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Fatigue behavior of hybrid continuous-discontinuous fiber-reinforced sheet molding compound composites under application-related loading conditions

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ABSTRACT

Hybrid continuous-discontinuous sheet molding compound (SMC) composites are considered suitable candidates for structural automotive applications, due to their high mass-specific mechanical properties combined with high geometrical flexibility and low costs. Since structural automotive parts are subject to repeated loading, profound knowledge of their fatigue behavior is required. This paper presents an experimental study on the bending fatigue behavior of hybrid SMC with discontinuous glass fibers in the core and unidirectional continuous carbon fibers in the face layers. Effects of hybridization on the S-N behavior and stiffness degradation have been analyzed in constant amplitude fatigue tests under 3-point bending load at different temperatures and frequencies. Microscopic investigations on polished specimen edges were used to study the damage behavior. The ultimate flexural strength at quasi-static (UFS^S) and fatigue strain rate (UFS^F) of the hybrid composite was 54 % and 59 % higher than that of discontinuous SMC, respectively. In contrast, the flexural fatigue strength at $2.6 \cdot 10^6$ cycles increased by 258 %. The relative stiffness degradation of the hybrid composites was smaller during most of their fatigue lives due to the continuous carbon fiber reinforcement. The carbon fiber ply on the compression loaded side was the first ply to fail. Fatigue stress significantly decreased at 80 °C due to early kinking of the continuous carbon fiber-reinforced ply on the compression loaded side. Variation of frequency had no significant effect on the fatigue behavior of both discontinuous and continuous-discontinuous SMC.

Introduction

The increasing demand to reduce vehicle weight has fueled efforts to design fiber-reinforced composite parts for structural applications. Discontinuous glass fiber sheet molding compounds (SMC) are well-established in the automotive industry. However, to date, their use is limited to non-structural and semi-structural applications, due to their moderate mechanical properties. In contrast, continuous carbon fiber-reinforced polymers (FRP) feature excellent stiffness and strength, but continuous fibers are expensive and place restrictions regarding feasible part geometries. This is why continuous FRPs are mainly used in aerospace, wind turbines and sporting goods. Several approaches have been presented in literature, that aim to combine the mechanical properties of a unidirectional fiber reinforcement with the advantages of flowable molding compounds, which include geometric flexibility, short cycle times and low costs. The approaches comprise reduction of filler content while increasing the fiber volume content [1], the use of semi-finished SMC sheets with aligned discontinuous fibers [2,3], alignment of discontinuous fibers during the compression molding process [4] and the use of discontinuous carbon fiber SMC instead of discontinuous glass fiber SMC [5,6]. Another promising approach that has been increasingly pursued in recent years is the local reinforcement of discontinuous glass fiber SMC with continuous carbon fibers [7].

The general idea of combining continuous and discontinuous fibers in the SMC process is not new. In 1978, Kliger [8] studied the mechanical behavior of SMC based on either a polyester or fast curing epoxy resin with randomly oriented chopped glass fiber-reinforcement in the core and continuous carbon fibers in the face layers under quasi-static loading conditions at different temperatures. Kliger observed positive effects of hybridization, particularly under bending load, which were a result of the sandwich-like structure. Trauth et al. investigated a similar material system based on an unsaturated

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polyester-polyurethane hybrid (UPPH) resin and determined effects of hybridization on mechanical properties in terms of enhanced tensile modulus of elasticity and tensile strength [4], compressive modulus of elasticity [4], flexural stiffness and strength [9] as well as puncture properties [10]. Investigations on the fatigue of continuous-discontinuous fiber-reinforced SMC were mainly limited to material system in which both the continuous and discontinuous reinforcement was realized by glass fibers [11,12]. Effects of hybridization on the fatigue resistance of those materials were not particularly pronounced. However, since hybridization effects strongly depend on the fibers' elastic properties, their fatigue strength distribution and failure strain ratio [13], results are not transferable to hybrids combining discontinuous glass and continuous carbon fibers. Dickson et al. [14] and Hofer et al. [15] studied the fatigue behavior of hybrid composites combining carbon fibers and glass fibers under tension-tension load, but only considered an entirely continuous reinforcement. Dickson et al. [14] showed, that hybrid composites combining unidirectional glass and carbon fibers in an alternating layer configuration (carbon fiber volume ration of 25 %, 50 % and 75 %) featured a higher fatigue ratio compared to both of the constituents. The fatigue ratio was defined as the fatigue strength at 10^6 cycles divided by the ultimate tensile strength. Hofer et al. [15] studied hybrid quasi-isotropic glass/carbon composites and found the tensile fatigue behavior to be comparable to that of entirely carbon fiber reinforced composites, when using a carbon to glass ratio of 2:1.

The only work on the fatigue of hybrid composites combining discontinuous glass fiber SMC with continuous carbon fiber reinforcement focused on effects of hybridization under tension-tension load [16]. These have been shown to be more pronounced under fatigue than under monotonic loading, which could be explained by the fact that the damage behavior under monotonic loading was dominated by the continuous SMC plies, while the damage behavior under cyclic loading was dominated by the discontinuous SMC plies. The fatigue ratio of the continuous-discontinuous SMC composites was higher compared to both that of the continuous and discontinuous constituent.

The fatigue behavior under bending, which represent a more relevant load case for structural automotive parts, has not yet been investigated. Furthermore, there have been no studies on the influence of frequency and temperature on the fatigue behavior of continuous-discontinuous fiber-reinforced SMC so far.

The influence of loading frequency on the fatigue behavior of discontinuous glass SMC [17] and unidirectional continuous carbon FRP [18,19] is known to be minor. However, a clear temperature-sensitivity can be noted for DiCo SMC [12,20–22]. Whether the fatigue behavior of carbon FRP is influenced by temperature depends on the load case and fiber orientation. Miyano et al. [23] showed that flexural fatigue strength of satin woven epoxy-based carbon FRP is sensitive to temperature. In contrast, Kawai et al. [24] came to the conclusion that unidirectional continuous carbon FRP exhibits no significant temperature-dependence under tension-tension load. Sjogran [25] studied continuous carbon fiber-reinforced epoxy subjected to mode I, mode II and mixed-mode fatigue loading and demonstrated that elevated temperatures result in accelerated delamination crack growth. Even though several studies have been published on the frequency- and temperature dependent fatigue behavior of DiCo SMC and continuous carbon FRP, the findings cannot simply be transferred to hybrid composites combining both materials, due to thermally induced residual stresses and uncharted properties of the interface region between the constituents. To the knowledge of the authors, the influence of temperature on mechanical properties of discontinuous glass SMC with continuous carbon fiber reinforcement has only been investigated by Kliger [8], who studied polyester-based and epoxy-based continuous-discontinuous fiber-reinforced SMC with a similar ply architecture compared to the one investigated in this work. Kliger determined a decrease in flexural strength of more than 40 % by increasing the temperature from ambient to 93 °C. Temperature-dependence was more pronounced for the hybrid composite compared to the discontinuous fiber-reinforced SMC constituent. Since Kliger only focused on quasi-static loading conditions, there are still no studies available on the temperature-dependent fatigue behavior of continuous-discontinuous SMC.

