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Ribbon/Fibre Length Budget

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1 Introduction

1.1 Purpose and Scope

In the quad noise prototype, the test mass must hang with its vertical centre line a specific distance below that of the penultimate mass: `tl3` in the nomenclature of the Matlab/Mathematica models. Also, the effective flexure points of the ribbons must be inset by distances `d3` and `d4` from the mass centre lines. To meet these constraints will require careful length budgeting at all stages from ribbon production, though ribbon characterization and bonding of ears, to welding of ribbons.

1.2 Version history

6/10/07: Pre-rev-00 draft #1. Basic description of desired sequence to get feedback.

8/22/07: Pre-rev-00 draft #2. Details of ear bonding calculations added.

8/27/07: Pre-rev-00 draft #3. Flexure correction calculation.

8/28/07: Pre-rev-00 draft #4 -> Rev. -00. Extended flexure correction calculation exploring effect of different dweld values. This is the version that was used for ear bonding at LASTI and so is released as -00, even though it contains a few known errors. These have been flagged with "Note added in proof: …".

2 Overview

The following section gives a list of the operations that need to be considered in the length budget.

A fused silica slide is mounted with adhesive into two roughly cylindrical "holsters" to form a "fuse". At the time of writing, the jig to do this already exists, and the dimensions of the fuse are taken to be fixed.

The holsters of the fuse are hooked into roughly U-shaped "master pulling clamps" which accompany the fuse for much of the rest of the processing and allow tension to be applied to the slide.

The fuse in the master pulling clamps is mounted into a frame comprising two "mount plates" and two "hanger plates", held apart by two "bracing bars". The bracing bars support and protect the slide by keeping the mount plates in a fixed relationship while they are attached to the carriages of the pulling machine. Micrometers on the mount plates allow them to conform to any slight departure from coplanarity of the attachment surfaces of the carriages. When the micrometers have been adjusted and the fasteners have been tightened, the bracing bars are removed. (This is possibly overkill and may be revisited in favour of just moving the holsters.)

A high power CO_2 laser beam is aimed at a TBD position on the slide and the pull is started. The lower carriage moves up very slowly to feed fresh slide material into the heating zone, and the upper carriage moves up at 25 times the rate to draw out a ribbon of approximately 1/5 both the width and thickness of the slide. After a TBD amount of travel, the laser is shut off and the pull is stopped.

The master pulling clamps are joined by two rather longer bracing bars (still being designed), removed from the pulling machine, and transferred to the profiler. (Again, this is possibly overkill and may be revisited.) One clamp is attached to the "base cartridge" at the bottom, and the other to the "alignment boss" at the top. The bracing bars are removed, and the ribbon is put under just enough tension (?) to hold it straight.

The profiler takes front and side pictures of the ribbon at regular intervals along the length and stitches them together to form width and thickness profiles.

After the profiling, the tension is relieved, the bracing bars are refitted (?), and the ribbon is transferred to the proof/bounce tester. There it is checked that the ribbon can withstand the required tension including safety factor, and the bounce mode frequency is measured with a reference mass so that the net longitudinal stiffness can be determined. After characterization, the pulling clamps are removed (?) and the ribbon is hung in a desiccator until needed.

For a representative sample of ribbons, the effective flexure point is calculated for each end, using the profiler data. Since it may not be possible for the profiler to capture the end of the fuse or another reference mark in a fixed relationship to it, it may be necessary to work relative to some feature of one or both necks that is easily recognizable from the profile data, e.g., the point where the width of the ribbon is half that of the slide. A relative position for the ribbon neck and ear is chosen that puts the flexure point a convenient distance off the tip of the ear for a typical ribbon.

The length of the pull is tuned such that the effective flexure points will be the required distance apart after allowing for the stretch of the ribbon under load.

The ears are bonded to the side of the masses. The flat on the side of each mass has a scribe line indicating the vertical centre, and the tip of the ear is located at a suitable offset from it to put the flexure point at the prescribed `d3/d4` value.

The slide is scored and snapped in two places so as to extract the central ribbon section plus two tags long enough to give the right amount of overlap with the flats on the ears.

The test mass and penultimate masses are loaded into the lower structure at the heights that they will eventually hang at. The test mass is then raised by the amount of stretch that the ribbons will have under load, so that the tags on the untensioned ribbon can be placed against the ears and held in place until welding with a slight pressure from a sprung finger or the like (yet to be designed).

After all the ribbons are welded, the test mass is lowered a small distance to put a slight tension on the ribbons, which are then heated to correct any slight difference in length.

The test mass is lowered to its final hanging level and then forced a small distance further down to check that the welded ribbons can support the full load with the desired safety factor.

3 Operation details

3.1 Fuse

A ribbon fabrication slide of thickness `tslide`, width `wslide` and length `dslide` is cemented into two "holsters" to form a "fuse". Each end of the slide is inserted a distance `dholster`, so the net length between holster inside faces is `dfuse` = `dslide` – 2*`dholster`.

