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The Comparison and Application of 3D-modeled Sutures in the Ironclad Beetle *Phloeodes diabolicus* for Use in Load-Bearing Construction

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Author's contribution

The sole author designed, analyzed, interpreted and prepared the manuscript.

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ABSTRACT

In this study, 3D printed breakboards based on the elytral suture of *Phloeodes diabolicus* were tested along with 3 other traditional joints with alterations in suture dimensions and variation in order to compare strength to weight efficiency, additionally accounting for displacement when under load. These models were then tested to measure both strength and displacement over time in order to quantify load tolerances. Our hypothesis suggests that the 2-layer thick ironclad suture-based board would have the most efficient load-bearing capacity compared to other sutures presented in this experiment. Ironclad beetles, also known as the diabolical ironclad beetle, are renowned for their impressive load-bearing capacities and have been studied extensively by researchers for use in real-world biomimetic applications such as construction in the forms of buildings or bridges where strong load-bearing joints are critical. The utilization of such biomimicry in infrastructures can significantly increase load and stress tolerances while simultaneously minimizing excess material,

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creating more efficient, cheaper, and safer infrastructures for use. Our findings for the 1st testing phase did not fully align with our hypothesis, as the ironclad-modeled sutures were not the strongest joint in terms of strength-to-weight efficiency when compared to the other joint types. However, the 2-layer thick boards were measured to be exponentially stronger compared to boards with only 1 layer. Overall, the ironclad-based sutures were strong, but it underperformed compared to the other joints presented in the experiment. Due to the fact that the ironclad-based sutures in the 1st phase of testing might have not been reflective of the natural counterpart, a second phase of testing aimed at testing variations of more accurately constructed ironclad-based sutures is being implemented. However, this study facilitates the fundamental understanding of the detailed mechanics of ironclad beetles.

Keywords: Insect; joint; 3D modeling; phloeodes; coleoptera; structure; engineering.

1. INTRODUCTION

Phloeodes diabolicus is a species of ironclad beetles in the family Zopheridae (Rivera et al., 2020). The beetle is found in wooded areas all over California, feeding off of detritus such as fungi and rotting logs (Rivera et al., 2020). Many studies have been conducted in order to find out the beetle's true limits of durability and how it was able to withstand such extreme pressures (Rivera et al., 2020, Rivera et al., 2017, Rivera et al., 2021). In a 2015 paper led by Jesus Rivera, the researchers compared the tensile strengths of four different species, three *Tenebrioids* and *P. diabolicus*, due to the *Tenebrioids presented in the experiment, E. grandicollis*, *A. verrucosus*, and *C. muricata*, adopting a similar elytral adaptation to *P. diabolicus* where their elytra are also fused together (Rivera et al., 2020). What they found was that *P. diabolicus* had a maximum load-bearing capacity at ~150 newtons, over twice the maximum of the runner up in maximum load-bearing, the *A. verrucosus*, the second most durable in the experiment, at ~60 newtons as illustrated in Fig. 3 (Rivera et al., 2020).