Although continuous-discontinuous SMC composites are considered a suitable candidate for structural applications due to their good mechanical properties, there is a lack of knowledge about their mechanical behavior under loading conditions, that are relevant for structural automotive applications. These include cyclic bending loads at alternating temperature and frequency. Since effects of hybridization were shown to strongly depend on the loading conditions [9], appropriate testing is required before the material system can be used for structural applications.

This paper presents the first study on the bending fatigue behavior of continuous-discontinuous SMC. Effects of hybridization are analyzed based on S-N data and stiffness degradation curves of both the hybrid material and the constituents (i.e., DiCo SMC and Co SMC). Results from interrupted fatigue tests combined with microscopic investigations contribute to a better understanding of the damage behavior of continuous-discontinuous SMC. Furthermore, the influence of frequency and temperature on the fatigue behavior, which has not been investigated to date, is discussed in this paper.

Materials and manufacturing

The materials examined in this study are discontinuous (DiCo) glass fiber SMC, unidirectional continuous (Co) carbon fiber SMC with the fibers being aligned in loading direction (0°) and hybrid continuous-discontinuous SMC ([Co/DiCo/Co]) composites combining both reinforcement types in a sandwich-like structure. The matrix is a two-step curing unsaturated polyester-polyurethane hybrid resin system [26] in all cases. The reader is referred to Trauth [9] for detailed information on the composition of the resin system.

Discontinuous semi-finished material was manufactured on a conventional conveyor plant type HM-LB-800 by Schmidt and Heinzmann at Fraunhofer Institute for Chemical Technology, Pfinztal, Germany. The material featured a nominal fiber volume content of 26 % and a fiber length of 25.4 mm. Continuous carbon fiber semi-finished material with a nominal fiber volume content of 64 % was manufactured on the same conveyor plant, which was slightly modified (Figure 1a). Additional heating and cooling sections at the end of the manufacturing line started the curing process by increasing the temperature to 80 °C and then stopped the cross-linking reactions by cooling the material down to room temperature again. The temperature profile was chosen in a way that the first reaction of the two-step curing was completed after this manufacturing step, thereby increasing the viscosity, which allowed for better handling and cutting. After maturation, the semi-finished material was cut into plies, stacked and compression molded into plaques of 800 mm length and 250 mm width on a hydraulic press (COMPRESS PLUS DCP-G 3600/3200 AS by Dieffenbacher). The temperature of the mold was set to 145 °C. A force of 2500 kN was applied during a mold-closing time of 112 s.

DiCo SMC plaques were manufactured with an initial mold coverage of 50 %, which enforced preferential flow in one dimension during molding and ultimately resulted in an anisotropic fiber orientation. Co SMC plaques were manufactured with an initial mold coverage of 100 %. Continuous-discontinuous SMC plaques were compression molded in one step, as depicted in Figure 1b. One continuous semi-finished sheet was placed into the mold (100 % mold coverage) followed by a stack of discontinuous SMC (50 % mold coverage) and another continuous sheet (100 % mold coverage), with the direction of the continuous fibers coinciding with the direction of flow of the discontinuous material. For additional information on the influence of one-dimensional flow on the microstructure of DiCo SMC and [Co/DiCo/Co] and the resulting anisotropy of the mechanical properties, the reader is referred to Trauth

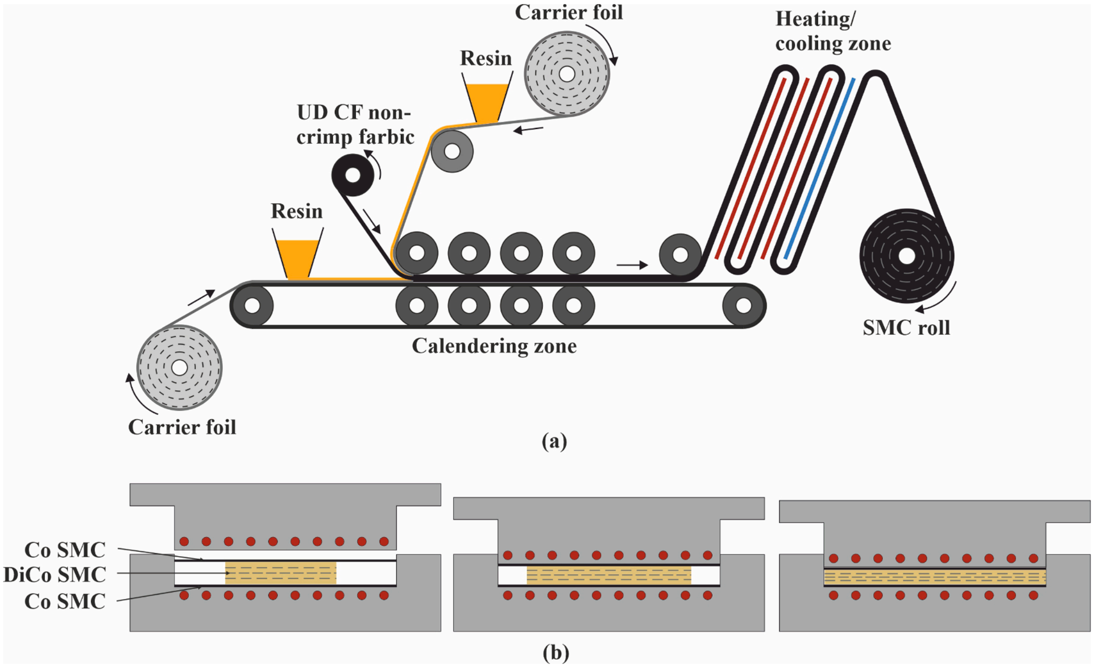

Fig. 1. Schematics of (a) the manufacturing process of semi-finished Co SMC and (b) the compression molding process of hybrid [Co/DiCo/Co] plaques.

