LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Bonded ear strength tests (Serial Numbers 0001, 0002 and 0011 to 0014)

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1 Summary

Main conclusions:

- Bond strength tested up to x 3.7 working load without failure of the bond.
- Minor design modifications required to ear design itself:
  - Modification of shape in region of horn to reduce stress concentration effects without jeopardizing ease of welding and repair. This is a minor design modification and can be achieved by using a larger radius at the horn/ear interface.
  - The ground finish is not acceptable from both a bond inspection point of view and from a stress concentration point of view. Future ears will have inspection polish
- Effect of heating on bond integrity requires further investigation
  - Heating due to ribbon/fibre welding
  - Heating due to flame polishing if required
- Further short-term failure and long-term loading tests will be performed.

2 Introduction

Preliminary test ears for the ETM/ITMs were fabricated to drawing number D050169-06 for initial bonded ear strength testing and visual inspection. The ears are made from various grades of Suprasil and have a bond area of 1.77cm^2 in accordance with the allowable limit set by thermal noise considerations[1]. They are designed in such a way as to accommodate a lap welded ribbon. The ears were manufactured by two different vendors. Table 1 summarises the details of the ear bonding material and manufacturers for the ears tested. The silica discs (Suprasil 312) to which they were bonded were manufactured to drawing number D050192-01 with ϕ = 50 mm and t = 7 mm.

Bonding and visual inspection of the bonded ears is described in a series of technical reports[2] [3] [4].

[1] Cantley et. al., "*Ear Bond Area Limit fro ETM/ITM Optics from consideration of Thermal Noise"*, T050216-00-K

[2] Rowan et. al., "*Bonding and Visual Inspection of Preliminary Test Ears (Serial Number 0011-0014)"*, T050121-00-K

[3] Rowan et. al., "*Bonding and Visual Inspection of Preliminary Test Ears (Serial Number 0001-0004)"*, T050209-00-K

[4] Armandula et. al., "*Bonding and Visual Inspection of Preliminary Test Ears (Serial Numbers 0005, 0006, 0015 & 0016)"*, T050210-00-K

Ear Serial Number	*Ear manufacturer*	*Ear material*	*Disk manufacturer*	*Disk material*	*Date bonded*	*Bond report*
0001	*Vendor 'B'*	Suprasil 2A	*Vendor 'A'*	Suprasil 312	15/07/05	T050209-00-K
0002	*Vendor 'B'*	Suprasil 2A	*Vendor 'A'*	Suprasil 312	15/07/05	T050209-00-K
0011	*Vendor 'A'*	* Suprasil 2	*Vendor 'A'*	Suprasil 312	14/07/05	T050121-00-K
0012	*Vendor 'A'*	* Suprasil 2	*Vendor 'A'*	Suprasil 312	14/07/05	T050121-00-K
0013	*Vendor 'A'*	* Suprasil 2	*Vendor 'A'*	Suprasil 312	14/07/05	T050121-00-K
0014	*Vendor 'A'*	* Suprasil 2	*Vendor 'A'*	Suprasil 312	14/07/05	T050121-00-K

* Grade 2A or 2B not specified.

Table 1 Details of the bonded ears

3 Bonded ear strength tests

The ribbon/fibre breaking machine was adapted using special clamps and hooks to hold the ear in position and load it vertically using a specially made loading hook. In this way the load could be applied at the correct offset from the bonded surface to mimic the welded situation.

