Biomimetic Silk Architectures Strengthened by “Welding” Perform Well in Strength and Toughness

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Introduction

Light, strong, and tough materials (LSTMs) are highly demanded in a variety of fields. However, constructing high-performance LSTMs is still a significant challenge recently. For instance, traditional inorganic materials with high specific strength and modulus are unsuitable for light weight applications. Also, advanced fabrication process such as 3D printing and two–photon lithography are energy and time consuming. Therefore, we are looking for innovative ways to construct an organic LSTM.

Silk possesses a well-established texture. Our biomimetic silk-LSTM(BS-LSTM) ’s structure is inspired by the herringbone structure of odonodactylus scyllarus ’ dactyl club. The structure is known for its outstanding mechanical behavior, which can deliver strikes with accelerations exceeding 105 m/s² and speeds of 23 m/s. (J. C. Weaver et al., 2012)

Still, the fabrics we made are too unwound and loose between the layers. Our experiments have confirmed that silk fibers can be successfully “welded” into a whole structure to increase its strength using hexafluoroisopropanol (HFIP).

Our study shows that the strategy of integrating textile processing and fiber “welding” can effectively improve the strength of the fabrics and it has potential to be used in different areas of studies.

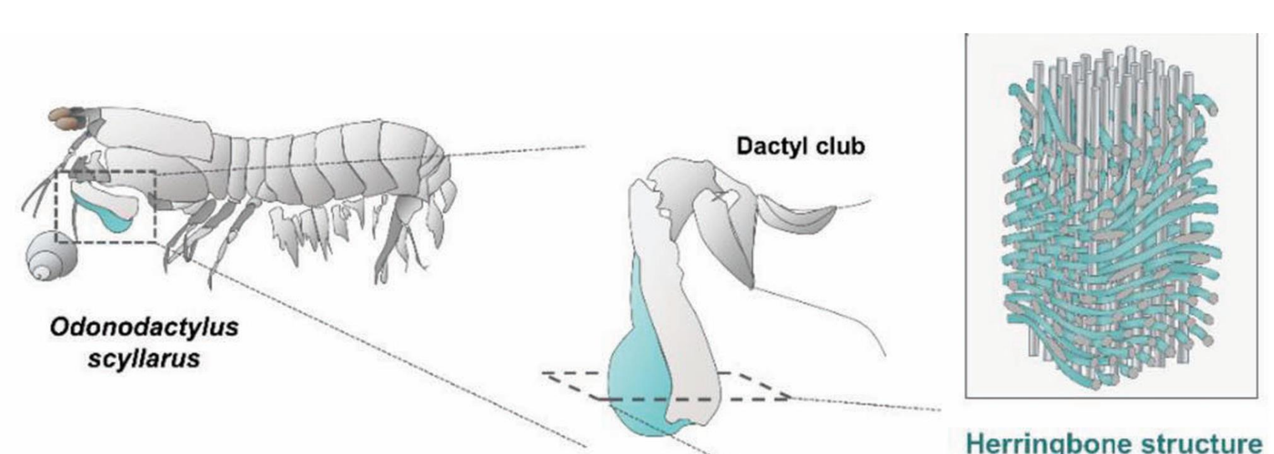

Fig 1. the dactyl club of odonodactylus scyllarus and its herringbone structure (Liu et al., 2023)

Research Questions

How to fabricate a kind of light, strong, and tough material (LSTM) inspired by odonodactylus scyllarus without using the advanced ways?

How to increase (biomimetic silk-LSTMs) BS-LSTMs’ strength and toughness?

How to validate the strength and toughness of BS-LSTM?