[9].

Specimens were extracted from the plaques via waterjet cutting. The cross-section of a hybrid [Co/DiCo/Co] specimen is schematically depicted in Figure 2. In this study, only specimens extracted in the direction of the continuous fibers or in the direction of flow of the discontinuous material were examined.

The length of Co SMC, DiCo SMC and [Co/DiCo/Co] specimens were 50 mm, 60 mm and 100 mm, respectively. The width was 15 mm in all cases. The average thicknesses of the specimens are summarized in Table 1. The thickness of individual plies in the hybrid [Co/DiCo/Co] composite was determined in four specimens at ten different positions over their length. The average thickness of one individual plies is depicted in Figure 2. It should be noted that the thickness of the Co SMC specimens was twice as high as the total thickness of both Co SMC plies in the hybrid specimens.

Experimental methods

Test setup

Monotonic and cyclic 3-point bending tests were carried out on an ElectroPuls E3000 servo-electric testing machine by Instron that was equipped with a 5 kN load cell and a temperature chamber. Deflection was determined from the displacement of the crosshead. Polytetrafluoroethylene tape was applied onto the lower support and the loading nose to keep friction to a minimum. The span length was set to 40 mm, 48 mm and 80 mm for Co SMC, DiCo SMC and [Co/DiCo/Co] specimens, respectively. The span length had to be adjusted to the specimen thicknesses to obtain a constant span-to-thickness ratio of approximately 1:28. Otherwise, a comparison of the results is not reasonable. It should be noted that the ratio of shear to normal stresses, that is dependent on the span-to-thickness ratio, is not similar for the different material system. Trauth [9] has illustrated clearly how the influence of shear decreases to different extents for the different materials with increasing span length. Based on these results, a span-to thickness ratio of 1:28 was considered a good compromise between a minimal influence of shear and a moderate deflection.

Table 1
Thickness dimensions of the examined plaques. The values present an average of all individually measured specimens, which were included in the subsequent evaluation of results.

	Co SMC	DiCo SMC	[Co/DiCo/Co]
Thickness in mm	1.43 ± 0.026	1.70 ± 0.039	2.88 ± 0.057

Monotonic tests

The crosshead velocity for the quasi-static tests was calculated by

Fig. 2. Schematics of the cross section of [Co/DiCo/Co] specimens. The longitudinal direction of the specimens corresponds to the flow direction of DiCo SMC and the direction of the continuous fibers.

$$v = \frac{\varepsilon^{\cdot} L^2}{6h} \quad (3.1)$$

with the target outer fiber strain rate $\varepsilon' = 0.01\ \mathrm{min}^{-1}$ [27], the span length L and the specimen thickness h, and rounded to a value recommended in DIN EN ISO 14125 [27]. The crosshead velocity was 2 mm/min for Co SMC and DiCo SMC and 5mm/min for the hybrid [Co/DiCo/Co] specimens. For the tests at fatigue strain rate, the crosshead velocity was set to 90 mm/s for Co SMC and DiCo SMC and 180 mm/s for [Co/DiCo/Co] to obtain final failure after around 0.1 s (half a period duration for a frequency of 5 Hz) according to ISO 13003 [28]. The ambient temperature was 21 °C. In case of DiCo SMC and [Co/DiCo/Co] specimens, additional test series were carried out at -20 °C and 80 °C to investigate the influence of temperature and flexural strength.

For those tests, the specimens were left in the temperature chamber for at least 15 min before starting the experiment. The specimens' surface reached the desired temperature after < 5 min, which was checked by using an infrared camera. Stresses and strains were determined by

$$\sigma = \frac{3FL}{2bh^2} \quad (3.2)$$

and

$$\varepsilon = \frac{6\delta h}{L^2} \quad (3.3)$$

with the applied force F, specimen width b and deflection δ (DIN EN ISO 14125 [27]). Of note, the hybrid composite is largely inhomogeneous on the macroscopic scale. Equation 3.2 and Equation 3.3 are only valid for homogenous specimens and do not specify actual stresses and strains in the individual plies. However, assuming macroscopic homogeneity of the hybrid composite using these equations allows for the comparison of the different material systems and evaluation of hybridization effects [29], which shall be the focus of this paper.

Fatigue tests

Bending fatigue tests were carried out on Co SMC, DiCo SMC and [Co/DiCo/Co] specimens under load control with a load ratio of $R = 0.1$ and a frequency of 5 Hz at ambient temperature. Additional tests were carried on with DiCo SMC and [Co/DiCo/Co] specimens at -20 °C and 80 °C ($f = 5$ Hz) as well as at 1 Hz and 10 Hz ($T = 21$ °C) to investigate the influence of temperature and frequency on the fatigue behavior. While typical test temperatures for automotive applications are between -40 °C and 80 °C, the minimum temperature of -20 °C was chosen due to the limited size of the liquid nitrogen container, which was used for cooling.

The maximum frequency of 10 Hz was chosen to exclude effects of temperature induced fatigue, whereas a minimum frequency of 1 Hz was chosen due to the long test durations.

The maximum number of cycles was set to $2.6 \cdot 10^6$ cycles. Specimens that did not fail within this number of cycles were declared as runouts. For analyzing the influence of frequency and temperature, experiments were evaluated up to $3.6 \cdot 10^5$cycles only, which is due to two reasons. First, the amount of liquid nitrogen required for cooling was limited by the container size and was not sufficient to hold the low temperature for a longer period. Second, the frequency of 1 Hz would have resulted in significantly longer test durations otherwise.

Results and discussion

Effects of strain rate and temperature on flexural strength

Results of the bending tests at quasi-static and fatigue strain rate carried out at ambient temperature are summarized in Table 2. Enhanced strain rate resulted in an increase of flexural strength of Co SMC, DiCo SMC and [Co/DiCo/Co] specimens by 3 %, 7 % and 10 %, respectively. Flexural strength of [Co/DiCo/Co] specimens was 54 % higher at quasi-static strain rate and 59 % higher at fatigue strain rate compared to the DiCo SMC constituent.

Table 2
Ultimate flexural strength of Co SMC, DiCo SMC and [Co/DiCo/Co] specimens at quasi-static strain rate UFS^S and fatigue strain rate UFS^F. CV is the coefficient of variation.

