



A Competitive Study of the Static and Fatigue Performance of Flax, Glass, and Flax/Glass Hybrid Composites on the Structural Example of a Light Railway Axle Tie

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Specialty section:

This article was submitted to
Polymeric and Composite Materials,
a section of the journal
Frontiers in Materials

Received: 16 December 2021

Accepted: 15 February 2022

Published: 13 April 2022

Citation:

Graupner N, Hohe J, Schober M,
Rohrmüller B, Weber D, Bruns L,
Bruns A and Müssig J (2022) A
Competitive Study of the Static and
Fatigue Performance of Flax, Glass,
and Flax/Glass Hybrid Composites on
the Structural Example of a Light
Railway Axle Tie.
Front. Mater. 9:837289.
doi: 10.3389/fmats.2022.837289

The most common studies in the literature are those analyzing fatigue life under cyclic loading for flax fiber-reinforced composites. A novel type of staple fiber yarn made from flax tow with almost unidirectional fiber orientation and a quasi-unidirectional fabric was developed for composite applications. Additionally, a hybrid material made of flax and glass was produced for a demonstrator component (an axle tie of a narrow-gauge railway). For such an application, the investigation of fatigue strength is of particular importance. Therefore, the fatigue behavior of flax, glass, and hybrid flax/glass composites was investigated in the high cycle fatigue range. A total of 10^6 load cycles were carried out. From about 7^3 to 8^3 loading cycles, the flax laminate was found to have higher fatigue strength than the glass fiber-reinforced composite. The hybrid materials tend to show a higher fatigue strength than the glass type from approximately 2×10^5 load cycles. Results based on a finite element method also demonstrate better fatigue properties at an increased number of load cycles for flax-based composites than the glass fiber-reinforced component. The flax/glass component's fatigue strength ranged between the flax values and the glass fiber-reinforced composites. Overall, the hybrid material shows significantly better static bending and impact characteristics than flax and considerably better fatigue properties than the glass fiber-reinforced composite making the hybrid material attractive for an application in an axle tie.

Keywords: hybrid composite, flax, staple fibre yarn, axle tie, fatigue, finite element method, simulation

1 INTRODUCTION

For the mechanical design of fiber-reinforced components, it is essential to consider and understand the fatigue behavior of this type of material. This is even more important if the relatively young material group of natural fiber-reinforced composites in structural components is intended to be used. The analysis of the fatigue behavior of, e.g., glass fiber-reinforced plastics (GFRP) under cyclic loading has been researched for a long time (Bledzki and Gassan, 1998; Keusch et al., 1998; Bernasconi et al., 2007; Towo and Ansell, 2008a; Lemanski and Sutcliffe, 2010; Shahzad et al., 2019).

Natural fiber-reinforced plastics (NFRP) have become increasingly important in recent years, and especially, flax fiber-reinforced composites are increasingly used for applications subject to higher mechanical loads, such as sports equipment and higher loaded construction materials (Misra et al., 2011; Alkibir et al., 2016; More, 2021; Rahman, 2021). However, dissemination is still limited (Staiger et al., 2008). The most prominent application area remains in nonstructural parts with randomly oriented fibers in the automotive and construction industry and is mainly driven by the lower price and environmental concerns rather than the reinforcing effect of the fibers (Karus and Kaup, 2002; Parikh et al., 2002; Dunne et al., 2016). Besides this, a problem with natural fibers exists in more variables, such as growing conditions and environmental influences, that determine their final properties and performance for composite applications (Misra et al., 2011; Baley et al., 2020).

Nevertheless, the processability of natural fibers and the development of high-quality semifinished products are enhanced considerably in recent years. Meanwhile, most of the processing methods used for GFRP can also be applied to natural fiber-reinforced composites, such as prepreg tape laying, winding, pultrusion, resin transfer molding, compression molding, or thermoforming (Jauhari et al., 2015). A major problem in the further spread of natural fibers for higher loaded technical products is the high price of semifinished products. The effort required to prepare natural fibers for high-quality semifinished products is high, and the price can approach the costs of semifinished carbon fiber products and, thus, does not represent an alternative for many industries (Deimann, 2020). Therefore, the development of semifinished products from cheaper fibers, leading to comparable reinforcement, e.g., high-quality flax rovings available on the market, may help establish natural fiber-reinforced plastics in higher loaded products (Deimann, 2020; Graupner et al., 2021).

In recent years, the fatigue and damping behavior of natural fiber-reinforced composites are increasingly investigated, and this led to interesting results. Natural fibers were found to have good damping properties, often exceeding those of glass fibers (Gassan and Bledzki, 1999; Rahman et al., 2016; Dhanraj et al., 2019; Liu et al., 2021; Rahman, 2021). Fatigue is a phenomenon causing progressive damage to materials under cyclic loading. The damage is induced by cracks and deformation and eventually leads to the final failure of the composite (Burhan and Kim, 2018). Plastics reinforced with different cellulose-based fibers are studied regarding fatigue strength, such as flax (Gassan, 2002; Liang et al., 2012; Shah et al., 2013; El Sawi et al., 2014; Liang et al., 2014; Bensadoun et al., 2015; Ueki et al., 2015; Bensadoun et al., 2016; Berges et al., 2016; Sodoke et al., 2016; Kumar et al., 2018; Mahboob and Bougherara, 2018; Nagabhooshanam et al., 2018; Habibi et al., 2019; Haggui et al., 2019; Jeannin et al., 2019; Malloum et al., 2019; Feng et al., 2020; Hallak Panzera et al., 2020; Islam and Ulven, 2020; Mahboob and Bougherara, 2020; Li et al., 2020; Szebényi et al., 2020; Liber-Kneć et al., 2015; Bambach, 2020), hemp (Yuanjian and Isaac, 2007; Shahzad and Isaac, 2009; Fotouh and Wolodko, 2011; de Vasconcellos et al., 2014; Fotouh et al., 2014; Shahzad

and Isaac, 2014; Barbière et al., 2018), kenaf (Abdullah et al., 2012; Asumani and Paskaramoorthy, 2020), jute (Gassan and Bledzki, 2000; Alia et al., 2018; Bambach, 2020), sisal (Towo and Ansell, 2008a; Towo and Ansell, 2008b; Belaadi et al., 2013; Kanny and T.P., 2013), coir (Osti de Moraes et al., 2015), cotton (Petrucci et al., 2015), cactus fibers (Bouakba et al., 2013), *Caryota urens* fibers (Prakash et al., 2020), birch fibers (Mejri et al., 2018), oil palm fruit bunch fibers (Kalam et al., 2005), or regenerated cellulose fibers (Ranganathan et al., 2016; Müssig et al., 2020).

The fatigue strength at 10^6 cycles is often used as an endurance limit to design infinite fatigue life in the high cycle fatigue (HCF) range (Shah, 2014). However, very high cycle fatigue (VHCF) investigations of up to 10^8 cycles are also performed (Jeannin et al., 2019). The results from fatigue tests are usually processed in S-N (Wöhler) curves (fatigue strength as a function of the number of cycles). Cyclic loading can occur in tension-tension, tension-compression, compression-tension, and compression-compression (Burhan and Kim, 2018). In the field of natural fiber-reinforced plastics, most cyclic lifetime analyses are induced under tension-tension loading. Only a few describe the cyclic loading induced by compression (e.g., (Lemanski and Sutcliffe, 2010; Bambach, 2020)). An increasing stress ratio leads to flatter S-N curves, indicating that the fatigue life was improved, which is attributed to the reduction in stress amplitude leading to less damage to the structure (Feng et al., 2020). Loading frequencies of 5 and 30 Hz have not significantly influenced the S-N curves of flax/epoxy composites under high cycle loading (Jeannin et al., 2019).

The fatigue behavior of NFRP is dependent on internal (material) variables, such as the matrix, which may be brittle or ductile; the surface treatment of the fiber; fiber content; and the effect of physical/chemical modification of fiber and/or matrix and external variables, such as stress amplitude or stress intensity factor (Misra et al., 2011; Abdullah et al., 2012; Shah et al., 2013; Mahboob and Bougherara, 2018). As described for GFRP (Subramanian et al., 1995; Keusch et al., 1998; Towo and Ansell, 2008a), good fiber/matrix adhesion also leads to higher long-term durability in the case of cellulose fiber-reinforced composites (Gassan, 2002; Shahzad and Isaac, 2009; Liang et al., 2014; Shahzad et al., 2019; Asumani and Paskaramoorthy, 2020; Feng et al., 2020; Müssig et al., 2020). Besides the strength of the composite, fiber orientation significantly influences durability. Composites with higher static strength are generally more durable; the fatigue endurance strength of NFRP is proportional to their tensile strength (Gassan, 2002; Shah et al., 2013; Shah, 2014; Bensadoun et al., 2016). A deviation of the fiber orientation from the longitudinal axis leads to a lower fatigue strength (Bernasconi et al., 2007; Haggui et al., 2019; Feng et al., 2020). Usually, the best fatigue properties are achieved with unidirectional (UD) fiber orientation (Gassan, 2002; Feng et al., 2020). These composites are less sensitive to fatigue-induced damage than woven-reinforced composites (Gassan, 2002; Haggui et al., 2019). The constitution of the semifinished product also plays an important role. When using woven fabrics, the integration of the weft threads or the crimp of the threads significantly influences the fatigue damage

and the critical collapse load of a composite (Lemanski and Sutcliffe, 2010; Feng et al., 2020). Minimized yarn crimp improves resistance to fatigue damage (Shah et al., 2013; Asgarinia et al., 2015; Bensadoun et al., 2015; Lessard et al., 2015; Bensadoun et al., 2016; Feng et al., 2020), whereas stiffness degradation is not clearly affected by the crimp (Haggi et al., 2019). The textile architecture and fiber content significantly influence the static composite properties, but they have little impact on the slope of the S–N curves (Shah et al., 2013). The S–N curves show no apparent differences between composites reinforced with woven fabrics and cross-ply laminates nor between the UD and quasi-UD reinforced composites (Bensadoun et al., 2016). Flax/epoxy composites show a larger energy dissipation in the early cycles as shown by the analysis of hysteresis loops in tension–tension (Bensadoun et al., 2015). Additionally, they offer delayed damage initiation and increased fatigue life with a reduced damage propagation rate combined with higher energy dissipation in the early stages of fatigue loading compared to glass fiber–reinforced composites (Bensadoun et al., 2016). It should be noted that a reinforcing effect with natural fibers is usually achieved up to approximately 40%–50% fiber volume fraction. Above this critical limit, mechanical performance starts to drop (Feng et al., 2020).

