Original Research Article

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

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Abstract

Ironclad beetles are renowned for their impressive load-bearing capacities and have been studied extensively for potential real-world applications such as construction in the forms of buildings or bridges where load-bearing joints are crucial. 3D printed breakboards based on the elytral suture of *Phloeodes diabolicus,* along with 3 other traditional joints, were tested with alterations in suture dimensions and variation in order to compare strength to weight efficiency, additionally accounting for displacement when under load. These models are tested utilizing a Vernier Structures and Materials tester to measure both strength (N) and displacement (cm) over time (s). Our hypothesis suggests that the 2-layer thick ironclad suture-based board would have the most efficient load-bearing capacity. 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. 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 nonetheless facilitated a further understanding of the detailed mechanics of ironclad beetles.

Keywords: Insect; Joint; 3D Modeling; Phloeodes; Coleoptera; Structure; Engineering

1) INTRODUCTION

1.

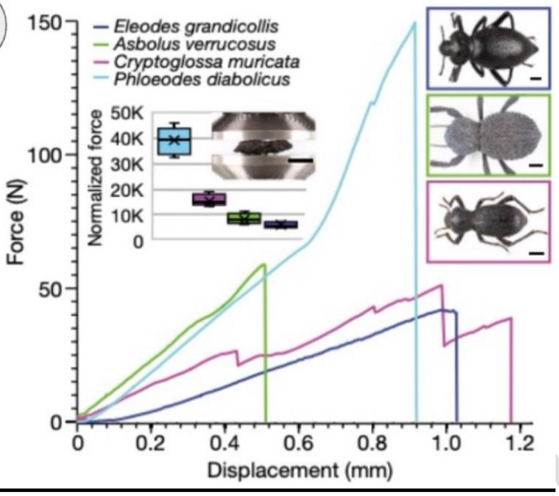

Fig. 1) Graph comparing P. diabolicus [light blue] with multiple Tenebrioids
(top to bottom: E. grandicollis [dark blue], A. verrucosus [green], C. muricata [magenta])
(Credit: Springer Nature Unlimited)

Phloeodes diabolicus is a species of ironclad beetles in the family Zopheridae [1]. The beetle is found in wooded areas all over California, feeding off of detritus such as fungi and rotting logs [1]. 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 [1,2,4]. 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 [1]. 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 [1].

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 [1]. Many other beetles from other families such as *Tenebrionidae*

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also share this adaptation to an extent, yet they cannot withstand nearly as much pressure before collapsing [1]. 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 [5-7]. 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 [1]. 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 [1]. 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 [1,2]. 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 stronger material as a whole [3]. 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?

This study hypothesized that the break boards, which are boards with a suture in the middle designed for controlled structural failure, 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.

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2. EXPERIMENTAL METHODS

2.1) Materials and Settings

2.1.1) Equipment

- Our Bambu Lab P1S 3D Printer as shown in Fig. 4c 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.

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

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.

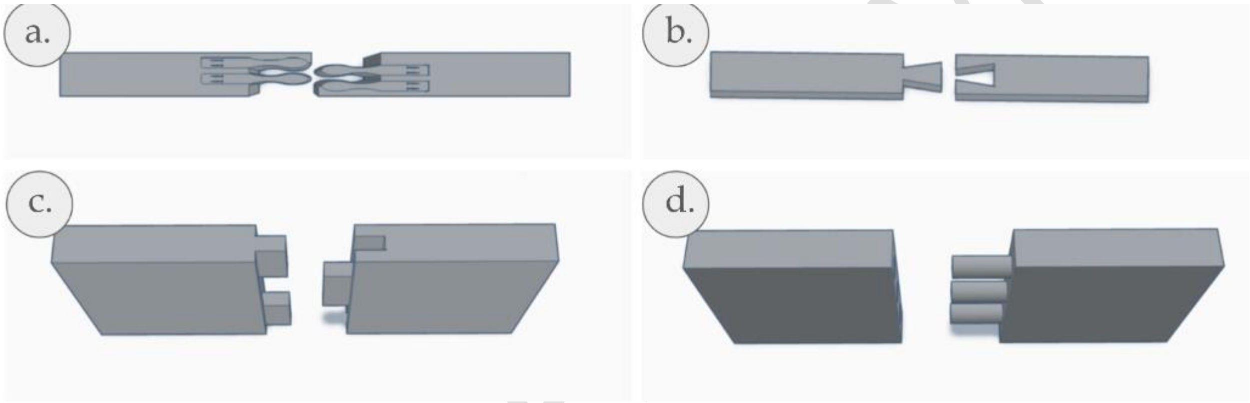

Fig 3D models [Tinkercad] of each joint variation are presentation in:

3a) Ironclad

3b) Dovetail

3c) Stub tenon

3d) Dowels

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

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    - 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

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

3.3) Experimental Set up:

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

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joint, and the other being the same joint being the same joint scaled to better fit the joint parameters of phase 1 testing.

