LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

LIGO-T030242-00-D *ADVANCED LIGO* 9th October 2003

Summary of Cantilever Blade Wire Clamp Testing

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1. INTRODUCTION

This document covers the testing of a variety of blade wire clamp concepts, to be used in low mass suspensions for the Advanced LIGO project, completed in the Institute for Gravitational Research (IGR) at the University of Glasgow. The experiments undertaken expand upon and compliment those undertaken in summer 2001[1]. The reason for completing these experiments was to understand if the current baseline design could be improved upon, increasing the overall breaking stress of the wire.

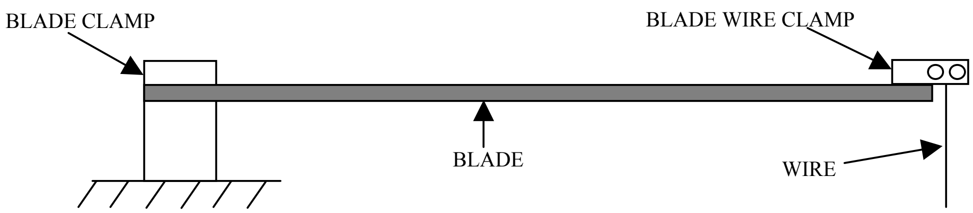


DIAGRAM SHOWING A SIDE VIEW OF THE BASELINE BLADE WIRE CLAMP ON A CANTILEVER BLADE

The blade wire clamp attaches to the tip of the cantilever blades connecting them to the wires that suspend the upper stages of triple and quadruple pendulums. Cantilever blades in Advanced LIGO will be required to support loads of up to 62kg. It is therefore important that suitable wires are chosen for this task and that the optimum clamp design is implemented to reduce the stresses in the wire, minimizing the chance of a wire breaking. Please note however, this document provides background to blade wire clamp designs for low mass suspensions and that further analysis is required prior to incorporating such a design in, for example, an Advanced LIGO quadruple suspension.

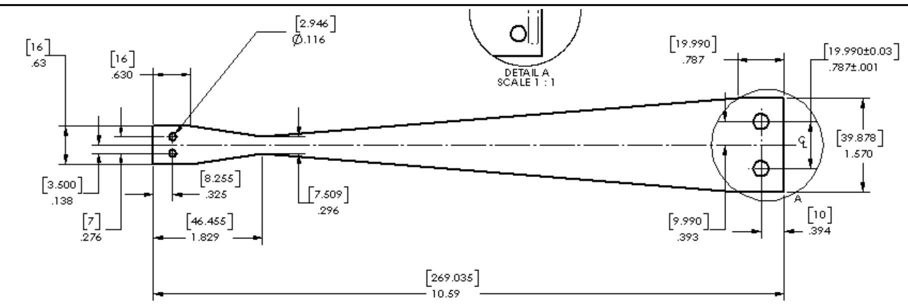
The baseline clamp design considered in this document is the one currently used in the LASTI controls prototypes and it is similar to the clamp design adopted in the GEO 600 project. The final GEO wire clamp designs were manufactured from titanium rather than stainless steel to achieve optimum isolation characteristics for the suspensions[2]

Introduction continued overleaf…

[1] Documents T030150-00 and E020811-00 completed by John Veitch and Dan Mason respectively. Both were students on the SURF program at California Institute of Technology, supervised by Dr Calum Torrie.
[2] Refer to Documents ALUKGLA0007aJUL03 by K.A. Strain and ALUKGLA0010aJUL03 by N.A. Robertson on blade spring design and blade internal modes.

Earlier testing on the breaking stress of suspension wires concluded that significant increases in breaking stress could be made to the baseline design by i) tightening tolerances of the clamp to ensure a well defined break off point and ii) wrapping the wire around a cylinder prior to clamping[1].

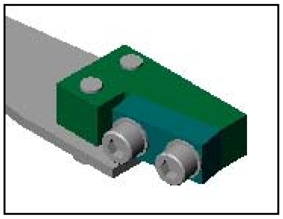
The five concepts that were tested and included in this document, integrate these two design improvements. Each concept was designed to fit the geometry of an existing LASTI Mode Cleaner Upper Blade (see below).