Different results are discussed in the literature when comparing the fatigue behavior of NFRP and GFRP. It should be considered that natural fibers have an irregular shape compared with glass fibers. Natural fibers refer to both fiber bundles consisting of single fiber cells and single fibers (single cells). In general, the smaller the fiber bundle, the better the mechanical properties. Accordingly, small fiber bundles have higher strength than coarse fiber bundles, whereby the single cells have the best characteristic values due to size effects, making a direct comparison of results difficult when natural fibers from different processing stages are used (Müssig et al., 2010). Some studies report comparable fatigue behavior of NFRP compared with GFRP (Yuanjian and Isaac, 2007; Bensadoun et al., 2016; Mahboob and Bougherara, 2018) or even better (Liang et al., 2012; Mahboob and Bougherara, 2018); other authors describe that the absolute fatigue performance of GFRP is far superior to NFRP. However, the fatigue strength degradation rates of NFRPs are lower, indicating a lower fatigue sensitivity (Shah et al., 2013; Shahzad and Isaac, 2014), which is evident by a steeper slope of the S–N curve of GFRP compared with NFRP (Abdullah et al., 2012; Liang et al., 2012; Shah et al., 2013; Shahzad and Isaac, 2014). The structure and composition of natural fibers usually lead to slower damage, fatigue strength, and stiffness degradation than for GFRP (Shahzad et al., 2019). Microscopic analyses show for NFRP that damage mechanisms appear with cracks first nucleating through the interface between the single fibers within the bundles, suggesting that the bonding agent pectin is the weakest component in the flax/epoxy composite (El Sawi et al., 2014); cracks then propagate through the fiber/matrix interphase to the matrix with an increasing number of fatigue cycles (Shahzad et al., 2019). In contrast, fatigue failure in UD-oriented GFRP is described as occurring throughout the material volume. Debonding of the fiber and matrix, fiber breakage, matrix cracking, delamination, and transverse ply cracking occur either

interactively or independently. The difference in the structure and composition of natural fibers compared with glass fibers results in different behavior in fatigue loading of the composites. Fracture mechanisms and modes are the same for composites made from different bast fibers but depend on fiber content, textile architecture, and stress ratios (Shah et al., 2013).

Another unique feature of NFRP under cyclic load is the stiffening effect (Ueki et al., 2015; Feng et al., 2020), which could be related to the straightening of the microfibrils in the fiber cell wall (Liang et al., 2012; Liang et al., 2014). Stiffness change over the fatigue life in NFRP is lower than in GFRP and is shown to be complex (Shahzad and Isaac, 2014). Structural changes in the single fiber cell wall and damage development in the composite often have competing effects on the stress–strain curves. As a result, the design of components must be adapted due to the different stiffness evolution of NFRP compared with GFRP (Shah, 2016). It is shown that flax fiber–reinforced composites offer a more stable cyclic performance than GFRP (Liang et al., 2012). The stiffness degradation of flax and GFRP exhibit no dependence on the loading level (Liang et al., 2012). However, a linear relationship is found between the stiffening effect and the residual strain, and it is revealed that the frequency of cyclic loading influences the fatigue behavior. Lower frequencies lead to a higher stiffening effect and a shorter fatigue life, which means that fatigue damaging progresses simultaneously with the stiffening effect and is, therefore, essential to involve creep damaging to the failure criteria for these composites (Ueki et al., 2015). A further study investigates whether fatigue tests could also demonstrate this effect under strain control. All specimens show stiffness degradation, contradicting previous studies. The degradation is a function of applied load, leading to a proportional relationship between strain-rate and measured modulus. It is reported that the stiffening effect described in the literature does not reflect any physical improvement of material stiffness but is a consequence of stress-amplitude controlled loading conditions (Mahboob and Bougherara, 2020). For jute fiber–reinforced polypropylene, it is shown that a strong interface leads to a higher dynamic modulus and lower stiffness degradation with increasing load cycles and applied maximum stresses. However, the specific damping capacity results in higher values for the composites with weak fiber/matrix adhesion (Gassan and Bledzki, 2000). De Vasconcellos et al. identify three different zones in the hysteresis curves as a function of load cycles: 1) significant initial slope at the beginning of the curves, which is related to transverse matrix cracks through the thickness and initial fiber breakages; 2) almost constant slope, which is related to the period during which the matrix cracks may couple together and grow, especially along the interfaces; and 3) the slope gradually increases again just before failure, and fiber breaks initiated in phase 1) lead to strand breaks (de Vasconcellos et al., 2014).

Fiber-reinforced composites are used, e.g., in components subject to mechanical cyclic loads, such as in leaf springs (Rajesh et al., 2016); even NFRP were used for this product (Mouleeswaran, 2012; Kumar et al., 2018). Hybrid composites made of natural and glass fibers are also increasingly used for such applications (Graupner et al., 2021). The mechanical properties of

hybrid composites depend on several factors, including fiber content and stacking configuration (Feng et al., 2020). Hybrid composites usually display higher mechanical properties than NFRP (Lessard et al., 2015; Sharba et al., 2015; Sharba et al., 2016; Feng et al., 2020) regardless of the type of hybrid composites (Feng et al., 2020). However, studies present better properties when the stronger and stiffer industrial made fibers enclose the less strong and stiff natural fibers in a thermosetting matrix (Asgarina et al., 2015; Sivakumar et al., 2018). Nevertheless, the failure of the structure often starts in the interphase between GFRP and NFRP (Manteghi et al., 2019). Due to the lower sensitivity of natural fibers against fatigue load compared with glass fibers, the fatigue life performance is enhanced by hybridization (Feng et al., 2020). Hybrid jute and GFRP show that incorporating jute fiber within the hybrid composite reduced the fatigue sensitivity and stiffness degradation with increasing jute fiber content (Mostafa, 2019). In the case of flax/basalt hybrid composites, the normalized fatigue resistance was improved compared with the pure basalt composite due to the deflection of cracks by the presence of flax fibers. The mechanical properties of the hybrid material are in between those of NFRP and GFRP (Seghini et al., 2020).

A new type of staple fiber yarn with almost UD fiber orientation made of flax tow was developed for composite materials in a previous study. A unique feature of these yarns is that they are made from low-cost flax tow and provide reinforcement effects comparable to very high-quality and more expensive long flax rovings. The yarns were processed in quasi-UD fabrics, composite laminates from flax and glass, and a hybrid material for use in a demonstrator component (leaf spring or, more precisely, an axle tie of a narrow-gauge railway) was manufactured (Graupner et al., 2021). The shape of the axle tie was developed in a previous project for GFRP (Schönhuber et al., 2019). The practical suitability of this bogie made of GFRP has already been proven by numerical calculations of the strength and dynamic behavior. The fatigue strength is essential when investigating the use of flax fibers for the axle tie. Therefore, the fatigue properties of flax, glass, and hybrid flax/glass laminates were investigated in this study. To investigate the use in an axle tie, simulation calculations were carried out with regard to the load-bearing capacity and fatigue behavior. It is hypothesized that the hybrid materials of flax and glass have better static properties than the flax laminate and that the fatigue performance is better than that of a GFRP laminate.

2 MATERIALS AND METHODS

2.1 Composite and Axle Tie Manufacture

Yarns, the quasi-UD fabrics and composites, were produced from field-retted flax from a longitudinal fiber line of scutched tow provided by SachsenLeinen GmbH (Markkleeberg, DE) as described in Graupner et al. (2021). Yarns were produced from the flax slivers at 30 m/min. The fibers in the yarns were wound with a polyamide polyfil (78 dtex, 20 individual continuous fibres). The following two yarns were processed

into quasi-UD fabrics and composites (Graupner et al., 2021) and investigated within this study:

- Flax yarn V2, A γ 2, 213 tex, sliver (yarn V2).
- Flax yarn V9, A γ 9, 200 tex, restretched sliver (yarn V9).

Both yarns were manufactured from the same flax fiber bundles. Differences are that the sliver used to produce yarn V9 has been restretched to increase the uniformity of the yarn. As reference samples, a commercially available Lincore flax roving type FR 500 with a fineness of 500 tex and a density of 1.35 g/cm³ (Depestele, Bourguébus, FR) and a glass fiber roving type EC16 200 TD22C with zero-twist and a fineness of 200 tex (Saint-Gobain Vetrotex, Aachen, DE) were used. As a matrix, a bio-based epoxy resin PTP-L (polymer material made of triglycerides and polycarbonic acid anhydrides; density 1.1 g/cm³) produced by company Biocomposites and More (B.A.M., Ipsheim, DE)¹ was used for the production of composite laminates by a vacuum injection method in an autoclave from quasi-UD fabrics. The manufacturing process is described in Graupner et al. (2021). Five different composite laminates having a thickness of around 2 mm were produced in this manner from the quasi-UD fabrics (compare Graupner et al., 2021):

- Lincore flax: five layers
- Flax (yarn V2): five layers, fabric prepared from a flax yarn version 2 at the beginning of the project
- Flax (yarn V9): five layers, fabric prepared from a flax yarn version 9 at the end of the project
- Hybrid (flax yarn V9 and glass roving): 2 × 2 glass outer layers and 3 × flax inner layers
- Glass: nine layers

The manufactured demonstrator—an axle tie for a bogie of a narrow-gauge railway—shown in **Figure 1** was produced at Novacom Verstärkte Kunststoffe GmbH (Aachen, Germany) using resin transfer molding (RTM) with an epoxy resin (type Epikote RIMR 135 with hardener Epikure RIMH 137, Momentive Specialty Chemicals B.V., Rotterdam, Netherlands; mixing ratio 100:30; density 1.15 g/cm³) from the fabrics. Twenty-one fabric layers were used for the axle tie made of glass fibers; 14 for the one made of flax and four outer layers of glass on each side in combination with nine inner layers of flax were used to manufacture the flax/glass hybrid component. The fabrics were placed in a sub-mold and coated with a release agent. The upper mold was placed on top, and both forms were braced together, and the resin was added under pressure. After curing, the axle tie was demolded.

2.2 Static Mechanical Properties

The composite laminates were tested after climatic conditioning according to the DIN EN ISO 291 standard (Deutsches Institut für Normung, 2005).

¹In memory and honour of Uwe Schönfeld, the PTP resin developer, who passed away much too early.

Bending tests of the composite laminates were carried out for eight specimens, each with a width of 15 mm and a length of 100 mm following the DIN EN ISO 14125 standard (Deutsches Institut für Normung, 2003). A universal testing machine (Zwick/Roell Z020, Zwick/Roell GmbH, Ulm, Germany) was operated at a span length of 45 mm and a test speed of 1 mm/min. The flexural modulus was determined between 0.05% and 0.25% flexural strain via linear regression (strain was calculated from the traverse path of the testing machine).

The interlaminar shear strength (ILSS) of the composite laminates was determined following standard 14130 (Deutsches Institut für Normung, 1998) on eight test specimens, each with a width of 10 mm and a length of 20 mm using the Zwick/Roell Z020 testing machine. The span length was set individually for each test series and resulted from five times the sample thickness at a test speed of 1 mm/min.

Tensile tests of composite laminates of eight specimens per test series with a width of 25 mm and a length of 250 mm according to DIN EN ISO 527-2 (Deutsches Institut für Normung, 1996) were carried out with the Zwick/Roell universal testing machine equipped with a 20 kN load cell and a Galdabini Quasar 250 universal testing machine (Galdabini (S.P.A.), Cardano Al Campo VA, IT, load cell 250 kN) with a test speed of 2 mm/min. The Young's moduli of all composite laminates were determined using the Zwick/Roell universal testing machine. The elongation was recorded with a video extensometer (VideoXtens, Zwick/Roell GmbH, Ulm, DE) between 0.05% and 0.25% strain after reaching a preload of 50 N. The tensile tests of the flax-reinforced composites were performed with the Zwick/Roell universal testing machine at a testing speed of 2 mm/min until breakage. Due to the higher required forces, the GFRP and the hybrid materials were run to break on the Galdabini testing machine with the same testing speed of 2 mm/min.