3.4) 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

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.

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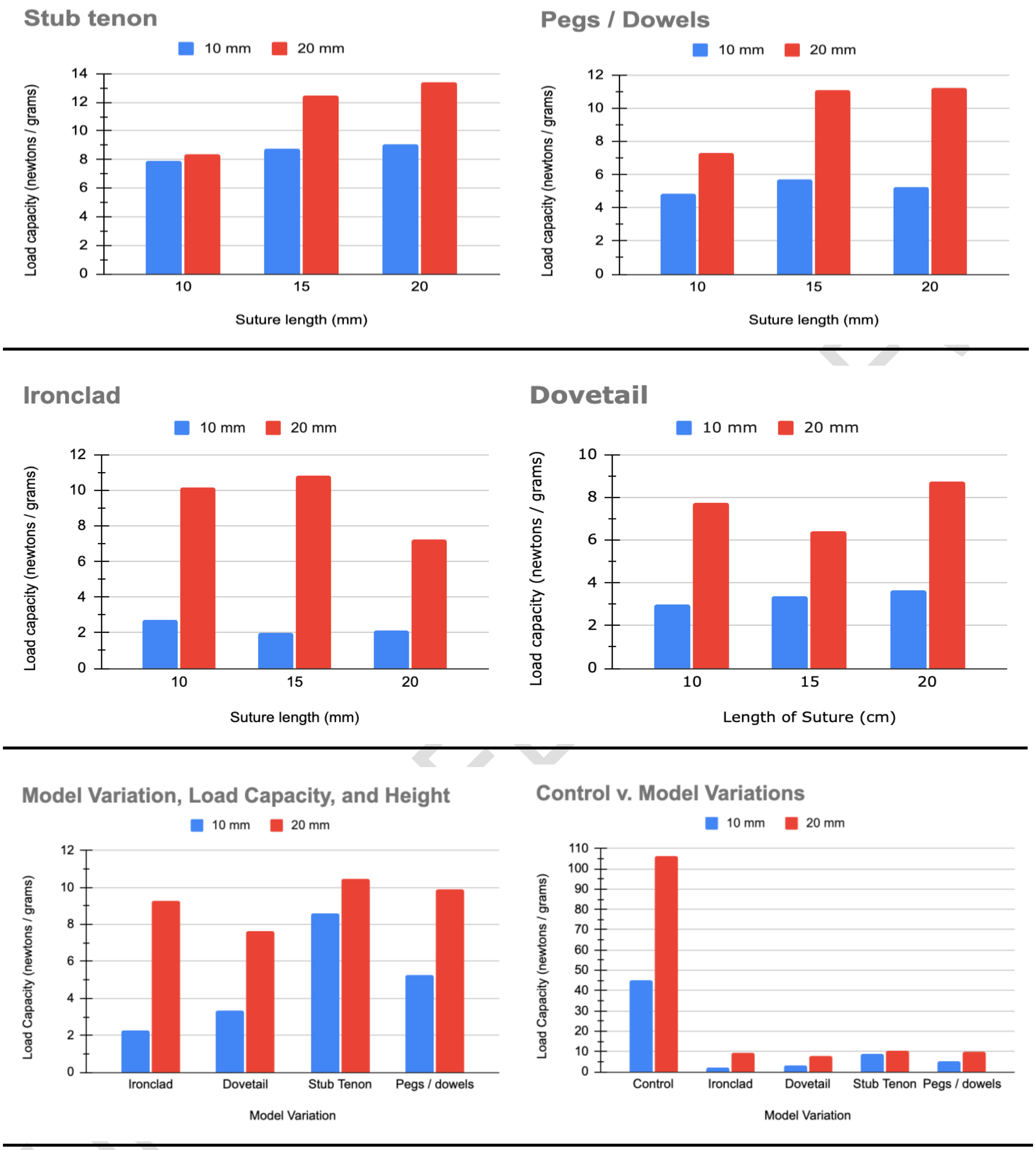

Fig. 5 presents summarized bar graphs for each non-control breakboard, displaying the maximum load threshold value for each board variation

The last two graphs display the comparison of the averaged load-bearing capacity values of each suture type

3.2) <u>Test Phase 1 Data Summary</u>

3.2.1) <u>Category results averaged</u>

Our data is summarized as in Table 1 below

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]

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

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

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3.2.2) 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 *(Fig. 6)*, 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.

3.2.3) 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

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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 currently are 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 dovetail-jointed 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.

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