	Co SMC	DiCo SMC	[Co/DiCo/Co]
UFS^sinMPa (*CV in %*)	930 ± 47 (*9.8*)	399 ± 91 (*11.9*)	616 ± 65 (*10.6*)
UFS^FinMPa (*CV in %*)	962 ± 60 (*6.2*)	425 ± 30 (*7.1*)	678 ± 21 (*3.1*)

While the tensile strength of unidirectional continuous carbon fiber reinforced composites is known to be insensitive to strain rate [30] compressive strength and shear strength show a strain rate dependent behavior [30,31]. The shares of shear and compressive stresses result in a slight strain rate-dependence of Co SMC under bending load. The ultimate strength of DiCo SMC under tension, compression and shear is known to be considerably strain rate-dependent [1,32], which could be demonstrated also for the material system investigated herein. This is due to the visco-damage behavior of DiCo SMC, which is characterized by a higher damage threshold at enhanced strain rate [1]. The enhanced flexural strength of the hybrid [Co/DiCo/Co] composite at the high strain rate is assumed to arise from an increased shear strength of the interface between the Co and DiCo plies.

Results of the bending tests at different temperatures are depicted in Figure 3. For DiCo SMC, increasing the temperature from 21 °C to 80 °C resulted in a decrease of flexural strength by 24 % at quasi-static strain rate and 14 % at fatigue strain rate. The influence was less pronounced compared to the polyester-based DiCo SMC studied by Kliger [8], who reported a 36 % decrease of UFS^S at 93 °C compared to ambient temperature. The enhanced temperature resulted in a lower damage threshold of DiCo SMC, similar to the behavior observed by Tamboura et al. [20] for polyester-based DiCo SMC under tensile load. By reducing the temperature to -20 °C, flexural strength increased by 2 % at quasi-static stain rate and 3 % at fatigue strain rate (Figure 3a).

The flexural strength of [Co/DiCo/Co] decreased by 7 % and 12 % at quasi-static strain rate and fatigue strain rate, respectively, due to a temperature increase from 21 °C to 80 °C, whereas flexural strength decreased by 25 % and 14 % at quasi-static and fatigue strain rate, respectively, at -20°C (Figure 3b). In comparison, Kliger [8], who investigated a hybrid polyester-based composite with a similar ply architecture, reported a 39 % reduced flexural strength at 93 °C compared to the flexural strength at ambient temperature. The high temperature-dependence of the flexural strength of [Co/DiCo/Co] is assumed to be mainly attributed to a reduction of compressive strength of the Co SMC ply and a reduction of the shear strength at the interface between the Co and DiCo plies at elevated temperature.

Bending fatigue behavior at ambient temperature

The S-N data of Co SMC, DiCo SMC and [Co/DiCo/Co] specimens is depicted in Figure 4. The fatigue ratio, which is defined herein as the maximum stress that resulted in runout specimens exclusively divided by UFS^F, was 0.5, 0.3 and 0.7 for Co SMC, DiCo SMC and [Co/DiCo/Co] specimens, respectively. While UFS^F of [Co/DiCo/Co] specimens was only 59 % higher compared to the DiCo SMC constituent, fatigue strength at $2.6 \cdot 10^6$ cycles increased by 258 %. Scatter was in the range of up to three decades of cycles for Co SMC and DiCo SMC, whereas it was more pronounced for [Co/DiCo/Co] specimens with up to four decades of cycles.

The damage variables of representative Co SMC, DiCo SMC and [Co/DiCo/Co] specimens, which are defined by

$$D(N) = 1 - \frac{E_{\mathrm{dyn}}(N)}{E_{\mathrm{dyn},4}}, \quad (4.1)$$

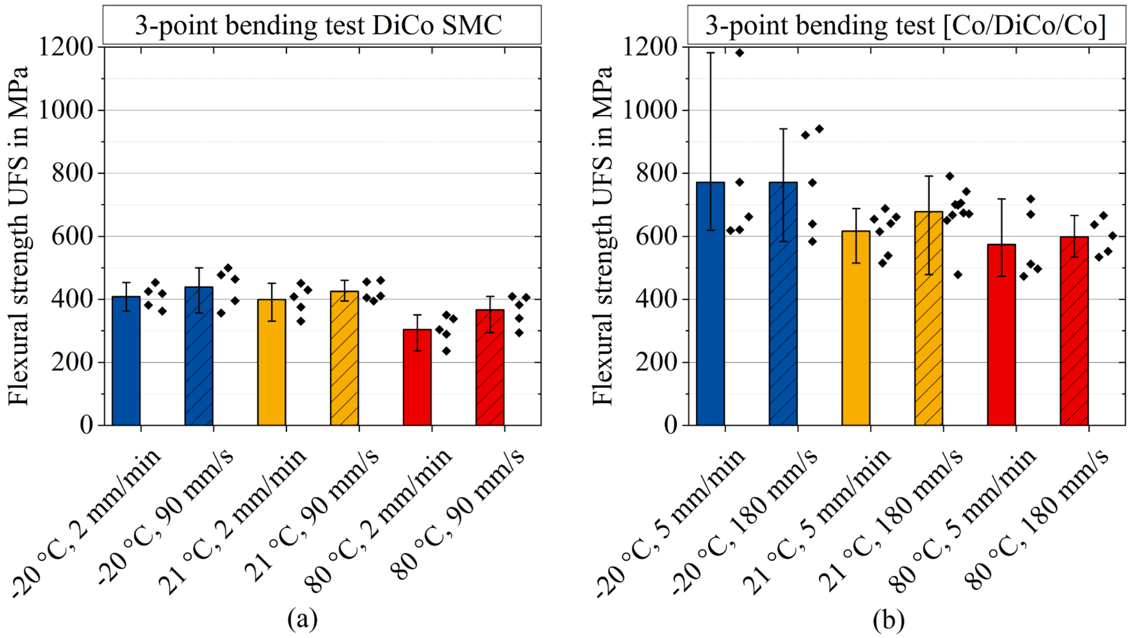

Fig. 3. Temperature-dependent flexural strength of (a) DiCo SMC and (b) [Co/DiCo/Co] specimens at quasi-static strain rate and fatigue strain rate.