LASTI MODE CLEANER UPPER BLADE

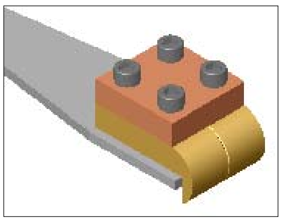
2. DESCRIPTION OF BLADE WIRE CLAMP CONCEPTS

2.1. Baseline Design



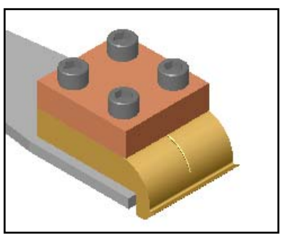
The baseline design is similar to that used in past GEO 600 models. This design includes the requirement for tighter tolerances and fly-cut that proved to be beneficial during the experiments by Veitch and Mason. The wire is sandwiched vertically between the L-shaped profile by clamping plate using two 4-40UNC bolts. Weight of clamp: 11.6g (with bolts)

2.2. Rounded Design



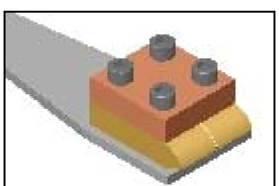
The rounded design was that proposed as a conclusion to the Veitch/Mason experiments and incorporates the tight tolerances and rounded profile that helped increase the breaking stress of the wire. The wire is fed through a v-shaped channel and clamped under a square plate clamping plate. It was assumed that the larger area of the clamping plate would better distribute the force on the wire. Weight of clamp: 13.5g

2.3. Rounded Design with Knife Edge



The rounded design with knife-edge was an evolution of the above blade wire clamp and was designed to introduce a clean break off point for the wire. The reason for introducing this design was because it was felt that the earlier rounded blade wire clamp was a poor design with respect to accuracy of the break-off point.
Weight of clamp: 13.9g

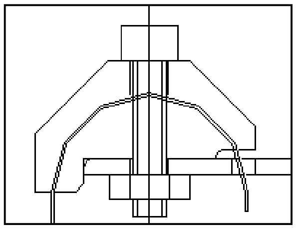
2.4. Revised Rounded Design



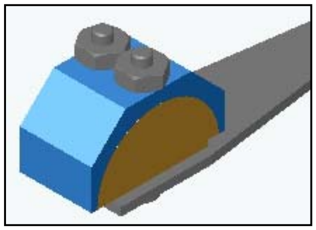
D030178 REVISED ROUNDED BLADE WIRE CLAMP

The revised rounded blade wire clamp displays a compromise between the rounded BWC and the knife-edge BWC. By keeping the same rounded profile as the initial rounded BWC however adding an angled cutaway we are able to introduce clean break off point.
Weight of clamp: 12.9g (with bolts)

2.5. RAL Rounded Design



RAL CONCEPT FOR A BLADE WIRE CLAMP



D030179_RAL_ROUNDED _BLADE WIRE CLAMP
Adapted RAL design to fit the LASTI Upper Blade

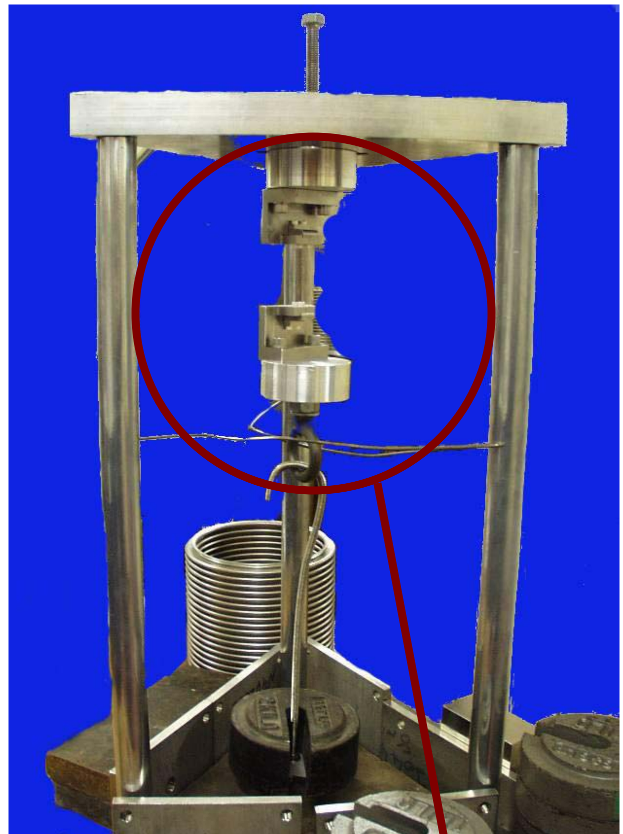
Finally the RAL Rounded Blade Wire Clamp design is a synthesis of a suggestion by Tony Jones of Rutherford Appleton Labs. The differences between the original and the synthesized design that the initial design was not designed for the LASTI mode cleaner blade and had a break off point at the lower edge of the blade rather than the upper edge – a requirement of the final Advanced LIGO suspensions[3].

