Factors Pertaining to the Strength of Four-Fiber Monolithic Silica Test Mass Suspensions

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Introduction

The sensitivity of future gravitational wave detectors in the low-frequency range could be improved by decreasing the thickness of the suspension fibers. Fibers of diameter < 300 μm were suggested in the article [1]. Experiments conducted in the University of Glasgow in the last decade confirm the conclusions of this article.

Background

Over the past 4 years the monolithic suspensions have been successfully installed at the aLIGO detectors sites. These suspensions are performing well in terms of robustness and violin mode quality factor. The 400 μm diameter of the silica fibers was chosen to provide the bounce frequency below 10 Hz, and violin modes above 500 Hz [2]. Further reduction of the fiber diameter was not considered as the performance requirements were met. Subsequent strength measurements of pristine silica fibers [1,3] suggests a decrease of d_{fib} down to ≈ 300 μm would be possible [1]. We would like to substantiate the arguments in Ref [1] and consider that 300 μm silica fibers will still maintain a factor 3 in safety margin.

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Enhanced characteristics of fused silica fibers using laser polishing

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Using a 288 μm diameter fiber in a future upgrade to the Advanced LIGO suspensions would allow the vertical bounce mode of the final stage of the suspensions to be moved from 9 Hz to just below 6.5 Hz. Perhaps most importantly, this relatively straight forward upgrade would require no infrastructure change while retaining the factor of 3 safety margin over the static loading.

Figure 1: Article [1] emphasises the relevance of thin fibers for future suspensions.

Strength of complex systems

Figure 2. The strength of a complex system can be modelled as a chain: each link represents a separate mechanism of potential fracture.

The overall strength is always determined by the weakest link in the chain. The right chain suspension is weaker than the left chain despite the presence of an over-strengthened element. The excess strength can be reduced without a detrimental effect on the total strength.

Multiple fibre suspensions

A series of breaking tests on single and double fiber welded assemblies were performed. The breaking stress of fibers is nearly independent of fiber diameter, up to d_{fib}≈450μm [3]. This (among other things) proved that micro-cracks on the surface of fused silica can be removed by laser (or flame) polishing. The strongest 400 μm fibers pulled from a laser-polished stock were broken at load of ~ 70 kg.

However these experiments showed that careful preparation of the final suspension is required; for example thermal stress in the ends of the fiber attachments. For this reason, in aLIGO we perform a final "anneal" of the fiber in order to reduce the thermal stress and the current 40 kg aLIGO suspensions show excellent long term durability.