2.3 Fatigue Strength

The fatigue strength of the composite laminates was characterized in Wöhler-type tensile fatigue experiments with a load ratio of $R = \sigma_{\min}/\sigma_{\max} = 0.1$. The choice of the purely tensile load ratio among the three basic loading types usually used in fatigue characterization (i.e., $R = 0.1$, -1 and 10) derives from the fact that the component considered later on in the case study is loaded in bending with superimposed high tensile loads and, thus, in a predominantly tensile mode on the highly stressed side. All experiments were performed on plain, nontapered test specimens with 10 mm width, approximately 2 mm thickness, and 150 mm length. The specimens for the material variants with higher static strength and, thus, higher expected fatigue loads, i.e., the specimens with glass fiber and hybrid reinforcements were supplied with cap strips. All other specimens could have been tested without cap strips. Specimens were fatigued in a hydraulic MTS 858 mini Bionix II testing machine (MTS Systems Corporation, Minnesota, United States) using a gimballed mechanical parallel clamping system. The specimens were supplied to cyclic loads at 10 Hz with different stress amplitudes till failure. A test frequency of 10 Hz usually allows for testing without substantial warming due to the inherent

internal friction of polymeric materials. The load amplitudes were chosen to ensure the number of cycles to failure was in the range of 10^3 to 10^6 cycles. Experiments reaching more than 10^6 cycles were considered as run-outs. All specimens were tested at an ambient temperature of approximately 23°C in a laboratory air environment. During the experiments, the temperature of the specimens was checked in intervals to detect possible warming due to viscous effects. In cases in which unacceptable warming was detected, i.e., for the GFRP and hybrid specimens tested at higher stress amplitudes and, thus, higher strains, the test frequency was reduced to 5 Hz and, in a few cases, to 2.5 Hz. For each of the material options considered in the present study, a total of 18 cyclic experiments were performed. Nevertheless, a few experiments did not provide valid results. The results were evaluated in terms of a S-N curve

$$\ln \Delta\sigma = m \ln N_f + b, \quad (1)$$

where $\Delta\sigma$ and N_f are the stress amplitude and the number of load cycles to failure, whereas the slope m and the intercept b of the S-N curve are material properties for the respective material option. Four types of composite laminates were investigated with fatigue tests:

- Lincore
- Flax (yarn V2)
- Hybrid (flax yarn V9 and glass roving)
- Glass

2.4 Fatigue Analysis for an Axle Tie of a Light Railway Bogie

As a structural example to demonstrate the capabilities of the proposed flax fiber-reinforced and hybrid materials, the axle tie for a narrow-gauge light railway bogie, according to **Figure 1**, is considered. The same component was briefly presented in a previous paper (Graupner et al., 2021). The axle tie connects the lower ends of the bogie's axle boxes. Under in-service conditions, the mass of the railcar body acts vertically on the top part of the bogie. The bending deformation of this part causes the axle bearings to rotate, resulting in a horizontal shift of their centers. The axle tie constrains the rotation and the lateral movement. It is deformed by bending with superimposed lateral stretching in the initial deformation range, resulting in limited reaction loads onto the axle boxes. After a complete stretching of the axle tie, a transition to a stretching dominated mode occurs, resulting in high reaction loads and, thus, high constraints to a further movement of the axle boxes.

In the sense of a case study, a fatigue analysis of the axle tie was performed, taking this component as a demonstrator. In a comparative analysis, the reference case of a GFRP for the axle tie was compared with two cases in which either a neat flax fiber-reinforced composite or a hybrid composite consisting of flax fiber-reinforced (inner layers) and glass fiber-reinforced plies (outer layers) were considered. The fatigue analysis of the component was carried out in the usual way using a linear elastic static analysis of the component, representing a single

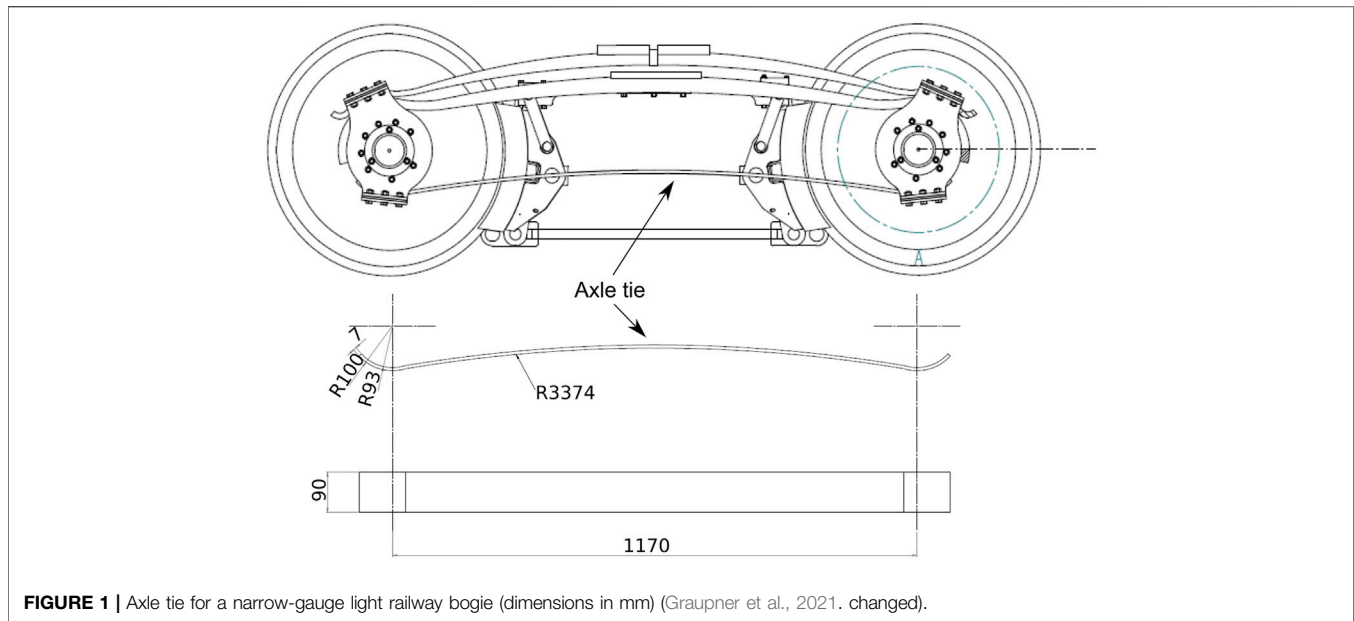


FIGURE 1 | Axle tie for a narrow-gauge light railway bogie (dimensions in mm) (Graupner et al., 2021, changed).

load cycle. Assuming that no substantial stiffness degradation of the material is induced during most of the fatigue life, this load cycle represents all load cycles at the considered load level. An assessment of the fatigue life can then be performed based on the local stresses at all spatial positions representing the stress range $\Delta\sigma$ (or twice the stress amplitudes σ_a) at these points in a load scenario with $R = 0$ (or $R = \infty$ when the stresses are compressive). For the local stress amplitudes, the respective fatigue life can be determined from the respective S-N-curve of the material in terms of the number of withstandable load cycles.

It should be noted that this type of analysis is limited to cases in which linear elasticity without substantial material nonlinearities due to flow and degradation provides a reasonable assumption for the material response. Nevertheless, due to the relatively low load levels in the HCF range, this is usually the case for FRP components under HCF loading scenarios. Therefore, the assumption of linear elasticity does not constitute any substantial limitation here.

For the analysis, the axle tie was meshed with standard four-node displacement-based finite shell elements with a size of $10 \text{ mm} \times 10 \text{ mm}$. The axle boxes were modeled as rigid bodies clamped to the axle tie in the center of the screwed connection they have with the axle tie in reality. The top ends of the rigid bodies representing the axle boxes were assumed to be pivoted in the range of their connection with the bogie frame. To keep the simulation effort within reasonable limits, the lateral movement of the axle box tops due to the bending deformation of the bogie frame was assumed to be of minor importance and, thus, was neglected. The finite element model was loaded by a prescribed rotation φ of the upper ends of the rigid bodies representing the axle boxes. During the analysis, the corresponding reaction force and stress couple F_r and M_r , respectively, were computed. The finite element model and the boundary conditions are sketched in

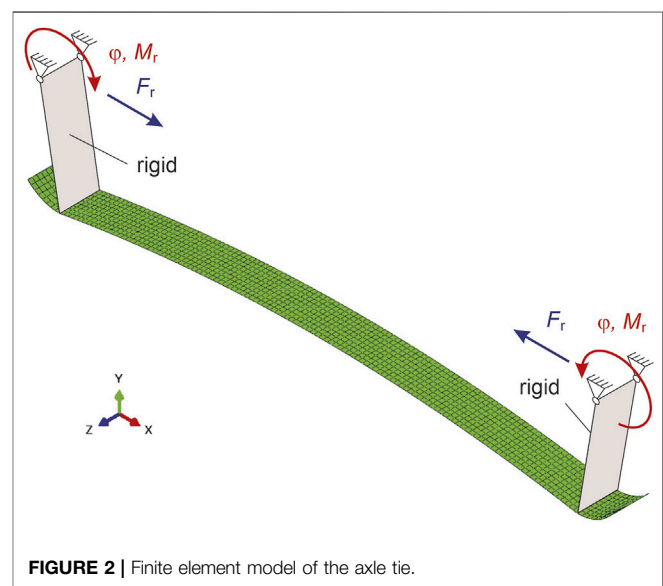
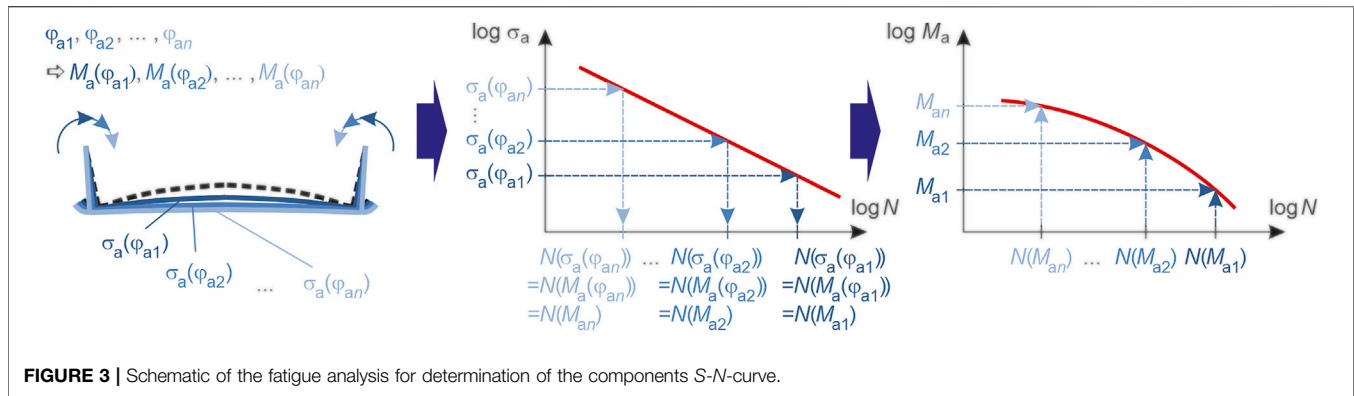


FIGURE 2 | Finite element model of the axle tie.

Figure 2. Three different materials and stacking sequences were considered for the axle tie:

- Glass fiber-reinforcement (reference case): 21 plies with 0.3 mm thickness each.
- Flax fiber-reinforcement: 14 plies with 0.5 mm thickness each.
- Hybrid-reinforcement: four glass-reinforced plies with 0.3 mm thickness at top and bottom and nine flax fiber-reinforced plies with 0.5 mm thickness in the center.

