Lens mount interface

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Introduction

In lens mount, there is a high stress near the contact area. Tensile stress will occur just outside the contact area and will form crack into subsurface of the glass. Yoder[1] suggested not make any damage to the glass, which means the tensile stress can not exceeding about 1000 psi . However, this suggestion may be too conservative. We need to answer the question: If damage does occur, will the component survive subsequent applied stresses? How does contact damage affect the strength of glass?

The project is to analysis this phenomena using finite element method and predict its effect on the glass strength with experimental data. More specific, we use a simulated lens mounting ring to load the glass. The objective is to make sure that due to common sharp corner radius and loads (R=0.01, F=50 and 200 lb), the strength of the glass (via double ring strength test[5][6]) won't degrade, because there is no deep enough flaws.

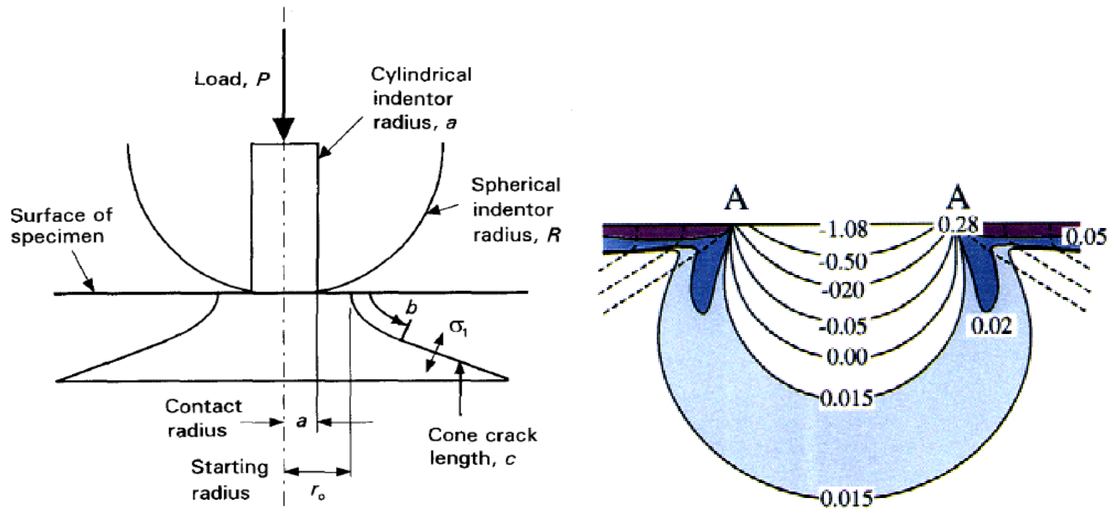
Background knowledge

1, Herzian contact (for cylinders)[1][3]

Contact pressure	$\sigma_c = \sqrt{\dfrac{PE^*}{\pi R^*}}$
Max tensile stress	$\sigma_t = \dfrac{1-2\nu_g}{3} \cdot \sigma_c$

By knowing Loading force P (lb/in), contact radii $R^* = \left(\dfrac{1}{R_m} + \dfrac{1}{R_g} \right)^{-1}$, Young's modulus $E^* = \left(\dfrac{1-\nu_m{}^2}{E_m} + \dfrac{1-\nu_g{}^2}{E_g} \right)^{-1}$, Poisson ratio ν_m, ν_g, solve for Contact stress field, especially

tensile stress (first principle stress σ_1). The important feature of the indentation stress field for the initiation of a conical fracture is the tensile region near the specimen surface just outside the area of contact.



(a) (b)

Fig 1 (a)Hertzian cone crack parameters[7], (b)Principle normal stress field[3]

2, Strength of glass[5]

Glass does not possess a single characteristic strength. The strength of the material is dependent on the distribution of cracks or surface flaws.

Stress intendity factor

Looking at a single flaw in a material the maximum bending strength depends on the size of the flaw and geometry in the material. For example in case of a flaw with a short depth in a thick plate with tensile forces acting normal to the crack plane one can define a stress intensity factor K_I by:

$$K_I \approx 2\sigma_0\sqrt{a}$$

σ_0 the nominal stress perpendicular to the stress plane

a depth of the flaw.

