Optimizing Knitted Fiber-Reinforced Composite Carabiners

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Abstract. Due to the looping geometry of the knitted fibers, composites reinforced by knitted fabrics excel particularly in their light weight, high impact strength, and adaptable contourability for complex shapes. Currently, knitted fiber-reinforced composites are mainly used in applications involving substantial impact stress, such as helmets and car crash guards, but the applications of knitted fiber-reinforced composites can be expanded if its weak tensile strength is improved. Carabiners are one possible application with high potential and a lack of extensive previous research. Optimizing knitted fiber-reinforced composites with improved tensile modulus can help create lighter, but still structurally strong, carabiners. Climbing-grade composite carabiners are not currently available, but these lighter carabiners can help stem the many issues caused by the excessive weight on climbers’ harnesses. To achieve this goal, we used computer-aided design and micro-scale simulations to optimize the design of the knitted-fiber reinforced composites to improve the tensile modulus to be comparable to standard carabiner materials.

1. Introduction
Knitted fiber-reinforced composites are characterized by extremely strong interlacing fibers knitted in various patterns. The two main types of knits are the weft and warp knits. Knitting horizontal rows one by one is considered the weft style of knitting, while knitting vertically and interlacing parallel rows is considered warp knitting. We focused on weft knits because their superior contourability is useful to account for the complexity of carabiner shapes [1]. As well as excellent contourability, knitted fabrics carry the advantages of high impact strength, low weight, and through-the-thickness strength that helps prevent delamination [2, 3]. These strengths make knitted fiber-reinforced composites a prime candidate for applications favoring low weight while maintaining strength, such as with carabiners.

Carabiners are widely used from rock climbing, sailing, construction, and even military applications. Carabiners are used to attach a climber’s harness to safety ropes but can also be used to attach various tools and equipment on one’s harness. Especially in the case of rock climbers, who often carry many various pieces of equipment on their harnesses, the cumulative weight of many metal carabiners can add up to a considerable weight. Carrying a heavy load is extremely dangerous for climbers who are often in dangerous and exposed positions high up. Having lots of heavy metal carabiners on one’s harness can cause dangerous weight shifts, disrupt balance, and waste substantial amounts of energy. Decreasing the weight of carabiners can help lower overall carrying weight, which is a priority in climbing, to make rock climbing more energy efficient and safe [4, 5].

Some have attempted to decrease weight by creating polymer carabiners; however, polymer carabiners are too weak to use for climbing [6]. Composites are another promising alternative with light
weight and substantially greater strength than polymers [7]. Additionally, the high impact strength of composites is beneficial because carabiners need to have high impact strength for if the carabiner is slammed against a mountainside or wall during climbing.

For its potential to decrease weight while offering many strength benefits, composites are a promising candidate for carabiner use; however, as far as the authors know, research done by Scott [4] is the only paper that has attempted to create a composite design for carabiners. His approach examined many different types of composites, materials, and knitting patterns for their viability in carabiners. This broad view is useful to holistically examine composites for their potential in carabiners, but there needs to be a more focused and detailed testing approach to optimize the use of specific composite types in carabiners [4]. Therefore, we are focused on optimizing, specifically, knitted fiber-reinforced composites for carabiner use in order to decrease weight while maintaining strength. Our optimization process is centered around improving the tensile modulus of a knitted fiber-reinforced composite model by adjusting structural parameters and incorporating additional structural modifications.

Through the use of various programming, computer-aided design (CAD), and finite element analysis (FEA) platforms, our contribution can be summarized as:
- Optimizing the plain weft-knitted fabric loop structure to have improved tensile modulus and be comparable to commercial carabiner standards.
- Setting the stage for incorporating composites into carabiners and decreasing carabiner weight drastically by 44%.

In the next section, the methodology of our research is explained. In Section III, results are presented and discussed, and lastly in Section IV, the findings are summarized with additional future work.

2. Predicting Mechanical Properties

The loop structure of weft-knitted fabrics is complex, which can lead to high computational costs. Thankfully, due to the patternability of knitted fabrics, we only need to model a representative volume element (RVE) to predict how an entire fabric structure would behave. Modeling a RVE allows us to lower computational costs while still accounting for the complexity of the entire fabric structure.