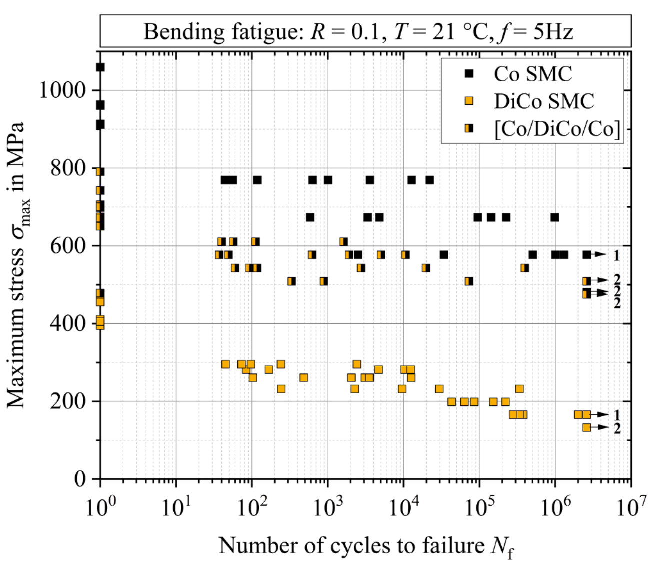

Fig.4. S-N data of Co SMC, DiCo SMC and [Co/DiCo/Co] specimens. Results from bending tests at fatigue strain rate are depicted on the y-axis. Runout specimens are marked by arrows. The numbers behind the arrows correspond to the numbers of runout specimens.

are plotted against their relative fatigue lives in Figure 5. $E_{dyn}(N)$ is the dynamic stiffness after N cycles, which corresponds to the secant modulus of the respective hysteresis loop. $E_{dyn,4}$ is the initial dynamic stiffness, which was measured during the fourth cycle, to exclude influences of the start-up behavior of the testing machine. The initial dynamic stiffness values of the examined materials are given in Table 3.

The curves obtained for Co SMC, especially those that represent specimens tested at high loads, showed jumps that resulted from fiber kinking on the compression loaded side. In most cases, D was below 0.05 after 50 % of fatigue life and below 0.1 shortly before final failure. The damage variable of the runout specimens was < 0.01 and thus negligible. DiCo SMC specimens showed a common course with a high initial increase within the first 5 % of fatigue life, a damage parameter D in the range between 0.12 and 0.16 after 50 % of fatigue life and $D > 0.23$ within the last 5 % of fatigue life. Only the specimen tested at the highest load of 69 % UTS^F showed a deviant behavior with a more continuous increase of D instead of an S-shaped curve. The damage variable of the runout specimen showed an almost constant value of 0.03. Damage behavior of [Co/DiCo/Co] was largely comparable to that of Co SMC. Small jumps in the curves, which resulted from partial kinking of a carbon fiber tow in the compression loaded Co SMC ply, did not result in immediate final failure, if the fractured region was small.

The damage evolution of [Co/DiCo/Co] specimens under fatigue loading was very similar to that under monotonic loading [9]. The Co SMC ply on the compression loaded side failed first, leading to load rearrangement, which results in rapid subsequent failure of the Co SMC ply on the tensile loaded side and ultimately a total loss of the specimens' load bearing capacity. Figure 6 shows microscopic images of the polished edge of a [Co/DiCo/Co] specimen, which was tested at 75 % UFS^F. The images on the left-hand side were taken after 1,000 cycles, after a small jump occurred on the stiffness degradation curve, which can be seen in the upper panel of Figure 6. Such jumps occurred due to partial failure of the compression loaded Co SMC ply. The images on the right-hand side depict the specimen edge after 164,674 cycles, shortly before final failure and immediately after the Co SMC ply on the compression loaded side failed completely. At this point, almost no signs of damage were observed in the tensile loaded Co SMC ply or in the DiCo SMC ply. Only a small matrix crack was observed in DiCo SMC after 1, 000 cycles, which did not grow during cyclic loading. Final failure occurred after a few more cycles.

The experimental observation show that the fatigue behavior of the hybrid [Co/DiCo/Co] composite was clearly dominated by the Co SMC plies due to the sandwich-like structure, even though the ratio of Co SMC to DiCo SMC was only 1:3. Hybridization led to a significant increase of the dynamic stiffness by almost 300 % compared to the DiCo SMC constituent, which was slightly less than the increase of flexural modulus of elasticity by 370 % determined by Trauth [9]. Furthermore, the stiffness degradation behavior was similar to that of Co SMC.

The experimental results also show that effects of hybridization on the strength were stronger under fatigue than under monotonic loading. UFS^S and UFS^F of [Co/DiCo/Co] increased by only 54 % and 59 % compared to DiCo SMC, respectively. The same tendency was reported by Trauth [9], who obtained a 101 % increase of flexural strength due to

