Very High Cycle Fatigue - Testing Methods

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Abstract. This paper presents several approaches for investigating the Very High Cycle Fatigue (VHCF) range of composite materials. Starting from the special challenges associated with high frequency testing of composite specimens, the paper shows some solutions as well as results for such investigations. The test set-up used in the research of the authors is a four point bending rig, which allows for relatively high load frequencies and widely avoids overheating. These bending tests provide fatigue limits for the development of microcracking, while showing no specific fatigue damage phenomena in the very high cycle fatigue range. The approaches found both, in literature and at the actual method utilised here, are discussed. The paper relates to glass fibre reinforced plastics (GFRP), and does not include either simulation approaches or results.

1. Introduction

Very High Cycle Fatigue (VHCF) characterises a fatigue life range in the order of $10^8$ loading cycles. It therefore exceeds the usual High Cycle Fatigue (HCF) range by approximately two orders of magnitude, which in turn results in significant challenges regarding appropriate test set-ups or test duration.

Usual HCF tests of composite specimens are conducted at a frequency of 3 to 10 Hz; mainly by making use of servo-hydraulic testing machines. But, even at 10 Hz a test up to $10^8$ cycles would last 116 days net duration, and by this would require high energy costs at the same time.

The main reason for restricting the frequency in such a drastic way is mostly the danger of overheating, which is much smaller for metallic specimens, and will to a certain degree depend on the actual lay-up of the specimen.

Other challenges are:
- self fatigue of the equipment
- resistance of the clamping/load introduction areas
- unsuitability of conventional measurement techniques like strain gauges

1.1. Motivation

The motivation for investigations on composite materials in the VHCF range is manifold. One - more or less intrinsic - motivation is the fact that specific Very High Cycle Fatigue phenomena have been found in the case of certain metallic materials [12]. These effects result in a drop of the fatigue endurance limit much later than the ordinary assumption of approximately $10^6$ cycles.
The phenomena are mainly found, if the preparation of the outer surface is performed so well that damage initiation will not occur at the surface, but instead at extremely small disturbances of the inner structure. This effect is called *internal fatigue limit* [26]. It is one of the questions with respect to composites, whether such effects may be found here, too.

The second, more extrinsic motivation, originates from windpower rotor blades and similar applications (helicopters etc.), where very high numbers of load cycles may occur. The question is, whether there are methods to gather reliable data by tests of limited cost and duration.

### 1.2. Literature

The number of publications on Very High Cycle Fatigue of composites is relatively low, compared with the number existing on High Cycle Fatigue.

Although there is a strong need, the VHCF of fibre reinforced plastics has not been sufficiently investigated yet [8]. The main reason for this is - as already said - that testing at standard frequencies requires very long testing times. Unfortunately, as polymers show relatively high material damping, an increase of frequency results in undesired specimen heating. A possible solution pursued in literature is the use of very thin specimens of thicknesses about 1 mm. E.g. Mandell et al. [23] to [25] conducted first comprehensive tests of wind turbine blade materials under the auspices of the U.S. Department of Energys (DOE) Wind Energy Program. Most tests were constant-amplitude cyclic stress against cycle to failure (SN) tests of thin test coupons. Additionally to SN-behavior, Hosoi et al. [15] to [18] investigated the effect of load level on transverse cracking and delamination. According to Hosoi et al., tensile load amplitudes below 30% of the average static tensile stress shift failure into the VHCF range. Furthermore, the order of appearance of transverse cracking and delamination changes. At laminate stresses lower than 20% of the static strength, no damage at all is found up to $2 \times 10^8$ cycles.

Other investigations were focused on the fatigue of UD-layers, loaded e.g. in fibre direction only. Gamstedt and Talreja [14] found specific types of damage and damage propagation in carbon fibre reinforced plastics (CFRP) layers, if the level of loading was very low. The paper presented here solely focusses on the fatigue and microcracking in off-axis layers of the GFRP material.

