CLOCK LINES – 2

Natural gut and synthetic lines

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Natural gut lines

Natural gut or 'catgut' is made from the natural fibre found in the walls of the intestines of animals (generally sheep intestines, but never cats). The premium grades are used for stringing musical instruments and tennis racquets. Gut supplied to the horological trade can be variable in quality and should be inspected before fitting; if it does not have a smooth wax-like (coated) finish but has hairy bits standing up like a piece of sisal cord it should be rejected (Figure 5), the inset right showing an in-service failure of the poor quality gut illustrated after less than one year.

Figure 5: A comparison of good quality natural gut (left), and poor quality natural gut (right). Inset: the failed poor-quality line

Perhaps a more reliable source of line might be tennis racquet string suppliers; for example, Babolat 1.30 mm diameter natural gut 'VS' string is recommended for a tension of 22kg (160 MPa) but comes at a cost of three times the gut available from horological suppliers.

Whatever its source, natural gut is affected by high humidity, though natural gut tennis strings do nowadays have a coating to provide a degree of short-term protection. Given the low duty cycle of tennis racquets (just enough protection for the duration of a tennis match held in the rain?), whether it provides any great long-term benefit for a clock kept in a humid (damp) environment I cannot say.

One benefit of natural gut is that it will absorb very little energy in bending around a fusee, barrel or pulley due to its low modulus of elasticity.

Synthetic lines

Synthetic line materials and type of construction are legion, and I cannot cover the whole range. The primary industries that use synthetic lines and have undertaken scientific research appear to be those concerned with sports racquets, musical instruments and surgical sutures. I shall not consider the latter two any further as their requirements are somewhat different (tonal vibration and short term duty (even solubility), which are properties not likely to be uppermost in the clockmaker's mind). Another industry would seem to be fishing lines but I have found little, if any, research on them.

There is considerable variability in the 'stretch' of nylon line, and much research has been undertaken on behalf of the tennis racquet and allied industries. Typical racquet string tensions are tennis: 225 to 300 N (which is up to five times greater than that in a clock line), squash: 100 to 160 N, badminton: 65 to 125 N. The tension in a tennis racquet string results in high string stresses close to failure, which are only acceptable because line creep, constrained by a relatively rigid frame, quickly reduces the tension. They also have a short life at this high tension (stress), creep leading to a professional player changing his racquet several times during a match. (As an aside, much the same can be said about musical instruments, the musician adjusting the instrument's string tension between (or even during) performances.) In clock lines under the tension of a weight or mainspring*, no stress relaxation can occur.

* Not entirely true for a mainspring/fusee combination as will be discussed later on.

Restricting my interest more narrowly to sports racquets, in essence they use monofilament or multifilament lines, wrapped or unwrapped. The materials from which the filament(s) are made include nylon, polyester and aramid (Kevlar) as well as natural gut. For tennis racquets (and clocks), nylon is by far the most common.

The term 'synthetic gut' is to be avoided. It is a term applied to synthetic multi-filament lines (usually a nylon) consisting of a core filament surrounded by one or more layers of smaller filaments (possibly encased in a braided sheath) in order to replicate more closely the response of the ball to a racquet strung with natural gut (eg. spin). Advocated by some horologists, I am unclear how imparting spin benefits a clock.

Another concern with lines sheathed in fine multi-filament fibres is that wear, due to the sheath and outer fibre thinness, may quickly result in the outer fibres fraying when rubbing (as they do in tennis racquets). Consequently, their use would seem questionable when the line rubs on a stop iron in a regulator clock or fusee, or a poor set-up results in longcase lines rubbing on the seatboard.

Lines from other synthetic materials might also be possible, perhaps notably aramid lines ('Kevlar'). Kevlar has a very high tensile strength with a lower creep than nylon-6, though its modulus of elasticity is fairly high. This would suggest it would need to be of multi-strand construction and may be subject to abrasion damage. But as the writer has no experience of Kevlar, I feel ill-qualified to offer any further comment.

Partly for these reasons and partly because it is what a majority of horologists tend to use as an alternative to natural gut, I shall now restrict my comments to synthetic monofilament line. Coupled with its very low modulus of elasticity and consequential small line bending losses, nylon-6 is by far the most popular choice.

Nylon-6

The majority of horological requisites suppliers limit their specification of synthetic monofilament line to an unqualified 'Perlon'. This is a little unspecific; originally in its unmodified form nylon-6, Perlon is also the registered name of a German company (Perlon GmbH) manufacturing many different types of polymers.

Line strength

Not generally being considered engineering ropes, the SWL for natural gut and monofilament nylon-6 is not generally specified. Typical tensile strengths are presented in Table 2, which give comfort that both materials have adequate capacity at normal room temperatures (as practising horologists know).