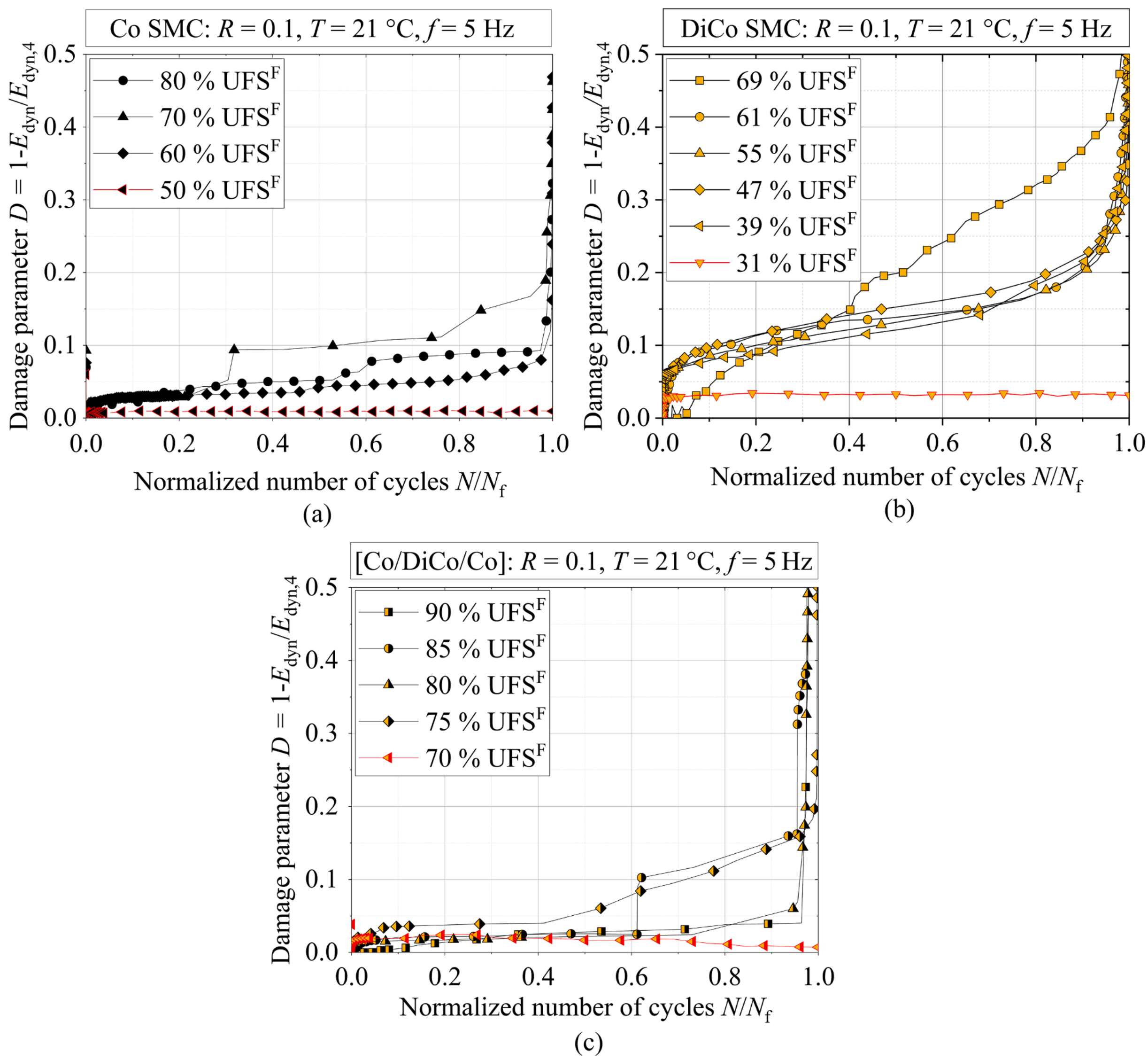

Fig. 5. Damage parameter of representative (a) Co SMC, (b) DiCo SMC and (c) [Co/DiCo/Co] specimens tested at different load levels. Data outlined in red represent runouts, for which N_f was replaced by $2.6{\cdot}10^6$cycles.

Table 3
Average initial dynamic stiffness of the examined materials including the respective standard deviation.

	Co SMC	DiCo SMC	[Co/DiCo/Co]
$\overline{E}_{dyn,4}$ in GPa	72.6 ± 1.9	12.6 ± 1.6	50.25 ± 1.85

the additional continuous reinforcement. At $2.6{\cdot}10^6$ cycles, fatigue strength substantially increased by 258 % and was almost as high as that of Co SMC. The fatigue ratio of [Co/DiCo/Co] specimens was even higher than both that of Co SMC and DiCo SMC. Even though effects of hybridization on the mechanical performance differed a lot under monotonic and cyclic loading, damage evolution due to fatigue was largely similar to that observed under monotonic loading [9].

Effect of temperature on the bending fatigue behavior

Figure 7 depicts S-N data of DiCo SMC at -20 °C, 21 °C and 80 °C. P-S-N curves for failure probabilities of P_S = 10 % and P_S = 90 % (dashed lines) are displayed to indicate the scatter range and to provide better comparability of the results obtained at different temperatures. Specimens that did not fail within $3.6{\cdot}10^5$ cycles were declared runouts and marked with an arrow in Figure 7. DiCo SMC specimens tended to have higher fatigue lives when tested at lower temperatures. Results obtained at 80 °C were within the scatter range of those obtained at room temperature, whereas the scatter range of S-N data at -20 °C was clearly beyond the fatigue lives of specimens tested at 80 °C. The fatigue strength of specimens tested at room temperature and 80 °C was comparable. The influence was less pronounced compared to polyester-based DiCo SMC materials previously studies by other authors [12,20].

Temperature had a far stronger influence on the fatigue life of the hybrid [Co/DiCo/Co] composite (Figure 8). The fatigue strength at -20 °C was approximately 100 MPa higher than at room temperature when comparing results at the same number of cycles. Increasing the temperature to 80°C had an even more pronounced effect than decreasing the temperature to -20 °C. At maximum stresses that went down to 407 MPa, which was 68 MPa below the stress at which all specimens were runouts at ambient temperature, almost all specimens failed in the low cycle fatigue range within less than 10^4 cycles. At a maximum stress of 305 MPa, both specimens tested at 80 °C withstood the conducted $3.6{\cdot}10^5$ cycles. This is approximately 170 MPa below the stress, at which all specimens tested at ambient temperature withstood