Some further approaches for VHCF composite testing are introduced in Chapter 2

### 1.3. Outline

The paper starts by discussing the approaches to investigate VHCF of composites found in literature, and tries to show that these are mainly quite different from those used in the case of metallic specimens (see Chapter 2). It then presents the set-up developed by the authors in previous years and discusses their pro's and con's (see Chapter 3). A separate chapter on online monitoring and offline analysis is added (see Chapter 4), although this is mainly not very different from HCF tests, but there are good reasons for VHCF tests to perform most of the monitoring online.

Some typical results of the current test method are presented (see Chapter 5). This has the advantage that some of the features may be discussed in a more direct way, and it also offers the opportunity to present the approach that is currently prepared for the next steps (see Chapter 6). A concise discussion is given in the conclusions.

This paper clearly does not include simulation approaches, although such results may help to understand the results of experiments in a better way. For further information on such subjects, please refer to Adam et al. [4], [2] or Adam [3].

### 2. Options for VHCF test set-ups

Several test principles for Very High Cycle Fatigue are found in literature. The simplest of course is to carry on with the usual servo-hydraulic testing of standard specimens as in HCF
testing, having the disadvantage that testing will last long and cost a lot at least for energy consumption. This approach is not really followed in the next two subsections.

2.1. Set-ups used for metallic materials
The main approach to test metal specimens in the VHCF regime uses tapered rotational probes at very high (ultrasonic) frequencies, i.e. 20 kHz, see e.g. Christ et al. [12]. Kolyshkin [20] shows in his PhD-thesis a set-up similar to the one depicted in Figure 1 (such set-ups are commercially available from BOKU Wien).

![Figure 1. Ultrasonic test set-up (after Kolyshkin [20]).](image)

An elastic wave is sent through the entire set-up which produces high stresses in the minimum cross-section of the specimen. Even though, this concerns a metallic specimen, heating is a problem at 20 kHz. Due to this fact a kind of pulse-pause-tactic is used.

2.2. Set-ups used for composite materials
There are several approaches available to perform VHCF tests on composite materials. One that directly follows the method used for metal materials, as discussed in section 2.1, is proposed by Backe and Balle [7]. They used a piezo-ceramic load actuator, which was able to reach 20 kHz, as in the above mentioned tests. The general principle of the test set-up though is a three-point bending test, where the piezo-electric actuator acts as central load introduction point. Due to the fact that the actuator only allows for very small deflections (about 50 \( \mu \text{m} \)), the bending stiffness of the specimens must be chosen as high as possible. In this case the material was CF-PPS fabric with a thickness of approximately 4 mm and only a very small distance of the two outer load introduction points. As pointed out later in chapter 3, three point bending bears
the disadvantage that the maximum longitudinal strains/stresses are located directly below the central load introduction point.

The test procedure reflects in a way the procedure sketched in section 2.1. Since the surface temperature increased by 4°C after only approximately 100 ms, a type of pulse-pause procedure had to be followed, in order to control the temperature.

The geometry of the specimens has a direct impact on the internal loading of the specimens and in therefore the damage type found in the tests. The length-to-thickness ratio suggests that the main internal loading is due to transverse shear. Damages found during testing support this analysis. Delaminations are found, especially in the region of the load introduction points.

While the Backe and Balle project used bending, where the high frequency was imposed by the actuator alone, Lorsch et al. [22] tried a set-up, where resonance of a piezo-electric actuator, specimen and mass system was used. This is in a way near to the set-up shown in Figure 1, but it needs an additional mass at the lower end to reach reasonable stresses. Both, flat and tube specimens have been used. It turned out that it was quite difficult to find parameters for the masses etc. which resulted in a reasonable frequency range for the entire life of the specimen, from virgin state to a highly damaged state. Additionally, non-symmetric damages could result in off-axis deflections of the specimen, which was not really controllable. In his PhD-thesis [21], Lorsch discusses these issues in a critical way, but he shows that this is a possible method.

Trappe et al. [30] developed a small ±9kN-test-rig, which was fitted into an x-ray-scanner. This meant that an online x-ray-diffraction measurement at flat specimens was applicable without demounting the specimen. The test-rig allowed for a frequency of 50 Hz without significant overheating at $R = 0.1$. Interesting insights were found. One is that in cases, where micro damages, and therefore initiation, were detected only after $10^6$ cycles, no final failure of the specimens occurred after $10^8$ cycles.

