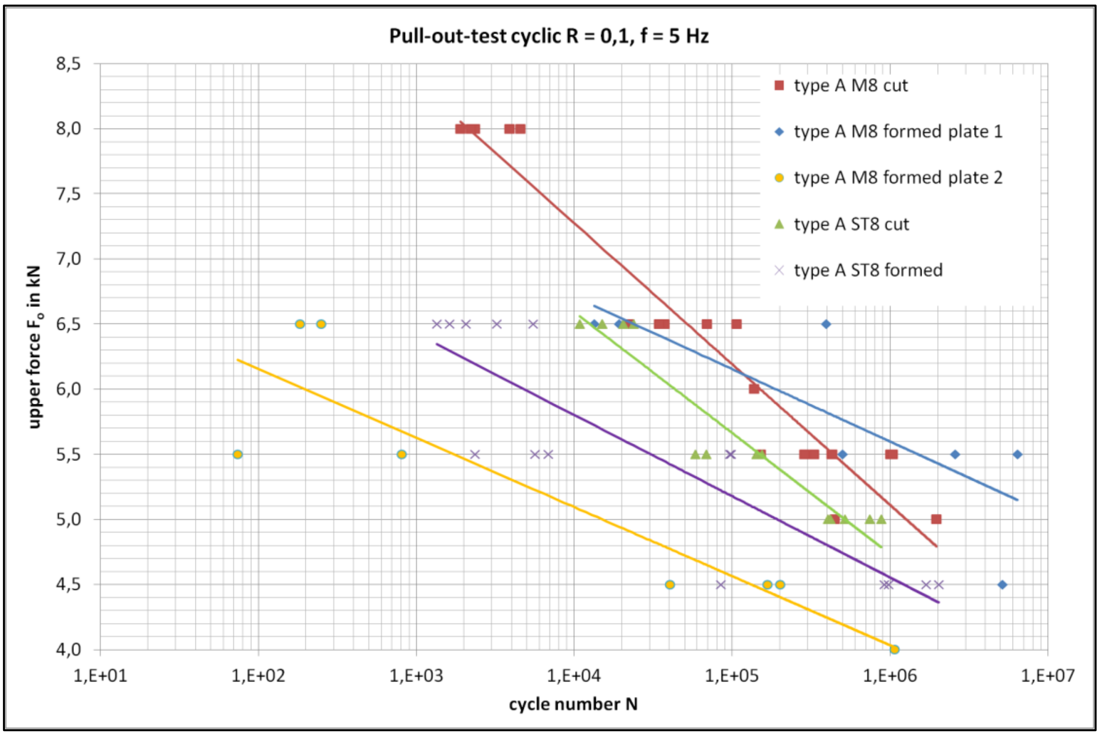

Figure 3. Woehler lines of the cyclic pull-out test of laminate type A

Figures 4 to 6 show further cyclic test results for the pullout test of laminate type B (figure 4) and the cyclic bearing tests of the laminate type A (figure 5) and type B (figure 6). In most cases the fracture occurs at lower cycle numbers at higher force levels for the formed threads. But in some cases the lines of the formed threads are crossing the lines of the cut ones; in consequence the formed threads behave better at lower loads. The sensitivity of the force level seems much higher when the threads are cut. A very considerable example is the lines of the bearing tests of the laminate type B, shown in figure 6.