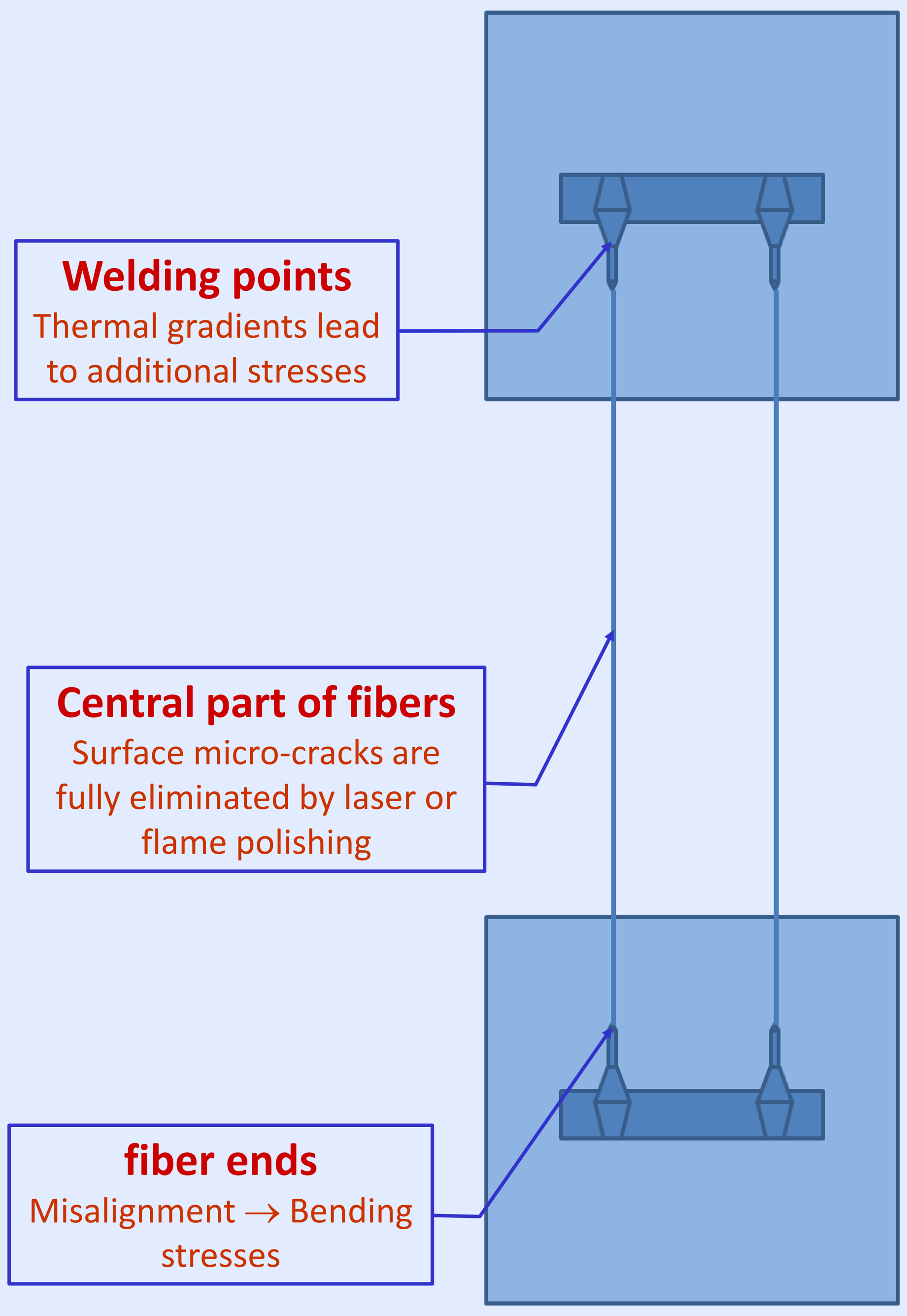

Figure 3: Location and physical mechanisms of potential fracture.