A flaw will result in a fracture if $K_I >$ fracture toughness K_{IC}

Weibull distribution

Basing on laboratory test results obtained under well defined conditions one can calculate design strengths for loads and conditions posed by special application requirements.

$$F(\sigma) = 1 - \exp(-(\sigma / \sigma_0)^m)$$

F(σ)	Probability of failure at bending stress s
σ_0	Characteristic strength (F(σ_0) = 63,21 %)
m	Weibull factor (scatter of the distribution.)

FEA model analysis

1, Contact damage

First, I tried to use COSMOSWorks in solidworks to do the analysis. But in the particular situation, contact radius is less than 1e-3 in. the finite element meshing needs to be really small and the contact property is hard to define. In addition, the phenomenon is a non-linear process; it took more than 12 hours to run a simple 3D model. Thus, I turn to Brian Cuerden, who is expert in ANSYS. With ANSYS, we can make a 2D cross-section model, which can save a lot time, and the contact of two materials can be well defined.

In fig 2, the left edge is the center of the contact area. Just half the stress field is shown because of the symmetry. The vertical pink arrows is the response force from the the glass sample, with length representing the relative value of the force. The color contour is the tensile stress field. Under 50 lb/in load with 0.01 in contact radius, the maximum stress is 966 psi. The numbers to the left of the fig is the depth of the element in micro-inch. And the numbers at every nodes are just node numbers.

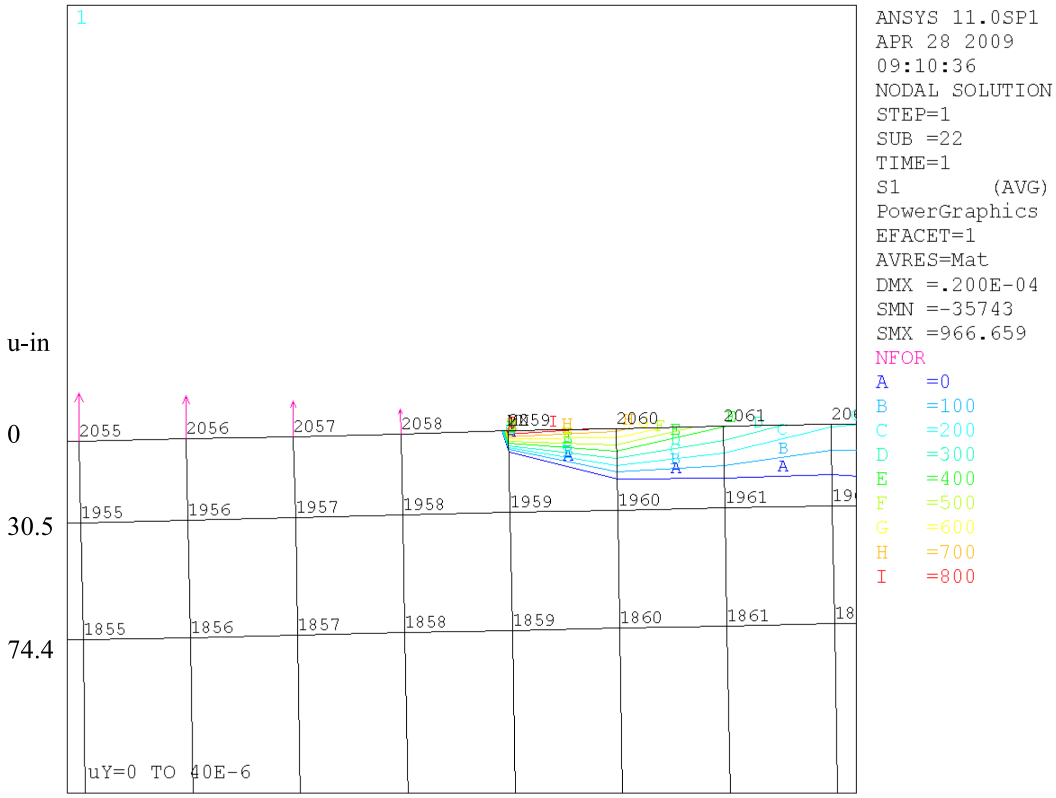


Fig 2 ANSYS FEA model of tensile stess field

We can see that from Fig 1&2, the contour is match from FEA and theory calculation. The high tensile stress field is just outside the contact area. But one thing need to mention is the maximum stress will change when we refine the mesh. That means smaller finite elements will get higher maximum stress on the surface. There is a maximum stress point acting as a singularity, which is due to abrupt material change at the edge. The depth of the stress field is less than 0.5um, which will not change when mesh is changed.