Further methods may be found in literature, namely, bending tests with larger specimens, as e.g. used in Koch et al. [19].

3. The set-up used at IFL for VHCF testing

In the frame of the Priority Programme SPP1466 *Infinite Life for Cyclically Loaded High Performance Materials* the IFL of Technische Universität Braunschweig developed a test-rig for VHCF testing of GFRP specimens in the project *Experimental and numerical investigation of very high cycle fatigue of high performance fibre-reinforced plastics*. A very comprehensive version is given in the PhD-thesis of Adam [3] (partly is a coverage in English by Adam et al. in [5]).

The developed test-rig should meet a set of requirements, namely:

- primarily intralaminar stresses or strains as prime trigger of damages; not, as in the Backe and Balle case, interlaminar shear and transverse shear
- a frequency range between 50 and 100 Hz; which means test durations of about a fortnight for $10^8$ cycles
- only marginal temperature increase after long cycle intervals
- relatively cheap specimens, i.e. flat specimens; different from the tube specimens mainly tested at the IFL up to that point (see e.g. [6] or [28]). This also has the sideeffect that cooling of the specimen is quite complex in the tube specimens case.
- high durability of both, the test-rig itself and the load introduction interface between specimen and load introduction/boundary
- a reasonable price of such a device was desirable, offering the chance to multiply it, and use for example 4 rigs in parallel; which in turn reduces the test duration for the completion of a test series considerably
• low energy consumption
• the opportunity to use as many online monitoring methods as possible, meaning that at least one complete surface should be accessible for optical and thermal Ganzfeld-measurements. This has the additional benefit that cooling by air may be used to restrict the temperature increase to an acceptable value.
• ...

The general idea occurred that bending of relatively thin flat specimens, which primarily causes high strains in the outer layers of the laminate could serve as a good solution with respect to the challenge of low temperature increases.

In addition, bending only requires relatively low forces to obtain high stresses in the outer layer of the laminate, resulting in turn in lower cost for both, the device itself and energy consumption.

The general principles offered here for bending are: a cantilever beam, three-point and four-point bending, as depicted in Figure 2.

![Possible Bending Principles](image)

**Figure 2.** Possible Bending Principles.

From Figure 2 it becomes clear that the cantilever beam configuration will only offer the maximum internal loading very localized in the clamping area itself, where in addition to the bending stresses three-dimensional stresses from clamping occur. For this reason this configuration was discarded. The only positive aspect would be that, due to the clamping the danger of undesired specimen movements is low.

Three-point bending offers a few more key aspects, namely a much lower three-dimensional stress state in the direct contact between actuation and support points, but it still bears the problem that the highest longitudinal stresses occur localized directly under the load introduction point. For this reason this type of general test-rig lay-out was also not chosen.

The four point bending configuration seemed to circumvent the problems arising with the two afore mentioned solutions. Although high stresses still exist below the actuation points, they are only half, and - as main advantage - the complete surface between the two actuation points is loaded by a constant bending moment, as first course technical mechanics reveals. Surely, there is a set of detailed problems, if the four point bending set-up is more closely analysed, as discussed in the next paragraphs. But, from an overall perspective this solution seems to be the most attractive one, and has been chosen for this reason.
One of the difficulties arising with four point bending is the fact that, due to Poisson ratio effects, the bended flat specimen shows a so-called anti-clastic bending in the perpendicular direction. This effect leads to the problem that the straight tubular pivots at the support and load actuation points will locally force the specimen to remain flat, while in the free surface area the specimen bends to a small extend, which causes a disturbance in the load introduction area and its vicinity.

In addition, it is a well-known effect that a clamping in longitudinal direction occurs, if the bending deflection gets larger, due to the four points. This results in a certain amount of superimposed longitudinal force. Therefore, it must be the aim to limit the deflection as much as possible, also in this case.