Weight of clamp: 31.7g (with nuts and bolts).

[3] Refer to Document ALUKGLA0010aOCT01

3. Procedure

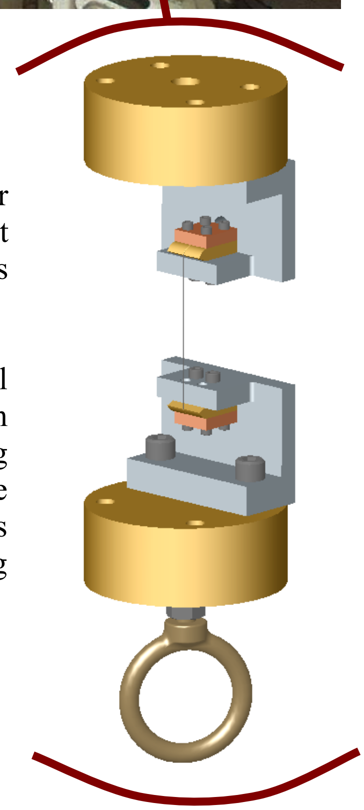
3.1. Setting Up the Experiment



In the blade wire clamp experiments, a wire of 0.22mm diameter was tested to breaking point using five different concept designs. The clamps were mounted on specially designed clamping jigs[4] and then the wire was attached at either end taking care to feed the wire through the middle of the clamp or where there was one, through the wire channel on the clamp (an example of the assembly is shown in the picture and rendering to the right).

3.2. Safety Precautions

Safety precautions were undertaken during the experiment. The cylinder, seen at the back of the picture (right), was used to shield the two clamps and tensioned wire, and the person carrying out the experiment wore Safety Glasses throughout.



3.3. Adding the Load

A mass was then suspended from the hook on the lower clamping jig until such a point that the wire broke. At this point the point of break was recorded along with the amount of mass suspended.

On the initial tests the mass was added in 1kg amounts until breaking, however in the repeated tests the mass was added in smaller increments to give a more accurate idea of the breaking stress and breaking point of the wire. For example, in the case of a wire clamp that had failed at 6.5kgs in initial tests, mass was added 0.5kgs until 6kg and then in 100g and later 20g increments.

[4] D020660 Assembly I-Blade Deflection Jig

3.4. Unforeseen Problems

Attaching the wire in the clamp assembly proved to be particularly tricky with the RAL Rounded Blade Wire Clamp to the pint where you may have wished for three hands. As the clamp was made up of two parts and a nut and bolt combination it was difficult to clamp these whilst keeping the wire in the fine groove on the wire clamp. As a consequence some tests may have been carried out with out the wire correctly in this groove throughout the clamp. Furthermore the wire may have been damaged whilst assembling the clamp, again potentially affecting the results.

Whilst undertaking the experiment, it was quite possible that damage to the wire may have occurred with several of the designs prior to suspension. This may have been an inherent problem with the test setup however it is not unlike the actual situation where a wire is being suspended from the end of a blade.

4. RESULTS AND ANALYSIS

The table in Appendix 1 shows the mass required to break the wire suspended from one of the five blade wire clamp designs. Also the failure location was recorded to understand if there was any apparent trend in the whereabouts of the break.

4.1. Failure Points

The breaking point of the wire was generally at either the upper or lower break off point. From this we can understand that the wire was not breaking at its breaking stress but at the point where the wire was highly stressed from the interface with the clamp. Why there was a tendency for the breaking point to alternate between top and bottom clamp is not quite clear, however we can assume that this may be due to the small shear stresses incurred during the assembly of the clamped wire.