Breaking of single fibers

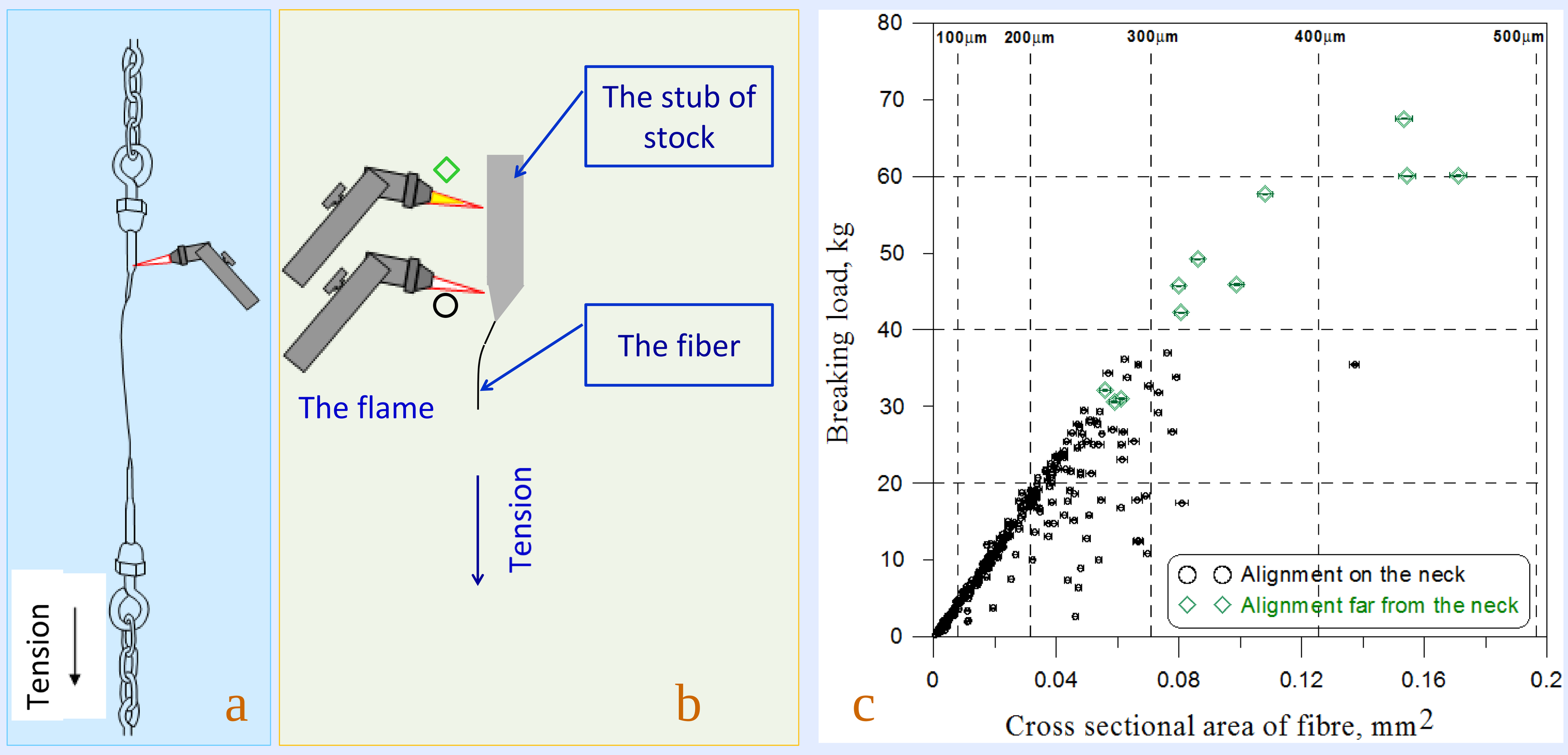

Figure 4: Breaking of single fibers welded to thick end attachments [3]. a) Alignment procedure. b) The point of melting was found crucial for the strength of fibers with d>250 μm. c) Strength of the flame pulled fibers aligned in two ways as shown in Fig. 4b.

Strength tests were performed on single fibers welded to 5mm silica stock (end attachments). In the experiment reported in figure 4 the thermally induced stress, which occurs in the fiber stock, can lead to a subset of fibers which break at the ends. This effect can be reduced by laser annealing (uniform heating) of the stocks after fiber welding.

The fibers represented in figure 4c were pulled from 3 mm stock. We estimate that fibers of the same diameter pulled from the stocks $d \geq 4$ mm would be less sensitive to the additional stresses on their ends. We also note that the fibers with $d \approx 300$ μm can provide safety margin >3 as it was noted in [1].

Destructive tests with prototype 40 kg 4-fiber suspension

A steel 40 kg mass suspended on 4 laser pulled fibers, welded to mock ears [4], was excited with a hammer. Longitudinal tension as high as ≈ 30 kg per fiber (triple the static load) was observed; and the suspension still was intact.

An interesting effect was observed during an "earthquake simulation". Backing off the earthquake stops to >4mm led to significant tilting of the steel block. We observed that fracture could occur at the point of excessive bending. To avoid fracture during powerful earthquakes the stops should be installed at a gap <1mm, which is the standard practice in aLIGO.

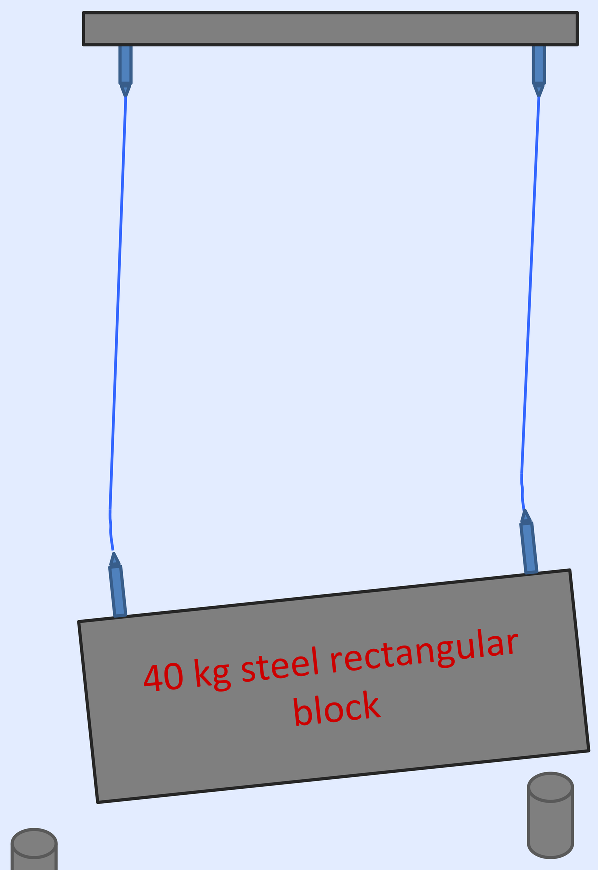

Figure 6: Jolting of the 40 kg prototype suspension

Thin fiber suspension

Four GEO test masses (16 fibres) have been hanging for 16 years, while the 8 aLIGO suspensions have been hanging ≈ 2.5 years; a total of 296 fiber-years. A 40 kg test mass prototype was suspended on four 330 μm fibers in Hanford in April 2015 (Figure 7). The stress in that experiment is higher at ≈ 1.1 GPa as compared to the specification of ≈ 0.8 Gpa for the 400 μm fiber. The bounce frequency was estimated to be ≈ 7.3 Hz. This test mass is still hanging in air. This experiment shows that there is comfortable safety margin for the strength.

Figure 7: Suspension with thinner fibres installed at LHO (April 2015)

Conclusion

The aLIGO suspensions currently installed provide a robust method for supporting the 40kg optics. Reducing of the fiber diameter down to ≈ 300 μm should not significantly affect the overall strength of the 4 fiber suspension, but will enable the bounce mode to be reduced to 6.6Hz. A test suspension at LIGO Hanford, with 330um fibers, has been hanging in air for over 1 year.

Acknowledgements

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