A third effect has to be taken into account for specimens, where microcracking already exists. Since the overall stress under bending is tension on one and compression on the other side of the specimen, and micro-cracks only significantly open under tension, the neutral axis moves accordingly. This of cause will in turn affect local stresses and strains. For detailed analyses this has to be taken into account. Further issues are discussed in chapter 5 in conjunction with experimental results.

Obviously, the type of actuator used in the set-up has a large impact on the design of the test-rig, and may allow for certain configurations, while others have to be excluded from the choice. In addition, they involve the question of achievable frequency, force, costs, duration etc. Adam [3] scrutinized several options both, from literature and industrial offers. Some of the possible means are named, as e.g. Bezazi et al. [10], Belingardi et al. [11], Couillard et al. [13], Bellenger et al. [9], Shenoi et al. [29], Sakin et al. [27], Van Paepegem et al. [31] and Zineb et al. [32]. He looked at servo-hydraulic, electro-linear, electro-mechanic and voice coil solutions for the actuation.

The final decision was to use an electro-magnetic actuator. This decision has the consequence that a load ratio $R = -1$ is imposed, if no special additional measures are taken. Since this is the case, the original four-point-bending configuration depicted in Figure 2 had to be altered in the way shown in Figure 3.

![Figure 3. Chosen 4-point-bending configuration.](image)

For sure, this configuration increases the clamping problem mentioned above to a certain extent, but it is very robust, also with respect to movements of the specimen. In order to reduce the clamping effect a very small gap between the tubular support load introduction points and the specimen surface is utilized.

Figure 4 shows a more detailed view of the set-up for a single four-point-bending device. The direct four-point-bending is mounted in a vertical orientation. The four tubular load introduction and support points on the outer surface are visible. Below the aluminium fitting, which holds these tubular parts, the two 1 kN load cells are visible. On the right hand side a laser triangulator is mounted in the way that the central deflection of the flat specimen can continuously be monitored. The specimen itself is only barely visible in this figure. The dimensions of the specimens are $82 \times 25 \times 2 \ mm^3$, where the distance between the support points is 80 mm.

Two fans are used to cool the surface by blowing air with an ambient temperature of $20^\circ C$. 

Figure 4. Actual set-up of a single test device. Laser triangulator (center right), fans (top and bottom right), four point bending points (center left), below the four-point bending device the two load cells are visible

±2°C along the surface. In order to keep this ambient temperature the entire rig is located in a housing (see Figure 6) which is cooled down by conventional airconditioning.

The single device is multiplied by a factor of 4, as visible in Figure 5. The figure additionally shows two horizontal rails including a fitting each to mount a camera, which is used to take high resolution pictures of the microcracking state of each device. Furthermore, a thermographic camera mounted on a tripod is visible in the lower left corner of the figure.

The four devices are mounted together on one massive concrete block. It turned out that such a massive basis was needed to assure that no acoustic interference of the four actuators with other parts of the testing hall occurred. This block is located in the housing shown in Figure 6.

The housing in Figure 6 has a further task, i.e. it is isolated in order to reduce noise emission significantly, since under certain conditions the four devices were quite loud. Figure 6 also shows some further features on the lefthand side. In the rear the control cabinet is visible and in the front the computers where Labview is running.

4. Online monitoring and offline damage analysis methods
It should be the intention of all researchers to measure many different parameters during the tests, as there are:

- stiffness changes
• internal damages, like microcracking and microdelamination
• damage propagation
• temperature development, both on average as well as localized

Many of these parameters may be monitored in an online procedure. It is advisable to do so, since testing at high frequencies always will introduce at least a small increase in temperature, which in turn means that stopping the test always changes the parameters a bit. Sometimes it is not possible to circumvent such interruptions, e.g. to measure the initial stiffness change of a specimen. But, the disassembly of the specimen from the test rig in order to perform an external measurement, e.g. by ultrasonics, would not only mean a large impact on the testing period, it also bears the danger that boundary conditions of the test are slightly changing.

