Effects of Tape Layering on Yield Strength of Jugger Cores

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***Abstract*—The sport of Jugger requires sparring equipment (or *pompfen*) which are lightweight, strong, and safe. The first two criteria create an engineering challenge; the third is a constraint which must be imposed by rigorous safety regulations. This paper seeks to investigate the behavior of carbon fiber tubes commonly used as the primary structural members of pompfen in "core contact" scenarios where two tubes collide, and aims to provide real-world testing data to motivate policy decisions surrounding minimum required protection of carbon fiber composite cores. In particular, we investigate the effect of adding layers of polypropylene adhesive tape to cores (as required by some regions) on yield strength.**

***Index Terms*—Carbon fiber, composites, safety, Jugger, contact patch**

I. Introduction

THIS paper aims to study the efficacy of thin layers of protective tape applied to carbon tubes towards increasing the contact patch size during of tube-on-tube contact and thus increasing resistance to breaking. In the sport of Jugger, lightweight carbon tubes are commonly used as rigid cores of the padded weapons (known as *pompfen*). They are well suited for this application, as the first-touch nature of the sparring rules tend to favor lightweight pompfen [1]. This in turn incentivizes that cores be chosen to be as thin and light as possible, making them barely stiff enough and strong enough to withstand normal use. These low safety factors mean that unexpected load cases can cause fractures, which not only make the pompf inoperable, but also pose a danger to all players on the field.

One common such load case, known as *core contact*, is when two pompfen are swung at each other in a way that the energy of the swing goes entirely into a small point where two cores are touching. This can create a large stress concentration in the core much higher than the loads it was designed for, which (when combined with the existing bending moments in the core) can lead to failure.

Existing pompf construction policy seeks to avoid this danger in several ways. Primarily, pompf are required to meet a minimum stiffness requirement, which typically correlates with ultimate strength. [2] This ensures that some nonzero safety factor is present. Specifically to combat the issue of core contact, however, some regions enforce a "no bare core" policy, which requires some thin layer of protection (typically packing tape, as recommended by rulebooks which enforce this policy) surrounding the core to spread out the point load into a larger area [3].

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Unfortunately, the current policy decisions have extremely limited first-principles or data driven justification. It is not clear whether the required protective layers are sufficient, or even helpful at all. As the volume of pompfen built, inspected, and used continues to grow with the sport, well-justified policy decisions are essential to maintaining player safety. To this end, we seek to gather quantitative data on the effects of the currently-recommended tape-based protection, and analyze results in search of a more rigorously supported policy recommendation. More concretely, this research is guided by the following questions:

- What, if any, affect do thin layers of packing tape have on the strength (and failure behavior) of Jugger cores?
- Is the current contact-area reasoning for the tape requirement reasonable?
- Ultimately, what is the best way to ensure core contact does pose a danger to players?

This paper's contributions are:

- A high-resolution dataset of force/displacement curves for carbon cores in 3-point bend tests with core-contact-sized contact patches.
- Data-driven policy recommendations that aim to ensure player safety by reducing the odds of pompf failure due to core contact.

II. Methods

A. Overview

To simulate core contact in a controlled environment, a 3-point bend test was performed, and force and displacement data were collected. This neglects the impact of the energy absorbed by the deformation of the tape layers as well as any energy in the plastic deformation of the cores, but the effect of both of these was deemed negligible– the tape was only at most 5 thou thick, so the total energy absorbed even if it were entirely squeezed, would be minimal, and the carbon tubes acted incredibly linearly until the first fracture, after which we were not interested in the behavior.

Future testing that includes a Charpy- or weight-drop-style impact test might prove insightful, but it is out of the scope of this work.

B. Calibration

First, in order to ensure our results were accurate, we performed a calibration procedure to the Instron. We first attached an indicator to the linear motion stage and moved the stage while watching the indicator. We determined that the Instron's positioning accuracy was correct to within the indicator's measurement precision (approximmately one thou) across the entire linear range of the indicator.