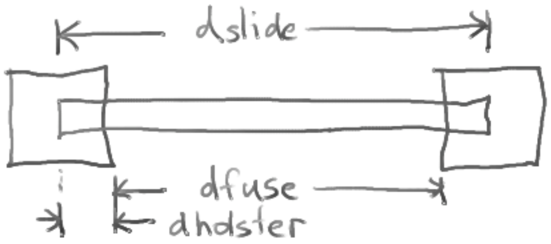

Figure 1: A "fuse" created from a slide and two "holsters"

3.2 Pulling

The fuse is installed between pulling clamps on the carriages of the pulling machine. A high power CO_2 laser is aimed at a spot `dlaser` from the bottom holster inside face. After the silica softens, the top carriage is moved upwards a distance `ddraw` to draw out a ribbon, while the bottom carriage moves up a somewhat lower distance `dfeed` to feed fresh material into the heating zone. The ratio of the carriage speeds will be approximately `rcarriage` = `ddraw/dfeed` = 18.9, so as to reduce the slide by a factor of 5/1.15 = 4.35 in each direction. After the pull the holster inside faces are a distance `dpulled` = `dfuse+ddraw-dfeed` apart.

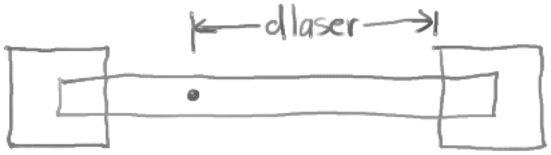

Figure 2: Pulling – before

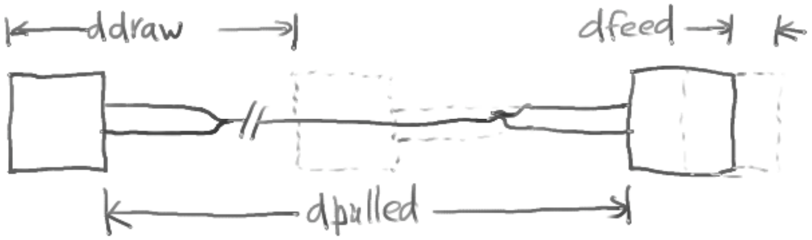

Figure 3: Pulling – after

3.3 Profiling

The ribbon is transferred, still in the holsters, to the profiler where the width and thickness profiles are measured. It is placed under very modest tension, enough to hold it straight but not change the overall length significantly from `dpulled`. Because the profiler head cannot move down all the way to the bottom holster (and could not focus on it in any case) it is convenient to do subsequent calculations relative to the two points where the ribbon is half the thickness of the slide. The half-thickness points are chosen because they are easy to identify accurately both in the profiler data and manually using a loupe with a graticle. Although as just noted the individual distances of the reference points from the holster inside faces are unlikely to be significant separately, we give them names `dhalf1` and `dhalf2`. (Here and subsequently we adopt the convention that names ending in `1` denote quantities describing the end of the ribbon to be used at the top near the penultimate mass, and symbol names ending in `2` indicate the bottom or test mass end.)

The remainder, `dribbon = dpulled-dhalf1-dhalf2` is an adequate approximation to the length of the ribbon for the purposes of calculating the stretch under load.

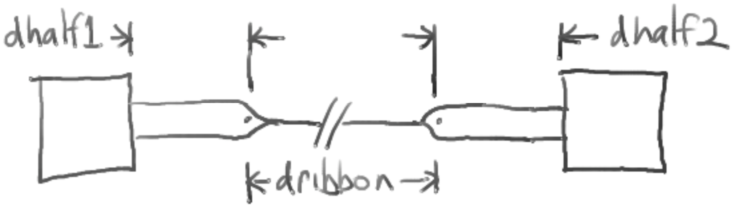

Figure 4: Profiling reference points

3.4 Strength testing

The longitudinal stiffness of the slide/ribbon

$$kribbon = \frac{Y}{\int_0^{dpulled} \frac{1}{A(l)} dl}$$

where Y is the Young's modulus of silica and A(l) is the cross-section as a function of length. Assuming that nearly all the stretch occurs in the central section of length `dribbon` stretches, this becomes

$$kribbon \approx \frac{Y * tslide * wslide}{dribbon * rcarriage}$$

The a priori value will be replaced as soon as possible by a measured value based either on the DC stretch for the proof mass, kproof = mproof*g/dproof, or on the vertical mode frequency with the bounce test mass, `kbounce` = `mbounce*`$(2\pi f)^2$.

3.5 Flexure correction; cutting and welding

Since it is unlikely to be feasible to weld the delicate ribbon directly to an ear, some of the taper between the slide and ribbon sections will need to be allowed to protrude off the ear. The point on the slide level with the end of the ear is the welding point, and the distance from the reference point to the welding point is `dweld1` or `dweld2`. The distance from the welding point to the flexure point is the `dflex1` or `dflex2`. The distance in the opposite direction to the end of the lap section is `dlap1` or `dlap2`. A cutter needs to be designed to score and snap the slide at a distance `dcut1` = `dweld1+dlap1` or `dcut2` = `dweld2+dlap2` from the reference points.