Herztian contact assumes that two materials is contacting without any friction [3][4], which is not the real case[7]. So with Brian's help, we make a model with friction coefficient while performing static load. Tensile stress will decrease while friction coefficient increases. In my opinion, this is due to different Poisson ratio between glass and steel. As we known, glass (0.21) has a smaller Poisson ratio than steel (0.28) does. When two materials are pressed together, they both are trying to squeeze out. Steel tends to expand more, but they cannot slide from each other because of friction. So glass will get a radial force from contact center to the edge, which will mitigate the tensile stress just outside the contact area.

In another case, when we apply a shear force to the indentor (sliding), tensile stress will increase in one side. This is a simulation when temperature changes. Two materials will get a shear force when the coefficient of temperature expansion. Since I have not enough sample to test this situation, I just try a few samples which will describe in the following section.

<u>2, Double ring test of strength</u>

In this bending test, the vertical load apply to the sample is read by a mini load cell, shown in fig 4. After that, the load will transfer to moment apply to the glass, and then the tensile stress on the upper surface. I used COSMOSwork modeling (shown in fig 3) and calculation from Roark's [10]. (Detail calculation steps are in the appendix).

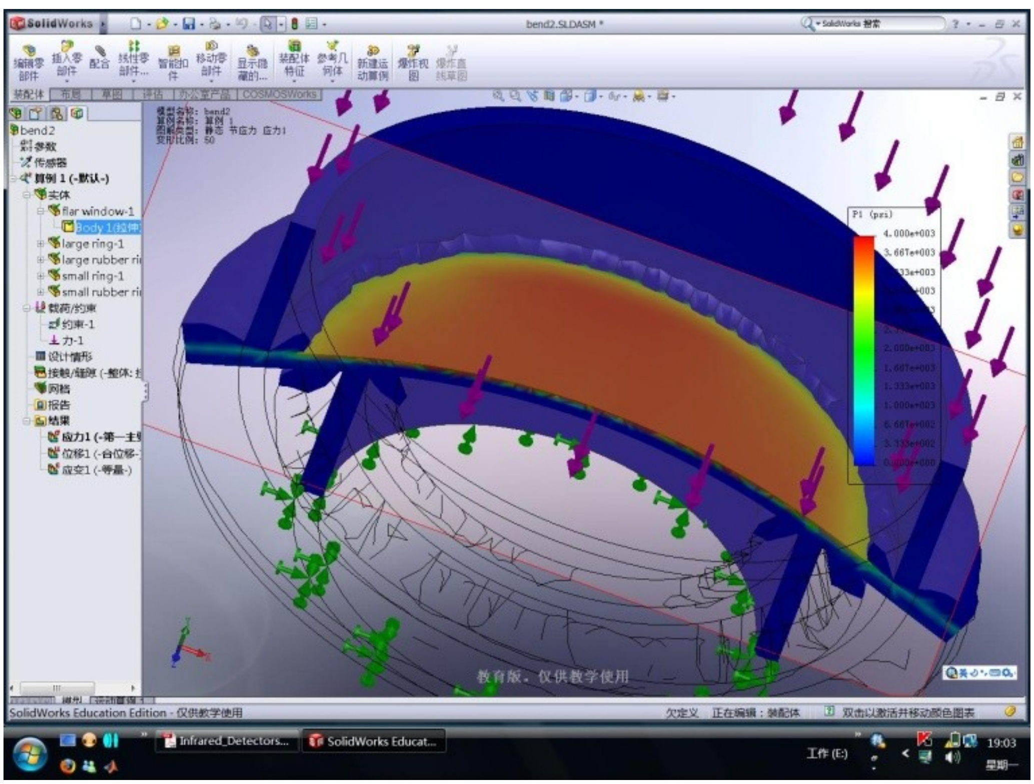


Fig 3 COSMOSWorks FEA model

Table 1 tensile stress due to bending Unit: psi

	30lb		200lb	
Sample thickness	Roark's	COSMOSWork	Roark's	COSMOSWork
1.15mm	3970	3695	26467	25750
0.9mm	6455	5800	43033	39130