With both natural gut and nylon-6 having very low modulus of elasticity, energy losses due to bending are small. It can also be inferred that, providing these lines are not repeatedly bent over sharp corners (as in Figure 3 in Part 1), bend diameters down to perhaps 10 mm will be acceptable.

Creep

Creep is a phenomenon from which both natural gut and nylon-6 suffer, some horologists claiming creep to be the reason they prefer stranded steel or brass lines. The writer cannot recall ever seeing a reasoned justification for this decision, and finding no published information on clock line creep, he decided to embark upon some preliminary trials during the first six months of the Covid-19 ‘Lockdown’ (March to October 2020). But before going any further, it is important to differentiate between ‘stretch’ and ‘creep’, which the writer defines as:

- Stretch: the fully recoverable elastic extension which all materials exhibit when loaded, and
- Creep: the largely irrecoverable (and hence non-elastic) extension over time.

The former is instantaneous on application of (or variation of) a load and is quantified by the modulus of elasticity. It is accounted for during the clock’s initial set-up and has no significant effect on a clock’s in-service performance any more than the stretch (elastic extension under load) in a steel or brass/bronze line. The latter (creep) takes place over time and is generally characterised as taking place in three stages (Figure 6):

- Stage 1 Primary creep: a rapid extension that takes place over the first few days of the application of a load,
- Stage 2 Secondary creep: a fairly steady extension of the loaded line over many years, and
- Stage 3 Tertiary creep: increasingly rapid creep leading to failure. In a clock it is only ever likely to be encountered after many tens of years’ service or because of damage to the line.

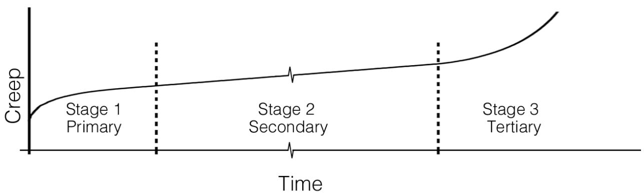

Figure 6: Stages of creep

Creep trials – first series

One natural gut and one nylon-6 line sourced from a reputable UK horological requisites supplier were loaded with a 3.45 kg weight, and the creep measured over 150 days. 3.45 kg is equivalent to a heavy (6.9 kg) driving weight supported on a 2-fall pulley system typical (if a little heavy) of a longcase clock. The line stress was calculated at a slightly pessimistic 20 MPa. The line was a nominal 1.5 mm diameter; this was measured and a slight correction made to the creep rate to account for the fractional difference in diameters (1.47 mm and 1.40 mm diameter for the natural gut and the synthetic line respectively). The lines were prevented from twisting as would be the case in a clock so the measured extension (creep) would not be influenced by twisting or untwisting.

With crimps – Figure 7 – at a nominal 750 mm spacing for measurement of the extension, any lack of rigidity in the support was eliminated. The initial elastic line extensions were measured from a 0.5 kg preload (the ‘zero load, zero extension’ condition to get the trial line straight) and, combined with the results from the second series trials, the average modulus of elasticity calculated from the elastic extension (stretch) on initial loading – Table 2.

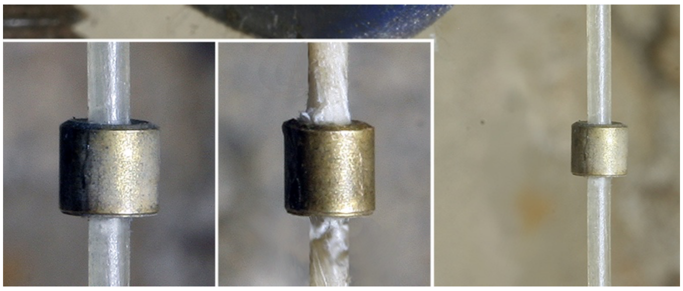

Figure 7: Measurement crimps from annealed clock bushes

Indicative properties from literature @20°C	Natural gut ‘high quality’	Nylon-6 monofilament
Tensile strength, dry	150 MPa	120 MPa
Tensile strength, 50% humidity	-	80 MPa
Modulus of elasticity, tension	2.0 GPa	1.1 GPa
Averaged properties measured during the first and second series trials		
Modulus of elasticity, tension	2.25 GPa	1.05 GPa

Table 2: Material characteristics

Temperature and humidity were recorded at each creep measurement. Over the trial period the recorded temperature ranged between 11°C and 25 °C, and the relative humidity ranged between 29% and 100% (absolute humidity 5.2 gm/m^3 and 16.7 gm/m^3). Both are typical of the environment in which a domestic clock might be situated.

Creep trials – second series

Conducted in parallel with the first series trials, these were identical in all respects save for being loaded with a 10 kg weight representative of the maximum line load in a typical English fusee clock. This induced a maximum stress of 60 MPa, which is a figure calculated from torque measurements taken from two bracket clocks in the writer’s workshop.