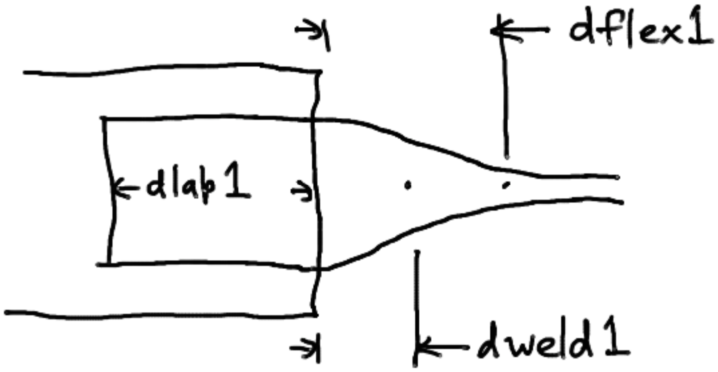

Figure 5: Welding and flexure points – top end

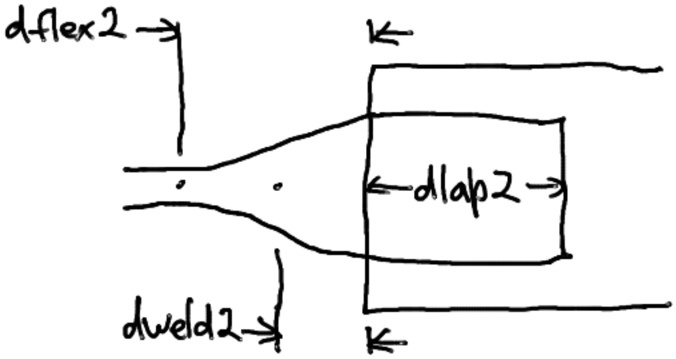

Figure 6: Welding and flexure points – bottom end

Unfortunately, `dflex1/2` is not a single number for a particular ribbon profile but depends on `dweld1/2`. The general form of the dependence is as shown in Figure 7.

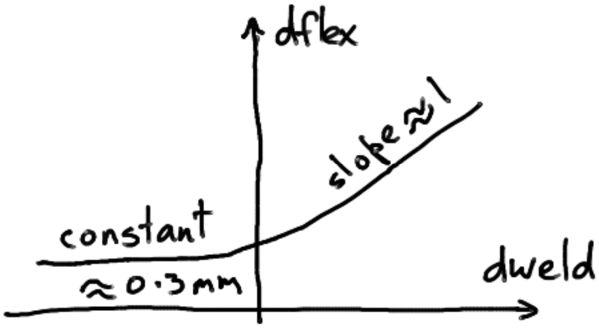

Figure 7: Dependence of dflex on dweld

For large positive `dweld1/2`, i.e., for a large section of slide off the end of the ear, the flexure point increases at approximately the same rate because the slide is stiff. Conversely, for negative `dweld1/2`, i.e., for the ribbon welded directly to the end of the ear, the flexure point is a small constant distance off the end (circa 0.3 mm) because the ribbon is thin and uniform. The final value will be in the roll-off region between the two simple regimes, so it will be necessary to plot the entire graph and read off the appropriate value when the smallest feasible `dweld1/2` is determined.

3.6 Ear position

The conceptual design calls for the flexure point at the top end of the ribbon to be `d3` = 1 mm below the COM of the penultimate mass, and for the one at the bottom to be `d4` = 1 mm above the COM of the optic. (These names are from the Matlab/Mathematica models and so do not follow the “`1`”/“`2`” convention.) The vertical COM for a wedged optic with flats is

$$\mathrm{zCOM} = \frac{(-\mathrm{wabv} + \mathrm{wafv})\left((\mathrm{tf}^2 + 6\,\mathrm{tr}^2)\sqrt{-\mathrm{tf}^4 + 4\,\mathrm{tf}^2\,\mathrm{tr}^2} + 24\,\mathrm{tr}^4\,\mathrm{ArcCsc}\left[\frac{\mathrm{tr}}{\sqrt{-\frac{\mathrm{tf}^2}{4} + \mathrm{tr}^2}}\right]\right)}{24\,\mathrm{tx}\left(\sqrt{-\mathrm{tf}^4 + 4\,\mathrm{tf}^2\,\mathrm{tr}^2} + 4\,\mathrm{tr}^2\,\mathrm{ArcCsc}\left[\frac{\mathrm{tr}}{\sqrt{-\frac{\mathrm{tf}^2}{4} + \mathrm{tr}^2}}\right]\right)}$$

where tx is the thickness, tr is the radius, tf is the length of the flats and wafv and wabv are the slopes of the front and back faces, with positive meaning increasing x (towards the front) for increasing z (up). That is, a top-heavy wedge (zCOM>0) has wabv<0 and/or wabh>0. The LASTI test mass has a 10’±5’ wedge, so zCOM = 0.106 mm, and the final ETM will probably have a 30’ wedge, so zCOM = +0.318 mm. The penultimate masses are unwedged(?).