To compare what it means for *P. diabolicus* to be able to bear up to ~150 newtons of force, with an average of 133±16 newtons, a few real-world comparisons are in order. This is the equivalent to it withstanding approximately 39,000 times its own body weight. In human terms, this would be as if a 70 kg person is able to withstand the combined weight of approximately 14 blue whales, each weighing up to ~180 metric tons [1]. Many studies found that the key to achieving this feat was the heavily modified elytra the beetle had, being thickened and fused at both the abdomen and elytra (Rivera et al., 2020). Many other beetles from other families such as *Tenebrionidae* also share this adaptation to an extent, yet they cannot withstand nearly as much pressure before collapsing (Rivera et al., 2020). The elytra are an adaptation unique to beetles where their forewings round and harden to form protective covers for their delicate hindwings and soft abdomen. This adaptation is incredibly useful to beetles as the elytra allow them to protect their weakest points while also giving most beetles the option of flight (Mavrikos and Grigoropoulos, 2024). Not only they were thicker than an average beetle elytron, the elytra of *P. diabolicus* were found to have sutures with multiple projections called blades, around 100 μm in width and running laterally with the elytral seam, that interlock with each other in a way that fused them together, akin to how a zipper functions (Rivera et al., 2020). This adaptation caused the seams, normally critical weak points of a beetle, to be just as strong as, if not stronger than the surrounding material. It was also found that the chitinous structure of the elytra formed in a layered fashion akin to an onion with irregular chitin fibers composing the endocuticle layers (Rivera et al., 2020). This not only allows minimal stress points within the elytra, leading to less fractures, but also in a potential case of a structural failure, the elytra delaminates in layers, rather than a sudden collapse, allowing the beetle to survive being run over by cars, albeit permanently damaged as they cannot regenerate from injuries due to them being holometabolous, having a distinguished larval, pupal, and adult phase that prevents regenerative molts from occurring post-maturation. This strong fusion between separate materials shows significant promise of modern use in biomimetic architecture (Rivera et al., 2020, Rivera et al, 2017). Aside from the physical architecture of the elytra, studies conducted on a closely related species known as *Zopherus nodulosus haldemani* showed the presence of additional minerals incorporated into the exoskeleton, allowing for a

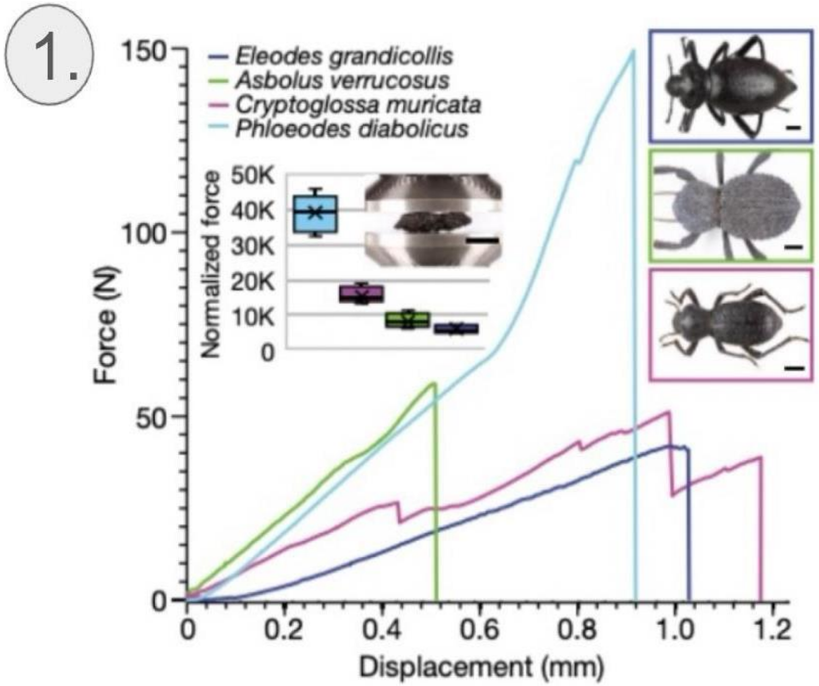

Fig. 1. Graph comparing P. diabolicus [light blue] with multiple Tenebrioids[1]
(top to bottom: E. grandicollis [dark blue], A. verrucosus [green], C. muricata [magenta])

[1] *Credit: Springer Nature Unlimited*

stronger material as a whole (Nguyen, 2017, Rivera, 2020). These factors make *Phloeodes diabolicus* incredibly compression-resistant, allowing it to survive strikes from birds and other predators in the wild. The research question for this paper was this: how do the sutures of ironclad beetles compare with man-made sutures, and is there a way to further improve the efficiency of these sutures by changing their dimensions to fit the load-bearing needs of our ever growing society?

1.1 Research Hypothesis

This study hypothesized that the break boards that utilizes the suture of the 3d printed structures modeling an ironclad beetle-like seam with a height of 2 units and a suture width of 20 mm would have the highest weight-carrying force capacity to mass ratio when compared to other variations of sutures and dimensions featured in this experiment. This is due to the assumption that ironclad beetles utilize their modern elytral suture over other varieties of joints due to being the most evolutionarily efficient at distributing vertical load, therefore the performance of such structures would be reflected in controlled experimentations.

