Flame welding tests for monolithic suspensions of a 40-kg test mass (as backup for Advanced LIGO).

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Introduction

The 40 kg mirrors of the Advanced LIGO interferometers [1] will be suspended on four cylindrical silica fibres with diameter 400 μm. The fibres will be pulled and welded to ears on the sides of the mirrors using a 10.6 μm CO_2 laser beam. Preliminary experiments have been conducted and these include fabrication, profiling, welding and breaking of silica fibres pulled and welded using a flame rather than a laser. The flame welding technique is not the main line of research required for Advanced LIGO. However, the technological process for a monolithic suspension is similar to a large extent. The comparison of both techniques at each stage in the suspension process aids in our understanding of physical mechanisms that are applicable to the future laser suspension of test masses in Advanced LIGO.

Fig 1. *The fibres were pulled and welded to ball shaped rods (Fig. 2) using a H_2-O_2 burner.*

Fig 2. *These ball shaped rods enable us to mount the fibres on a tensile testing machine.*

Strength testing of silica fibres

The fibres were flame pulled by hand from 1.5 or 3mm diameter Suprasil stock material, in a H_2-O_2 burner flame after flame welding the stock material to ball shaped rods (fig. 1, 2, and 4a). The fibres were stretched until they broke on a tensile testing machine. Two main mechanisms of fibres fracture are observable. The majority of the fibres break in the central section. These fibres fail on average ≥ 5 GPa and form the main high peak of the density function (see plots on Fig. 5-8). The fibres with a breaking stress < 4 GPa break at the ends of the fibre. The data from those forms the additional small and wide peak of the density function. The latter mechanism is more significant for fibres thicker than 220 μm. The weakening of such fibres is likely caused by thermo-induced stress in the area adjacent to its neck.

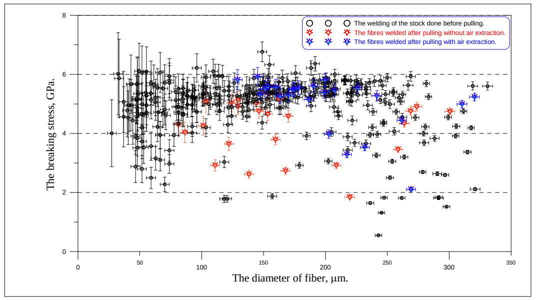


Fig 3. Plot of the breaking stress vs. minimum diameter of the flame pulled fibre. The blacks marks represent the data obtained for sequence **a** (see Figure 4), the red and blue marks correspond to sequence **b**.

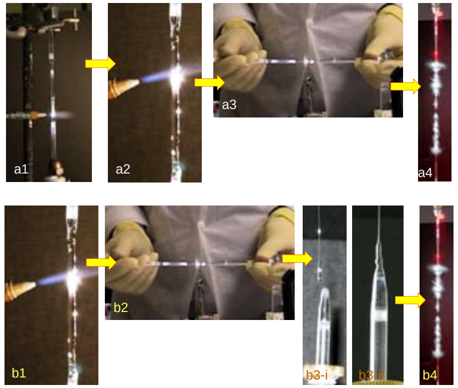


Fig 4. *Changing the order of fibre preparation has an effect on the distribution of the breaking stress of the fibres.* ***a1****- welding of thick rods to the stock,* ***a2*** *&* ***b1*** *– flame polishing of the stock,* ***a3*** *&* ***b2*** *– pulling the fibres,* ***a4*** *&* ***b4*** *– testing (breaking) of the silica fibre.* ***b3*** *– welding of the pulled fibre to the ball shaped rods (was done with and without air extraction).*

The statistical analysis of breaking stress of welded fibres

The statistical distribution of the breaking of the fibres can be described using a so called Weibull distribution (WD). The cumulative probability ***P*** is the relative quantity of fibres that break at a stress less than or equal to ***S***. [2]

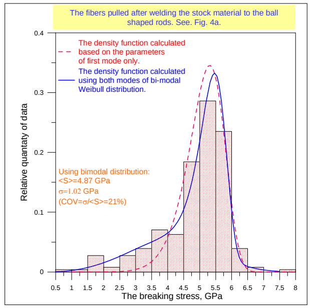
$$P(S) = 1 - \exp\left[-\left(\frac{S}{S_0}\right)^m\right]$$

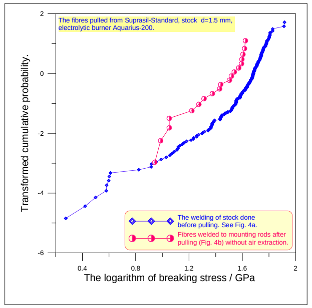
The expression for the cumulative probability can be transformed to give linear relationship with respect to *lnS*.