Then, having validated the displacement measurement, we placed a calibrated spring in a compression test and compared the measured force to the expected force based on the spring's stiffness. We observed no bias or scaling error, and the precision error was indistinguishable from the static noise of the load cell in steady state. Therefore, we decided to take the reported force and displacement values directly from the Instron with the uncertanties given by the Instron manual.

C. Sample Selection and Creation

In an attempt to capture the full breadth of scenarios that might occur in the real world, we chose to experiment with two different sample lengths and three different levels of tape. The longer samples were 34cm long so they could be tested at the Instron's maximum 3-point bend test length of 30cm. This case was meant to represent a bending-dominated load, where the bending stresses are relatively high compared to the magnitude of the force on the contact point. In contrast, the shorter samples (at 12cm long) were meant to represent a force-dominated load case, where the bending stresses are not as high compared to the force on the contact point. The three thicknesses of tape were none (control), one layer, and two layers. Each layer was 2.5 thou thick. Three bend tests were performed with each combination of the above samples. In order to ensure consistency across tests, all six tube samples for each test were cut from the same piece of tube. The tubes are cured in molds, not produced in a continuous line and cut, so this greatly reduces variation between samples. Samples were first wrapped in duct tape before cutting to reduce splintering. The extra length on the ends of the samples was designed to be sufficiently long that any edge effects incurred by cutting would not be relevant. This was validated by the fact that no samples showed any damage that reached the edges after breaking. After being cut, the samples were then labeled, sanded, and taped. The tape was applied lengthwise, and the width of the tape was chosen to barely overlap itself after one layer around the core. For samples with multiple layers of tape, the seam was place in the same place for both layers. Importantly, the tape was applied very carefully to ensure there were no air bubbles under the tape. After the tape was applied, the samples were bagged for testing to ensure that no carbon fiber shards could escape into the environment during or following the fracture.

D. Custom Support Pins

Because our test samples are cylindrical, the standard roller pins kept in Hesse would not be sufficient; we needed pins that would ensure perpendicularity and prevent the test sample from rolling out of the 3-point bend setup. For this reason, we made our own saddle-shaped support pins out of mild steel using the Etcheverry student machine shop, pictured in Figure 1.

Fig. 1. Custom saddle-shaped support pins

These pins were made out of 1" diameter mild steel bar stock. Holes were drilled and threaded on both ends to accommodate 1/4-20 socket head screws, which provided an attachment point for the rubber bands that hold the pins in place in the 3-point bend test setup. Each pin was then placed in a milling machine and given a shallow, cylindrical depression with a diameter of 0.625 inches (slightly larger than the 14mm diameter of the test samples) and a depth of 0.125 inches. Finally, a file was used to remove any sharp edges.

E. Bend Test Setup

For each bend test, the following procedure was followed:

1) Set the bottom pins to the correct distance apart (30cm for the long samples and 10cm for the short samples)
2) Set the bagged sample onto the pins and ensure it is centered
3) Rotate the sample so the seam was directly on the side of the sample
4) Set the Instron to a feedrate of 5 millimeters per minute
5) Run the Instron until the total displacement reached 15mm (for long samples) or 10mm (for short samples)

III. Results

A. Collected Data

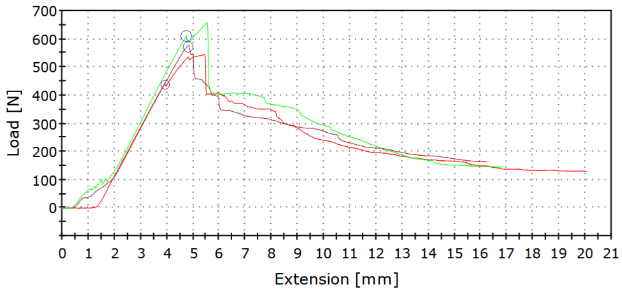

Fig. 2. Raw data from 34cm Sample A testing, burgundy = 0 tape, red = 1 tape layer, green = 2 tape layers. Blue circles represent points of initial failure

In order to determine the yield strength of each sample, we looked at the Load vs. Displacement data we obtained from the bend tests and selected the point at which we can see the first break in the sample. This point is represented by a sudden dip in the load experienced by the load cell (pictured in Figure 2). Uncertainty was determined to be $\pm 1\%$ from the Instron manual [4].