Some of the parameters which are monitored in the IFL set-up already has been mentioned in chapter 3. Force and deflection may be monitored by using the load-cells and the individual laser triangulator. Both sensors may be utilized to control loading conditions in a displacement or force controlled manner. In Figure 7 some further points may be seen. Here the constantly stressed part of the specimen is visible and the red dot in the center of the surface marks the laser point.
Not visible in the figure is the fact that there exists a background illumination behind each specimen and an optical camera is used to take photographs of the microcracking, where the transparency of the GFRP material is exploited. Stiffness changes in terms of changes in bending stiffness are measured in variable intervals, as mentioned already.

Obviously the amount of data is huge. Especially the characterisation of the microcracking state is cumbersome, if done manually. For this reason attempts are made to utilize automated procedures. This is not a simple task, mainly because crack shapes may be complex and micro-delaminations may occur. At IFL a set of researchers jointly developed a method to distinguish between microcracking and micro-delaminations by using laser light illumination along the edges of the specimen; see Adam et al. [1].

Figure 8 shows three photographs taken from the same specimen at the same number of cycles, namely, about 103000 tested at a stress level of 70% of the longitudinal strain to inter-fiber fracture of the outer 90 layer. The part depicted shows the evenly bend central part of the four-point bending specimen, described above. Depending on the illumination direction the selective laser illuminations allows to distinguish between microcracking and micro-delaminations within the plies in contrast to usually used backlight illumination. Thus, allowing automated image processing using a Matlab tool to determine crack- and delamination propagation. In order to determine i.e. the crack propagation a set of pictures showing the crack propagation during the experiment is superimposed and aligned using previously applied markings on the specimen. Next the pictures are transformed to negatives where the matrix appears black and any damages appear grey/white. By subdividing these pictures into predefined rectangular sections cracking can be detected by processing them using Hough-Transformations in a loop for crack line detection. Further steps connect the lines of different sections and remove parallel duplicates of neighboring sections which might occur for thick cracks. Using the total crack line length and the initial markings on the specimen the crack density can be automatically evaluated.

5. Some exemplary results

VHCF results of the tests performed at the test-rig described above have been published e.g. in Adam et al. [4] for [90/0]_s-specimen (cross-ply) and in Adam et al. [2] for [±45]_s-specimen
Figure 8. Microcracking of a [90/0]_S-specimen; (a) optical photograph by transmitted light; (b) line laser lighting from the righthand side to illuminate delaminations (small surface scratches visible, too); (c) line laser lighting from upper edge to illuminate microcracks (angle-ply). Only a small portion of these results is discussed here. For more detailed information please refer to the two papers mentioned above.

All tests have been performed with specimens made of 1200 tex glass fibre rovings Owens Corning OC111AX and Momentive RIM135i/RIMH137 epoxy resin, where the resulting layer thickness is approximately 0.5 mm. This has the effect that, in case of the cross-ply laminate, the inner 0°-layers mainly serve as some kind of backing-layer, while the 90°-layer is the highly stressed one, where microcracking occurs. In the case of the angle-ply laminate the situation is not as simple as that, due to the fact that very early delamination occurs between the layers. Attempts to test cross-ply laminates with outer 0°-layers have been made, too, but they were not leading to the intended results. Cracking of the 90°-layers occurred only at very high loading; they did not qualify as backing-layers at all. Cracking in the 0°-ayers did not occur. Results of the type found in Gamstedt et al. [14] for pure UD-specimens, as mentioned in section 1.2, were therefore not found.

5.1. [90/0]_S specimens
Tests have been performed at different load or strain levels, respectively. Table 1 lists these levels. By far not all of these load levels lead to real VHCF. Here, \( w_{max}^{90} \) is the maximum deflection at the first load cycle, and \( \varepsilon_{22,0}^{90} \) is the strain in x-direction of the (outer) 90°-layer.