The material was modeled using the orthotropic formulation of Hooke's law with the material properties determined in the



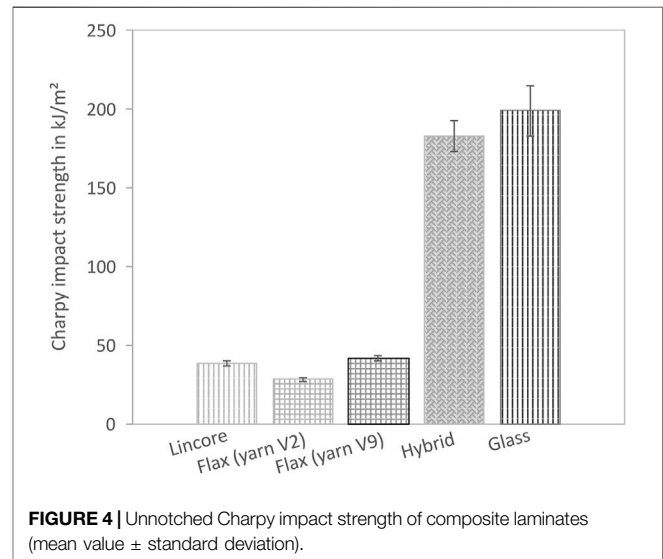
experimental investigation. All finite element analyses were performed within the geometrically nonlinear framework to account for the equilibrium in the deformed configuration.

As mentioned above, a fatigue strength evaluation of the static analysis was performed to compare the three axle-tie material options. Assuming a harmonic fatigue load with a load ratio of $R = F_{\min}^{\text{load}}/F_{\max}^{\text{load}} = 0$, the applied rotation φ was increased stepwise. In each load step, the resultant force and stress couple F_r and M_r , respectively, were computed together with the maximum longitudinal stress component σ_{11} anywhere in the axle tie (**Figure 3**). For the case of the hybrid material, the maximum stress analysis was performed separately for both material ranges (glass fiber-reinforced plies and flax fiber-reinforced plies, respectively). Subsequently, the critical number N_f of loading cycles for each load level φ (or the corresponding F_r or M_r) was determined. Assuming that the static load level φ (or F_r , M_r) were a fatigue load range $\Delta\varphi$ (or ΔF_r , ΔM_r), the corresponding maximum of the longitudinal stress σ_{11} anywhere in the glass or flax fiber-reinforced material ranges forms the maximum stress loading range $\Delta\sigma_{11}$, where x_1 is the fiber direction, coinciding with the component longitudinal direction. Adopting Puck's FRP failure criterion, this stress component is directly responsible for failure within the fiber direction (Puck and Schürmann, 2002). Taking the stress loading range $\Delta\sigma_{11}$ into account, the corresponding number of cycles N_f to failure can be determined directly from the S-N-curve for the respective material. Since the stress loading range $\Delta\sigma_{11}$ is the maximum one occurring anywhere in the component, N_f also forms the number of cycles to failure for the corresponding applied loading range $\Delta\varphi$ (or ΔF_r , ΔM_r). In this way, a component related S-N-curve was obtained; a schematic sketch of the procedure is presented in **Figure 3**.

3 RESULTS AND DISCUSSION

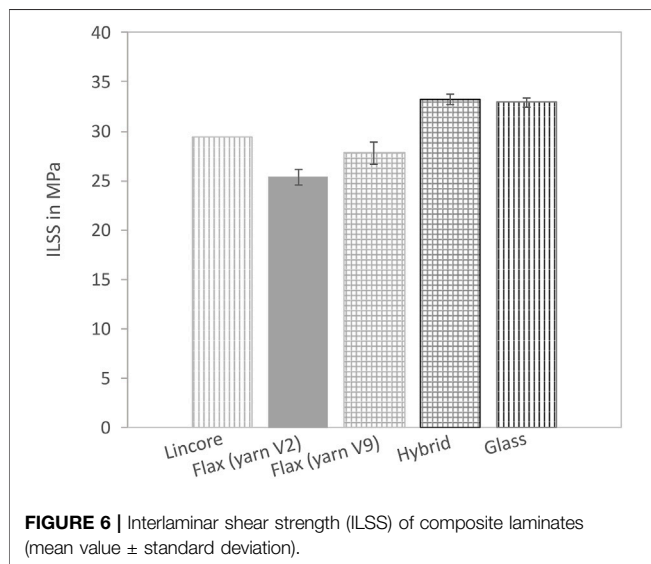
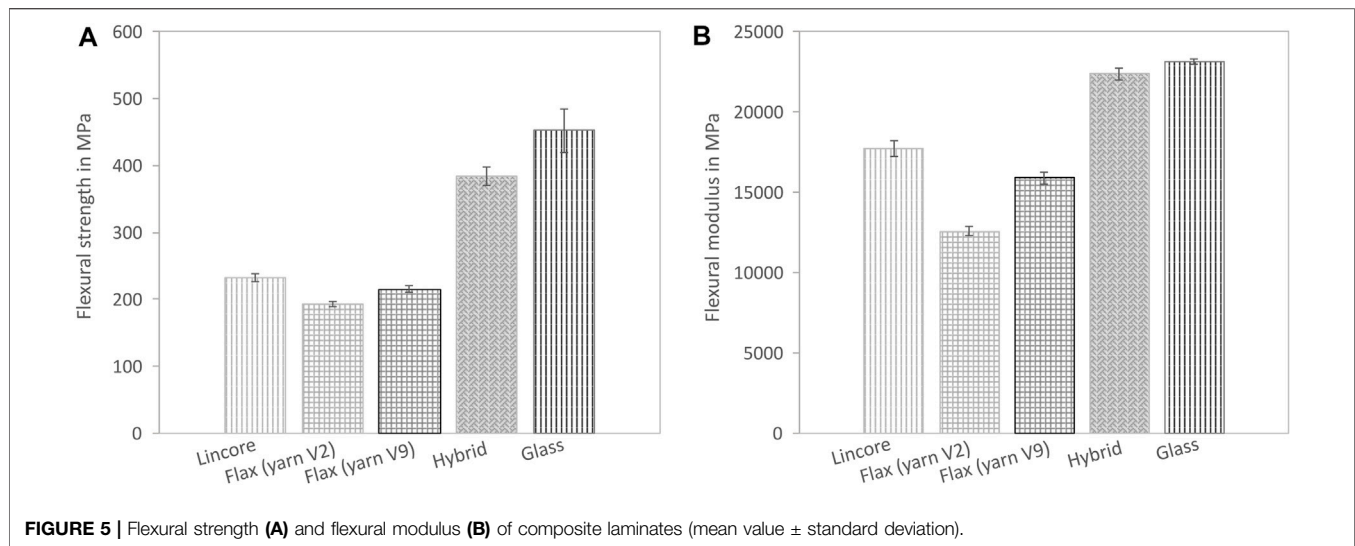
3.1 Static Mechanical Properties

The fabrics made from yarns and rovings were processed by autoclave injection to test composite laminate processability and mechanical properties (details can be found in Graupner et al. (2021)). The influence of the development of semifinished products and fiber properties on the composite characteristics



is also described in (Graupner et al. 2021). Hybrid materials made from flax and glass fabrics were produced to use the composite materials in an axle tie of a narrow-gauge railway bogie to combine the positive properties of both fiber types (resistance against environmental influences of glass and good damping properties of flax). Lincore flax and a glass fabric were processed into composite laminates for comparison. The fiber volume fractions were calculated as 48% for the Lincore laminate, 53% for the flax laminate (yarn V2), 51% for the flax laminate (yarn V9), 43% for the glass laminate, and 47% for the hybrid composite laminate (Graupner et al., 2021).

Results of the unnotched Charpy impact strength are shown in **Figure 4**. It becomes apparent that the glass and hybrid laminate have significantly higher impact strength values than the flax-based laminates. Furthermore, it is evident that a more advanced structure of the semifinished product positively affects the impact strength. The laminate made of yarn V9 has a higher impact strength than the laminate of yarn V2. The yarn V9 fabric laminate (42 kJ/m²) is comparable to the laminates made from the Lincore fabric (39 kJ/m²). The impact strength of the hybrid composite is much closer to the GFRP values than to the flax fiber-reinforced composite.



The results of the flexural tests are shown in **Figure 5**. By improving the yarn structure from yarn V2 to yarn V9 (restretching the flax sliver), the flexural properties were enhanced, but the reinforcing effect of the Lincore fabric was not achieved. The hybrid materials show significantly better flexural properties than the flax laminates. In particular, the flexural modulus was highly increased and closer to the values of the GFRP than to the flax fiber-reinforced composite.

Fiber/matrix adhesion was characterized by short beam shear tests to determine the apparent interlaminar shear strength (ILSS). The performance trend is similar to the flexural properties; the difference is that the ILSS of the glass and the hybrid laminate do not deviate as much from the flax-based materials (**Figure 6**).

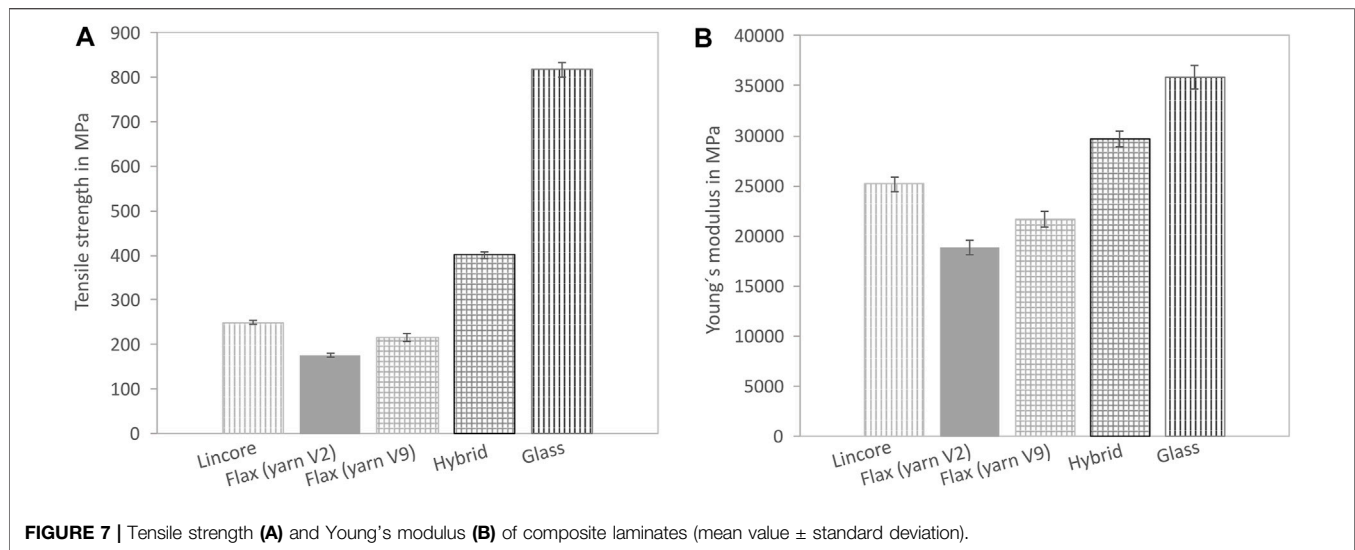
Again, improved fiber/matrix adhesion was observed from flax laminate (yarn V2) to flax laminate (yarn V9), which can be attributed to the more uniform yarn properties due to the

restretching of the sliver. Restretching resulted in a reduction of fiber ondulation and better fibre orientation in the yarn.

The tensile properties are summarized in **Figure 7**. By improving yarn V2 to yarn V9, tensile strength (**Figure 7A**) and tensile modulus (**Figure 7B**) were significantly increased; however, the values of the Lincore laminate were not reached. The GFRP laminate displays the highest characteristic values, followed by the hybrid material; compared with the flexural properties, the tensile properties of the hybrid material are significantly lower than those of the GFRP laminate.