Methods

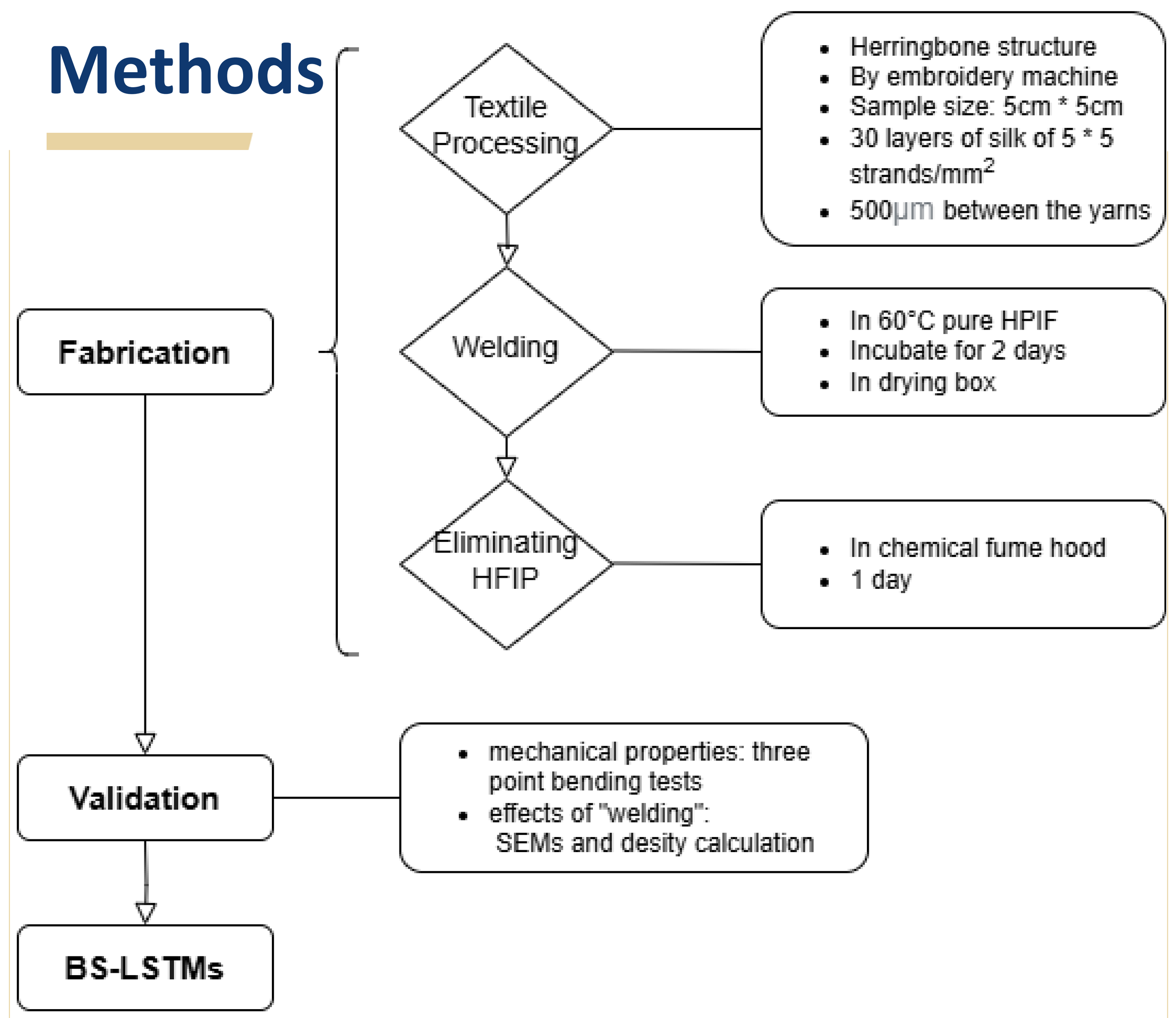

Fig 2. the process of fabricating and validating the mechanical performance of our BS-LSTM

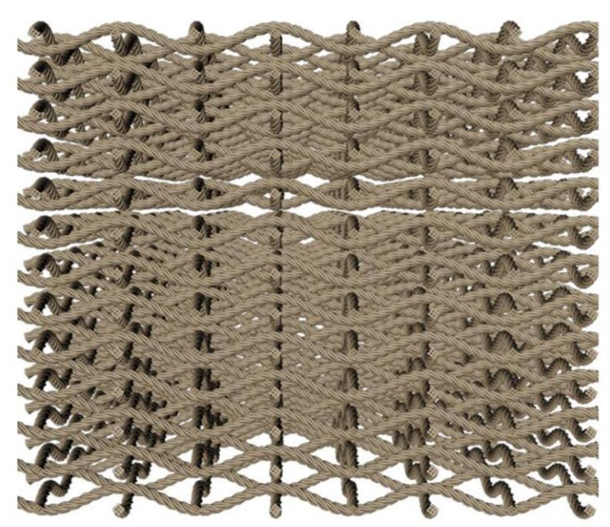

Fig 3. the structure of our herringbone BS-LSTM (Liu et al., 2023)