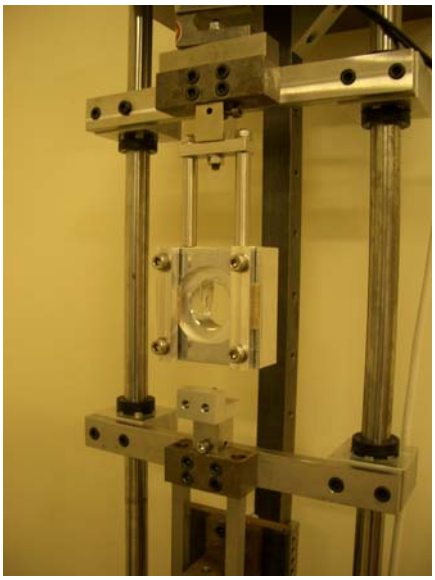


Figure 1 Test setup prior to loading hook installation

Figure 2 Bonded ear aligned vertically

Figure 3 Loading hook with 1 mm loading edge

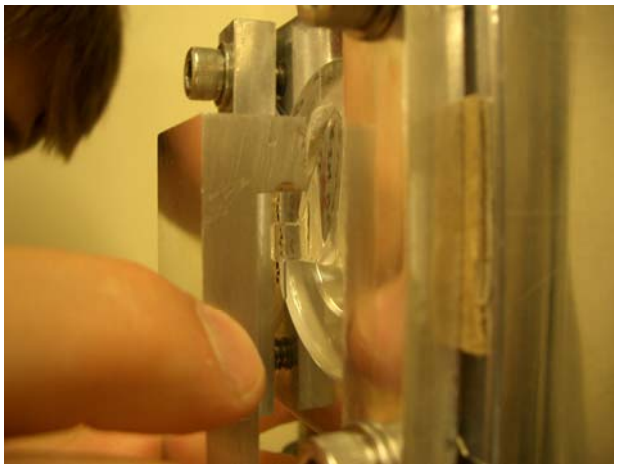
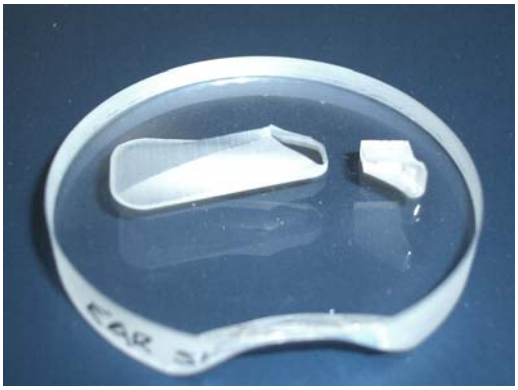


Figure 4 Loading hook being placed on horn

Below are notes that were recorded during each loading test.

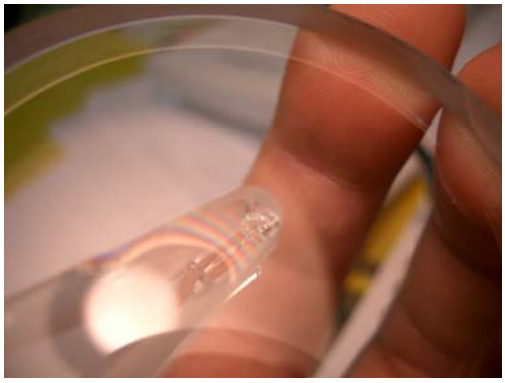
Strength Test on Bonded Ear Serial Number SN 0012	
Drawing Number	D050168-06
Description	Preliminary test ear (triangular faced) – flat to λ/10, with ground finish elsewhere
Manufactured by	Vendor 'A'
Material	Suprasil 2
Bonded to	Suprasil 312 disk (Vendor 'A')
Bond date	14/07/05
Strength test date	10/08/05
Set-up	Loaded at groove location using rigid aluminium hook device. Load increased over several seconds.
Result & conclusion	Ear horn failed at 9.3 kg (25.4 lbs minus 4.9 lbs correction for mass of clamp). Premature horn failure due to stress concentration at sharp transition from horn to ear main body. Problem exacerbated by rough ground finish on ear providing prime sites for crack propagation. Bond did not fail at this load.
Photo 1 *Horn failure which propagated from transition between horn and main body of the ear.* *Photo 2* *Broken horn placed on top of ear shows clearly the failure location*	 