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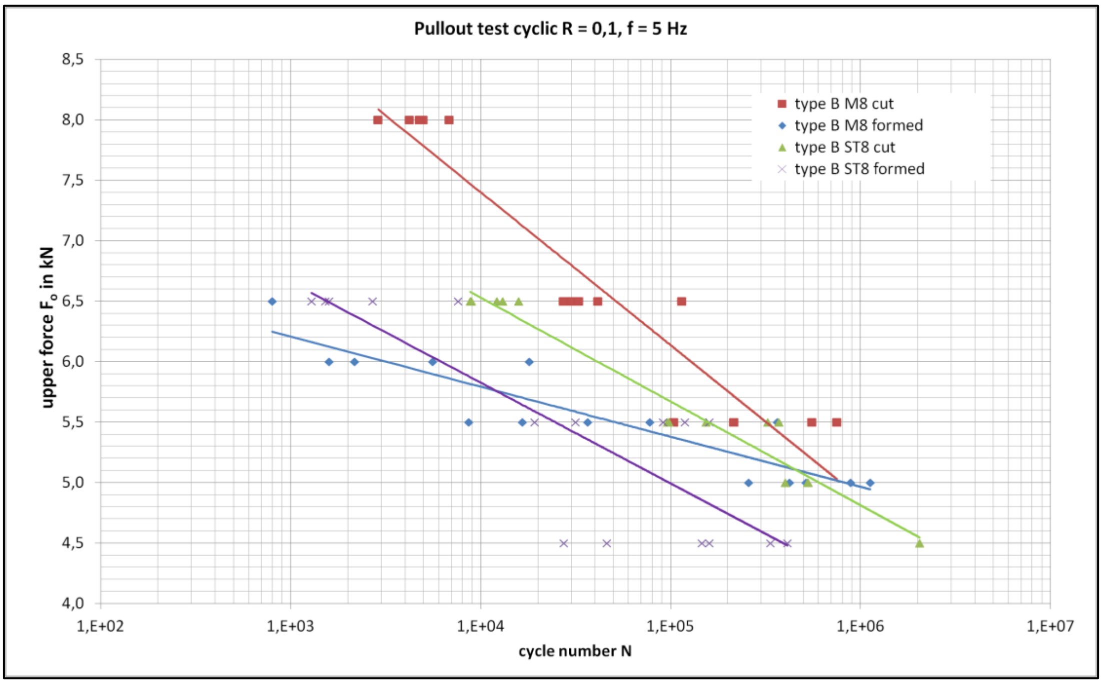