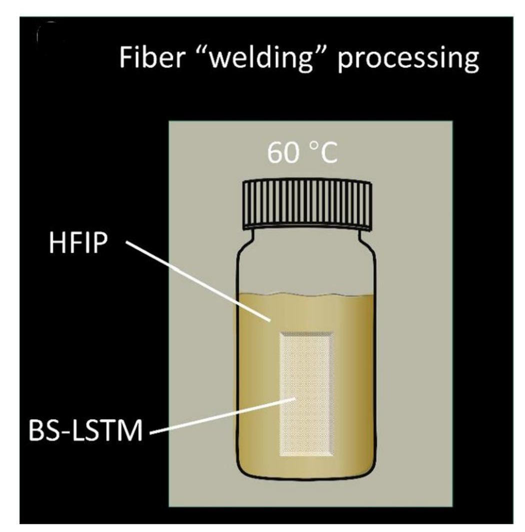

Fig 4. the process of “welding” (Liu et al., 2023)

The theory of “welding

The HFIP partially dissolved the silk fibers, resulting in the formation of adhesive surfaces. The dissolved fibers would be sticked into a tight whole body.

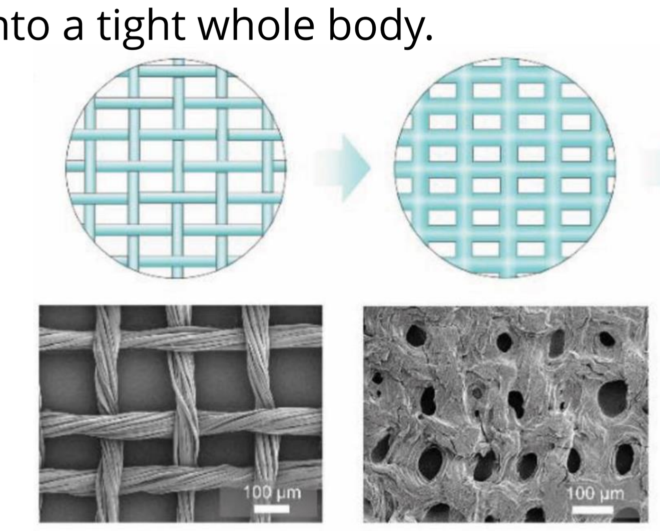

Fig 5. the schematic and SEM photography of BS-LSTMs welded for 0 days and 2 days (Liu et al., 2023)

Findings

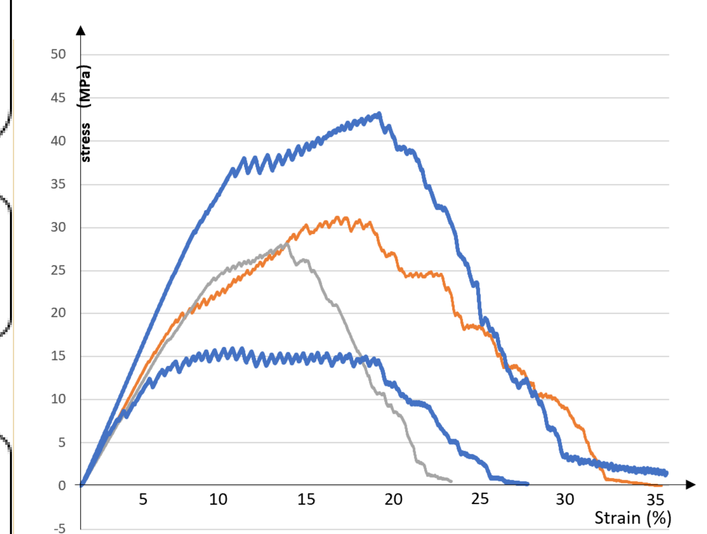

Fig 6. the stress-strain curve of the samples of silk fabrics we choose during the tension test

The maximum stress the silk fabrics we choose is about 43.24MPa, and the average Young’s modulus of the material we choose is about 224.63 MPa. The data shows that silk itself is a kind of light but strong material, and that is also the reason of choosing it to fabricate our BS-LSTM.