TABLE I
Yield stress for each sample, in N

Sample Name	0 Tape Layers	1 Tape Layer	2 Tape Layers
A, 34cm	440 ± 4.4	580 ± 5.8	610 ± 6.1
C, 34cm	480 ± 4.8	510 ± 5.1	540 ± 5.4
D, 34cm	230 ± 2.3	180 ± 1.8	600 ± 6
A, 12cm	550 ± 5.5	600 ± 6	670 ± 6.7
C, 12cm	520 ± 5.2	550 ± 5.5	600 ± 6
D, 12cm	470 ± 4.7	590 ± 5.9	660 ± 6.6

Tabulated above in Table I are the forces at first break for each sample. Already, we can see a general trend of yield strength increasing with added tape layers, with a few outliers in sample D.

B. Hypothesis Testing

Having collected our yield strength data for all of our samples, we next conducted hypothesis testing in order to determine if we can draw statistically significant conclusions from our experiment.

For this, we selected the one-sided Wilcoxon Signed Rank test, for several reasons. The first reason is that we have a relatively small sample size. The second reason is because our samples are from different lots of carbon fiber manufacturing. While we do see the yield strength increasing with tape layers within each sample (with the exception of the 34cm D sample), the values between samples vary quite a bit.

TABLE II
0 Layers vs. 1 Layer: Differences and signed ranks

Sample Name	Strength difference	Signed Rank
A, 34cm	140 ± 10.2	1
C, 34cm	30 ± 9.9	5.5
D, 34cm	-50 ± 4.1	-3.5
A, 12cm	50 ± 11.5	3.5
C, 12cm	30 ± 10.7	5.5
D, 12cm	120 ± 10.6	2

TABLE III
1 Layer vs. 2 Layers: Differences and signed ranks

Sample Name	Strength difference	Signed Rank
A, 34cm	30 ± 11.9	5.5
C, 34cm	30 ± 10.5	5.5
D, 34cm	420 ± 7.8	1
A, 12cm	70 ± 12.7	2.5
C, 12cm	50 ± 11.5	4
D, 12cm	70 ± 12.5	2.5

TABLE IV
0 Layers vs. 2 Layers: Differences and signed ranks

Sample Name	Strength difference	Signed Rank
A, 34cm	170 ± 10.5	3
C, 34cm	60 ± 10.2	6
D, 34cm	370 ± 8.3	1
A, 12cm	120 ± 12.2	4
C, 12cm	80 ± 11.2	5
D, 12cm	190 ± 11.3	2

In Tables II, III, and III are the calculated differences and signed ranks, comparing each sample to its counterparts with different amounts of tape applied. Because we want to determine if the strength is greater with 2 tape layers when compared to 1 or 0, or with 1 layer when compared to 0, we will be using the negative rank sum T_{-} as our test statistic. Computing this value for each of our tests, we get:

$T_{-,0\text{v}1} = 3.5$
$T_{-,1\text{v}2} = 0$
$T_{-,0\text{v}2} = 0$

Using an $\alpha = .05$ (95% confidence) and an n=6, we may consult the table of critical values for the Wilcoxon Signed Rank Test in the ME103 Formula Sheet [5] to find our critical value $T_0 = 2$. Because $T_{-,1\text{v}2} \leq T_0$ and $T_{-,0\text{v}2} \leq T_0$, but $T_{-,0\text{v}1} > T_0$, **we reject the null hypothesis in the 1 layer vs. 2 layer and 0 layer vs. 2 layer cases, but not in the 0 vs. 1 layer case.** We can say that 2 layers of tape produces a measurable increase in yield strength over 1 layer or 0 layers with statistical significance, but we cannot say the same about 1 layer when compared to 0 layers.