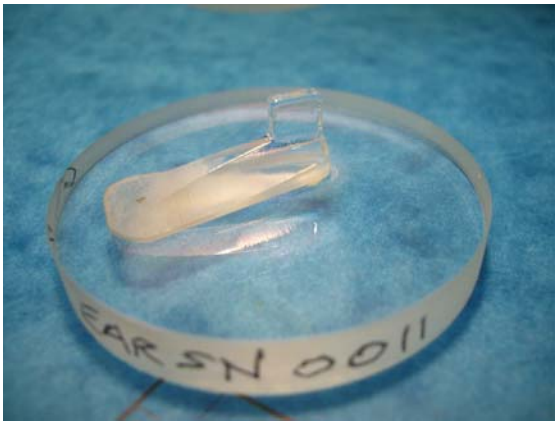
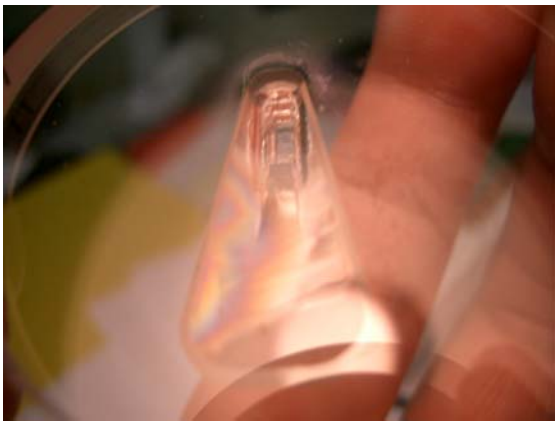
Strength Test on Bonded Ear Serial Number SN 0014	
Drawing Number	D050168-06
Description	Preliminary test ear (triangular faced) – flat to λ/10, with ground finish elsewhere – *flame polished whole ear four weeks after bonding*
Manufactured by	Vendor 'A'
Material	Suprasil 2
Bonded to	Suprasil 312 disk (Vendor 'A')
Bond date	14/07/05
Strength test date	11/08/05
Set-up	Loaded at groove location using rigid aluminium hook loading device. Load increased over several seconds.
Result & conclusion	Loaded to around 18 kg but loading hook slipped. Potential for damage to have occurred during this. Reloaded to 27.2 kg (64.6 lbs minus 4.6 lbs correction for mass of clamp) when horn failed. Note: prior to the initial test the bond was inspected and was seen to have a semicircular fracture-like feature towards the toe of the bond. This may have resulted due to thermal stresses between the dissimilar grades of Suprasil during flame polishing. In addition to the failure at the horn there was another smaller fracture evident in this region but at a higher vertical inclination to the fatal fracture.
Photo 1 *Flame polished bonded ear prior to testing. Note the residual silica vapor deposits around the bond.*	

Strength Test on Bonded Ear Serial Number SN 0013	
Drawing Number	D050168-06
Description	Preliminary test ear (triangular faced) – flat to λ/10, with ground finish elsewhere – *flame polished horn region mostly towards the front*
Manufactured by	Vendor 'A'
Material	Suprasil 2
Bonded to	Suprasil 312 disk (Vendor 'A')
Bond date	14/07/05
Strength test date	11/08/05
Set-up	Loaded at groove location using rigid aluminium hook loading device. Load increased over several seconds.
Result & conclusion	Loaded to 37.5 kg (87.2 lbs minus 4.5 lbs correction for mass of clamp) when horn failed. Bond still intact and not tested to destruction. This is a factor of x 3.7 above Advanced LIGO working load. Corresponds to a maximum stress on bond area of 2.1 MPa compared to operating stress of 0.6 MPa (10 kg per ear).
Photo 1 *Bonded ear with flame polishing of horn mainly towards the front of the horn in high stress region.*	

4 Effect of flame polishing on the bond

Ears SN 0001 and 0011 showed obvious bond degradation probably due to thermal stresses introduced by flame polishing.

Flame Polishing of Bonded Ear Serial Number SN 0001	
Drawing Number	D050168-06
Description	Preliminary test ear (triangular faced) – flat to λ/10 (comment from bonding report T050121-00-K more like λ/4), with ground finish elsewhere – *flame polished horn region mostly towards the front*
Manufactured by	Vendor 'B'
Material	Suprasil 2A
Bonded to	Suprasil 312 disk (Vendor 'A')
Bond date	14/07/05
Flame polishing date	12/08/05
Result & conclusion	Fringes evident after polishing indicating bond peeling due to thermal stresses introduced by flame polishing.
Photo 1 *Bonded ear with flame polished horn.* *Photo 2* *Fringes near toe indicate bond peeling due to thermal stresses induced by flame polishing (photo date 19/08/05, one week after flame polish). Checked on 22/09/05 and fringes still evident as before.*	 