The value of zCOM in the previous paragraph is relative to the axis of the barrel of the optic. This can be identified by scribe lines called out to be placed halfway up each flat. We define the distance from the tip of the ear to the scribe line to be `dear1` or `dear2`. The distance from the scribe line to the COM is `dCOM1` or `dCOM2`. For symmetry we choose the sign convention for `dCOM1` to match `d3` (but opposite to `dCOM2`, `d4` and the formula for zCOM above), i.e., positive down.

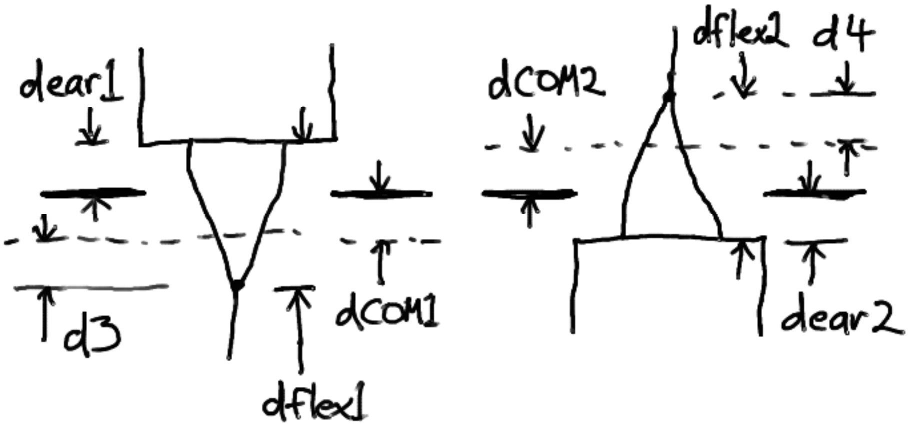

Figure 8: Ear positions

This implies

$$\mathtt{dflex1} = \mathtt{dear1{+}dCOM1{+}d3}$$

and

$$\mathtt{dflex2} = \mathtt{dear2{+}dCOM2{+}d4}$$

3.7 Ear bonding jig

The ear bonding jig clamps lightly to the side of the penultimate mass or optic and holds the ears in the correct position for bonding. It can be slid up or down to allow for different positions. On each side of the jig is a slot through which the scribe mark on the flat can be seen. Aligning the scribe marks on the flat with ones next to the slots centres the jig on the flat, which is approximately the correct position. In this neutral position the tips of the ears are a distance `djig` = 2.25 mm from the scribe height.

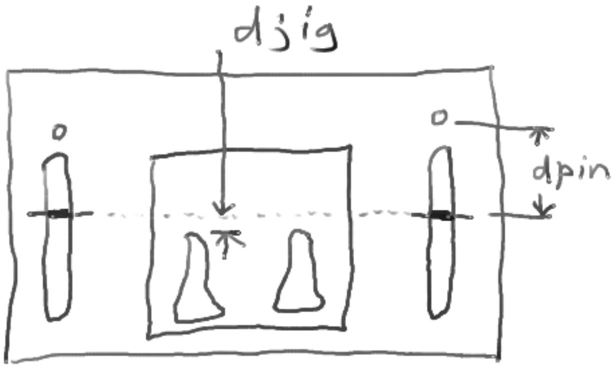

Figure 9: Bonding jig in neutral position – sliders not shown

Each slot has a slider which serves two purposes: (i) it can be set with calipers at a precise location relative to a locating pin to define a non-neutral position of the jig and (ii) by sighting down the edge of the slider, the position set at the top of the slot can be compared to positions on the flat below without parallax error.

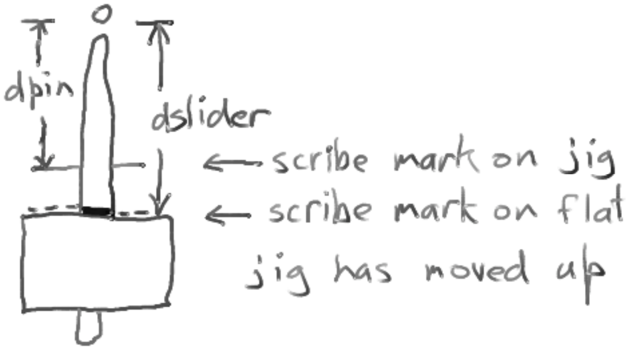

Figure 10: Use of slider on bonding jig

The distance from the pin to the scribe mark on the jig is `dpin`. If the distance to the slider is set to some other value `dslider1` or `dslider2` and the edge of the slider is aligned with the scribe mark on the flat, then

$$\texttt{dslider1-dpin} = \texttt{djig-dear1}$$

or

$$\texttt{dslider2-dpin} = \texttt{djig-dear2}$$

That is, increasing the slider distance decreases the distance from the tip of the ear to the centre of the flat or the COM.