2. EXPERIMENTAL METHODS

2.1 Materials and Manufacturing Technique

2.1.1 Equipment

Our Bambu Lab P1S 3D Printer as shown in Fig. 4 was purchased from the official Bambu Lab website. An electric scale, having accuracy of 10 mg was used to measure our model weight to hundredth of a gram. Bambu PLA "matte" (Ash Gray) filament was used as base material, while both the Vernier Structures and Materials Tester (VSMT) and the LabQuest 2 was provided by the Dwight-Englewood School for student use. A Macbook Pro was employed for saving, retrieving, and graphing data.

2.1.2 3D model specifications

All the models printed for the experiment were break-board-style structures, meaning that the boards were designed to break at the sutures in a controlled manner. They each were two slabs of plastic connected in the middle with various connection points, ranging from dovetail joints to ironclad suture to dowels (Fig. 3 a-d). The final combined structure is 10 cm by 5 cm in the X and Y axis, respectively, and each "unit" of connection points is 1 cm in the Z axis. All models will be printed on a Bambu P1S (Fig. 2) using "Bambu PLA Matte" filament, each using the default Bambu slicer settings.

2.1.3 Bambu settings [Printer + Slicer Settings]

The Bambu Lab P1S 3D Printer was setup as follows:

All models were printed usingBambu Lab's PEI "Gold" Plate, a standard 0.4 mm stainless steel nozzle,

- Bambu Lab P1S 3D Printer
- PEI gold build plate
- 0.4 mm Stainless Steel nozzle
- Layer Specifications
    - 0.2 mm layer height
    - Layer width between 0.42-0.5mm
- Infill Specifications
    - Rectilinear solid infill pattern
    - Grid sparse infill pattern
        - 15% infill
    - Monotonic surfaces
    - 2 layer thick walls
- Temperatures
    - 220˚C Nozzle Temperature
    - 55˚C Bed Temperature

2.2 Experimental Setup

The experiment was planned with 9 data points for each variant of suture, with three different sets of variables for each model, being the variation of sutures, the width of the sutures holding the boards together, the number of "units" of sutures stacked to see which option had the best strength to mass ratio. For the 1st round of testing, the dimensions of the boards were 10 cm in length, 5 cm in width, and 1-2 cm in height, depending on suture count, while the actual ledges of the VSMT were 8 cm apart. The second round of testing was solely composed of standard 10 cm * 5 cm * 1 cm (L*W*H) breakboards. Apart from board dimensions, the second phase utilized different variations of sutures, aimed at more accurately translating the internal structure of ironclad beetles into the experiment, with one being an accurate reconstruction of the joint, and the other being the same joint being the same joint scaled to better fit the joint parameters of phase 1 testing.

2.3 Experimental Protocol

The boards were first modeled and printed using Tinkercad and the P1S, respectively. Each half was then connected using their respective sutures, weighed, and placed into the VSMT, which was then connected to a computer via the internet via the Labquest 2. Each board was then stressed to the point of structural failure using the clamping mechanism of the VSMT, and their data points, such as strength and displacement, were fed into the LabQuest 2 which was then further relayed onto the EMMI program on a MacBook Pro. The recorded data points were then extrapolated from the EMMI and quantified into graphs.