Single layer of silk

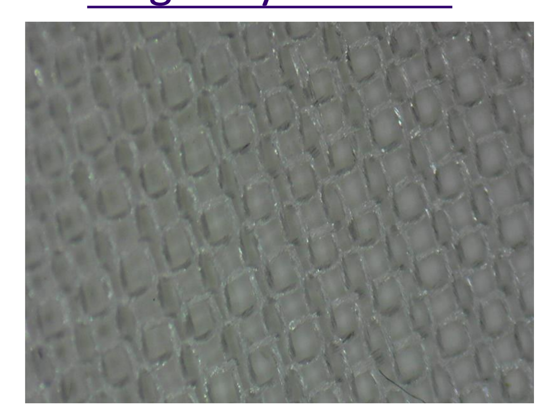

Fig 7. single layer of silk before “welding” with density of 0.1131 g/cm³

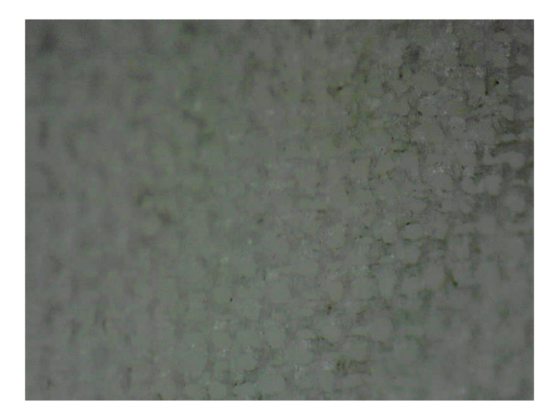

Fig 8. single layer of silk after “welding” with density of 0.1525 g/cm³

Fabrics with herringbone structure

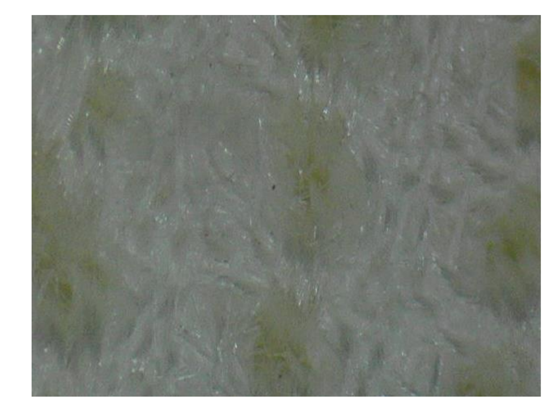

Fig 9. BS-LSTM before “welding” with density of 0.3836 g/cm³

Fig 10. BS-LSTM after “welding” with density of 0.5198 g/cm³

From the comparison of silk and BS-LSTM, we can see that the fibers are partially dissolved by HPIF. Also, the density of the “welded” fabrics increases. These findings show that the “welding” process can effectively increase the tightness of the BS-LSTMs.

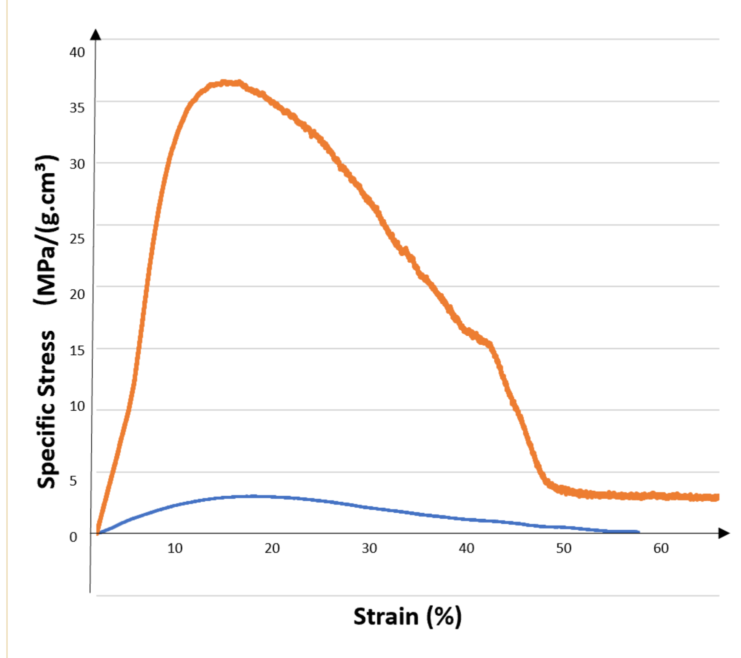

Fig11. the specific stress-strain curve of the BS-LSTMs “welded” for 2 days and 0 days during the three points bending test