4 Implications for ear bonding

Combining the relationships in the previous sections gives the following values for `dslider1` and `dslider2` for use in ear bonding (see associated Mathematica notebook T070138-00.nb.):

$$\mathtt{dslider1} = \mathtt{d3} + \mathtt{dCOM1} - \mathtt{dflex1} + \mathtt{djig} + \mathtt{dpin}$$

and

$$\mathtt{dslider2} = \mathtt{d4} + \mathtt{dCOM2} - \mathtt{dflex2} + \mathtt{djig} + \mathtt{dpin}$$

Using the values in the table gives

$$\mathtt{dslider1} = 19.29$$

and

$$\mathtt{dslider2} = 19.40$$

Quantity	Value (mm)	Note
`dweld1`	2.56	From profile of "fibre 2" taken 08/23/07
`dweld2`	2.56	From profile of "fibre 2" taken 08/23/07
`dflex1`	2.96	From profile of "fibre 2" taken 08/23/07
`dflex2`	2.96	From profile of "fibre 2" taken 08/23/07
`dCOM1`	0	no wedge on PM
`dCOM2`	0.11	10' wedge, top-heavy
`dpin`	19	from drawing by RAJ; TBC by IW
`djig`	2.25	from drawing by RAJ; TBC by IW

Table 1: Guesstimated values for LASTI installation

5 Appendix: CAD analysis of ribbon neck

5.1 Ribbon profile

The top neck of "fibre 2" was chosen as representative of what could be expected, and profiled by Alan Cumming on 08/23/07.

