Badminton String: Structural and Stress Analysis of Nylon 6,6

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Executive Summary

Badminton strings are usually made of composite materials and synthetic polymers. Our paper discusses Nylon 6,6's property and function as the string material since it is one of the most popular materials in the industry. Nylon 6,6 has long molecular chains with great strength, elasticity, abrasion resistance and flexibility. Through analyzing the impact stress and static stress of the string based on a simplified model, we conclude that impact stress is higher than static stress by around 0.5%. From our analysis, we also conclude that fatigue has no significant contribution to fracture mechanism. Further studies need to done to determine the significance of other factors in fracture mechanism. In addition, alternative materials can be explored such as Kevlar.

1 Design Objective

Badminton has been a popular racket sport since its invention at 1800s [1]. It is arguably second most prevailing sport in China besides the table tennis after the rise of world champions Dan Lin. Along with development of badminton, badminton rackets had undergone revolutionary changes.

Given limited scope, this paper focuses on exploring the polymer applications in the string designs. Badminton strings are designed to be elastic yet strong enough to withstand repeated impacting forces especially around the sweet spot [2]. Strings also need to be light-weighted so they do not hinder athletes' movements [3]. Moreover, badminton strings need to be replaced periodically so they should be cost efficient. This paper examines the mechanical and structural performances of using Nylon 6,6 as badminton strings material.

2 Background

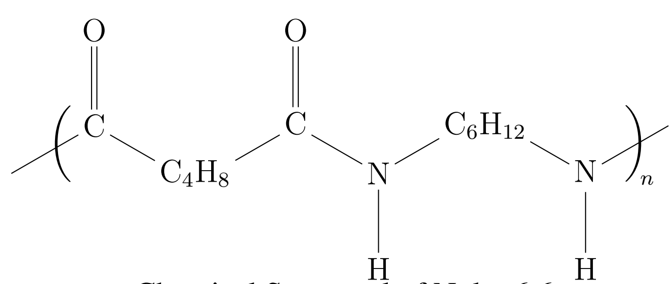
The earliest badminton rackets were made from wood frame and animal gut strings [1]. The cow or sheep intestines were chemically treated to extract natural fibers. The fibers were then dried and twisted together to make strings. Animal gut strings are very resilient, however they are delicate and expensive to manufacture.

The modern badminton rackets are usually made of composite materials and synthetic polymer strings. Some of the popular string materials include Nylon, polyester and Zyex. Among them, Nylon appears as the industry's favorite due to its low-cost and thermoplastic property [1].

3 Structural Analysis of Badminton Strings

3.1 Analysis of Nylon 6,6 Properties

Nylon 6,6 is one type of semi-crystalline material with 12 carbon atoms [4]. Its structure is shown in below. Nylon 6,6 has long molecular chains with many hydrogen bond targets (nitrogen and oxygen). With light crosslinking, Nylon 6,6 has excellent elasticity and tensile strength of $60 - 90MPa$ (Table 1) [4]. Due to its relatively higher glass transition temperature compared with the ambient temperature $25\,°\mathrm{C}$, Nylon 6,6 is mostly in solid state.



Chemical Structural of Nylon6,6

3.2 Manufacturing Process of Badminton Strings

Nylon 6,6 is first manufactured through linear condensation polymerization into nylon salt by adding hexamethylene diamine and adipic acid togehter. [?]. In order to avoid oxidation during the manufacturing process, the mixture is required to be heated up to $280\,°\mathrm{C}$ under nitrogen environment. The purified liquid polymer is then extruded in ribbon form and cut into small pellets after cooling [?]. These pellets are put into a hopper, melted and pushed along the system to a spinneret. The nylon filaments

Table 1: Properties of Nylon 6,6 (At Room Temperature) [?, 5, 6]

Commercial Name	Nylon 6,6
Chemical Name	poly(hexamethyleneadipamide)
Chemical Formula	$(C_{12}H_{22}N_2O_2)_n$
Synthesis Method	Condensation polymerization
Glass Transition Temperature (T_g) (°C)	50
Melting Temperature (T_m) (°C)	250-272
Degree of Crystallinity (%)	10-60
Density (g/cm^3)	1.0-1.4
Tensile strength (MPa)	60-90
Compressive strength (GPa)	0.1
Young's Modulus (GPa)	3.3
Elongation at Rupture(%)	200-300

are extruded through the spinneret in form of desired sizes in cool air [?]. The ready-made nylon filaments are wrapped around bobbins; they are now named yarns, used as the main material to produce badminton strings [?].