Fig. 2a. Inside of printer midway through printing models
Fig. 2b. Models on build plate after finishing print
Fig. 2c. Bambu Lab P1S used to print the models

Fig. 2. Bambu Lab P1S printer used in the experiment

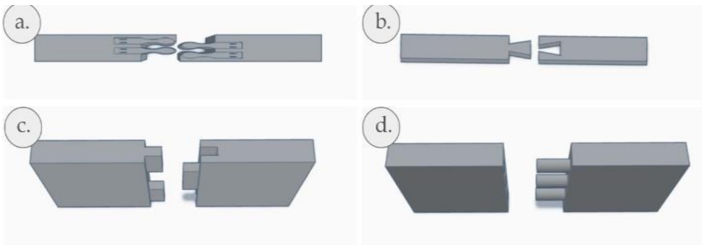

Fig. 3. 3D models [Tinkercad] of each joint variation are presentation in: 3a) Ironclad, 3b) Dovetail, 3c) Stub tenon, 3d) Dowels

Fig. 4a. Example of test model loaded into the VSMT for data-gathering

Fig. 4b. View of the experimental set up, displaying [left to right]
Computer with google slides to record model weights, scale to measure model weights, Vernier Structures and Materials Tester to measure model load capacity and displacement, Labquest 2 to record VSMT data and transfer to computer via internet

3. RESULTS AND DISCUSSION

3.1 Individual Graphs + Comparison of Various Sutures

There were four types of suture structure as below in Fig. 5, as listed stub tenon, pegs/dowels, ironclad and dovetail. Fig. 5 presents their load capacity for different lengths. At first, we found that the load capacities of 20 mm suture were mostly significantly greater than those from 10 mm suture. It might mean that the length of the suture played an important role like a mechanism of fulcrum. The load capacities from ironclad beetles were comparable to other suture types in 20 mm, while it was smaller when tested with 10 mm suture.

3.2 Test Phase 1 Data Summary

3.2.1 Category results averaged

Our data is summarized as in Table 1

Control

- ~ 44.98 N/g [10 mm height]
- (range in-between ~54.6 - ~183.68 N/g) [20 mm height]

Ironclad

- ~2.27 N/g [10 mm height]
- ~9.27 N/g [20 mm height]

Dovetail

- ~3.34 N/g [10 mm height]
- ~7.65 newtons /gram [20mm height]

Stub tenon

- ~8.60 N/g [10 mm height]
- ~10.44 N/g [20 mm height]

Pegs/dowels

- 5.26 N/g [10 mm height]
- 9.89 N/g [20 mm height]

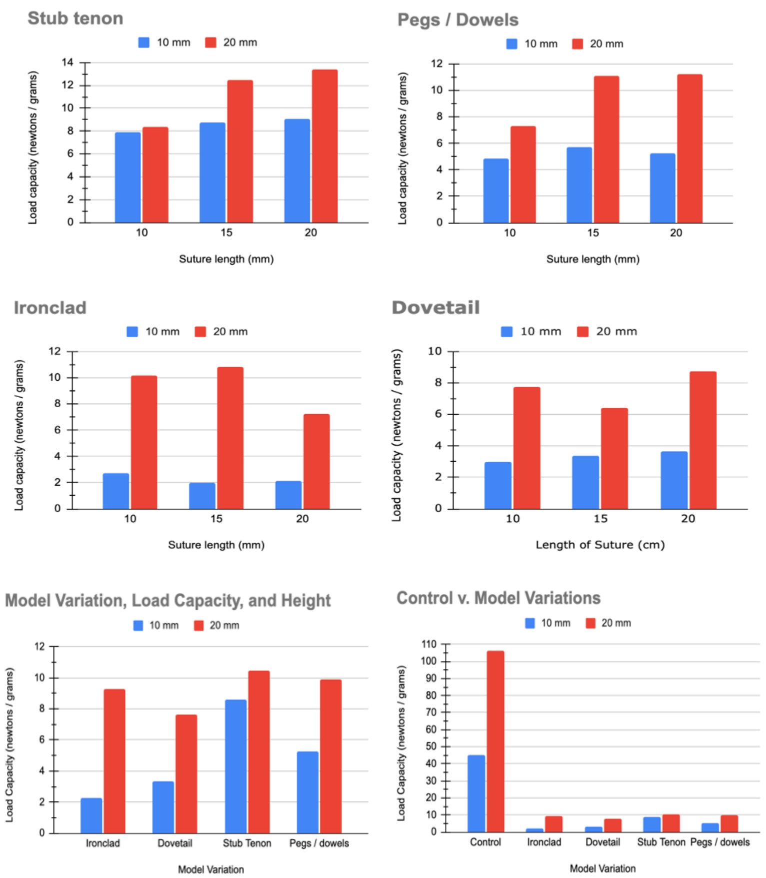

Fig. 5. Summarized bar graphs for each non-control breakboard, displaying the maximum load threshold value for each board variation The last two graphs display the comparison of the averaged load-bearing capacity values of each suture type