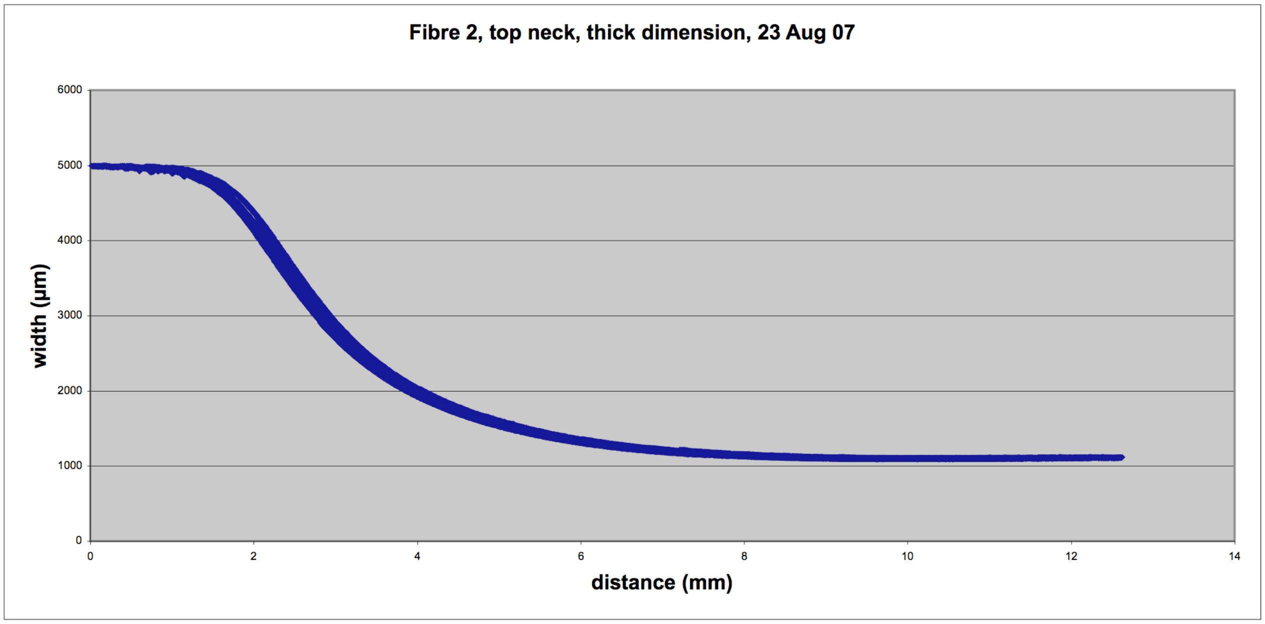

Figure 11: Fibre profile - width

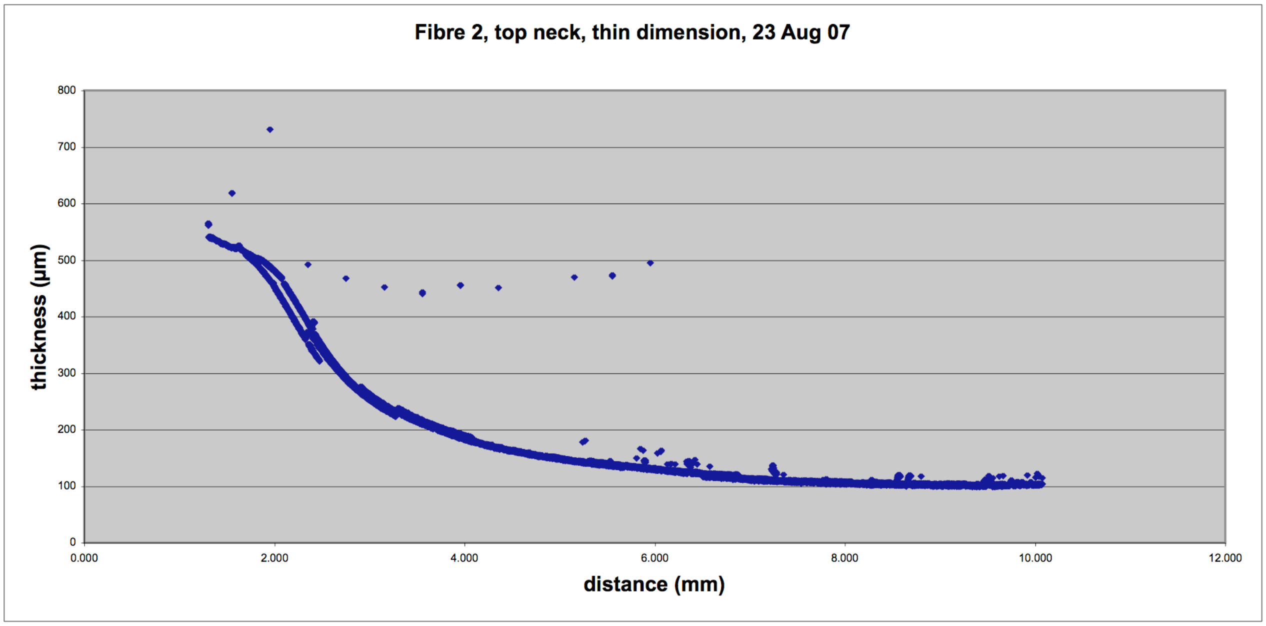

Figure 12: Fibre profile – thickness

5.2 CAD model

The shape of the ribbon through the neck section was fitted as a piece-wise linear taper from the slide to the ribbon (assumed rectangular) via four intermediate rectangular cross-sections as shown in the **bold** section of Table 2. An ANSYS model incorporating this shape was constructed as follows:

Coordinate system: X longitudinal, Y vertical (+ve up), Z transverse

Element Types: Beam189.

Material Models: fused silica, density 2202, Young's modulus 7.2E7, Poisson's ratio 0.17.

Real Constants: none.

Sections: rectangular sections as per Table 2, with B=thickness, H=width, Nb=0, Nh=0, plus taper sections, taper1=slide to sect1, taper2 = sect1 to sect2, taper3 = sect2 to sect3, taper4 = sect3 to sect4, taper5 = sect4 to ribbon.

Keypoints: as per Table 2.

Lines: between all consecutive pairs of keypoints (#1-#2, #2-#3, etc).

Loads: Displacement constrained in all DOFs at keypoint #1; UX displacement constrained at #2, #3, #4; displacement UX=0.01 and load force FY=-97 at #11.

Meshing: All lines meshed with Beam189 with maximum element length of 0.0002 m and cross-sections as per Table 2.

Analysis Type: Static

Solution Controls: Large Displacement Static.

ANSYS keypoint	ANSYS Y coord (m)	Profiler coord (mm)	Width (µm)	Thickness (µm)	ANSYS section name
1	0		4990	555	slide
2	-0.003		4990	555	slide
3	-0.005		4990	555	slide
4	-0.006	**3.7**	**4990**	**555**	slide
5	-0.0066	**4.3**	**4851**	**429**	sect1
6	-0.0071	**4.8**	**4337**	**494**	sect2
7	-0.0086	**6.3**	**2440**	**210**	sect3
8	-0.0110	**8.7**	**1410**	**138**	sect4
9	-0.0146	**12.3**	**1122**	**108**	ribbon
10	-0.050		1122	108	ribbon
11	-0.100		1122	108	ribbon

Table 2: Simplified ribbon profile used for CAD. (Note added in proof: the numbers in the profiler coordinate column are too large by 3mm, but have been left as-is for historical reasons.)