The badminton strings are consisted of core and wear layer. Both components combine yarns but use different knitting methods. The core, located at the center of the strings, acts as loading-bearing member that bears most of impacted force and provides resiliency and strength. Multifilament and microfilament yarns are the two major types of cores shown in Figure 1. The microfilament is approximately 10% thinner than multifilament, which allows the strings to reduce wind resistance and hit the shuttlecock faster [?]. Numerous yarns are straightened and risen through a machine, which allows another yarns to come off the bobbin weave around them to braid a textured surface. Two wear layers are wrapped around the cores to increase the strings' abrasion resistance [?].

After the raw strings are produced, they are coated by a waterproof material and then run through a funnel device to ensure its homogenous coating surface [?]. Eventually, the coated strings undergo gamma radiation to increase resilience. Gamma radiation works to cut long molecular chains to short molecular chains; short chains can move more freely, hence increasing the resilience [?]. However, the durability

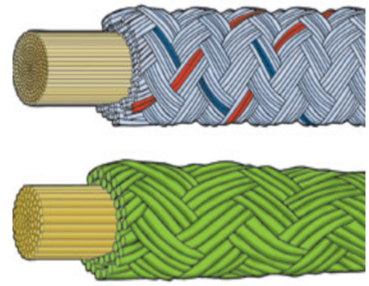


Figure 1: Microfilament braiding and multifilament braiding models [?].

of the strings would not be affected by this process because chains are pacted closely [?].

3.3 Degradation Analysis of Nylon 6,6

Due to the polyamide bond, nylon is most susceptible to hydrolysis reaction other than thermal or oxidative degradation. However, according to accelerated aging study of Nylon 6,6, even at elevated temperature of $65\,°C$ and 100% relative humidity, Nylon 6,6 takes 370 days to lose 8% of its tensile strength [7]. The expected life of badminton strings ranges from one to two months, depending on the frequency of the play. Badminton is mostly played indoor and the rackets are stored in cases when they are not used; hence, strings are almost always shield from UV and water. Therefore, in the short period of service life, chemical degradation of strings is insignificant compared to mechanical degradation of strings such as impact stress applied to the string.

4 Stress Analysis

4.1 Overview of Badminton Strings Tension

All badminton strings gradually lose tension as time passed by due to the consequence of viscoelasticity of Nylon 6,6, especially its stress relaxation character [8]. UC Berkeley Cal badminton team suggests their players to replace badminton strings at least once a month; by calculating the total number of smashes for a single racket, 20,000 times was estimated for $0.68mm$ thick Yonex BG 80 string with $26lbs$ preloading tension. The stress of the string is plotted against time in Figure 2. Two types of stress are shown on the y-axis. The lower stress is

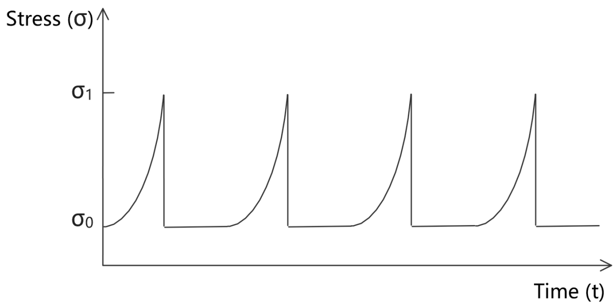


Figure 2: σ_0 and σ_1 denote *static* and *impact* stresses.

the static stress (σ_0), which is defined as the initial string tension without any external impact from the shuttlecock. The higher stress is the impact stress (σ_1), which is defined as the stress when hitting the shuttlecock.

4.2 Assumptions

According to 4.1, the badminton string will be subjected to two loading cases: long-term *static* tensile stress and short-term *impact* tensile stress.

The *string* usually refers to a mechanical model that cannot withstand either shear, compressive stress or strain; hence leads to a uniaxial tensile stress in the string material only. The *string* model applies to mechanical model which contains simple boundary conditions but not applicable in stress analysis of complicated woven string bed for the following reasons.

First, the string bed of a badminton racket is formed by one continuous string, a long string goes through the holes back and forth on the racket frame. There are only two knots at two specific positions on the racket frame to hold the tension in the string. We assume that the stress and strain are uniform along the string in both static and impact situations. And there is a constant *static* tensile stress along the string before the shuttlecock hits the string (denote as σ_0) [9].

Secondly, when the shuttlecock hits the string bed, there exist frictions between the shuttlecock and the string (denote as Cf_{sb}), between the string and the racket frame (Cf_{sr}) and between one string and another string (Cf_{ss}). It is assumed that the all the friction coefficients are 0 [10].