The optimization of the yarns by restretching the sliver can be summarized as follows: Concerning the impact strength (**Figure 4**), flexural properties (**Figure 5**), tensile characteristics (**Figure 7**), and even the interlaminar shear strength (**Figure 6**), it is shown that the optimization of the yarn structure from V2 to V9 led to a significant increase in the mechanical properties of the laminates. Our previous study shows that the fiber properties (tensile characteristics and length of the fiber bundles) did not show any significant differences. The increase in the characteristic values can be solely attributed to the yarn and fabric structure as the composite production and the fiber volume fraction were identical. It was found that fiber ondulation was present in yarn V2, which was almost eliminated in yarn V9 by restretching the sliver. Even with this optimization, it was impossible to achieve the composites' property profile from the Lincore roving completely.

Previous work shows that flax yarn V9 achieves the same reinforcing effects as Lincore roving in UD-reinforced pultruded rods (Graupner et al., 2021). To understand why, despite the same reinforcement potential between Lincore roving and yarn V9, the properties in the fabric-based composites differ, further analyses were carried out. The fabrics based on yarn V9 showed some crimp and, thus, a deviation of the fiber orientation from the longitudinal axis. In contrast, no crimp was visible in the Lincore fabrics, which justifies a better reinforcement effect in the fabric-reinforced laminates. It is well-known that a deviation of fiber orientation



from the load direction leads to a considerable reduction of strength and stiffness in the composite (Goutianos et al., 2006; Baets et al., 2014; Scida et al., 2017). It is expected that by eliminating the crimp in future research, the reinforcement effect can be significantly increased.

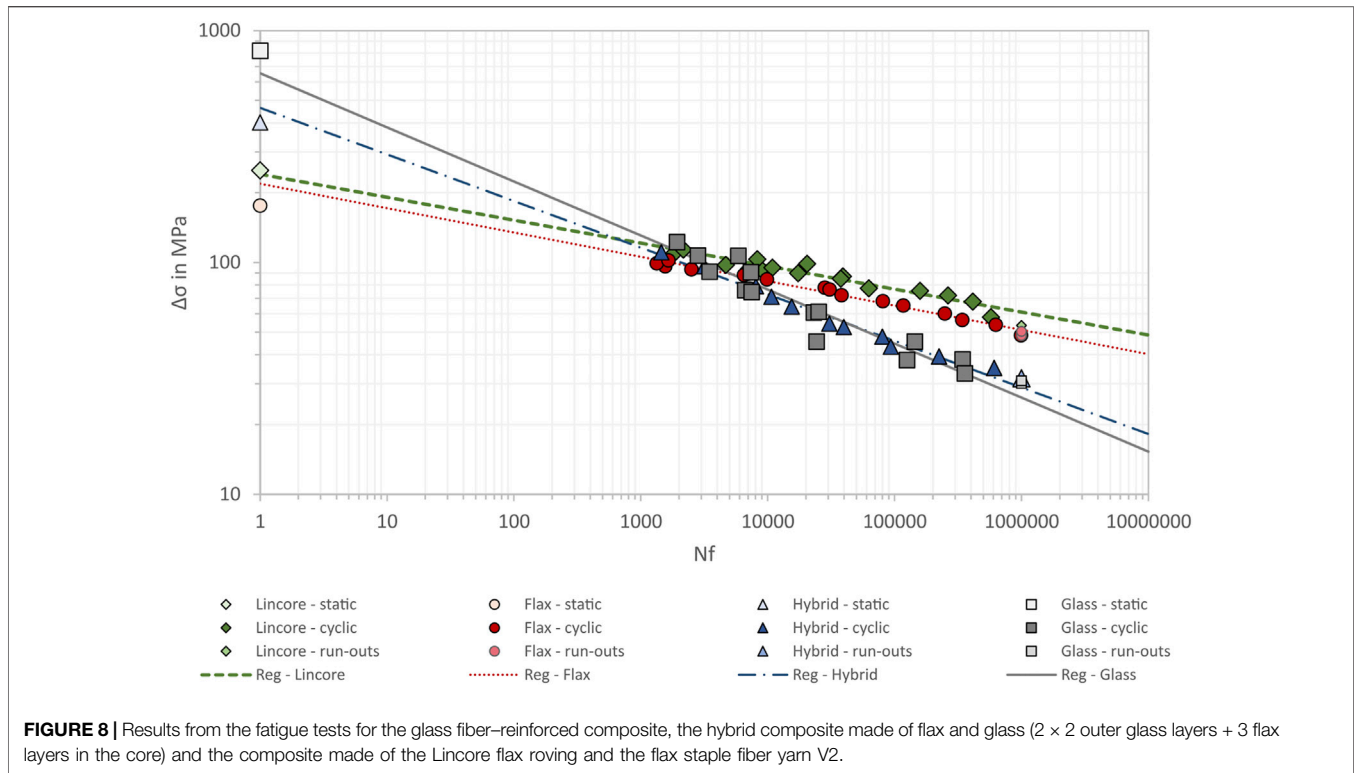
The hybrid materials show significantly improved flexural and impact properties compared with the flax laminates and significantly better density-related properties, especially in terms of flexural stiffness, in comparison to the GFRP (Graupner et al., 2021). Several authors describe comparable results (Calabrese et al., 2019; Fiore et al., 2018; Jusoh et al., 2017; Selver et al., 2018; Cerbu and Botis, 2016). The presence of external layers of glass fabric in a hybrid glass/flax/epoxy laminate positively influences the mechanical performance. In our study, the flexural modulus was clearly increased, and the values were closer to the GFRP than to the flax fiber-reinforced composite (Figure 5B). This trend is more pronounced for the flexural modulus than for the tensile modulus (Figure 7B), which the loading direction may explain: The outer glass layers in the hybrid material are mainly loaded on the compression and tension side. Under tensile load, the entire cross-section of the specimen is loaded, which is also described in the work of Selver et al. (2018) for flax/glass hybrid composites. Selver et al. found that a changing stacking sequence did not significantly affect the tensile strength and Young's modulus of composites. Nevertheless, they realized notable differences in flexural strength of composites when the outer layers contained glass fibers. The flexural modulus of the hybrid composite was even comparable to that of the pure GFRP. When using flax as outer layers and glass as inner layers, flexural modulus and strength were considerably lower (Selver et al., 2018).

Since the determination of the modulus takes place in the linear-elastic initial slope at relatively low forces, it is assumed that the influence of the outer glass layers is more substantial under bending load. An increasing number of outer glass layers in a hybrid material with flax increases strength and modulus (Saidane et al., 2016).

To sum up, the hybridization of flax and glass was successful in our work. For most mechanical properties, the characteristic values are close to those of the GFRP, especially under bending and impact stress. Both properties are essential for an axle tie element. Besides improving mechanical properties, water absorption or swelling of the flax laminate are hindered by the outer glass layers (Calabrese et al., 2019). In addition, the presence of flax is shown to improve the damping of the hybrid material compared with a pure GFRP (Selver et al., 2018; Liu et al., 2021). The authors determined the damping by dynamic mechanical analysis and found that NFRPs and some hybrid composites had higher damping characteristics than GFRPs, whereas the described effect seems to apply independently of the material pairing. Studies on hybrid materials made of stiffer bast fibers and more ductile regenerated cellulose fibers show that the tensile properties do not change significantly due to the layer arrangement. The toughness of the composites could only be increased when the stiffer bast fibers are used as outer layers and the tougher regenerated cellulose fibers as inner layers. A reversed layer structure led to a reduction in toughness, showing that using stiffer outer layers can significantly improve the mechanical performance of the composite (Graupner et al., 2017a; Graupner et al., 2017b).

3.2 Fatigue Strength of Composite Laminates

The results of the fatigue experiments for the four materials considered here are presented in Figure 8 in a double logarithmic representation. Symbols mark the individual experimental results. The static strength results, converted to nominal cyclic stress range $\Delta\sigma$ with $R = 0.1$, are added as failure points for a single stress cycle. The S-N curves for the individual materials are computed as the linear regression line to the experimental data from failed specimens, thus not considering static results and run-outs. It can be seen that the S-N curves adjusted to the cyclic



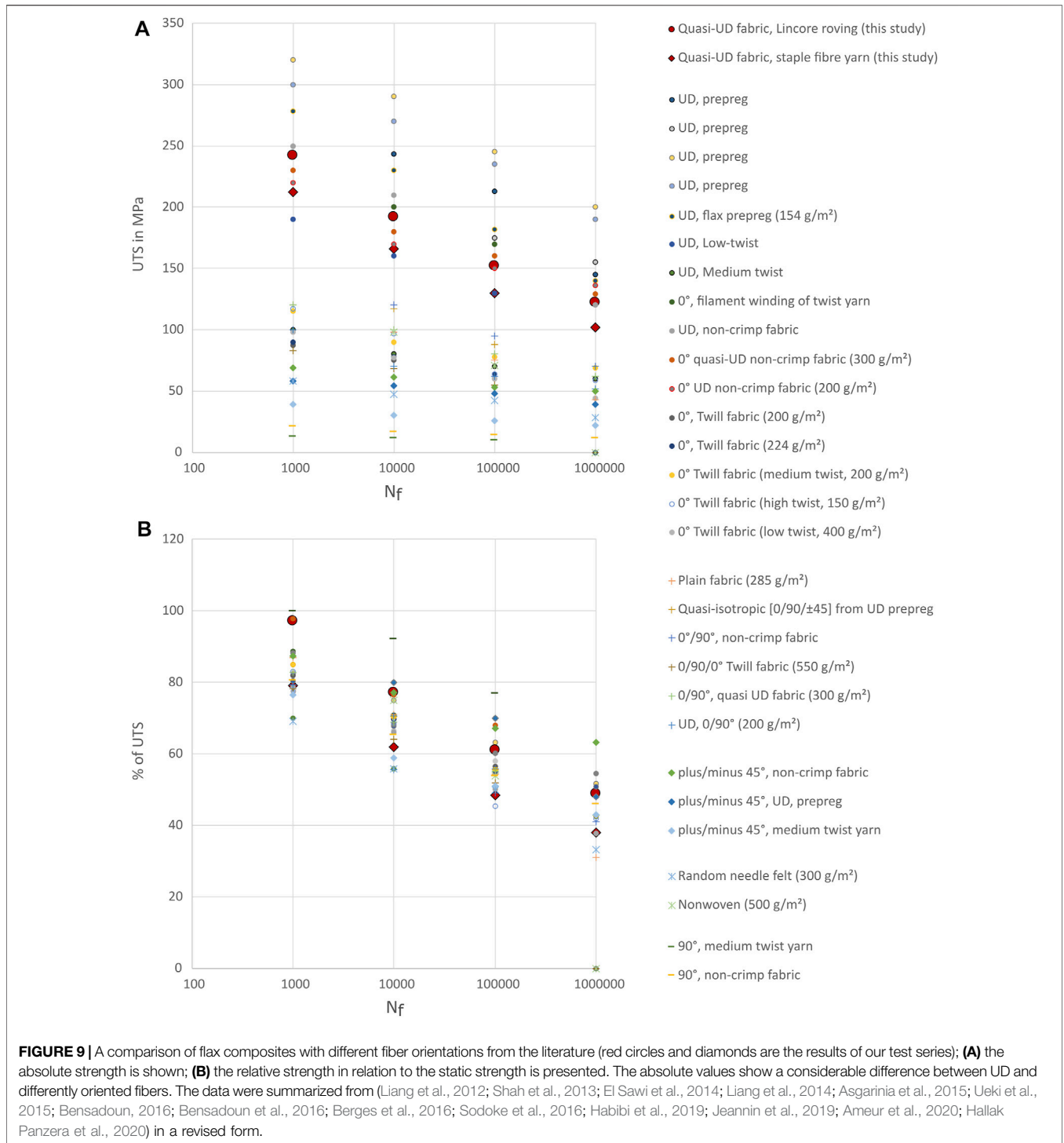
experiments are approaching the static results with a rather good agreement.