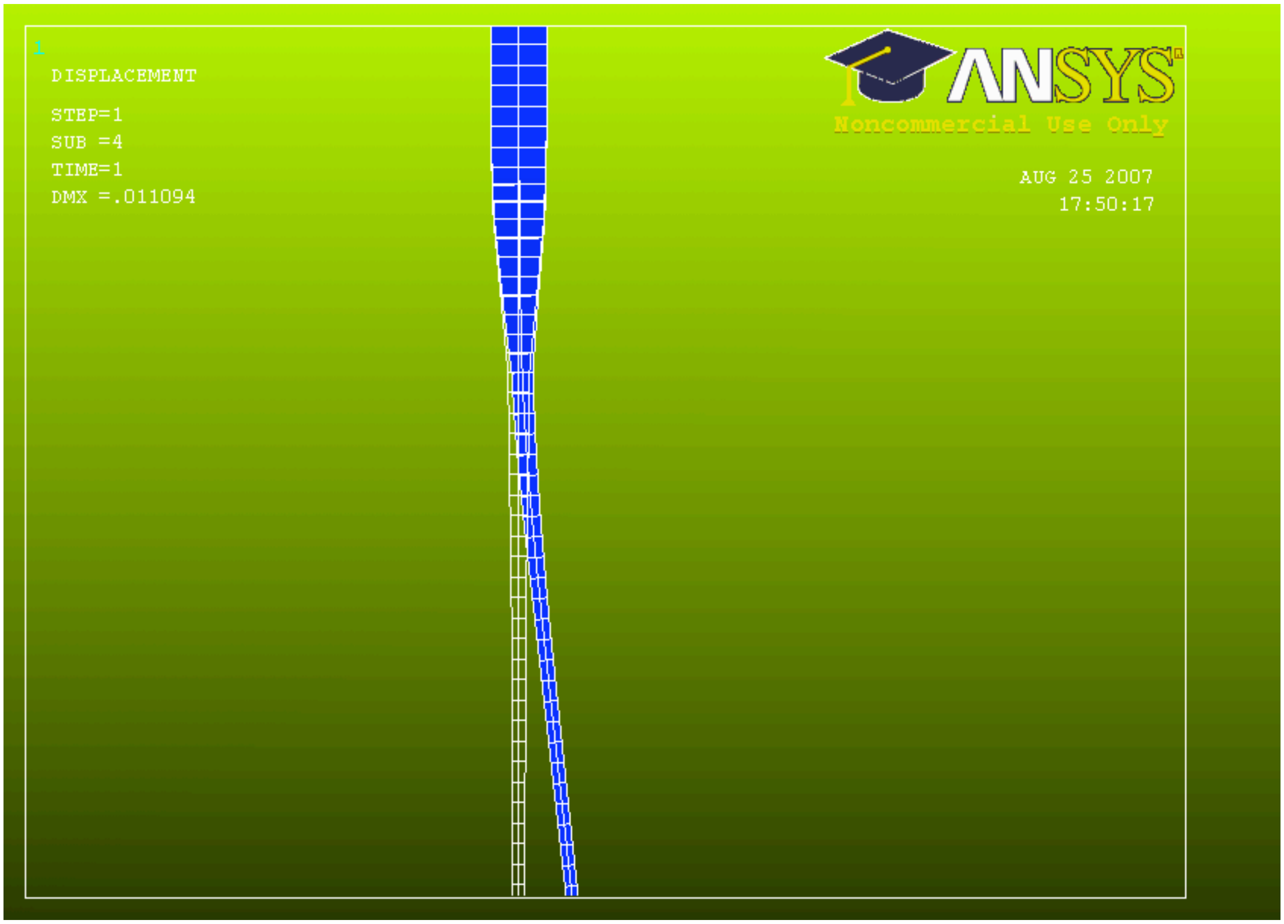

Figure 13: Deformed shape of neck

Keypoints #1, #2 and #3 were introduced to explore the effects of varying `dweld1/2`, but initially we took the welding point to be at keypoint #4 by applying constraints in UX at all four of #1, #2, #3 and #4.

With these constraints, the model gave a plausible neck deformation as shown in Figure 13.

5.3 Analysis

The flexure point is defined as the point where the line of a section of the ribbon remote from the neck intersects the unbent line. This can be found by parameterizing the end of the ribbon as

$$x = m*(y-c)$$

and using values from two different points to eliminate m and determine c. Keypoint #10 was introduced halfway along the ribbon to allow this test to be performed in conjunction with #11 at the end.

With the mesh parameters described above, 1103 nodes were generated. Using the Utility Menu List->Nodes… command, nodes #150 and #504 were identified as keypoints #10 and #11. Using the Nodal Solution command in the Main Menu twice (once for UX and once for UY), the deformed positions of the nodes were identified.

This resulted in the following equations:

$$0.0045074 = m\,(-0.05 - 0.00020943 - c)$$

$$0.01 = m\,(-0.1 - 0.00047922 - c),$$

which give a flexure point of c = -0.00895646 (in the ANSYS Y coordinate).

To test the accuracy of the modeling, the model was regenerated with a maximum element length of 0.0001 (i.e., half the initial value) and parameters Nb=5, Nh=5 on all the sections (which selects for more elements laterally). This gave

$$0.0045082 = m\,(-0.05 - 0.00020916 - c)$$

$$0.01 = m\,(-0.1 - 0.00047884 - c)$$

or c = -0.00894295, which is only about 0.01 mm different. We take -0.0089 as close enough.

To relate this to the conventions in earlier sections we need the half-width point. For simplicity we take this as meaning half the nominal width, i.e., exactly 2500 µm. From inspection of the somewhat noisy profiler data, this is somewhere in the range 6.233-6.298 mm in the profiler distance coordinate, or around -0.0086 m in the ANSYS.

To evaluate `dweld1/2` we assume, as noted above, that the tip of the ear is level with keypoint #4, at Y = -0.006. That gives `dweld/1/2` = 8.6-6.0 = 2.6 mm. In the same way, `dflex1/2` = 8.9-6.0 = 2.96 mm.

5.4 Effect of welding point

To explore the effect of different welding points, we added or removed constraints in UX at the keypoints, keeping the principle that the constrained set was contiguous from the top. For example, for the slide constrained down only as far as #3, i.e., for `dweld1/2` = 8.6-5 = 3.6 mm,

$0.01 = m\,(-0.1 - 0.00048262 - c)$

$0.0045273 = m\,(-0.05 - 0.00021042 - c)$

or c = -0.00862266, `dflex1/2` = 8.6 - 5 = 3.6 mm.