The exceptions to the rule that the wire was breaking at the clamp's break-off point was with:

i) The Rounded blade wire clamp where the wire tended to break off below the rounded surface of the clamp, and

ii) The knife-edge design where the wire broke where the wire broke, unsurprisingly, at the knife-edge.

In the case of the rounded blade wire clamp we are clearly seeing that this design was improving the clamp for the wire strength however the design did not fit the specification for a well-defined break-off point.

4. 2. Notes and Theory

The mass of the clamping jig has been added to the suspended mass after the experiment was completed, hence the reason for the overall breaking mass not ending in a round number, i.e. in the first Revised rounded BWC test the total mass to break the wire is equal to: 6.5kg suspended + 0.59kg clamping jig =7.09kg.

The Breaking Stress of the wire has been calculated using the following equations:

$$B.S. = F/A = F/\pi r^2$$

Where F is the force on the wire and r is the radius.

And by taking the breaking force to be equal to the weight of the suspended mass, m, under gravity, g:

$$F = mg$$

4.3. Analysis

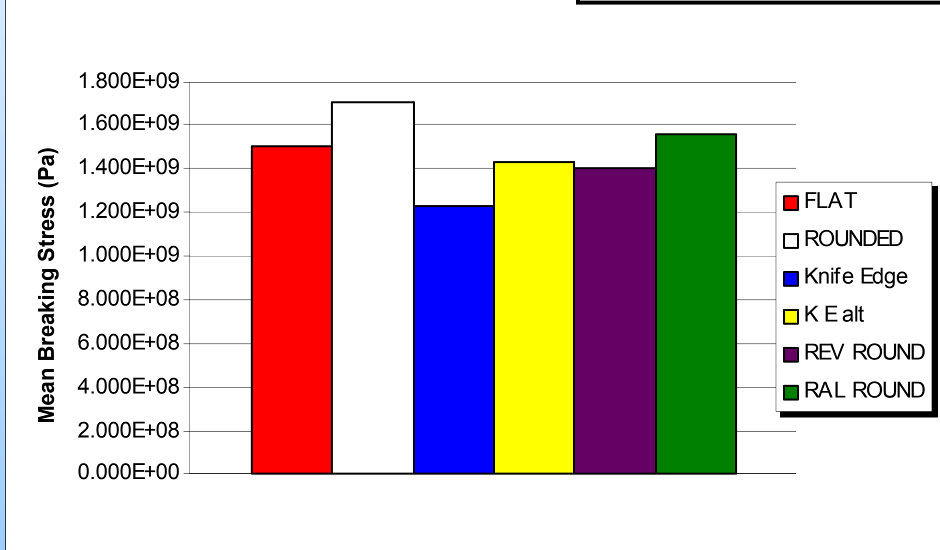
As you will see from the above results the overall improvement by moving from the existing baseline design to several new and more complicated models has not been substantial and in many cases has given worse results. This is highlighted well by the following table and graph (figure 2):

	MEAN B.S. (Pa)	% improvement
FLAT	1.505E+09	-
ROUNDED	1.704E+09	13.18%
Knife Edge	1.229E+09	-18.33%
K E alt	1.433E+09	-4.81%
REV ROUND	1.398E+09	-7.09%
RAL ROUND	1.562E+09	3.79%

FIGURE 2: Comparison of Breaking Stress of concepts against Baseline Design.

NOTES:

1. FLAT Blade Wire Clamp is Baseline Design
2. KE alt is the remachined Knife Edge Blade Wire Clamp design with a more rounded edge



As you will see from the above, there are only two blade wire clamps that give an improvement over the baseline clamp.

This improvement is only significant in the case of the Rounded Blade Wire clamp, however this design was quickly dismissed as the break-off point is very poorly defined. It is critical that this is clearly defined so that the characteristics of the suspension can be predicted as accurately as possible.

The RAL rounded design which also offers some improvement can be dismissed on the grounds that it is more than three times heavier than the baseline design and not easy to assemble – an important characteristic when a complex assembly such as a triple suspension is considered.

5. Conclusions

Overall the several rounded blade wire clamp concepts have given no great improvement on the baseline design. This confirms that we currently have the optimum design for low mass suspensions systems.