The maximum specific stress that the “welded” BS-LSTMs is about 36.61 MPa/(g.cm³); and the maximum specific stress that the not “welded” BS-LSTMs is about 3.04 MPa/(g.cm³). The maximum specific stress the “welded” BS-LSTMs can receive is about 12 times greater than the not “welded” ones. The great difference shows the significant effect of “welding” on BS-LSTM’s strength and toughness.

Through comparison between BS-LSTMS and other materials, we can see that BS-LSTMs have high specific toughness and specific strength. It performs well mechanical properties such as rigidness.

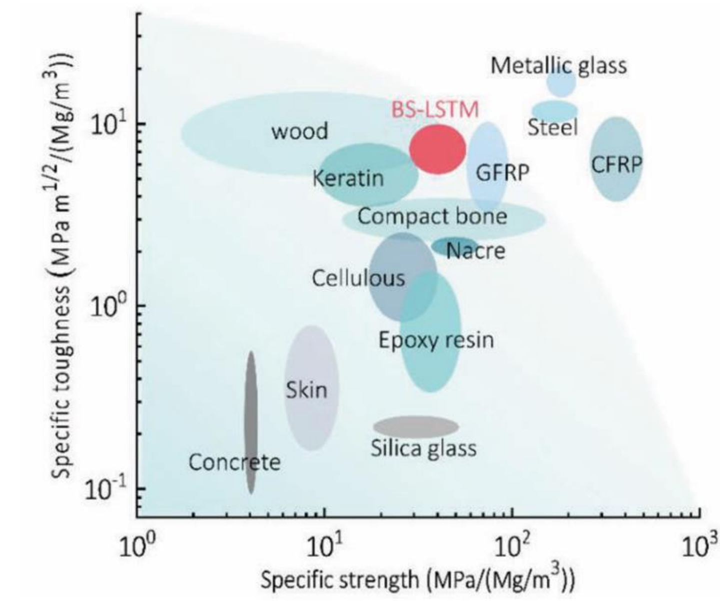

Fig12. the specific toughness-strength curve of the BS-LSTMs “welded” for 2 days and other materials (Liu et al., 2023)

Discussion

Our LSTM avoids using consuming advanced technologies. We used silk as raw material, combined the bioinspired way of textile processing and the innovative “welding” process to fabricate a kind of BS-LSTM. Furthermore, we use different validation ways such as three points bending test and stereo microscopy to prove that our BS-LSTMs perform well mechanical properties such as strength and toughness. Therefore, our method of fabrication is rational, cost-effective, and efficient.

Because of the great mechanical properties our BS-LSTMs have performed, BS-LSTMs have the potential to be used in different areas such as biomedicine, mechanical engineering, intelligent textiles, aerospace industries, and beyond.

Furthermore, we anticipate that the future studies can be based on the following topics. First, we want to further enhance our BS-LSTMs, and we can try by “welding” for a longer time. Second, HPIF is a kind of corrosive solution, and it is hard to completely eliminate the remaining HPIF after “welding”. Therefore, people need to consider about the safety issue of BS-LSTM, and that would limit the application of the material. We would like to find other solution for “welding” or ways to eliminate HPIF efficiently. Lastly, we want to research about how to mass produce BS-LSTMs. The main challenges we are facing is that HPIF is a little costly for mass production, and the efficiency of the embroidery machine is not high enough. We want to improve the procedure and mass produce out BS-LSTMs.

Acknowledgement

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Reference

Y. Liu, Y. Li, Q. Wang, J. Ren, C. Ye, F. Li, S. Ling, Y. Liu, D. Ling, Biomimetic Silk Architectures Outperform Animal Horns in Strength and Toughness. Adv. Sci. 2023, 10, 2303058 https://onlinelibrary.wiley.com/doi/10.1002/advs.202303058

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