The results are summarized in Table 3 and Figure 14.

Lowest constrained keypoint	Lowest constrained position (m)	Flexure position relative to top (m)	`dweld1/2`	`dflex1/2`
1	0	-0.00619	8.6	6.19
2	-0.003	-0.00768	5.6	4.68
3	-0.005	-0.00862	3.6	3.62
4	-0.006	-0.00896	2.6	2.96
5	-0.0066	-0.00908	2.0	2.48
6	-0.0071	-0.00915	0.9	2.05
7	-0.0086	-0.00950	0	0.9
8	-0.0110	-0.01131	-2.4	0.31
9	-0.0146	-0.01481	-6.0	0.21

Table 3: Data for dflex and dweld. (Note added in proof: this table is not affected by the error in Table 2 and Figure 14.)

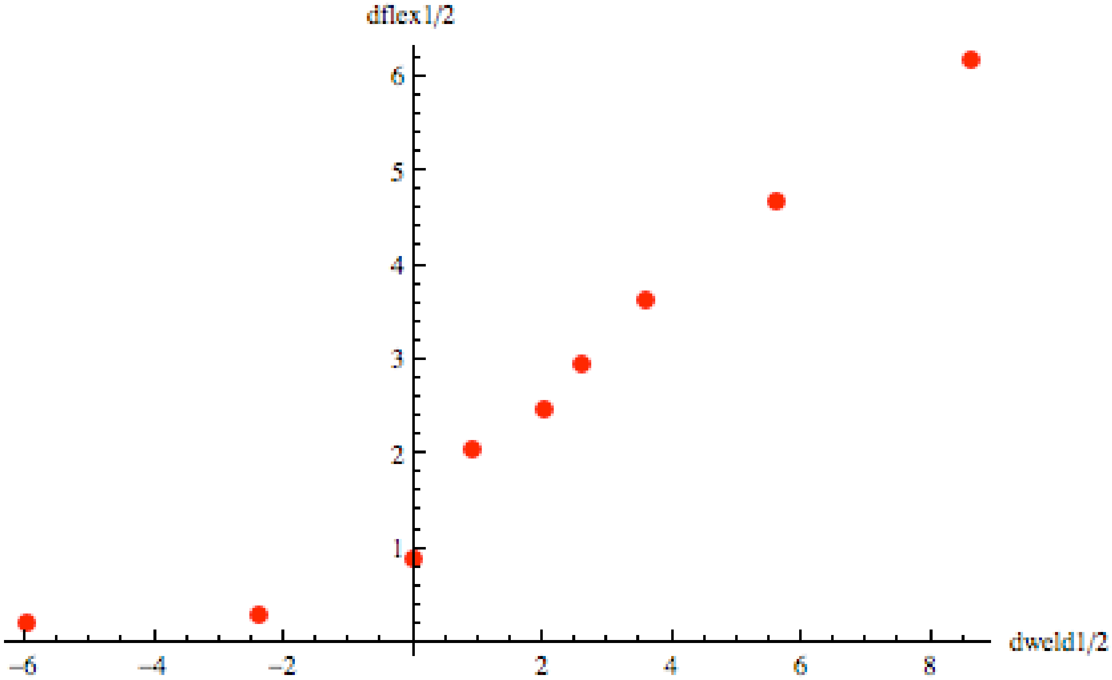

Figure 14: `dflex1/2` as a function of `dweld1/2`. (Note added in proof: this plot is wrong due to the same 3 mm offset error as in Table 2, but has been left as-is for historical reasons.)

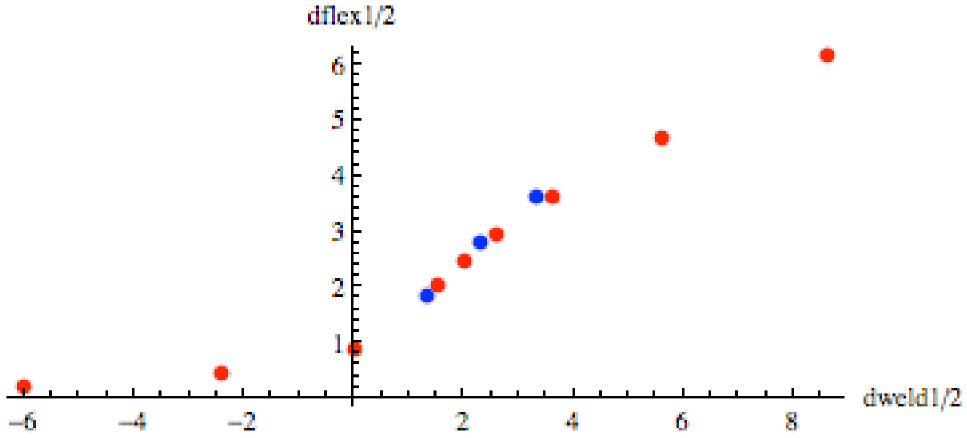

Figure 15: Corrected version of previous plot with results of independent calculation by Phil Willems (in blue) for comparison