Before a RVE can be modeled and tested, an established geometric model must be used to output coordinate points for the RVE. From those coordinate points, a CAD platform is used to create a 3D visualization of the structure, which is then tested in an FEA platform to predict the mechanical properties of the structure. In the following subsection, the creation of the 3D structure of our composite is described.

2.1. Geometric Modeling of Plain Weft-Knitted Fabric

Vassiliadis et al. [8] have created a geometric model for plain weft-knitted fabric that has improved on past models, so we used their methods to create our fabric structure.

The geometric model is based on a few main structural parameters: the course spacing $c$, wale spacing $w$, and the thickness of the yarn $D$. Variables other than $x$, $y$, $z$, $c$, $w$, and $D$ have their own separate pre-defined functions that ultimately contribute to the three main functions in the following column [8]. The model ultimately uses the following three main functions to output coordinate points $(x, y, z)$ for part ΣΜΚΛ of Figure 1. Part ΣΜΚΛ describes a quarter loop, which can be later duplicated and reoriented to create the structure shown by Figure 1. Figure 1 represents our eventual loop model, which consists of two interlocking half loops. These half loops serve as a RVE because an entire fabric structure is just composed of identical repeated interlocking loops.
The following equations (1-6) describe the coordinates \((x, y, z)\) of the three parts of \(\Sigma\)MKΛ:

**Part \(\Sigma M\) \(\{0 < y < \frac{c}{2}\}\):**

\[
x(y) = -\frac{d}{c}y
\]
\[
z(y) = \sqrt{(r + \frac{d}{2})^2 - y^2} - (r + \frac{d}{2})
\]

**Part \(MK\) \(\{\frac{c}{2} < y < \frac{c}{2} + R\}\):**

\[
x(y) = h - a\sqrt{1 - \left(\frac{y - \frac{c}{2}}{b}\right)^2}
\]
\[
z(y) = \sqrt{(r + \frac{d}{2})^2 - y^2} - (r + \frac{d}{2})
\]

**Part \(\Lambda\) \(\{x(y = \frac{c}{2} + R) < x < w/4\}\):**

\[
z(x) = OZ - \sqrt{A^2 - (x - OX)^2}
\]
\[
y(z) = \sqrt{(r + \frac{d}{2})^2 - (z + r + \frac{d}{2})^2}
\]

These equations are inputted into a programming platform to output hundreds of coordinate points along the quarter loop \(\Sigma\)MKΛ. These coordinates are then imported into a CAD platform where the quarter loop is given a thickness, duplicated, and reoriented to create the interlocking half loop RVE.
Next, a matrix must be incorporated with the fabric to form a composite. The matrix must be tight-fitting in order to obtain accurate fiber volume percentages, so we surrounded the fabric by a tight-fitting box that represents the matrix. Finally, based on simulation results, additional designs, such as inlays were incorporated into the structure to reinforce certain aspects.

The final structure includes a vertical inlay to reinforce the strength of the composite in the wale direction. As for materials, we used carbon fibers and a Victrex PEEK 90HMF40 matrix. These materials were selected for their high tensile modulus, abrasion resistance, toughness, low density, and environmental durability [4]. The final model is as shown in Figure 2 above.

2.2 Finite Element Analysis of the Unit Cell
The 3D representative unit cell created in the CAD is then imported into an FEA platform to perform stress analysis tests. We tested the models in the wale (axial) and course (transverse) directions by fixing one side and applying a fixed displacement to the opposite side while calculating the volumetric stress as an output. Stress strain curves were then created based on the results of these tests.

We used initial results to modify the inlay design and thickness and to optimize fiber volume percentage. The highest-performing parameters were implemented in the final design as mentioned in the previous subsection.

Once the optimal composite design and parameters were determined, the optimal composite was then compared to standard carabiner materials subjected to the same loading circumstances. To account for variability in mechanical performance due to structural geometry, the aluminum and steel models were the same dimensions as the composite matrix. The full detailed results and analysis of the optimization of our composite model is presented in the following section.

3. Predicting Mechanical Properties

3.1. Optimization of the Composite Structure
Before our composite was compared to standard carabiner materials, it was first optimized. Additionally, comparisons were made to show the advantages of knitted fiber-reinforced composites over unidirectional (UD) fiber-reinforced composites and lone knitted fabrics.