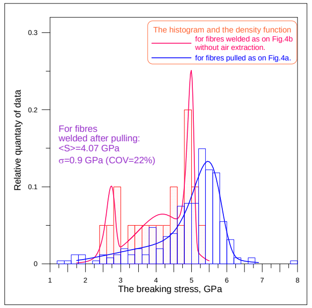
$$\ln\left[\ln\left(\frac{1}{1-P}\right)\right] = m \cdot (\ln S - \ln S_0)$$

After deriving parameters ***m*** and ***S_0*** one can calculate the density function ***dP/dS*** as well as the average stress ***<S>*** and variance ***σ*** [3]. The data for breaking caused by two mechanisms forms a plot comprised of two segments of straight lines, representing the modes of a bi-modal WD or the different peaks in the density function.

The Adv.LIGO fibres will be welded to ears of the test mass *after pulling.* To investigate this process the flame pulled fibres were welded to mounting rods (Fig.4b). Plotting a distribution for the breaking data of the fibres welded to the ball shaped rods (Fig.6,7) one can see the reduction of the breaking stress in comparison with the breaking of fibres pulled after welding as in Fig.4a – the main peak of the density function moves left. The reduction in strength of the flame welded fibres is probably caused by deposition of silica vapour on the surface of the fibres. This effect can be attributed to the reduction of the activation energy of crack formation. When extraction of the welding vapour was carried out during welding, the distribution of breaking stress was fully restored. See Fig. 8.







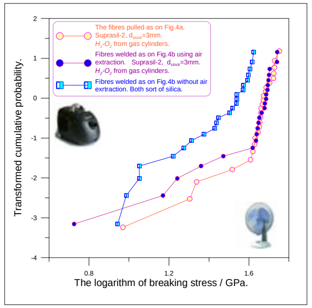


Fig.5-8. Plots of density function and Weibull plots for the newly pulled fibres and fibres welded to ball shaped mounting rods.

The flame welded simulation of a 40-kg test mass suspension.

A 40-kg steel mass was suspended using the flame welding technique.

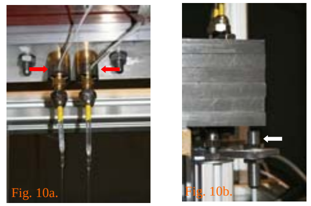


Fig 9. *The 40 kg steel mass suspended on 4 laser pulled silica fibres.*

Fig 10. *To investigate the movement of the mass, additional sensors have been installed.* ***a*** *– strain gauge at the top of each fibre (red arrows),* ***b*** *– position sensor below each corner of the mass (white arrow).*

To simulate the behaviour of suspension in case of a fibre failure we intentionally cut one fiber with a knife. The adjacent fiber was also broken. Presumably the second fiber (far left on Fig.11) was peppered with shrapnel.

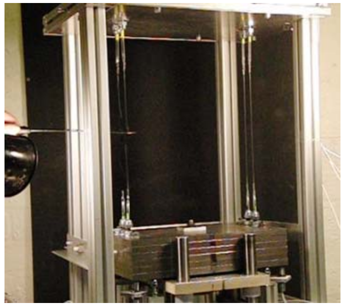


Fig.11 Cutting the front left fiber with a knife. The adjacent fiber was broken and a large fragment of it flew away. It is likely that the end of this fibre was overstressed during welding.

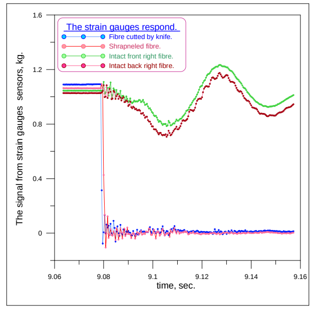


Fig12. The second fiber was destroyed 2 ms after cutting of the first fiber. The test mass dropped onto the stoppers installed 1mm below.

We repaired the suspension twice and repeated the experiment shielding the fibres with a special fiber-guard. Only the cutting fibre failed; all other fibers were intact. Possibly the fiber-guards will be useful in the real LIGO suspension.

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