Results are agreed well with each other. But due to mash refined issue, the COSMOSwork model is more likely deviation from the true value. So I decide to trust data from Roark's.

Experiment

General procedure

A piece of glass breaks when two conditions coincide. The first is the presence of tensile stress at the surface and the second is the presence of a flaw in the region of the tensile stress. So we first make some flaws due to contact stress on a glass. Then exert different tensile stresses to the cracks on the glass.

The two steps

1, Make contact damage (static load, shock load, grind while load)

1.1 static load

Settings are shown in fig 4. INSTRON hardness test machine provide a good vertical load force (manually) and a platform. Use a ball tip against the load cell to prevent a side force. Load cell is attachment to the indentor. Use clamp fork and bamboo fork to concentrically align the indentor, glass sample and the supporting ring. The load value will show from computer screen instantaneously via use interface. The maximum indenting load will hold for 5 seconds before release.

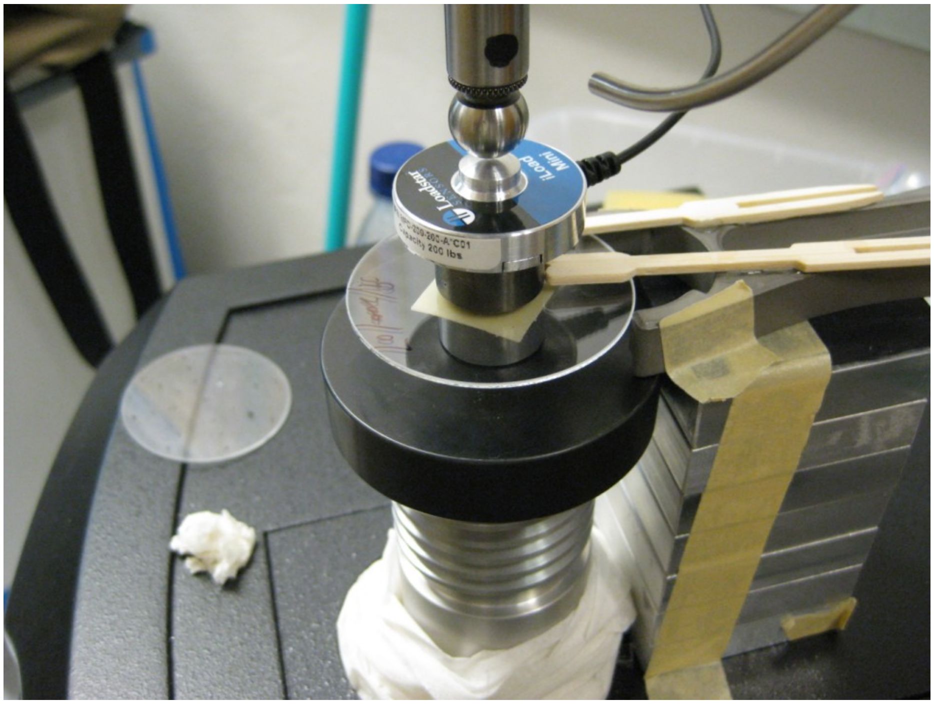


Fig 4 load the glass with a sharp edge indentor

Detail drawings and specs of indentors will be provided in the Appendix.

1.2 shock load[11]

Use the bench handling procedure from MIL-STD 810D to do the shock load.