Flame Polishing of Bonded Ear Serial Number SN 0011	
Drawing Number	D050168-06
Description	Preliminary test ear (triangular faced) – flat to λ/10, with ground finish elsewhere – *flame polished horn region*
Manufactured by	Vendor 'A'
Material	Suprasil 2
Bonded to	Suprasil 312 disk (Vendor 'A')
Bond date	14/07/05
Flame polishing date	12/08/05
Result & conclusion	Fringes evident after polishing indicating bond peeling due to thermal stresses introduced by flame polishing.
Photo 1 *Bonded ear with flame polishing of horn.* *Photo 2* *Fringes near toe indicate bond peeling due to thermal stresses induced by flame polishing (photo date 19/08/05, one week after flame polish). Checked on 22/09/05 and fringes still evident as before.*	 

Additional Comments:

The specified flatness for the bonding surface on the ears was λ/10. Results show that the flatness was not as specified (more like λ/4). The manufacturer has revealed that there was a production problem in so far that the average flatness was in fact 0.19λ due to the ears being tested for flatness whilst still mounted in their polishing fixtures. When the parts were freed from polishing fixtures there may have been re-exertion of internal stresses causing the piece to bend.

The other surfaces of these initial ears were specified as ground finish.

The ground finish was not ideal from two perspectives:

Bonding

1) the ground surfaces hindered inspection of the cleanliness of the polished bonding surface of the ear
2) the ground ear surfaces meant that the bonded interface could not be seen when the ear was put in place on the flat – so it was not possible to check that the bonding fluid had spread out correctly from above. However inspection could be carried out through the disc/flat after initial bonding.

Stress concentrations

3) Aside from causing visibility problems with respect to assessment of bond quality, it was considered that the ground finish could lead to undesirable concentrations of stress on the surface/edges of the ears when loaded. This was to be further investigated during loading tests on the bonded samples. It was considered that in these existing bonded test ears the surface quality could be improved by flame polishing. Future ears would be fabricated with an inspection polish to remove this problem.

5 Long term loading test

5.1 Introduction

Bonded ear Serial Number 0002 has been used for a long term loading test. This consists of a *Vendor 'B'* Suprasil 2A ear bonded to a *Vendor 'A'* Suprasil 312 disk (refer to Table 1). During bonding it was reported that the flatness of the *Vendor 'B'* ears in batch SN 0001 to 0004 did not appear to meet the λ/10 flatness specification (more like λ /4).

Since the rough surface finish (ground finish) in the region of the horn had proven to cause undesirable concentration of stress in this region leading to premature failure of the horn it was decided to flame polish the horn region. This was done lightly to minimize the effects of any residual stress across the bond due to the heating and potential differences in thermal expansion coefficient between the Suprasil 2A and the Suprasil 312. Approximately one hour after flame polishing the bond was inspected and there were no fringes visible hence no visible sign of bond degradation due to thermal stresses.

Proof testing of the ear bonds to a factor of 1.2 over the maximum in-service load is an Advanced LIGO requirement[5]. This is the philosophy behind the choice of a 12 kg load with 10 kg being the maximum in-service load.

5.2 Test set-up

The bonded ear-disk assembly was mounted vertically in a specially designed clamp which was rigidly mounted to an optical bench. The preliminary test ear has a specially extended horn to enable the loading to occur in the plane of the weld in an actual ear. A wire loop was slipped over the horn at the location marking the plane of the weld. Figure 1 shows the arrangement.