Table 1. The enduring force capability per mass for the structure types in this study

Structure Type	10 mm Height (N/g)	20 mm Height (N/g)
Control	~ 44.98	~106.47*
Ironclad	2.27	9.27
Dovetail	3.34	7.65
Stub tenon	8.60	10.44
Pegs/dowels	5.26	9.89

3.2.2 Summarized results

Overall the stub tenon joint outperformed other suture variations by a significant margin, having the largest load tolerances in both 10 mm and 20 mm categories. The peg and dowels variant had the second largest load tolerances in both 10mm and 20 mm categories. The ironclad-modeled suture had the third largest load tolerance in the 10 mm category, yet was the weakest joint tested for the 20 mm category. The dovetail joint conversely had the lowest measurements for the 10 mm category while averaging higher than the ironclad-modeled joint in the 20 mm category.

3.2.3 Relationship between model load capacity and height

The results displayed that the height of the model significantly impacted load capacity within the models in a positive-exponential relationship. This is most effectively displayed by the ironclad-based sutures, where the 10 mm high models averaged ~2.27 N/g while the 20 mm high models were a much higher ~9.27 N/g. This is approximately a strength ratio of 1:4.08 every time the model's height is doubled.

3.2.4 Relationship between suture length, displacement values, and load capacity

The suture width also had a noticeable positive effect, although less consistent, with both the load capacity and the displacement value at maximum load. This is exemplified by the majority of the models 20 mm in height, where the models with longer joints not only the displacement value before structural degradation is greater, but also have a small but consistently higher load tolerance. However, several 10 mm tall models as well as notable exceptions such as the ironclad-based models were an exemption to this relationship. This may be due to printing inconsistencies as such a scale, or could simply be outliers. Due to lack of sample sizes, this relationship cannot be determined yet to be exponential, like the model width with load capacity, or linear. Further research is needed to further contextualize this relationship between suture length, displacement, and load capacity.

3.3 Summarized Discussion

In short, our testing displayed that the thickness of sutures increases the weight threshold on an exponential rather than linear scale, leading to several issues associated with the limitations with data-gathering. The VSMT used in the experiment was a dated model, meaning not only there were little resources on operation, but there were bugs and limitations that came unexpectedly. Firstly, the machine itself only had a maximum load threshold of 1000 newtons before operational failure, which became a large issue as several models I tested went well above the 1000 N threshold. This included the 20 mm high control and the majority of a third category comprising 30 mm high models. While I was able to somewhat substitute the 20 mm control by applying the exponential relationship consistently found within the other suture variation to the control, I had to abandon the 30 mm high models due to insufficient data and the possibility of equipment damage from attempting to measure. Despite such limitations and setbacks, I was ultimately able to gather sufficient data for a baseline study, and plans are currently being rectified in order to further expand on this experiment.

4. CONCLUSION

Our findings showed that the ironclad-modeled sutures were not the strongest type of joint presented in the experiment, as it averaged as the third place in durability when having two layers, averaging around ~9.27 N/g of material, and last place when having only one layer, averaging ~2.27 N/g of material, both of which fell below expected results. Comparatively, the type of joint that averaged as the most durable consistently were the models with the stub tenon joints, averaging ~8.60 N/g for one layer and ~10.44 N/g for two layers. The models utilizing pegs/dowels came next with ~5.26 N/g for one layer and ~9.89 N/g for two layers, with dovetailjointed models following behind with ~3.34 N/g for 1 layer and ~7.65 N/g for two layers.