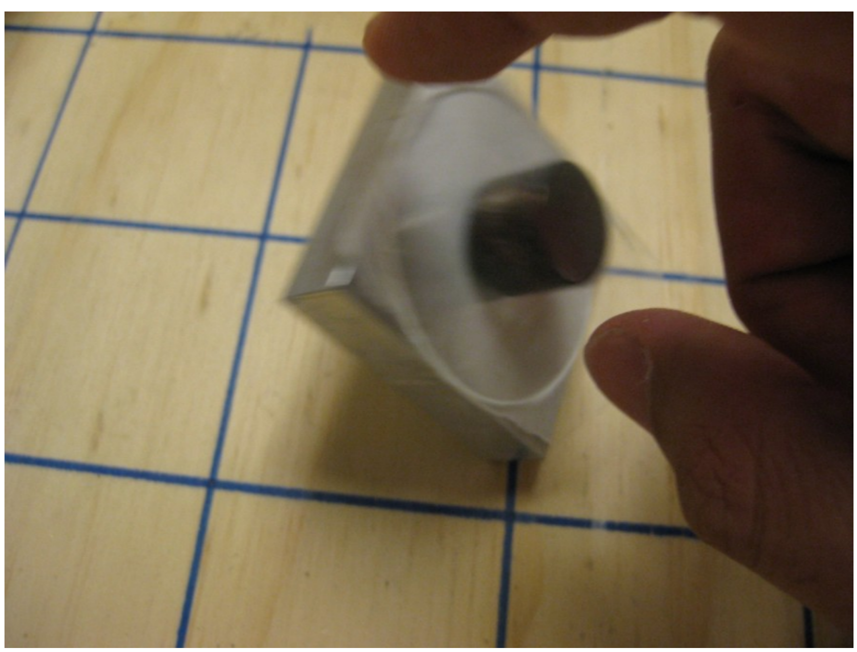


Fig 5 shock load test

Use tape to clamp the indentor sample and aluminum substrate together. In case of the irregularity on the Al plate damage the sample, put a paper between the glass and the Al. Using one edge as a pivot, lift the opposite edge. Let the lifted edge is just below the point of perfect balance, then let the whole package drop back freely to horizontal bench top. Repeat, using other edges for a total of four drops.

2, Double ring test of strength of the glass

Settings are shown in fig 6. Use three clamping forks to align the double rings and the glass sample. Gently apply the load tilt it breaks. The software will automatically record the maximum load.

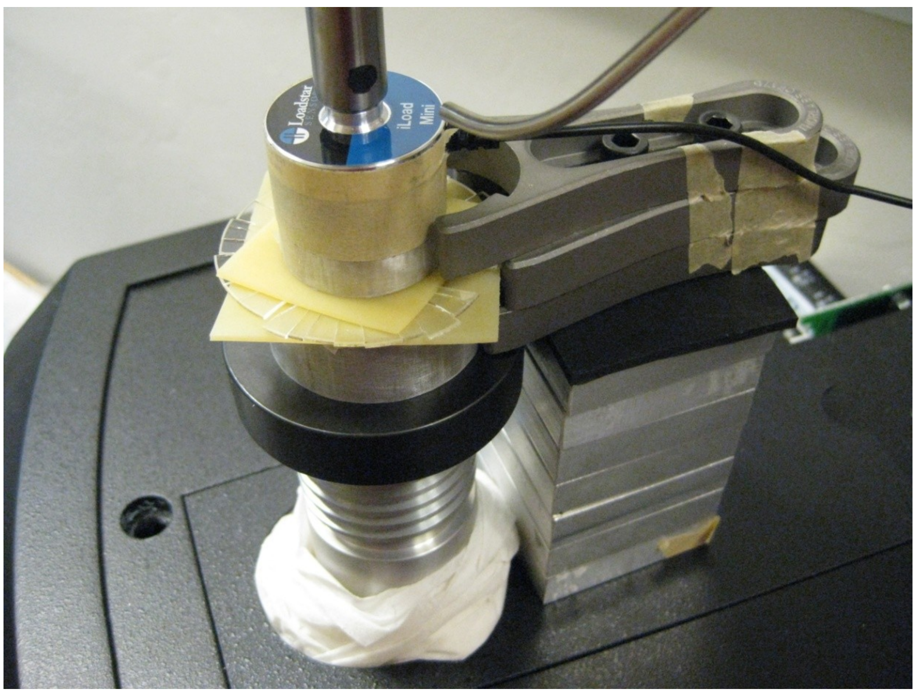


Fig 6 double ring strength test

<u>Statistical Analysis</u>

Now we got a set of tensile stress data. Then assign a probability to each data point using Harris' method and then fit the Weibull distribution[8]: $F(\sigma) = 1 - \exp(-(\sigma / \sigma_0)^m)$ (Detail steps are provided in the appendix VI).