IV. Discussion

A. Sources of Error

When looking at our data, we can see a clear outlier that is different from the other samples: the 34cm Sample D.

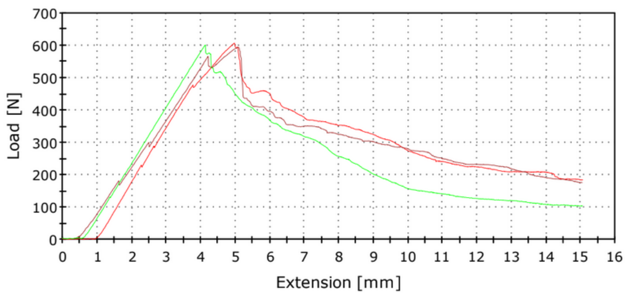

Fig. 3. Raw data from 34cm Sample D testing, red = 0 tape, burgundy = 1 tape layer, green = 2 tape layers.

In Figure 3, we can see that the 0 layer test has its first failure at 230 N, but the 1 layer test has its first failure at 180 N. This could be either a result of inconsistencies in carbon fiber manufacturing, or a mistake in our methodology. We tried to be very careful when applying our tape layers, avoiding all air bubbles and keeping the tape seam in the same place every time, but there is a chance we made a mistake. Alternatively, the jam nuts on the Instron machine could have been under-tightened for this test, causing the carriage to slip slightly under the load. Whether this was due to a manufacturing mistake or a methodology mistake, this demonstrates the importance of sample sizes; if we had had just one more sample, we would have been able to reject the null hypothesis despite an outlier value.

Another error we saw during our experiment was a nonlinear section in the force reading at the very beginning of the test, before we saw the data settle into the linear elastic regime.

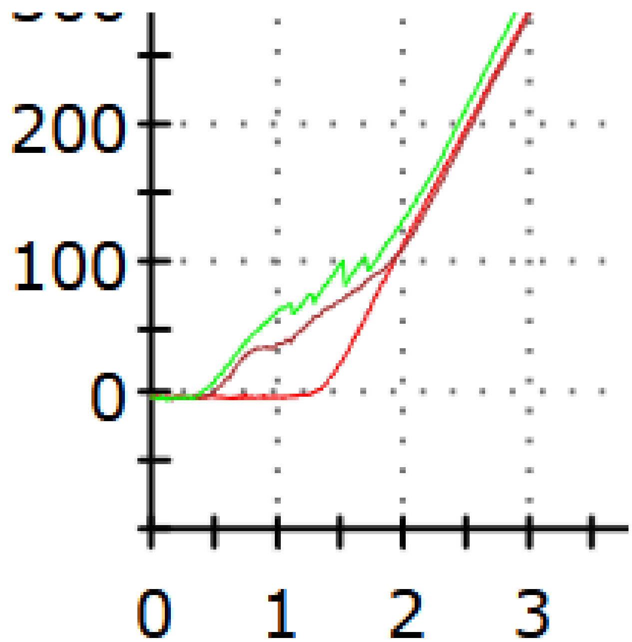

Fig. 4. Raw data from 34cm Sample A testing, burgundy = 0 tape, red = 1 tape layer, green = 2 tape layers. Zoomed in to show nonlinearity at beginning of test

This is shown in Figure 4; while our 1 layer test transitioned cleanly from 0 force to linear elastic, the 0 layer and 2 layer tests had some strange readings. We later determined that this was due to our custom saddle-shaped 3-point bend pins. If the pins were not perfectly flat before starting the test, there would be some initial force spikes as some of the load was going into flattening out the pins. This mechanism is illustrated in Figure 5.

