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Monolithic suspensions of the mirrors of the Advanced LIGO gravitational-wave detector

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Introduction

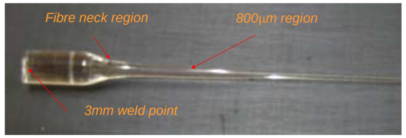
The 40 kg mirrors of the Advanced LIGO interferometers will be suspended on four circular silica fibres with diameter 400 μm. The fibres will be pulled and welded to ears on the sides of the mirrors using a 10.6 μm CO_2 laser beam [1].

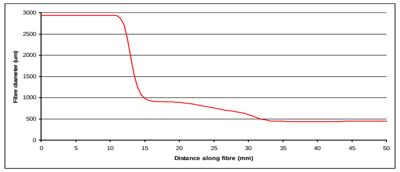
Fibre loss theory and optimising design

To reduce suspension thermal noise the mechanical loss of the fibre should be minimised. Contributing factors to the total loss are surface, bulk and thermoelastic, where the dominant contribution is thermoelastic loss [2]. This results from local spontaneous temperature fluctuations in the fibres, causing a temperature gradient, and subsequently bending, to occur in the fibre due to thermal expansion. This bending results in mirror motion in the detector. For fused silica the thermal elastic coefficient β is positive [3], meaning that the thermoelastic loss ϕ_{t-e} can be reduced by application of an appropriate (tensile) stress σ_o, and in principle nulled entirely when $\sigma_0 = Y/\beta$, see eq. (1). Here Y is the Young's

$$\phi_{t-e}(\omega) = \frac{YT}{\rho C}\left(\alpha - \sigma_o \frac{\beta}{Y}\right)^2 \left(\frac{\omega\tau}{1+(\omega\tau)^2}\right) \quad (1)$$

modulus, α is the linear thermal expansion coefficient, T is the temperature, C is the specific heat capacity and ρ is the density of fused silica; τ is the parameter of the Debye peak describing the frequency dependence of the thermoelastic loss. For 40 kg mass this nulling occurs for a fibre diameter of 800 μm, so fibres are pulled with ends of approximately this diameter (≈1.5 cm long at each end) to minimise the thermoelastic loss. Only the ends of the fiber needs to be made thicker, since that is where the thermoelastic dissipation is greatest. The central section is 400 μm diameter, chosen to reduce the vertical bounce mode frequency to below 10 Hz.

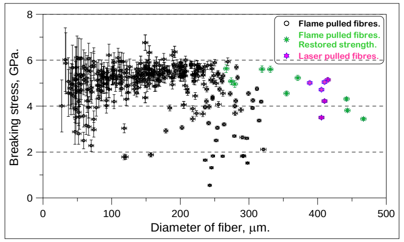




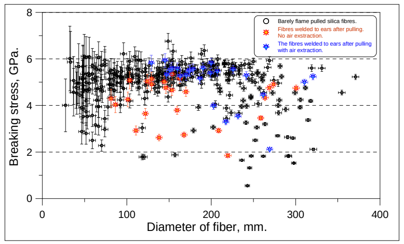
Laser pulled silica fibre

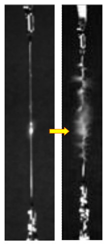
Strength of the silica fibers

To gain experience, preliminary experiments have been performed that include fabricating, profiling, welding, and breaking of flame-pulled, rather than laser-pulled, silica fibres. The strength of the fibres pulled from flame polished rods reached up to 6 GPa and did not depend on the fibre length. Similar silica fibres are called in the literature as 'pristine fibres'. The origin of breaking in this case is not related to surface microcracks, which is different from the behaviour of other bulk glass objects.



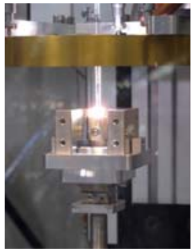
The thick fibres manifested smaller breaking stress. The origin of weakening was associated with thermal stress induced on the fibres ends during alignment of fibers on the test machine. The fibre on the right photograph broke in the point of heating at stress ≈ 2.16 GPa. By contrast, the strong fibres break in the middle near the thinnest point. The heating employed for alignment was displayed far from the fibres ends whereupon the breaking stress was restored (see green marks).





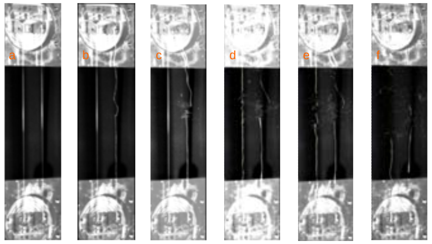
The aLIGO fibres will be welded to the interferometer mirrors, which can result in SiO_2 vapour deposition on the fibre surface. To investigate the strength in this case, fibres were welded to "ears" mounted on a strength test machine. The distribution of breaking stress for these fibres was different. However no distinctive features of the process of breaking were observed on the photographs. Probably the stress reduction is attributed to decreasing of the energy of activation of surface crack formation. Air extraction removes silica vapours and improves the breaking stress again so that it is as good as it was for fibres not welded to ears.

Humidity test



An aLIGO fiber pulled with a CO_2 laser beam was suspended in a moist atmosphere for a week. The load was 12 kg, the stress was 0.93 Gpa; the humidity was close to 100%. The fibre did not break.

Breaking of dual fiber suspension



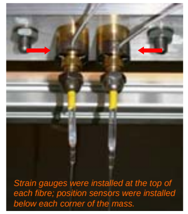
To test the laser welding technique, two laser pulled fibres were welded to the ears designed for the aLIGO mirrors. This dual-fibre assembly was stretched until breaking on a test machine. The maximal breaking load of a 400 μm fibre was 70 kg for a single fibre and 100 kg for the dual assembly, which is 5 times higher than the nominal load.

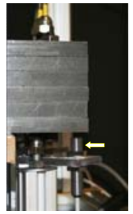
Suspension of a full size metal prototype

Twelve full scale test suspensions were built, during which tooling and procedures were refined. These test suspensions use two aluminium masses (with silica disc inserts) of the same weight as the actual interferometer silica mirrors.

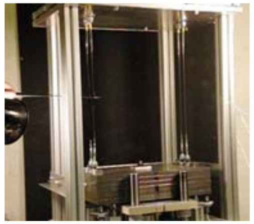
Tests with a 40-kg suspension

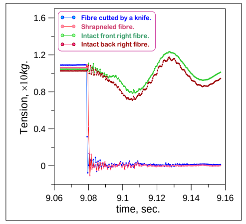
A 40-kg steel mass was suspended on 4 laser pulled silica fibres using the flame welding technique. The flame technique is not the main line of the required research. However, the technological process is similar to a large extent. The comparison of both techniques aids in our understanding of the mechanisms that are applicable to the suspension of mirrors in aLIGO using the CO_2 laser.





To simulate the behaviour of suspensions in the case of a fibre failure we intentionally cut one fibre with a knife. The adjacent fibre was also broken with 2 ms delay. Presumably that fibre was peppered with shrapnel. To prevent damage caused by flying sharp silica particles special protective shields will be installed in between the fibres in aLIGO.





Full prototype suspensions

The first full monolithic fused silica suspension of the aLIGO design was successfully hung in May 2010 at MIT. This suspension is a prototype to test various aspects of the design. The first aLIGO suspension will be installed in early 2011.

Acknowledgements

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References

1. Heptonstall et al, Class. Quantum Grav. 27 (2010) 035013
2. A. Gretarsson et all, Physics Letters A 270 (2000) 108.
3. G. Cagnoli, P. Willems, Physical Review B 65 (2002) 174111.

SUPA IGR LSC Science & Technology Facilities Council

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