At higher cycle numbers, i.e., above 7^3 to 8^3 load cycles, the fatigue strength of the composite laminates made of flax is higher than that of the GFRP (**Figure 8**). On the one hand, this finding of higher fatigue strength of flax than glass is particularly important for the use of cyclically loaded components. On the other hand, the flax fiber-reinforced materials are outperformed by their GFRP and hybrid counterparts in the low cycle fatigue and static ranges. Although quantitatively less distinct, similar effects are observed compared with the GFRP and hybrid composites. The hybrid materials tend to show higher fatigue strength than the GFRP from about 2×10^5 load cycles.

Figure 8 shows a steeper slope of the S-N curve of GFRP compared to the NFRP, which is also reported by different authors (Liang et al., 2012; Shah et al., 2013; Abdullah et al., 2012; Shahzad and Isaac, 2014). The results of the fatigue tests show a lower decrease in strength at a higher number of load cycles for the flax laminates compared with the glass laminate and the hybrid material (**Figure 8**). In general, the lower slopes of the flax fiber-reinforced composites indicate that flax as the main load-carrying constituent is less sensitive to fatigue than glass fibers. From the literature, it is known that bast fiber-reinforced composites tend to have lower fatigue sensitivity and lower stiffness degradation with an increasing number of loading cycles and a higher resistance to crack propagation in fatigue tests compared with GFRP (Abdullah et al., 2012; Liang et al., 2012; Shah et al., 2013; Shahzad and Isaac, 2014). Flax fiber-reinforced composites offer a more stable cyclic performance than GFRP (Liang et al., 2012). Qualitatively similar results are obtained from the fatigue tests from the present study.

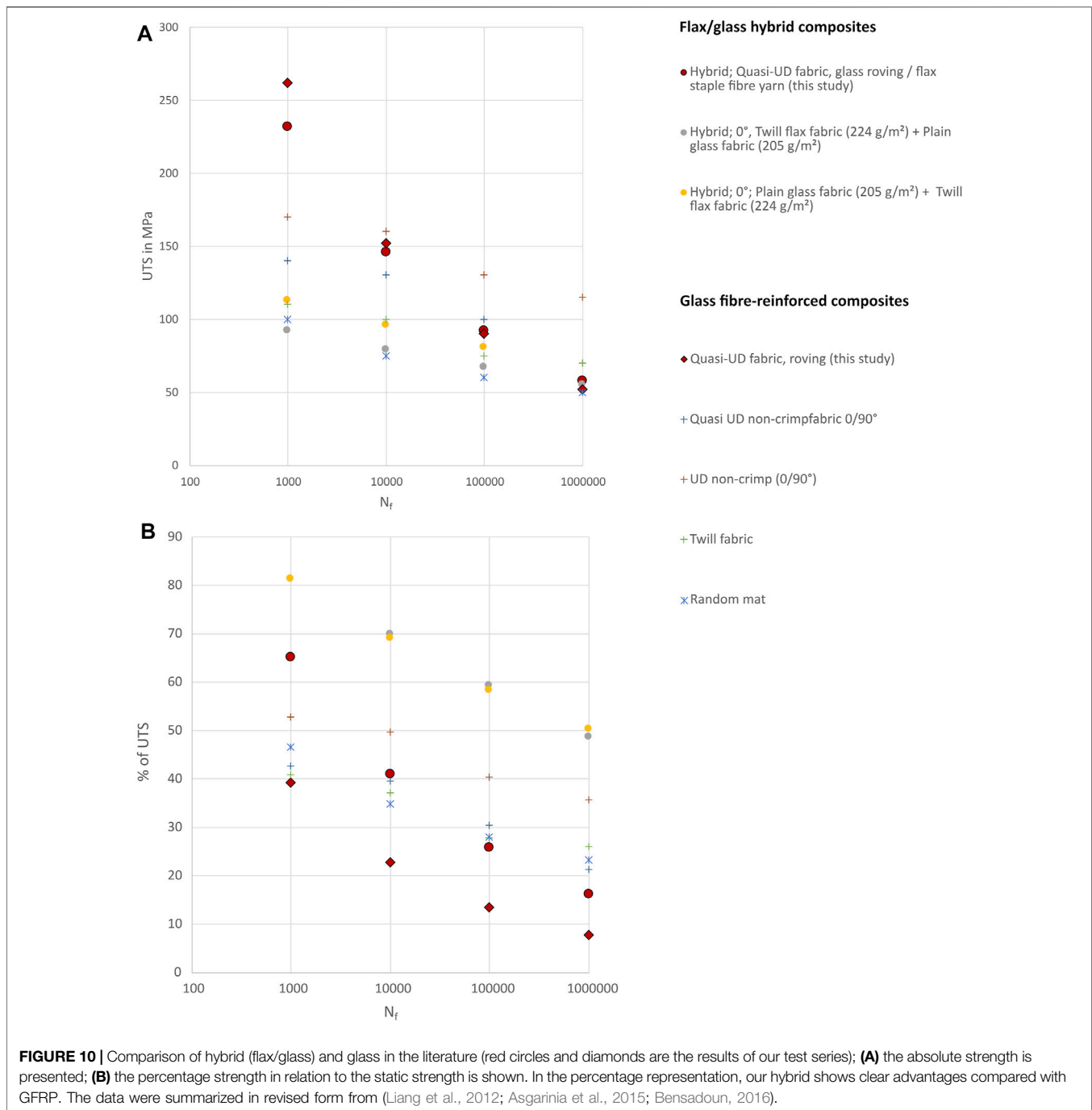
As already shown in the static mechanical properties, the laminate made of Lincore flax also displays better fatigue properties compared with the laminates made of flax yarn. For the interpretation, it should be taken into account that the laminates made from flax yarn V2 also had lower static mechanical properties than laminates made from yarn V9. When comparing the Lincore roving with the yarn results, it is important to remember that the flax yarn laminate exhibits some crimp in the fabric (Graupner et al., 2021), which negatively affects the fatigue properties. These hypotheses can be confirmed with a literature comparison: (Bernasconi et al., 2007; Shah et al., 2013; Asgarinia et al., 2015; Bensadoun et al., 2015; Lessard et al., 2015; Bensadoun et al., 2016; Haggui et al., 2019; Feng et al., 2020). Unidirectional fiber orientation leads to the best properties (Gassan, 2002; Feng et al., 2020), and it is shown that minimized crimp in the yarns significantly increases the resistance to fatigue damage (Shah et al., 2013; Asgarinia et al., 2015; Bensadoun et al., 2015; Lessard et al., 2015; Bensadoun et al., 2016; Feng et al., 2020). Furthermore, the critical collapse load of the composite is strongly dependent upon the magnitude of the waviness of a fabric (Lemanski and Sutcliffe, 2010; Feng et al., 2020).

Figure 9A shows a comparison of flax-reinforced composites made from different semifinished products and with different orientations; data of this study are compared with data from the literature. The ultimate tensile strength (UTS) of different materials is plotted as a function of loading cycles. The UD-reinforced materials display the highest absolute fatigue strength values. The properties of the composites reinforced with quasi-UD fabrics from the present study are slightly lower. Composites with $0/90^\circ$ or $\pm 45^\circ$ still show low results, and the lowest values are



for composites with a fiber orientation of 90°. In **Figure 9B**, the fatigue strength is related to the static strength in percent, and no clear trends depend on the fiber orientation. This trend is also justified in the literature because the textile architecture significantly influences the static properties but only slightly changes the slope of the S–N curves (Shah et al., 2013; Bensadoun et al., 2016).

There is further potential to improve the fatigue behavior of laminates made of flax yarn V2. Due to the improved mechanical characteristics and the higher fiber orientation of the laminates produced from yarn V9, it is expected that the fatigue strength can also be further increased since higher static strength usually leads to higher resistance to fatigue loads (Gassan, 2002; Shah et al., 2013; Shah, 2014; Bensadoun et al., 2016). Additionally, improvement in



fiber/matrix adhesion can be used to increase fatigue strength (Gassan, 2002; Shahzad and Isaac, 2009; Liang et al., 2014; Shahzad et al., 2019; Asumani and Paskaramoorthy, 2020; Feng et al., 2020; Müssig et al., 2020). As **Figure 6** shows, the interlaminar shear strength of the flax yarn V9 laminate is higher than that of the flax yarn V2 laminate. Taking into account these considerations, it is reasonable to expect that using the V9 yarn increases fatigue strength.

The S–N curves between the GFRP laminate and the hybrid material show no significant differences (**Figure 8**). However, the hybrid material tends to reach higher fatigue strength with

more load cycles; the slope of the regression line is lower. For the interpretation, it is essential to consider that the hybrid material consisted of four layers of glass and three layers of flax. In contrast to the static properties, the fatigue behavior is not increased by a higher number of glass layers. It is hypothesized that the fatigue strength can be further improved by using more layers of flax or by reducing the number of glass by two layers. The hybrid material investigated contains approx. 27 vol% flax and 21 vol% glass (Graupner et al., 2021).

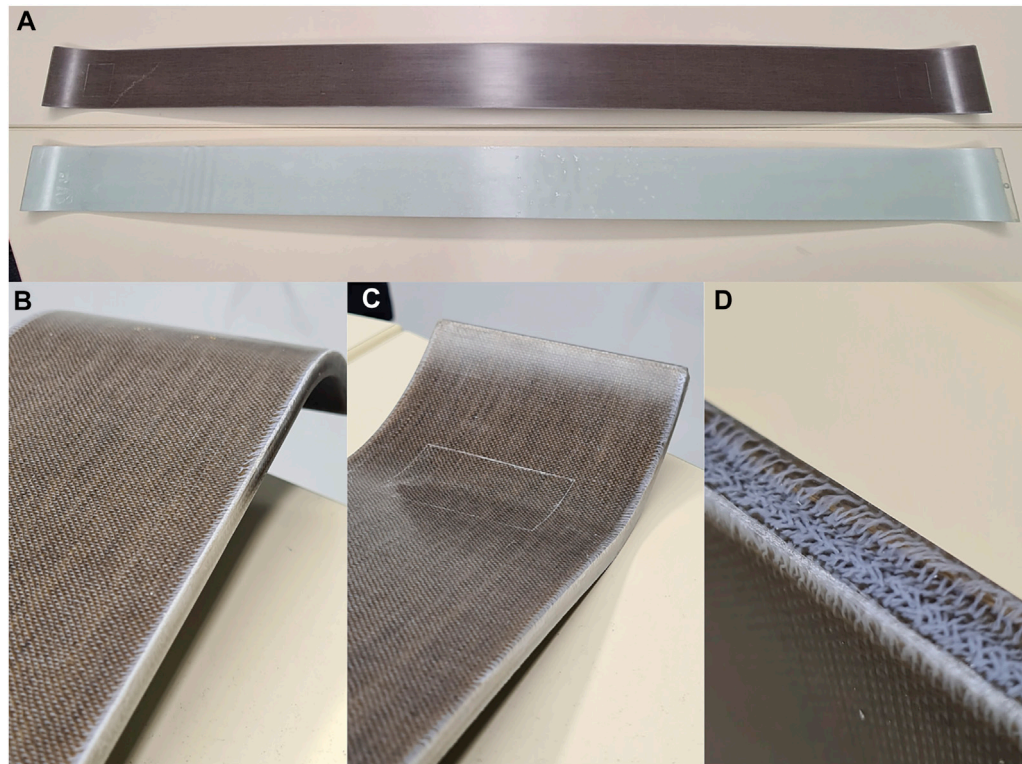


FIGURE 11 | The lower axle tie of the bogie of a narrow-gauge railway, manufactured using the RTM process. **(A)** Flax/epoxy axle tie (top) compared with the conventional glass fiber-reinforced axle tie (bottom), **(B,C)** detailed views of the curved ends of the axle tie, **(D)** detailed view on the side of the axle tie (component thickness: 70 mm, length approx. 1.2 m).