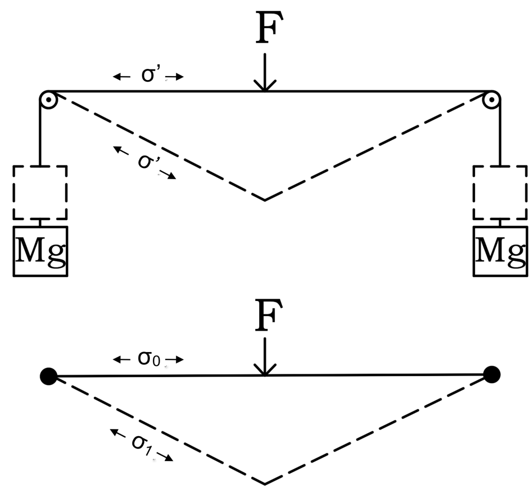


Figure 3: The model on the top reveals a string with a constant tension under loading F, the stress along the string will be σ' before and after deformation. The model on the bottom stands for a string with fixed ends, the stress along the string is σ_0 before loading, and will be σ_1 after loading.

Next, during the games, the stress will increase when the string is deformed under the loading from shuttlecocks' hitting, we assume that the maximum *impact* stress in the string will be σ_1. Figure 3 shows the relationship between external loading and internal stress in different string models.

Then, the string bed has a highly complex woven structure. A string in one direction goes below and above a string in another direction alternatively. This woven structure implies that under the impact loading, the contact stress will decrease and increase at corresponding *crosslinked* points. We do not assume two crossed strings are welded here. Figure 4 is the sketch of woven structure of string bed.

Addtionally, we assume that the shuttlecock can be modeled as a rigid and perfect sphere with mass M_b [9].

The last two assumptions we made are all the stress analysis in the impact process will be linear elastic [9], and the impact process is isochoric [10].

4.3 Maximum Stress Calculation

To calculate the maximum stress σ_1 in the string, we assume a ball with velocity v_1 hitting the string bed,

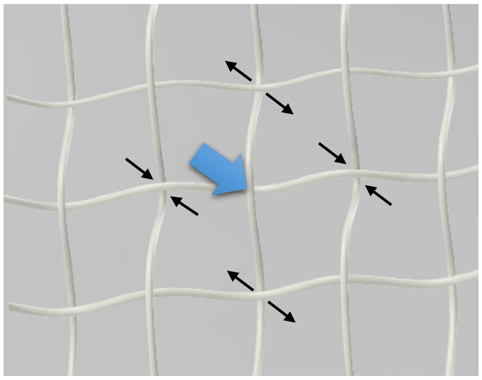


Figure 4: Woven structure of the badminton string bed, assuming load is applied as blue arrow, the contact stresses at adjacent crosslinked points will be different respectively as black arrows indicate.

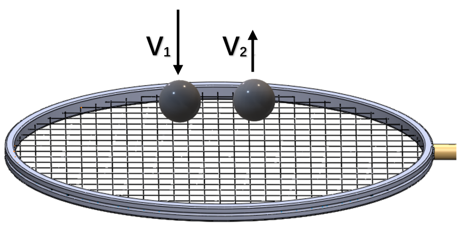


Figure 5: The ball hits the string bed with v_1 and leaves with v_2.

then rebounding with velocity v_2 [11]. The coefficient of restitution (COR) can be defined in equation (1) [12, 13, 14]

$$COR = \frac{v_2}{v_1} \tag{1}$$

where v_1 is the ball incident velocity, v_2 is the ball rebound velocity. Figure 5 illustrates the collision between a ball and a string bed complying with the COR theory.

We also define the length of relaxed string L_r and the length of string on the string bed in a static situation L_0. Then the strain in the static string ϵ_0 will be

$$\epsilon_0 = \frac{L_0 - L_r}{L_r} \tag{2}$$

The stress σ_0 and strain energy W_0 in the static string will be

$$V_0 = L_0 * A \tag{3}$$

$$W_0 = \int_V \frac{1}{2}\sigma_0\epsilon_0 \mathrm{d}V = \frac{1}{2}\frac{\sigma_0^2}{E}V_0 \tag{4}$$

where V_0 is the volume of static string, A is the cross sectional area of the static string, E is the Young's modulus of string.