First, an ideal fiber volume percentage was determined by tensile modulus, or stiffness. We tested 3.95%, the base model fiber volume; 7% and 11%, two intermediate values; and 20%, the maximum fiber volume percentage that the loop geometry allows space for. As shown in Figure 3, we determined the optimal fiber volume percentage with the highest stiffness to be the maximum fiber volume of 20%. This result was expected because the modulus of the carbon fibers is much higher than the modulus of the matrix, so increasing the fiber volume percentage increases the overall strength of the structure.

Next, the inlay structure was optimized. As shown in Figure 4, the knitted fiber-reinforced composite is stronger in the course, or horizontal, direction than the wale, or vertical, direction, so we added a vertical inlay that improved the strength in the wale direction by 2 GPa. We also found that the thicker the inlay, the better the stiffness of the fabric. To maximize the knitted loop yarn thickness and given the limited space with 20% fiber volume of the knitted fabric, we determined the optimal inlay thickness to be the same diameter as the knitted yarn thickness. Now, with this optimized model, it must be established that a knitted fiber-reinforced composite is superior to a knitted fabric without a matrix.

Making carabiners out of solely knitted fabrics is not feasible because the fibers would be susceptible to environmental factors and abrasions that could compromise the fibers’ strength. A matrix must be incorporated with the knitted fabric to provide structural integrity, toughness, protection from harmful environmental conditions, and prevent friction between fibers.

Finally, as shown in Figure 4, in comparison to a UD fiber-reinforced composite, our knitted fiber-reinforced composite is weaker in the longitudinal, or fiber, direction but is stronger in the transverse direction. Despite being weaker in the longitudinal, or wale, direction, knitted fabrics have closer similarity in both the wale and course direction strength. The superior biaxial strength of knitted fabrics is beneficial for rock climbing where stresses are not always unidirectional. Additionally, knitted fabrics offer the benefits of increased impact strength and contourability. Based on these results, it can be
established that our optimized knitted fiber-reinforced composite is superior to UD fiber-reinforced composites.

**Figure. 3.** Tensile modulus of various knitted fiber-reinforced composite fiber volume percentages. This shows that increased fiber volume leads to an increased tensile modulus.

**Figure. 4.** Comparison of tensile modulus of UD and knitted fiber-reinforced composites in different directions shows the advantage of UD in the longitudinal direction and the advantage of the knitted in the transverse direction.

**Figure. 5.** Stiffness comparison of optimized composite and standard climbing-grade aluminum and steel. The labeled tensile moduli show the similar stiffnesses for our composite and aluminum.
3.2. Comparison to Standard Materials

The final step is to gauge the viability of our optimized knitted fiber-reinforced composite by comparing it against aluminum 7075-T6 and steel, which are common climbing-grade carabiner materials. First, our composite was compared in terms of stiffness, or tensile modulus. Figure 5 shows how our composite is very comparable to the stiffness of aluminum, which indicates that our composite should have adequate stiffness for carabiner use. Steel had a much higher stiffness than both aluminum and our composite. However, steel is almost three times heavier than both aluminum and our composite, so its strength to weight efficiency is inferior to the excellent strength to weight efficiency of our composite.

We quantified strength to weight efficiency by calculating specific stiffness, which is tensile modulus divided by the density of the material. Figure 6 shows that the specific stiffness of our composite is almost double the specific stiffness of both aluminum and steel, which demonstrates that our composite can greatly decrease the weight of a carabiner, approximately 44%, while maintaining strength.

4. Predicting Mechanical Properties

We have shown that knitted fiber-reinforced composites have the potential to drastically reduce the weight of carabiners and still maintain strength. We also found that the course direction of our composite design is the strongest, so for future reference, we recommend that the course direction of the composite is aligned with the longitudinal axis of a carabiner structure.

These results establish the promising potential of knitted fiber-reinforced composite carabiners, but many future steps must be taken before climbing-grade composite carabiners can be made commercially available. To start, we focused exclusively on plain weft-knitted fabrics, but many other knitting patterns should be investigated, such as milano, full-cardigan, and ribbed knits. Additionally, we only tested a representative structure in simulation, so the next step would be performing real physical tests, such as impact drop tests and stress tests that extend to fracture point, on a full carabiner structure. Finally, a viable and cost-efficient production process must be laid out to show the commercial practicality of composite carabiners.

There is much more work to be done, but with this paper providing an optimized knitted fiber-reinforced composite design, a solid foundation has been set with the hope that eventually knitted fiber-reinforced composites can make rock climbing more energy-efficient and safe.
5. References

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