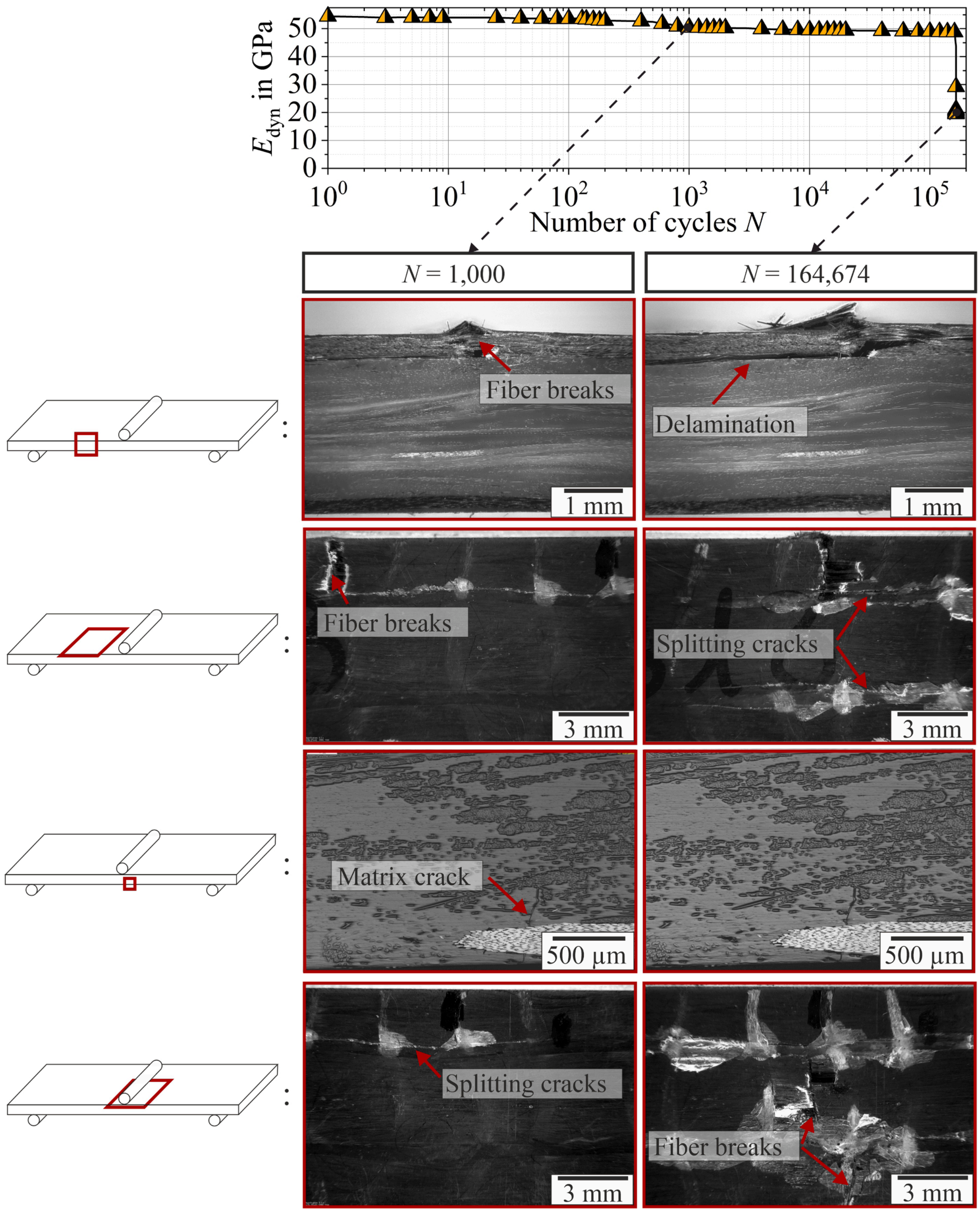

Fig. 6. Stiffness degradation curve and damage evolution of a [Co/DiCo/Co] specimen tested at 75 % UFS^F under cyclic bending load. The damage pattern is depicted at four different positions after 1,000 and 164,647 cycles, respectively.

the same number of cycles. Failure occurred due to early kinking of the Co SMC ply.

The evolution of the damage parameters at -20 °C was similar to those at ambient temperature for both material systems. The only difference in damage evolution was observed for [Co/DiCo/Co] specimens at 80 °C (Figure 9). While total failure of the compression loaded Co SMC ply resulted in total loss of the specimens' load bearing capacity at -20 °C and at ambient temperature, the DiCo SMC ply and the tension loaded Co SMC ply were able to take up the additional load at 80 °C. This resulted in the specimen still featuring considerable fatigue resistance at $D > 0.5$.

As discussed in Chapter 1, the influence of temperature on the fatigue of unidirectional continuous carbon FRP depends on the load case. Barely any temperature-dependence is observed under tension-tension load [24], where mechanical performance is fiber-dominated, whereas fatigue strength degrades under matrix dominated loading conditions [25]. These findings are in agreement with the damage evolution observed in [Co/DiCo/Co] specimens. While the compression loaded Co SMC ply was largely affected by temperature, the Co SMC ply on the tensile loaded side was not significantly affected and was thus able to

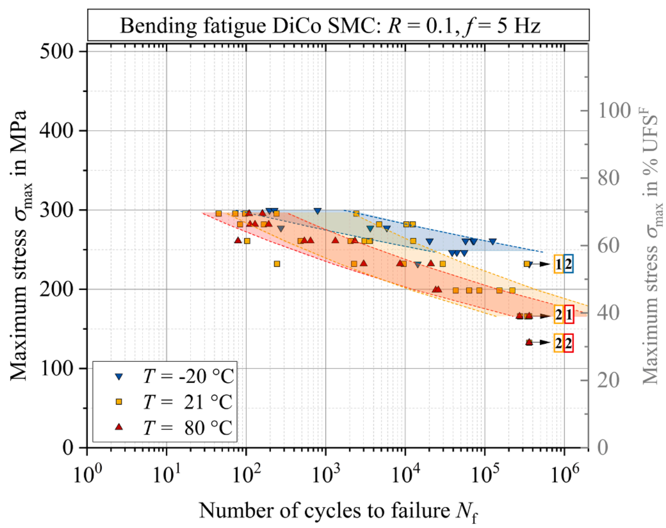

Fig. 7. S-N data of DiCo SMC under bending fatigue load at different temperatures. Colored areas, which are laterally bounded by the corresponding P-S-N curves for failure probabilities of P_S = 10 % and P_S = 90 %, indicate the scatter range of the data at the respective temperature.

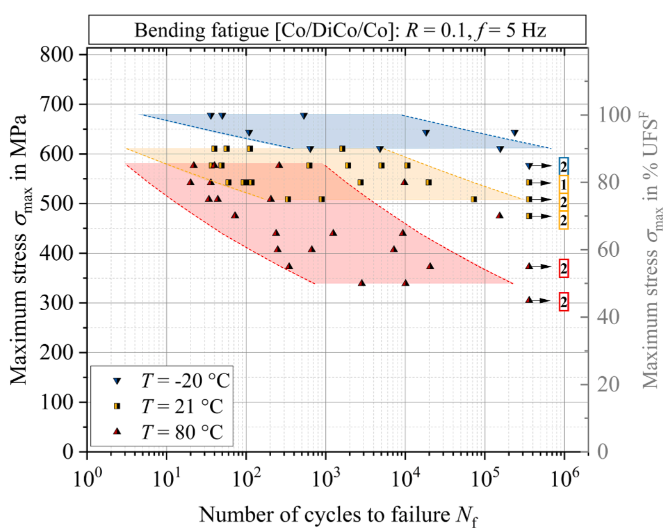

Fig. 8. S-N data of [Co/DiCo/Co] specimens under bending fatigue load at different temperatures. Colored areas, which are laterally bounded by the corresponding P-S-N curves for failure probabilities of P_S = 10 % and P_S = 90 %, indicate the scatter range of the data at the respective temperature.

take over additional load after the compression loaded ply failed. In contrast, failure of the compression loaded ply at ambient temperature resulted in rapid subsequent failure of the whole specimen.

Effect of frequency on the bending fatigue behavior

A higher frequency resulted in slightly higher fatigue lives at high applied loads in the low cycle fatigue range. No such trend was observed in the high cycle fatigue range, where fatigue strength seemed to be independent of frequency within the investigated range. First runouts occurred at a maximum stress of 166 MPa for all considered frequencies (Figure 10).