Figure 4. Woehler lines of the cyclic pull-out test of laminate type B

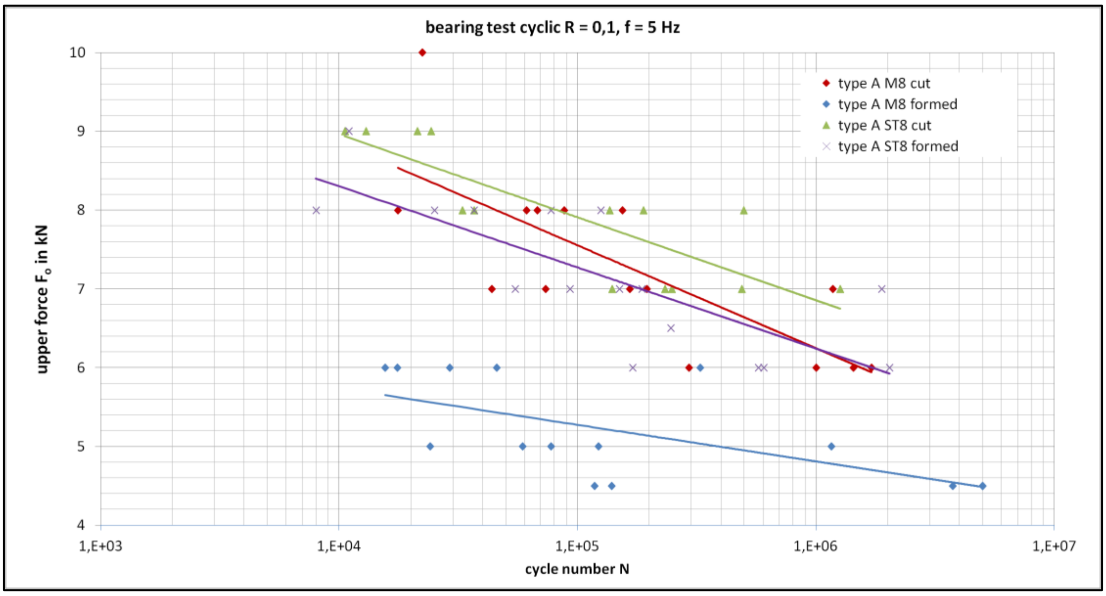

Figure 5. Woehler lines of the cyclic bearing test of laminate type A

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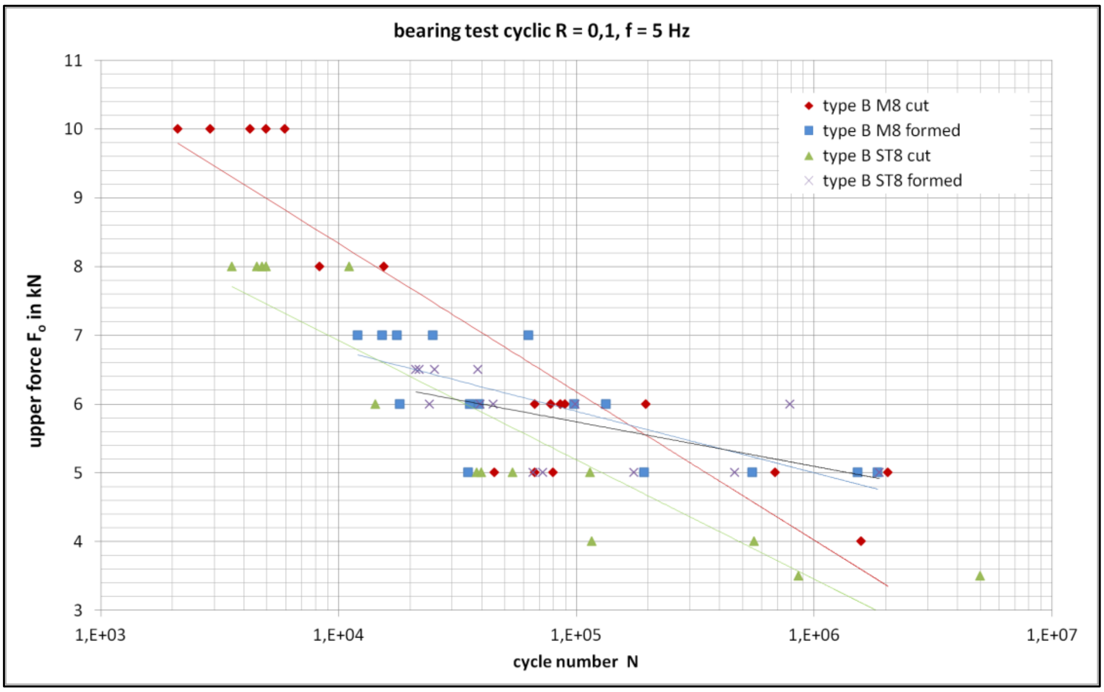

Figure 6. Woehler lines of the cyclic bearing test of laminate type B

A comparison of the gradients of the woehler lines of all test series supports the conclusion, that most lines of the cut threads show higher gradients in absolute values (see figure 7). The seven lowest gradients are all formed threads and only two gradients are reaching values higher than the lowest gradients of the cut series.