During the impact process, when the velocity of ball decreases to 0, all the kinematic energy of shuttlecock E_k will be stored in the string bed as strain energy, and released back to shuttlecock which enables the shuttlecock to have a velocity v_2. Then the maximum strain energy W_1 in the string bed will be

$$\begin{aligned} W_1 &= W_0 + E_k && (5)\\ &= \frac{1}{2}\frac{\sigma_0^2}{E}V_0 + \frac{1}{2}m_b v_2^2 && (6)\\ &= \frac{1}{2}\frac{\sigma_0^2}{E}V_0 + \frac{1}{2}m_b(v_1 \times COR)^2 && (7)\\ &= \frac{1}{2}\frac{\sigma_1^2}{E}V_0 && (8) \end{aligned}$$

where σ_1 is the maximum stress in the string during the impact process, which can be calculated by equation (9)

$$\sigma_1 = \sqrt{\sigma_0^2 + \frac{E}{V_0}m_b(v_1 \times COR)^2} \tag{9}$$

The material and geometry information can be retrieved from Fakhrizal et al.[11].

$$\begin{aligned} L_0 &= 8.8 \times 10^3\ mm\\ A &= 0.34\ mm^2\\ E &= 7.2 \times 10^9\ Pa\\ M_b &= 0.023\ kg \end{aligned}$$

The literatures also provide the data of COR for different string tensions showing Table 2 [1].

The incoming velocity of the shuttlecock is assumed to be 92.2 m/s, then the maximum stress during the impact process can be calculated from equation (9) for different string tensions. Table 3 and Figure 6 show the results.

Table 2: Experimental relation between string tension and Coefficient of Restitution [11]

String Tension (lbs)	COR
14	0.9054
20	0.8967
24	0.8729
28	0.8645
34	0.8568

Table 3: The stress along string in static and impact situations

Static (MPa)	Impact (MPa)	Increase(%)
182.09	183.14	0.57
260.13	260.85	0.28
312.15	312.72	0.18
364.17	364.66	0.13
442.22	442.61	0.09

From Table 3, the difference between impact and static stresses is negligible for different preloading string tensions. The increment of stress is 0.57% for preloading tension of 14 lbs, and 0.09% at 34 lbs. The larger preloading tension is, the less increment of stress will be (6). Combining with Figure 2, the magnitude of cycling loading ($\sigma_1 - \sigma_0$) can be ignored compared to the mean loading (σ_0). In other words, the badminton string will be subjected to almost constant stress during usage, no matter the shuttlecock hits it or not.

Since there is no significant difference in stress before and during impacting, we can conclude with confidence that the fracture mechanism of badminton string is not mainly due to fatigue. It might be related to wear property of the outer protection coating [**?**] or the fracture of single nylon fiber in braided structures [15]. It should be mentioned that, the tension strength of braided structure can be greatly larger than the strength of homogeneous nylon string of the same diameter [16, 15, 17, 18], which explains that the badminton string can be intact though the static stress is much larger than the tensile strength of the nylon material.

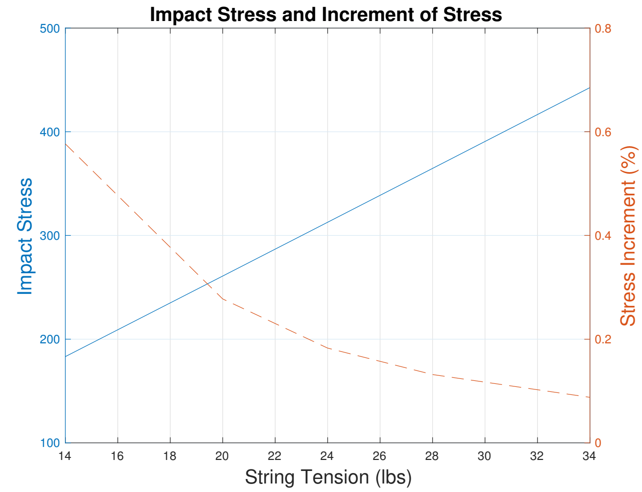


Figure 6: The blue solid line shows the relationship between string tension and the maximum impact stress along string, the red dashline shows the relative decrement of stress between *static* and *impact* stress

5 The Alternative Design

In summary, Nylon 6,6 has excellent chemical and mechanical properties to be made into badminton strings. Further studies could be done to compare Nylon 6,6 with other popular string materials of the industry, such as Kevlar. Kevlar has higher tensile strength, tensile modulus and tenacity than Nylon 6,6 [19]. Moreover, Kevlar-made badminton strings also exhibit longer life expectancy due to better fatigue and wear resistance data [20]. However, Kevlar is much more expensive than Nylon 6,6 and might be considered too stiff to be used in badminton strings. Additional researches could be extended to comparison of two materials and even their hybrid materials.

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