Trials results – first and second series

The creep extension of each line (ie. excluding the elastic extension (elastic stretch)) was recorded at frequent intervals during the first few days of Stage 1 creep, daily intervals for the next thirty days and two-daily intervals thereafter. These equations were then extrapolated to 7000 days (about 20 years) – Figure 9. Annexe C gives greater detail of the extrapolation method used.

Commentary

Most noticeable it the significantly higher creep rate of nylon-6 compared with natural gut for the more heavily loaded (60 MPa) line, but the creep rates were comparable for the less heavily loaded (20 MPa) lines. Over the first 24 hours (not visible in the Figures presented above), the creep rate of nylon-6 was higher than that of natural gut in both trials. Stage 1 creep takes place over the first 10 days or so in both trials, but thereafter settles down to Stage 2 creep.

The writer could discern no correlation between creep and temperature. However, the creep of natural gut was found to be more affected by humidity than nylon-6, the natural gut creep undergoing a step increase the first time high humidity occurred (around day 15 in Figure 8), which was most noticeable for the higher loaded line). This step increase was decreasingly evident in subsequent periods of high humidity, the creep rate decreasing in periods of low humidity even to the extent of becoming negative. This is perhaps most evident if one looks at the 60 MPa natural gut measured data in Figure 8 between days 37 and 40 (and between days 66 and 69).

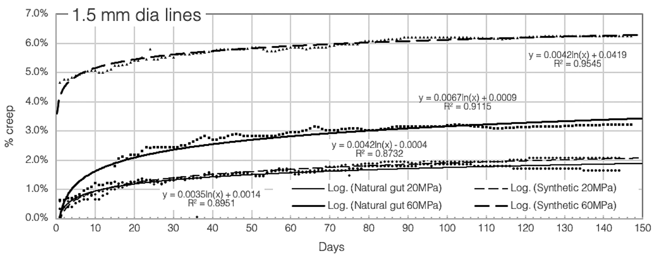

Figure 8: Measured creep data from the 150 day trials, along with derived curve fit equations

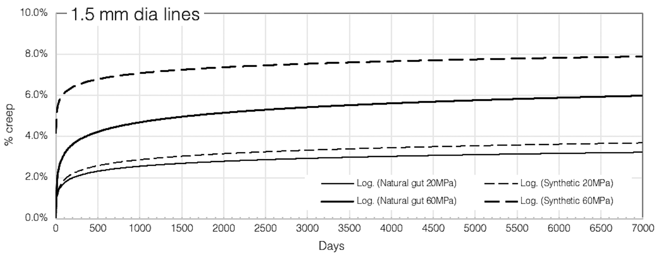

Figure 9: 7000 day extrapolated natural gut and nylon-6 creep at stress levels representative of a longcase and fusee clock

Validity of the results

Always a concern to a researcher, the best I can offer is opinion coupled with the support of R-squared values not too far away from the perfection of unity. Moreover, the results seem plausible, but I freely acknowledge that these are preliminary trials that would benefit from corroboration by further research.

To the writer, this would seem an excellent final year project for a student at a teaching establishment or an intern at a museum. And here is an offer: if such an establishment thinks a better understanding of creep in clock lines worthy of pursuit, I would be pleased to offer my services and data to them and their researcher.

Annexe C. Regression analysis

The writer spent many hours researching the best methods for creep extrapolation of material such as nylon-6. Nothing was found on natural gut so, rightly or wrongly, he just used the same extrapolation method.

For both natural gut and nylon-6 monofilament, power curve fits initially seemed like a good approach, but these produced implausible results. Logarithmic curve fit equations were eventually chosen, which comfortingly appeared to be the type of curve fit equation determined by other researchers as appropriate for nylon-6. The equations that fitted the data points determined using the Microsoft *Excel* Trendline function.

The writer found that the data measured during the first two weeks of the fast-changing Stage 1 creep had a profound effect on the resulting 7000 day extrapolations. In hindsight, the data collection intervals were far too long during the first few days (every hour would have been better), which would really need automated data collection equipment to improve the extrapolations.

The writer's perhaps crude solution to this problem was simply to eliminate the Stage 1 data collected during the first 14 days from the extrapolation, the 7000 day extrapolation (Figure 9) effectively being based on data collected over the last 136 days of the 150 day trial. It is a choice that the writer at least partly justifies by Stage 1 creep occurring during initial testing and trials, and consequently being of limited interest to the lifetime performance of the clock.

My sincere thanks to Adrian Garner of the London Society of Model and Experimental Engineers for his hugely valuable advice on regression analysis and extrapolation. The final decisions made are, however, solely my responsibility.

Next time: The significance of creep and overall concluding remarks

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