Figures 9 to 11 show three generally visible effects. All diagrams got 1 to 10^8 load cycles at the abscissa. The first figure depicts the change in (normalized) stiffness over the load cycles, i.e. the normalized bending stiffness in this case. Bending stiffness has been defined by

\[
\bar{E}_{xb} = \frac{\hat{F}}{\bar{w}_{max}} \frac{(l_P - l_L)}{bh^3} \left( \frac{1}{4} (l_P - l_L)^2 + \frac{3}{4} l_L (l_P - l_L) + \frac{3}{8} l_L^2 \right)
\]

(1)

where \( \hat{F} \) is the maximum force, \( \bar{w}_{max} \) is the maximum deflection at the centre of the specimen,
Table 1. Load Levels of [90/0]_s tests.

| Load Level | t_{spec} | w_{max}^0 | ε_{22,0}^{90°} |
|------------|----------|-----------|----------------|
| LL1        | 2.06     | 3.05      | 0.43           |
| LL2        | 2.07     | 2.55      | 0.36           |
| LL3        | 2.09     | 1.79      | 0.25           |
| LL4        | 2.01     | 1.61      | 0.22           |
| LL5        | 2.01     | 1.35      | 0.19           |
| LL6        | 2.01     | 0.95      | 0.13           |

l_P the distance of the outer support points, l_L the distance of the load introduction points and b and h width and height, respectively. In this sense, the ordinate simply represents the ratio of current and initial displacement.

From this figure it becomes obvious that at load level LL1 and LL2 more or less initial microcracking and as a consequence stiffness reduction sets in. This is also underlined by Figure 10, where the crack density is plotted vs. the number of load cycles.

Figure 9. Normalized bending stiffness vs. number of load cycles at different load levels

Load level LL3 and LL4 still show damage accumulation by the decrease of stiffness and increase of microcracking, although this happens after a significant number of load cycles, and after initiation of the microcracks, obviously some kind of crack propagation happens. This is different for LL5 and LL6, where only marginal cracking is found, while the stiffness does not really change. Here, only occasional crack initiation occurs; Adam interprets the results in the way that only weak areas, i.e. slightly less durable points/locations, allow for crack initiation. Crack propagation is extremely low or even does not take place.

This result is interesting in the way that the change in character between LL4 and LL5 seems to be at about 10^6 cycles, which is exactly what was found by Trappe et al. [30], as mentioned above, by means of flat specimens and using x-ray-diffraction for detection of small first damages.

Another effect mixes up with microcracking in lowering the bending stiffness. This type of microdelamination occurs at the tips of the microcracks, as already seen in Figure 8. In the
Figure 10. Microcrack density vs. number of load cycles at different load levels

In the case of load levels LL1, LL2 and LL3 such delaminations occur between the 90°-layer and the backing layer. Several observations on the type of delamination growth are described in Adam et al. [4]. At load levels LL4 to LL6 this does not occur.

Figure 11. Delamination fraction vs. load cycles

Another effect, which has to be discussed is not visible in the preceding Figures. This is the fact that most of the microcrack initiation happens at the edge, i.e. obviously the stress state is usually more damaging at the edges also in this case. In Figure 8 c.) this can be observed in a few cases. Different from microcracking in flat specimen under tension etc. the microcrack growth is very slow for specimens at such low load levels, which lead to the VHFC range. As mentioned already, it nearly stops completely in the case of the VHCF load levels LL5 and LL6. In a sense this result shows a big difference between the a.m. observations in metal specimens and those found here in composites. In the metal case, the surface preparation was so well done that no surface initiation occurred, while in all cases with composites the microcracking mostly still occurred at the edges, i.e. the surface.

In addition, all three figures indicate an amount of scatter between the different individual tests. This must be regarded as normal.
5.2. \([+45/ -45]_S\) specimens
A quite comprehensive description of the results of \([+45/ -45]_S\)-specimens are found in Adam et al. [2] and again Adam’s PhD-thesis [3]. The following results are not comprehensive at all; they just show some typical problems. Again many tests at several load levels (LL1 to LL7) have been performed (see Table 2). Here \(\varepsilon_x\) is the strain component in x-direction of the outer layer.

| Load Level | \(t_{\text{spec}}\) mm | \(w_{\text{max}}^0\) mm | \(\varepsilon_x\)% |
|------------|----------------------|----------------------|-----------------|
| LL1        | 1.99                 | 3.94                 | 0.54            |
| LL2        | 1.99                 | 3.51                 | 0.48            |
| LL3        | 2.01                 | 3.25                 | 0.44            |
| LL4        | 2.05                 | 2.62                 | 0.37            |
| LL5        | 1.99                 | 2.49                 | 0.34            |
| LL6        | 2.03                 | 2.22                 | 0.31            |
| LL7        | 2.04                 | 1.84                 | 0.25            |

Figure 12 depicts a typical example for the succession of damage types occurring in a \([+45/ -45]_S\)-specimen under four-point-bending, and the drop of bending stiffness at the same time. The load level is a medium one in this case.