The thickness of each board additionally significantly affected the strength required for structural failure at a positive exponential relationship, making it significantly more difficult to break boards of two times thickness than boards of just normal thickness. This was the leading cause of needing to discontinue the usage of a 3rd height category of models due to them exceeding the 1000 newton limit of the VSMT. The length of each suture also had an effect on the models' strength, as models with longer suture generally had a higher displacement rate when at peak load capacity and were able to on average, albeit inconsistently, increase the strength of the joint marginally. Additionally, the time to break the models did not have significant effects on the study, as the results were highly variable due to human inconsistency and had no effects on the other variables. In future experimentation, I plan to adopt a more proportionally accurate suture to represent the ironclad beetles, as well as experiment with different 3D printing techniques to minimize part tolerances as well as adding more anatomical detail to the sutures. New results based on future experimentation may reveal the sutures of ironclad beetles to have practical applications in modern construction, allowing connections between support structures such as beams and framework to consume less fastening materials in the form of screws and bolts while simultaneously providing greater load tolerances, creating stronger and safer structures for societal use.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author hereby declares that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Author has declared that no competing interests exist.

REFERENCES

Castelvecchi, D. (2020, October 21). This beetle's stab-proof exoskeleton makes it almost indestructible. *Springer Nature Unlimited*, *586*, 543–548.

Lee, N., Berthelson, P. R., Nguyen, V., et al. (2021, March 19). Microstructure and nanomechanical properties of the exoskeleton of an ironclad beetle. *Bioinspiration & Biomimetics*. https://doi.org/10.1088/1748-3190/abe27b

Mavrikos, S., & Grigoropoulos, C. P. (2024, March 12). Profile and microstructure accuracy of two-photon polymerization fabricated structures: The case study of *Phloeodes diabolicus*. In *Laser-based Micro-and Nanoprocessing XVIII* (Vol. 12873, pp. 79-85). SPIE.

Nguyen, V. N. (2017). Structure -property relations of the exoskeleton of the ironclad beetle (*Zopherus nodulosus haldemani*). ProQuest LLC., 10642091, 60. https://www.proquest.com/openview/48d637569b7a72c5e360ff983e7dd0a0/1?pq-origsite=gscholar&cbl=18750

Rivera, J. (2020, September). Structure-property relationships, and biomimetic designs from the compression-resistant cuticle of the ironclad beetle. https://www.proquest.com/openview/19b15b37506d2af2b267f8e56368fe5a/1?cbl=18750&diss=y&pq-origsite=gscholar

Rivera, J., Hosseini, M. S., Restrepo, D., Murata, S., Vasile, D., Parkinson, D. Y., Barnard, H. S., Arakaki, A., Zavattieri, P., & Kisailus, D. (2020). Toughening mechanisms of the elytra of the diabolical ironclad beetle. *Springer Nature Unlimited*, *586*, 543-548.

Rivera, J., Hosseini, M. S., Trikanad, A. A., Murata, S., James, R., Pickle, A., Yaraghi, N., Matsumoto, N., Yang, W., Parkinson, D. Y., Barnard, H. S., Arakaki, A., Zavattieri, P., & Kisailus, D. (2021). Structural design variations in beetle elytra. *EBSCO Industries, Inc.*, *31*(50), 8. https://research.ebsco.com/linkprocessor/plink?id=6735a3c9-8b84-34b7-973a-2098b956f868

Rivera, J., Yaraghi, N., Arango, D. R., Zavattieri, P., & Kisailus, D. (2017). Compression resistant designs from the exoskeleton of a tough beetle. https://iccmcentral.org/Proceedings/ICCM21proceedings/papers/4300.pdf

Wickramasinghe, S., Al-Ketan, O., Peng, C., Tee, Y. L., Kajtaz, M., & Tran, P. (2023). Influence of design parameters on the flexural properties of a bio-inspired suture structure. *Virtual and Physical Prototyping*, *18*(1).https://doi.org/10.1080/17452759.2023.2204845

Wickramasinghe, S., Do, T., & Tran, P. (2022, May 26). Flexural behavior of 3D printed bio-inspired interlocking suture structures. *Materials Science & Additive Manufacturing*, *1*(9).

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