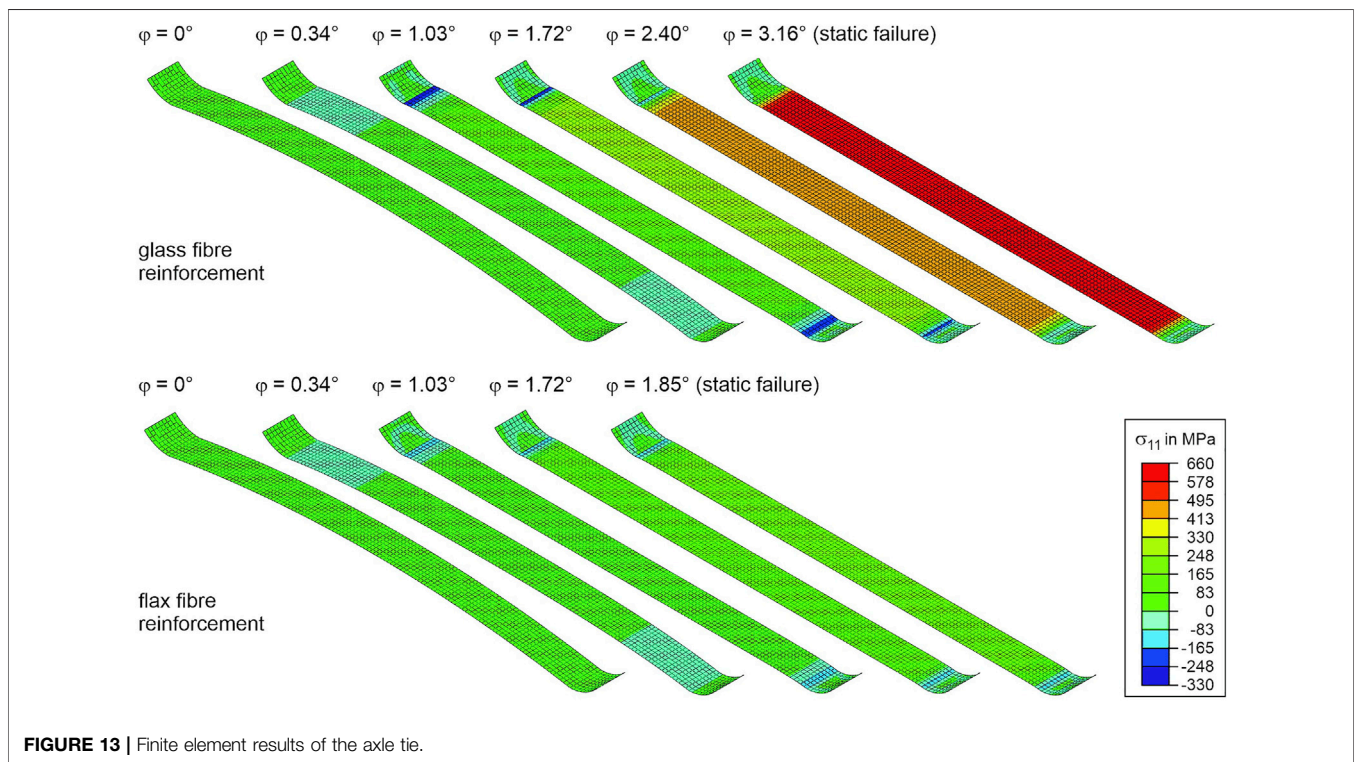
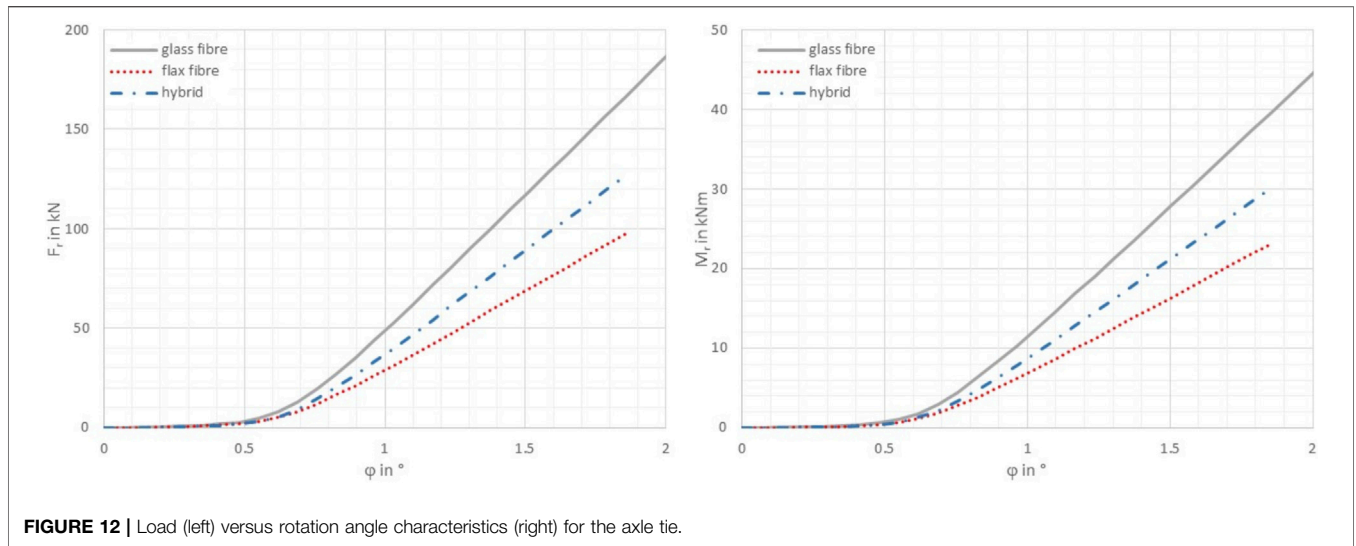
A comparison of the results at different numbers of loading cycles of flax/glass hybrid materials and GFRP with data from the literature is shown in **Figure 10A**; an influence of the fiber orientation is less evident than for the flax laminates shown in **Figure 9A** (when comparing, the different amount of data must be taken into account). The data from the present study show that at a lower number of cycles, the GFRP has higher strength, whereas the hybrid material achieves a higher strength at a higher number of cycles. Other hybrid materials from literature show significantly lower values at a lower number of cycles but converge at a higher number of cycles. Hybrid materials tend to offer the highest values in the relative representation (fatigue strength related to static strength) (**Figure 10B**). For GFRPs, no clear trend can be identified depending on the fiber orientation. From the literature, it can be generally concluded that plant fibers can improve the damping behavior of composite materials. Ashby plots can be created in which different fatigue properties are plotted to select appropriate fibers, making it possible to find the compromise between loss factor and stiffness for engineering design considerations (Liu et al., 2021).

3.3 Fatigue Analysis for an Axle Tie of a Light Railway Bogie

The demonstrator components produced in the RTM process are presented in **Figure 11**; **Figure 11A** shows an axle tie made from quasi-UD flax (top) and glass fabric (bottom). **Figures**

11B,C represent detailed views from the top and bottom. The cross-section of the axle tie is shown in part (**Figure 11D**), on which the warp threads (white) are visible. The composite manufacturing of the flax and the flax/glass hybrid material was straightforward compared with the GFRP processing.

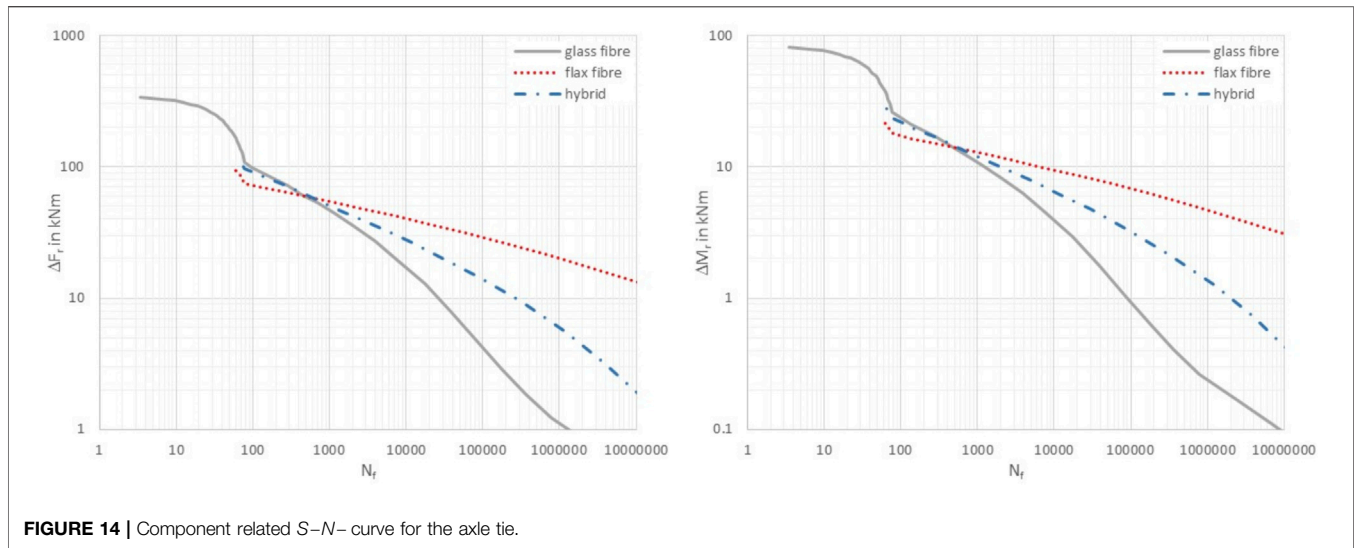
Theoretical component $S-N$ curves were determined for the GFRP reference case and the flax fiber-reinforced and hybrid alternatives, using the numerical procedure described in the *Materials and Methods* section. For the hybrid component, both material ranges were analyzed separately, considering the material range leading to the lower number N_f of cycles to failure as the relevant one. The underlying force and stress couple versus rotation angle characteristics are presented in **Figure 12**, where the first subfigure is related to the resultant axial force F_r , whereas the second subfigure is related to the resulting stress couple M_r . In both cases, an initial strongly nonlinear load vs. rotation characteristic is followed by a nearly linear characteristic at larger rotation and, thus, related levels. In the initial range, the deformation of the axle tie is dominated by bending deformation with low resultant force and stress couple levels. The curves were computed and plotted up to the load level at which the maximum of the longitudinal normal stress σ_{11} in the most critical ply first reaches the static strength of the respective material. In this case—according to the weakest link concept—complete failure of the entire component or at least the development of an unacceptable state is assumed. The transition between nonlinear and linear load versus rotation characteristics is



caused by the transition from bending to nearly pure stretching deformation once the axle tie is bent to a straight shape (see **Figure 12** and discussion therein). The largest resultant forces and stress couples are obtained for the reference case of the GFRP structure since this design option features the highest stiffness, followed by the hybrid option and the neat flax fiber-reinforced case with the lowest stretching and bending stiffness.