Similar results were obtained for the hybrid [Co/DiCo/Co] composite (Figure 11). While specimens, which were tested at 1 Hz tended to fail few cycles sooner compared to specimens tested at 5 Hz and 10 Hz in the low cycle fatigue range, no trend was observed in the high cycle

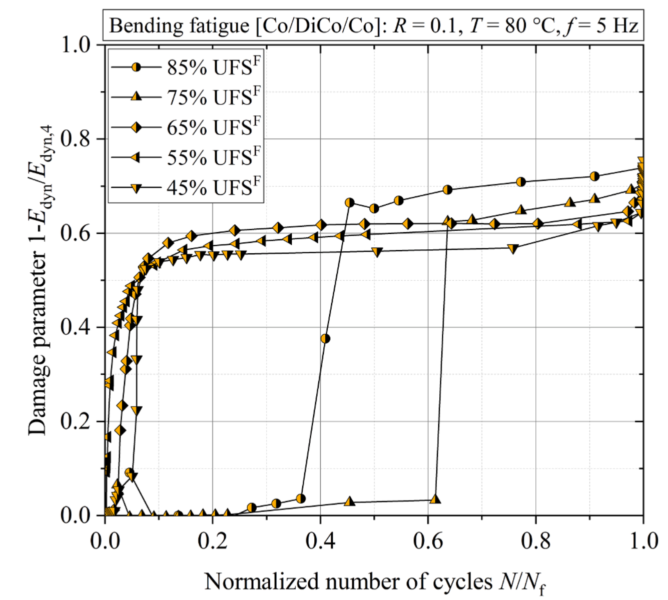

Fig. 9. Damage parameter of [Co/DiCo/Co] specimens under different cyclic bending load at 80 °C.

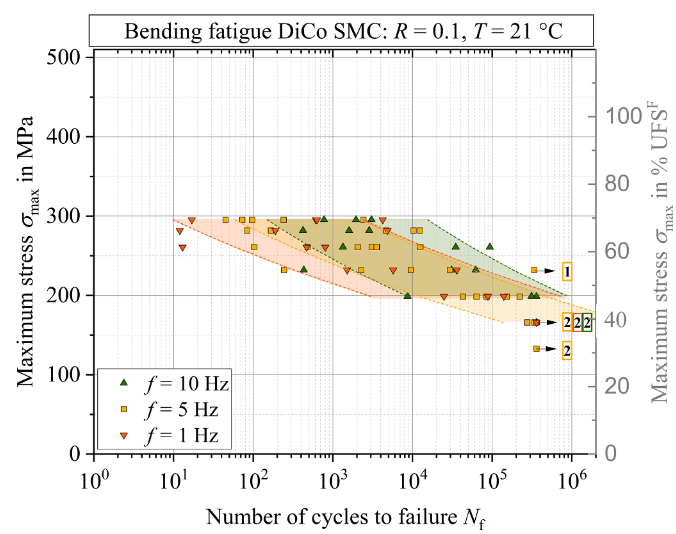

Fig. 10. S-N data of DiCo SMC specimens under bending fatigue load at different frequencies. Colored areas, which are laterally bounded by the corresponding P-S-N curves for failure probabilities of P_S = 10 % and P_S = 90 %, indicate the scatter range of the data at the respective temperature.

fatigue range.

The fatigue behavior of conventional DiCo glass fiber SMC [17] and unidirectional carbon fiber composites [18,19] is known to be largely insensitive to different frequencies, especially as long as they are in a range where thermally induced fatigue plays a minor role. The results presented in this work confirmed that hybrid [Co/DiCo/Co] composites are also unaffected by frequency, at least in the investigated frequency range between 1 Hz and 10 Hz. The slight frequency dependent in the low cycle fatigue range is assumed to have two reasons. First, the target maximum stress was reached after a slightly higher number of cycles at higher frequencies, due to the transient response of the machine. Second, DiCo SMC exhibits a visco-damage behavior [1], which results in a higher damage threshold at increased strain rate. This effect is observed when the test duration is low and diminishes for long test durations.

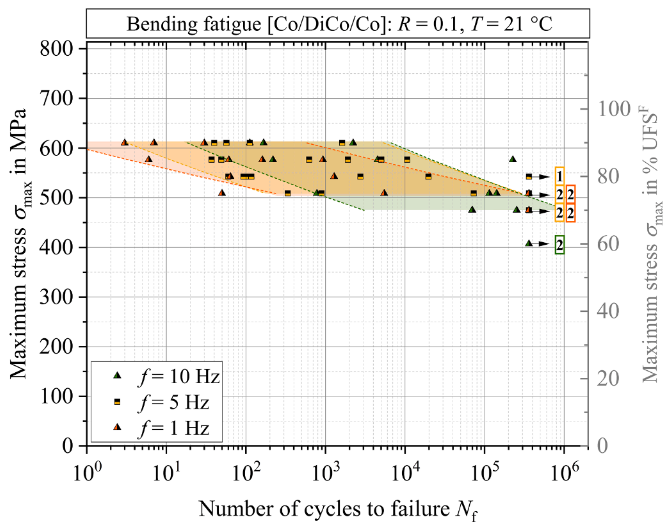

Fig. 11. S-N data of [Co/DiCo/Co] specimens under bending fatigue load at different frequencies. Colored areas, which are laterally bounded by the corresponding P-S-N curves for failure probabilities of $P_S = 10$ % and $P_S = 90$ %, indicate the scatter range of the data at the respective temperature.

Conclusions

Hybrid SMC composites with a discontinuous glass fiber reinforced core and continuous carbon fiber reinforced face plies showed excellent fatigue properties under bending fatigue load. With a ratio of continuous to discontinuous SMC of 1:3, the fatigue strength in the high cycle range increased by more than 250 % compared to discontinuous SMC and was almost as high as that of the continuous carbon FRP constituent. The fatigue ratio of the hybrid composite was higher than both that of the continuous and discontinuous constituent. Positive effects of hybridization were higher under fatigue loading than under monotonic loading. Between 1 Hz and 10 Hz, no significant frequency-dependence could be observed. In contrast, an enhanced temperature resulted in early kinking of the continuous carbon fiber ply on the compression loaded side, which led to lower hybridization effects at enhanced temperature. The temperature sensitivity of the hybrid composite was significantly higher than that of discontinuous SMC. The experimental results highlight that hybridization effects are strongly dependent on the load case and should always be characterized under loading conditions relevant for the potential application.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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