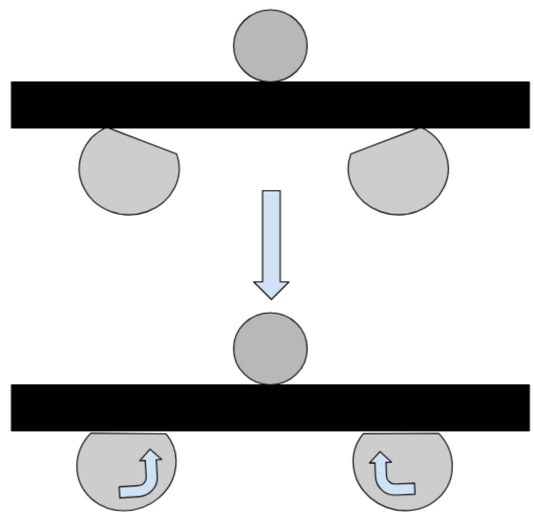

Fig. 5. Illustration of pins being flattened

B. Abandoned Approaches

Due to Hesse safety policies, all of our test samples had to be placed in sealed plastic bags that we could not open during our testing time slot. This was to prevent carbon fiber dust from being released into the air and inhaled by us or the shop staff. However, because our experiment is about the effects of a thin plastic layer on the test sample, we worried that adding a plastic bag between our sample and the loading pin would muddy our results. We decided to make a set of 6 individual loading pins that could be placed inside the bags with the samples, allowing for direct contact while still complying with Hesse rules, pictured in Figure 6.

Fig. 6. Individual loading pin

These pins had a diameter of 0.625", closely approximating the diameter of the cores, and were made from 6061 aluminum. However, when we ran tests with these pins, we got results that didn't quite match up with our expectations, shown in Figure 7.

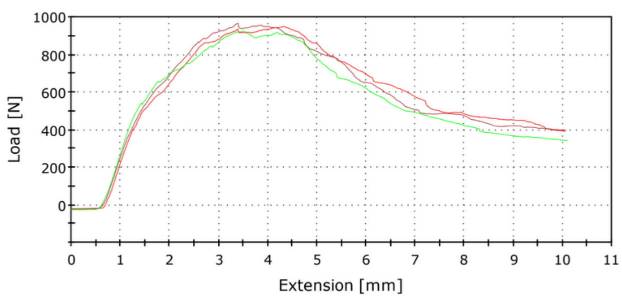

Fig. 7. Raw data from 12cm Sample B testing, burgundy = 0 tape, red = 1 tape layer, green = 2 tape layers. Used AL loading pin

These results did not show any clear patterns; in fact, they seemed to remove any differences that might have been caused by the application of tape layers. We determined that this was due to poor material choice; we naively assumed, without proper calculations or verification, that 6061 aluminum would be suitable for this application. When we compare these results to the other tests using mild steel pins, we can see that this is not true. The soft aluminum pins would have created a very large contact patch compared to the steel pins, which is exactly what we were trying to avoid by having individual pins to put inside the bags. As such, we abandoned this approach. If we had planned more effectively, we would have purchased some extra steel stock in advance, allowing us to make these pins out of an appropriate material.

V. Conclusion

In this paper, we aimed to determine whether adding layers of tape had a measurable, statistically significant effect on the strength of hollow carbon-fiber tubes used as cores for Jugger pompfen. We were able to show with 95% confidence that adding 2 layers of tape did produce an increase in yield strength when compared to 1 or 0 layers, but we were unable to show that adding 1 layer of tape produced an effect. This increase in strength at first break should result in greater longevity and safety when using these cores; however, the strength increase is relatively small. Before making a policy recommendation regarding the current rules to any Jugger organizations, we would ideally conduct further research, trying to better approximate real conditions. The data we have gathered so far are insufficient to support or deny the adequacy of the current rules, so the only recommendation we can safely make is to increase the stiffness requirement for all pompf, as this will increase the overall strength required and thus the safety factor present for core contact events. More specifically, one major limitation of our methodology was the speed of the Instron machine; real core contact in Jugger games occurs at high speeds, but our experiments were run at 5 mm/min. A more effective experimental setup would be one that can better evaluate impact toughness, such as a weight drop or pendulum test.

References

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