Result and analysis

From the cracking pattern in fig 7, we can see that the initial crack is from the center region of the sample, where the tensile stress is applied while bending. Because the tensile stress is uniform inside the smaller ring, the initial crack will occur at the location where the deepest existing flaw is.

Fig 7 use double tape to hold the crack pattern of the sample

To compare the strength before and after the indentation, we need a group of 25 samples to test the strength with any damage

Table 2 characteristic strength σ_0 and scatter of the distribution m

situation	quantity	characteristic strength σ_0 (ksi)	scatter of the distribution m
Before indentation	25	25.9	4.4
100lb/in, R=0.01 in	25	24.2	4.9
100lb/in, R≈0.002 in	10	21.3	4.0
Shock load	10	27.3	3.8
Grind with 25um compound	7	10.5	7.2

Using the table of student's distribution [13], we have 80% confidence to say 7% degradation before and after (100 lb/in, R=0.01 in) indentation is due to statistical issue. That means the strength of glass won't degrade in the level of load. (Details to determine the confidence of the result is in the Appendix)

40% confidence to say 18% degradation before and after (100 lb/in, R=0.002 in) indentation is due to statistical issue. That means the strength of glass begins to degrade in the level of load.

More load may yield the steel, then the sharp corner will be flattened and stress is decreased.

Steel poisson ratio is larger than glass', if there is friction in the contact area, the steel try to pull the glass outward, and the tensile stress at the contact edge will decrease, as the FEA shown, for 50lb/in, without friction, maximum tensile stress is 10ksi while with 0.5 friction coefficient is 1ksi. Another problem in FEA is the steel stress is much less than the Al stress, although both of them are really shallow.

We can see from the Roark's equation from appendix, sample thickness is inverse square to the tensile stress value. And the sample thickness has a 10% variation. Unfortunatly, I fail to measure the first half samples. So I measure all the samples left, and assume the average value to be the thickness of the whole set of samples.

Conclusion

1, Opti-polish glass is really strong. And the surface quality of the glass is very important.

2, It is safe to say Yoder's assumption is too conservative

3, At 50 lb/in static load with R=0.01 in, the strength of glass will not degrade.

4, Shock load seems do not have catastrophic effect to the glass contacting with sharp edge.

Reference

[1] Paul R. Yoder, *Opto-Mechanical Systems Design*, 3rd ed., SPIE Press, 2005.

[2] Paul R. Yoder, *Mounting optics in Optical Instruments*

[3] Brian R. Lawn, *Indentation of ceramics with sphere: A century after Hertz*

[4]Brian R. Lawn, *Fracture of Brittle Solids*, Cambridge University Press, Cambridge, U.K., 1993.

[5] Schott Glass, *TIE-33: Design strength of optical glass and ZERODUR*, 2004

[6] Keith B. Doyle and Mark A. Kahan, *Design strength of optical glass*, SPIE Proceedings **5176**, p. 14 (2003).

[7] A. C. Fischer-Cripps and R. E. Collins, *The Probability of Hertzian Fracture*, *J. Mater. Sci.*, **29**, 2216–30 (1994).

[8] Eugene Salamin, The weibull distribution in the strength of glass, Opti 521 Tutorial.