Figure 12. Damage evolution and stiffness decrease in a \([+45/ -45]_S\)-specimen at a medium load level

The damage types indicated by numbers in Figure 12 are:

1. initiation, matrix cracking in outer plies \([+45]\)-plies
2. crack initiation in \([-45]\)-plies, first edge delamination
3. steady and predominating delamination growth
4. accelerated delamination growth, final failure
A photograph of a corresponding damage state is also given in the figure. Damages 3 and 4 lead to a very early and massive damage.

Figure 13. Normalized bending stiffness vs. load cycles for $+45/ -45$ specimens.

Figure 13 again shows the decrease of normalized bending stiffness vs. two different scales of load cycles. From this figure the damage behaviour at different load levels may be concluded. Table 3 summarizes the results. For the cases, where delamination does not become the primary damage, i.e. LL5 to LL7, the test procedure obviously is still of interest with respect to VHCF. But, the interpretation is more complex than in the $[90/0]$ case.

| Table 3. Failure at Load Levels of $[+45/ -45]$ tests. |
|-------------------------------------------------------|
| LL1, LL2 | steep decrease, abrupt final failure between 60 % -70 % of initial stiffness failure at $N < 2 \times 10^6$ cycles |
| LL3, LL4 | initial stiffness decrease levels off before accelerating to final failure |
| LL3: $2 \times 10^6 < N < 8 \times 10^6$ cycles |
| LL4: $8 \times 10^6 < N < 3.5 \times 10^7$ cycles |
| LL5, LL6 | extremely slow stiffness decrease, degradation comes to rest, mostly no failure up to $1.5 \times 10^8$ cycles |
| LL7 | no failure at all up to $1.0 \times 10^8$ cycles, residual stiffness between 80 % - 98 % |

6. Next steps
Currently, several modifications are being performed and tested on the VHCF-test-rig. To enhance the temperature boundary conditions of the specimen, the strain rate i.e. the testing frequency shall be controlled by monitoring the specimen temperature. Furthermore, efforts are made to modify the test-rig to conduct tests with swelling loads ($R = 0$). With this testing method it becomes possible to differentiate between tension- and compression-related fatigue damage phenomena. Furthermore, it is planned to make use of the laser light illumination discussed in section 4, to better distinguish between microcracking and microdelamination.

Besides the modifications to the test-rig, a thinner state of the art roving ( SE2020 ) will be used for further test series to maintain the technological relevance. This will result in thinner layers ($t = 0.25 ; 600$ tex) to evaluate the already found approaches on fatigue behaviour of thicker layers tested before ($t = 0.5mm ; 1200$ tex), where the inner layers acted as backing layers. Thinner layers may show a different delamination mechanism, due to the different
stacking sequence and resulting stress levels. Also, known stackings from literature (Mandell et al. [25] and Hosoi et al. [17]) will be tested; the results compared and the characterization of damage mechanisms added. Investigations on endurance limits, damage initiation, influence of stress ratio.

7. Conclusions

Some conclusions may be drawn from the statements given above, namely

- four-point bending is obviously a principle that allows for VHCF testing up to high numbers of cycles at frequencies between 50 and 100 Hz.
- edges in (bended) flat composite specimens are the primary initiation points in these tests, which is totally different from the type of internal damages in metals in VHCF
- also, no special damage phenomena have been found in the VHCF tests of the flat bending specimens, the phenomena widely reflected the type of microcracking and -delamination, as they are known from HCF.
- at stress levels below a certain limit, no growth of microcracking was found
- ...

All of these data were found for $R = -1$, i.e. alternating constant amplitude testing.

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