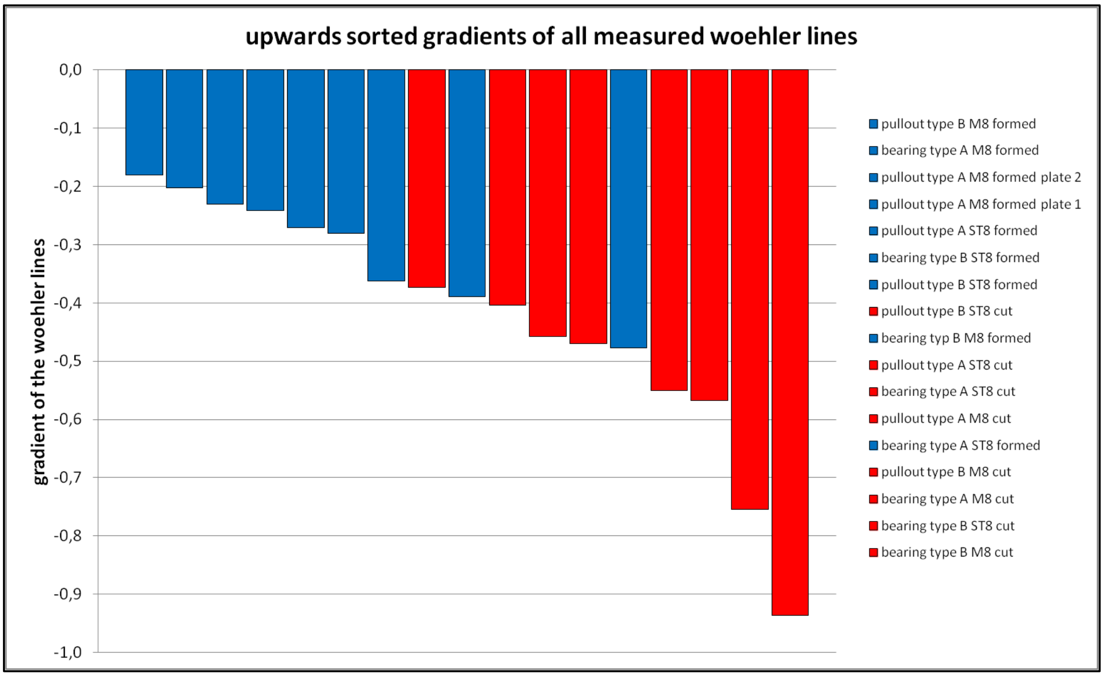

Figure 7. Upwards sorted gradient of all measured woehler lines

With the gradients the crossing points of the paired woehler lines can be calculated, the results are presented in table 2. Is the maximum force level lower than the corresponding crossing point, forming the threads gets an advance. The crossing point can be found in 6 out of 8 pairs, as listed below. For the pullout test of the laminate type B with a ST8 screw no technical relevant crossing point can be calculated. The crossing point would be at a negative cycle number. In this particular case the formed thread shows higher cycle numbers at all load levels. Only for the "bearing test type A ST8" the cut thread shows higher cycle numbers at all load levels. The two woehler lines are nearly parallel and will also not cross each other in a technical relevant range.

Table 2. Crossing points of the paired woehler lines.

test	*thread*	*laminate*	*Crossing point at upper force in kN*
pullout	M8	A plate 1	6.11
		A plate 2	3.02
		B	5.01
	ST8	A	4.19
		B	No crossing point
bearing	M8	A	4.01
		B	5.68
	ST8	A	No crossing point
		B	6.06

3. Conclusions

For quasi-static loading the formed threads show a higher mean strength in bearing tests. At pullout test the conventional cut threads are advantageous. But in both cases not all test series showed the same result. It seems that the quality of the manufacturing is heterogeneous and causes the inconsistent result. This can also be seen by the fatigue results. In one case the reached fracture cycle number depends very much on the quality of the plate the specimens are made of. In general the formed threads reached lower cycle numbers than the cut ones when the upper cyclic force is relatively high. But in seven of eight cases the corresponding woehler lines are crossing each other, when lowering the force level. Beyond this crossing point the formed thread reaches higher cycle number and get advantageous to the cut ones. Usually the requested safety factors at cyclic loads based on the quasi-static strength are relatively high. So the allowed limit of the maximum force is lower than the crossing points. In consequence the formed threads are a reasonable way to increase the life time of a screw joint in a technical application with cyclic loads. In the GFRP rotor of the electric engine a bearing force of maximum 1.818 kN is expected. Table 3 shows the theoretical reached cycle number according to an extrapolation of the corresponding woehler lines. When forming a metrical thread M8 instead of cutting it, the cycle number can be increased from 10 million to 3.5 billion. With a ST8 thread the number can even be increased from 10 million to over 100 billion. An increase of the cycle number of more than 4 decades!

Table 3. Theoretical reached cycle number at bearing load of 1.818 kN

tread	M8 cut	M8 formed	ST8 cut	ST8 formed
cycle number	$1.05x10^{7}$	$3.52x10^{9}$	$9.79x10^{6}$	$1.15x10^{11}$

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References

[1] Lin, H.; Tsai, C.: Failure analysis of bolted connections of composites with drilled and moulded-in hole. Composite Structures, Vol. 30, S. 159–68, 1993.

[2] Durante, M.; Langella, A.: Bearing Behavior of Drilled and Molded-in Holes. Applied Composite Materials, Vol. 16, S. 297–306, 2009.

[3] H.J. Lin; Y.J. Lee: Strength of composite laminates with continuous fiber around a circular hole. Composite Structures, Vol. 21, S. 155–62, 1992.

[4] ASTM D 7332/D 7332M-07 – Standard Test Method for Measuring the Fastener Pull-Through Resistance of a Fiber-Reinforced Polymer Matrix Composite. American Society for Testing and Materials, 2009.

[5] ASTM D 5961/ D 5961 M-08 – Standard Test Method for Bearing Response of Polymer Matrix Laminates. American Society for Testing and Materials, 2008.

[6] Bücker, M., Magin, M.: Testing of the strength of an alternative manufacturing Method for bolted joints used in a GFRP-rotor of an axial-flux electric motor for serial production in automotive, 16. European Conference for Composite Materials ECCM16, Seville, Spain, 22. – 26. June 2014.

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