The distributions of the levels of the longitudinal normal stress σ_{11} in the most critical ply for the glass and flax fiber-reinforced demonstrators are presented in **Figure 13** for selected levels of the

applied rotation φ till static failure of the component. For clarity, all results are shown in the deformed configuration for the respective load level. For both cases, the transition from the initial curved shape to a stretched configuration is observed at approximately $\varphi = 1^\circ$. Below this deformation level, bending is the dominating deformation mode of the structure, resulting in limited levels of the maximum of the longitudinal normal stress σ_{11} . Beyond this point, a rapid increase in the local stress level is observed due to the higher stiffness in stretching compared with the bending stiffness.



For similar levels φ of external deformation, the glass fiber-reinforced design option features larger stress levels σ_{11} compared with its flax fiber-reinforced counterpart due to the higher material stiffness of the GFRP (compare **Figure 5B** and **Figure 7B**). The higher static strength of the GFRP (**Figure 7A**) results in a static failure prediction for larger external deformation φ than for the flax fiber-reinforced design option. As expected, approximately constant stress distributions are observed over the axle tie in all cases. Similar results are obtained for the hybrid design option, but these are not presented here for reasons of clarity. In this context, a similar external deformation to failure φ as for the neat flax fiber-reinforced design option is obtained since failure occurs in a stretched deformation shape and, thus, a similar strain and stress level in the (weaker) flax plies of the hybrid design than in the neat flax fiber-reinforced option (see **Figure 12**).

The resulting component related $S-N$ -curve are presented in **Figure 14**. Again, the overall load range is considered in terms of both the resulting force F_r and the resulting stress couple M_r for the applied rotation φ . Due to the nonlinear dependence of the maximum of the longitudinal stresses in the different plies on the applied rotation, a nonlinear characteristic of the $S-N$ -curve in the double logarithmic representation is obtained.

In the initial part of the low-cycle fatigue range below approximately $N_f \cong 500$ load cycles, the reference case of the GFRP laminate provides the best fatigue resistance case among the considered design options. For larger load cycle numbers, the flax fiber-reinforced composite becomes the leading option with the highest $S-N$ -curve and, thus, the highest fatigue resistance. This effect is partially due to the lower slope of the material $S-N$ -curve for the flax fiber-reinforced material compared with its GFRP counterpart (**Figure 8**). Nevertheless, the transition from bending- to stretching-dominated deformation of the axle tie (**Figure 12**) also plays an important role. Since the flax fiber-reinforced composite is significantly more compliant compared with the reference case of the classical GFRP one, similar strains caused by the applied rotation φ cause lower

longitudinal stress levels σ_{11} and, thus, a lower local fatigue load. Therefore, the fatigue resistance increases under the present deformation-controlled load case, especially in the bending dominated ranges at lower loads and, thus, in the high-cycle fatigue range on the right-hand side of the $S-N$ -curve plots. It should be noted that the high cycle fatigue resistance is most important in the present application.

The $S-N$ -curve for the hybrid composite in both representations is found between the $S-N$ -curve of the neat glass or neat flax fiber-reinforced components, respectively (**Figure 14**). In the bending dominated high cycle fatigue range on the right-hand side, the curve for the hybrid composite is found well in between its counterparts for the neat GFRP and flax fiber-reinforced composites. In the low cycle fatigue range below $N_f \cong 500$ load cycles, the $S-N$ -curve for the hybrid reinforcement follows the $S-N$ -curve for the glass fiber-reinforcement although at lower load range levels. In this stretching dominated deformation range, the GFRP plies of the hybrid composite carry most of the longitudinal load due to their higher stiffness. Thus, a qualitatively similar behavior as for the neat GFRP is obtained.

3.4 Assessment of the Different Material Options in Numerical and Experimental Studies

In general, composites having higher static strength are more durable, and the fatigue endurance strength of NFRPs is proportional to their tensile strength (Gassan, 2002; Shah et al., 2013; Shah, 2014; Bensadoun et al., 2016). The results of the fatigue tests and the simulation show that flax fiber-reinforced composites display superior characteristics to the GFRP beyond a specific number of load cycles despite their lower static strength as reported in the literature (Gassan and Bledzki, 1999; Liang et al., 2012; Rahman et al., 2016; Mahboob and Bougherara, 2018; Dhanraj et al., 2019; Liu et al., 2021; Rahman, 2021). The low cycle fatigue strength of flax composites

is slightly lower than that of GFRP but still in the same order of magnitude. In this sense, the results of the fatigue experiments on GFRP and flax-reinforced specimens are in line with the simulation data of the axle tie although the loading of the component in the case study was different from the neat tension–tension fatigue on specimen level (see **Sections 2.3** and **2.4**). As described for the fatigue tests of the laminates, the axle tie made of GFRP exhibits significantly higher strengths than the axle tie with flax fiber-reinforcement at a lower number of load cycles ($N_f < 500$) in the LCF range (**Figure 8**). This effect might be caused by the different load types and higher bending deformation of the (woven) flax fibers under tension with a lower sensitivity to fatigue under bending than glass fibers.

In the literature, it is reported that the fatigue strength degradation rates of NFRP are lower, indicating a lower fatigue sensitivity (Shah et al., 2013; Shahzad and Isaac, 2014). Other authors carried out microscopic analyses and show that fatigue cracks are nucleated at the interfaces between the single fibers and the matrix within fiber bundles. The assumption is made that the pectin bonding agent, in the middle lamella of the fiber bundle, is the weakest component in the flax/epoxy composite (El Sawi et al., 2014) and the crack further propagates through the fiber/matrix interphase to the matrix with an increasing number of fatigue cycles (Shahzad et al., 2019). In contrast, fatigue failure in UD GFRP is described to occur throughout the material volume. Debonding between fiber and matrix, fiber breakage, matrix cracking, delamination, and transverse ply cracking occur either interactively or independently. In general, matrix cracking and delamination start early, whereas fiber/matrix debonding and fiber fracture begin during the component life but accumulates rapidly toward the end, leading to the final failure (Subramanian et al., 1995). However, it should be noted that the damage mechanism of crack propagation through the different plies has not been considered in the numerical case study where, in the sense of the weakest link model, failure was assumed once the first material point is predicted to experience failure.

In the fatigue tests, the hybrid material only shows a higher fatigue strength at a high number of load cycles ($\sim 2 \times 10^5$) compared with the case of the GFRP material. The hybrid material's S-N curve was closer to the GFRP laminate than the flax fiber-reinforced laminate curve. In the simulation, the curve of the hybrid material was between the curve of the glass fiber-reinforced axle tie and that of the flax fiber-reinforced axle tie (**Figure 14**). As discussed in **Section 3.2**, the hybrid laminate with a thickness of approximately 2 mm consists of a total of four layers of glass fiber reinforcement and three layers of flax fiber reinforcement. On the other hand, the demonstrator consists of eight layers of glass and nine layers of flax fiber reinforcement, respectively, which means that the volume proportion of flax fiber reinforcement in the axle tie is higher than for the laminate resulting in better damping of the hybrid material.

Particularly under bending stress, the outer glass fiber-reinforced layers are subjected to tensile stress and, thus, carry a large portion of the load, which is also shown

by the results of the impact and bending tests. On the one hand, the characteristic values of the hybrid material are closer to the values of the GFRP laminate (**Figures 4, 5**). On the other hand, the specimen's cross-section is loaded more uniformly under tensile load. Thus, the glass and flax fibers are loaded simultaneously. The characteristic values range between those of flax fiber-reinforced and GFRP laminates (**Figure 7**). In addition to the higher proportion of flax fiber reinforcement in the demonstrator compared with the laminate, the type of loading used in the simulation can lead to the hybrid material having a significant advantage over the GFRP material in terms of fatigue resistance. Compared to the literature, a hybrid composite made of flax and carbon fibres resulted in improved fatigue performance and fatigue resistance with an increasing carbon fibre content. But the damping ratio and the fatigue life increase with a higher flax fiber volume fraction [103]. This finding makes the use of hybrid materials with flax particularly interesting for the application of a cyclically loaded axle tie in a bogie, also because of the improved lightweight construction potential compared to GFRP.

4 CONCLUSION

The results presented show that flax is very well-suited as a reinforcing fiber for components under cyclic loads. It is particularly noteworthy that the flax composites have a significantly higher fatigue strength than GFRP at a higher number of loading cycles. These properties are often only achieved with very high-quality semifinished flax products. The present study shows that low-cost flax tow could be processed into low-twist yarns and fabrics with little undulation and, in the composite, has comparable properties to composites made from higher quality and more expensive long flax rovings. Due to the lower strength of flax fiber-reinforced composites compared with GFRP, a hybridization is a suitable option for the considered application. Glass fibers in the outer part of the axle tie protect the inner flax fibers from moisture and lead to increased strength and stiffness of the entire component. The hypothesis stated at the beginning that hybridization of flax and glass fibers could achieve improved static properties compared with flax fiber-reinforced composites and improved fatigue properties at a higher number of load cycles than GFRP cannot be rejected. The present study demonstrates that the developed material is suitable for an axle tie. Therefore, the optimal ratio of glass to flax fibers for the mentioned component should be determined to achieve the best fatigue properties and lightweight potential in future work. It would also be fascinating to see the axle tie tested in a practical application.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article. Further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

Conceptualization: NG, JH, JM. Experimental studies: NG, MS, BR, DW, LB. Methodology: NG, JH, AB, JM. Project administration: NG, JM, JH. Validation: NG, JH, MS, BR. Writing—original draft: NG, JH, JM. Writing—review and editing: NG, JH, MS, BR, DW, JM.

FUNDING

The research project, Innovative yarn structures and their competitiveness as part of the project fibre-reinforced composites for structural applications based on novel, low-twist bast fibre yarns (NF-CompPlus), was carried out in the framework of the industrial collective research programme. This work was supported by the Federal Ministry of Food and Agriculture (BMEL) on the basis of a resolution of the German Bundestag (funding No. 22026215, 22014817 and 22015417). The funder was not involved in the study design, collection, analysis, interpretation of data, the writing of this article or the decision to submit it for publication.

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The fee for open-access publication is covered by the Bremen State and University Library.

ACKNOWLEDGMENTS

The research project, Innovative yarn structures and their competitiveness as part of the project fibre-reinforced composites for structural applications based on novel, low-twist bast fibre yarns (NF-CompPlus), was carried out in the framework of the industrial collective research programme. The authors would also like to thank the project partners, without whom the NF-CompPlus project could not have been implemented: Institut für Textiltechnik of RWTH Aachen University (Dr.-Ing. Karl-Heinz Lehmann, Erik Bell, Herbert Randerath), Wenzel and Hoos GmbH (Hans-Willi Hilgers, Stefan Kunst), INVENT GmbH (Isabell Walenta, Marc Jouliau, Maik Wonneberger), SachsenLeinen GmbH (Torsten Brückner, Kay Kölzig) and BAFA neu GmbH (Bernd Frank).

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- Conflict of Interest:** The company Novacom Verstärkte Kunststoffe GmbH received proportionate funding in the form of subcontracts from the Federal Ministry of Food and Agriculture (BMEL) and is represented by the authors LB and AB. Novacom Verstärkte Kunststoffe GmbH was responsible for the production of the axle tie and received proportionate funding in the form of a subcontract from the Federal Ministry of Food and Agriculture (BMEL). The remaining funding was provided by the companies in the form of machine and labour hours.
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