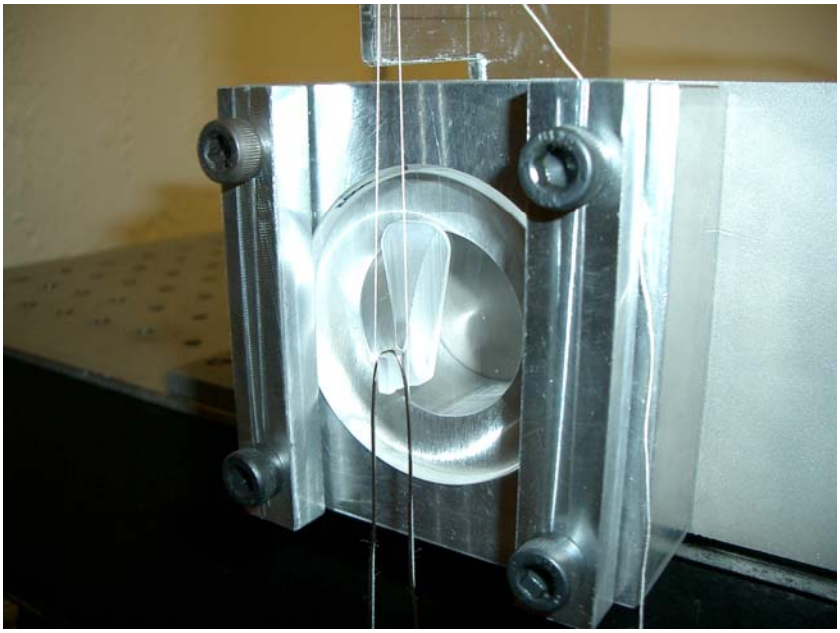


Figure 1 *Bonded preliminary test ear arrangement for long-term loading test. The light flame polish in the horn region is just visible.*

The wire loop was loaded with a 12 kg mass. A cotton thread was attached to an adapted clock to act as a crude timer unit should failure occur out of hours. Figure 2 shows the load hooked on to the wire loop which in turn is hooked across the horn of the ear.

[5] Universal Suspension Subsystem Design Requirements Document", T000053-03-D

Figure 2 View showing 12 kg load on bonded ear

Figure 2 shows more clearly how the 12 kg load acts on the plane of the weld position.

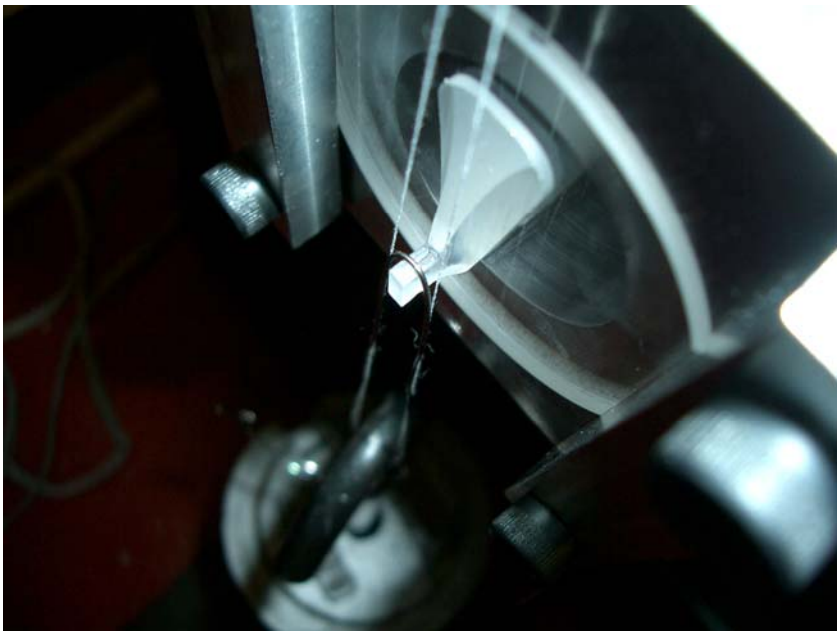


Figure 2 Load acting on bonded test ear on plane of the proposed ribbon weld to produce correct moment

The bonded ear was loaded on Friday 19th August 2005 at approximately 17:30 hrs (GMT).

5.3 Conclusion

This could be considered as a worst case scenario long-term load test with:

- Reported poor flatness of ear bond surface (λ /5 instead of λ /10).
- Dissimilar grades of Suprasil between ear and disk (Suprasil 2A ear bonded to Suprasil 312 disk).
- Ground finish on surface of ear leading to potential stress concentration spots in region of loaded horn area. Mitigated by light flame polishing in the horn region. This in itself could potentially cause problems due to heating across bond where differences in thermal expansion co-efficient could potentially lead to residual thermal stress across the bond.

The test will be left in place indefinitely.

Another long term loading test will be set up in the near future with a “good” bond with a λ /10 flatness and similar Suprasils.