With considerable effort we have not been able to improve wire breaking point by more than 13% and although the Rounded Blade Wire Clamp and RAL Rounded Blade Wire Clamp offer some improvement on the baseline design they fall down on not matching the design specification and being tricky to assemble, respectively.

Some important notes that should be stressed at this time are:

1) In the final GEO designs Titanium was used to reduce the overall weight of the Blade Wire Clamp. This is important to reduce the internal mode of the blade and wire clamp assembly keeping it closer to that specified in the model.
2) The design may need to be redesigned for use in large suspension systems, for example the Advanced LIGO Quadruple pendulum suspensions.

APPENDIX 1: TABLE OF BLADE WIRE CLAMP TEST RESULTS

Wire Diameter : 0.22mm				
CSA : 4.85E-08 m^2				
Clamp Type	**Test No.**	**Mass (kg)**	**Breaking Stress (Pa)**	**Failure Location**
FLAT	1	7.52	1518959588	Bottom @ Clamp
"	2	6.92	1397722474	Bottom @ Clamp
"	3	7.42	1498753402	Bottom @ Clamp
"	4	7.53	1520980206	Bottom @ Clamp
"	5	7.56	1527042062	Top @ Clamp
"	6	7.55	1525021443	Top @ Clamp
"	7	7.59	1533103918	Top @ Clamp
"	8	7.52	1518959588	Top @ Clamp
ROUNDED	1	8.49	1715626392	break @ clamping point
"	2	8.39	1695420206	break below upper rounded break-off
"	3	8.09	1634801649	break below upper rounded break-off - BUT, w ire damaged during setup
"	4	8.64	1745935670	break below upper rounded break-off
"	5	8.54	1725729485	break below upper rounded break-off
Knife Edge	1	6.08	1229142268	break @ lower knife edge (but upper was necking too)
	2	6.08	1229142268	break @ upper knife edge
alteration...	Gave clamps to Steve Craig who milled a bit off knife edge, and rounded the corners.			
	1	7.09	1432739794	break @ upper knife edge
		We stopped tests here as it was clear that this geometry was having a negative effect		
REVISED ROUNDED	1	7.09	1432739794	Bottom @ Clamp
	2	7.09	1432739794	Bottom @ Clamp
	3	6.79	1372121237	Bottom @ Clamp
	4	6.84	1382224330	Bottom @ Clamp
	5	6.79	1372121237	Bottom @ Clamp
RAL ROUNDED	1	8.19	1655007835	Top @ Clamp
	2	7.59	1533770722	Bottom @ Clamp
	3	7.59	1533770722	Top @ Clamp
	4	7.49	1513564536	Bottom @ Clamp
	5	7.79	1574183093	Top @ Clamp

APPENDIX 2: INTERESTING NOTES ON BLADE WIRE CLAMP DESIGN

Excerpts from notes taken by Calum Torrie during the Glasgow Suspension Design Summit, August 2003.

QUESTIONS RELATED TO BLADE WIRE CLAMP DESIGN.

1) QUES: Did we beef up the thickness of the radius of the wire in the 2001 Quad compared to 1/3 of the BS?

ANS: Norna and I looked at this over lunch and decided that we would like to comment that when there is 2 wires off one blade the effect of the wire is bigger due to the effect of the wires to the spring constant, k.

2) QUES: It should be noted that the effect of the angled wire is not modelled correctly in the MATLAB Suspension Model!
ANS: 2 wires off one blade - Mathematica model shows the real effect of the angled wire of the blade and does this need to be looked at

3) QUES: KAS conclusion to Blade Wire Clamp Tests?
ANS: MPL started looking at blade wire clamp due to big difference seen with round clamp by Dan. Results show that the multiple designs tested gave similar results.

4) SUGGESTION: BLADE WIRE CLAMP – GC
ANS: Geppo recommended that from experience (of assembling small blades) he learned in GEO it would be easier in terms of assembly if we used slots instead of holes at the tip of the blade (for the bolts from the blade wire clamp).

Regarding point 4 above. This technique of adding slots instead of holes so that a blade wire clamp can be slid into place rather than bolting has been tested (September 03). It is recommended for small blades such as the Mode Cleaner Lower Blades where space to fit the blade wire clamp below the upper mass is at a premium that slots should be used rather than holes.