[9] Handbook of optomechanical engineering

[10] Roark's

[11] MIL-STD-810D

[12] Brian Cuerden, Excel file: Zerodur strength.xls

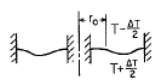
[13] I. Robert Parket, *Statistics for business decision making*. Appendix G

Appendix I

Calculation from Roark's and compare with COSMOSWorks

TABLE 24 Formulas for flat circular plates of constant thickness (*Continued*)

Case no., edge restraints: 8h. Outer edge fixed, inner edge fixed



Boundary values:

$y_b = 0 \quad \theta_b = 0 \quad y_a = 0 \quad \theta_a = 0$

$$M_{rb} = \frac{-\gamma(1+\nu)\,\Delta T D}{t}\,\frac{C_6 L_2 - C_3 L_5}{C_2 C_6 - C_3 C_5}$$

$$Q_b = \frac{\gamma(1+\nu)\,\Delta T D}{at}\,\frac{C_5 L_2 - C_2 L_5}{C_2 C_6 - C_3 C_5}$$

$$M_{ra} = M_{rb} C_8 + Q_b a C_9 - \frac{\gamma(1+\nu)\,\Delta T D}{t}(1 - L_8)$$

$$Q_a = Q_b \frac{b}{a}$$

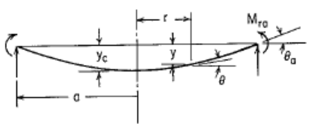
Special cases:

If $r_o = b$ (ΔT over entire plate), all deflections are zero and $K_{M_r} = K_{M_t} = -1.30$ everywhere in the plate.
If $r_o > b$, the following tabulated values apply.

b/a	0.1		0.5		0.7
r_o/a	0.5	0.7	0.7	0.9	0.9
$K_{M_{rb}}$	0.9224	1.3241	0.2640	0.5063	0.5103
$K_{M_{ra}}$	−1.4829	−1.1903	−1.6119	−0.8592	−1.2691
$K_{M_{ta}}$	−1.3549	−1.2671	−1.3936	−1.1677	−1.2907
K_{Q_b}	−10.4460	−10.9196	−5.4127	−3.9399	−7.1270

Cases 9 to 15. Solid circular plate under the several indicated loadings

General expressions for deformations, moments, and shears:



$$y = y_c + \frac{M_c r^2}{2D(1+\nu)} + LT_y \qquad (\textit{Note: } y_c \text{ is the center deflection})$$

$$\theta = \frac{M_c r}{D(1+\nu)} + LT_\theta \qquad (\textit{Note: } M_c \text{ is the moment at the center})$$

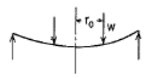
$$M_r = M_c + LT_M$$

$$M_t = \frac{\theta D(1-\nu^2)}{r} + \nu M_r \qquad (\textit{Note: For } r < r_o,\ M_t = M_r = M_c)$$

$$Q_r = LT_Q$$

For the numerical data given below, $\nu = 0.3$ (*Note:* ln = natural logarithm)

Case no., loading, load terms: 9. Uniform annular line load



$$LT_y = \frac{-wr^3}{D} G_3$$

$$LT_\theta = \frac{-wr^2}{D} G_6$$

$$LT_M = -wrG_9$$

$$LT_Q = \frac{-wr_o}{r}\langle r - r_o\rangle^0$$

Edge restraint: 9a. Simply supported

Boundary values:

$y_a = 0 \quad M_{ra} = 0$

$$y_c = \frac{-wa^3}{2D}\left(\frac{L_9}{1+\nu} - 2L_3\right)$$

$$M_c = waL_9$$

$$Q_a = -w\frac{r_o}{a}$$

$$\theta_a = \frac{wr_o(a^2 - r_o^2)}{2D(1+\nu)a}$$

Special cases:

$y = K_y \frac{wa^3}{D} \qquad \theta = K_\theta \frac{wa^2}{D} \qquad M = K_M wa$

r_o/a	0.2	0.4	0.6	0.8
K_{y_c}	−0.05770	−0.09195	−0.09426	−0.06282
K_{θ_a}	0.07385	0.12923	0.14769	0.11077
K_{M_c}	0.24283	0.29704	0.26642	0.16643

(*Note:* If r_o approaches 0, see case 16)

Edge restraint: 9b. Fixed

Boundary values:

$$y_c = \frac{-wa^3}{2D}(L_6 - 2L_3)$$

$$M_c = wa(1+\nu)L_6$$

$$M_{ra} = \frac{-wr_o}{2a^2}(a^2 - r_o^2)$$

$y_a = 0 \quad \theta_a = 0$

Special cases:

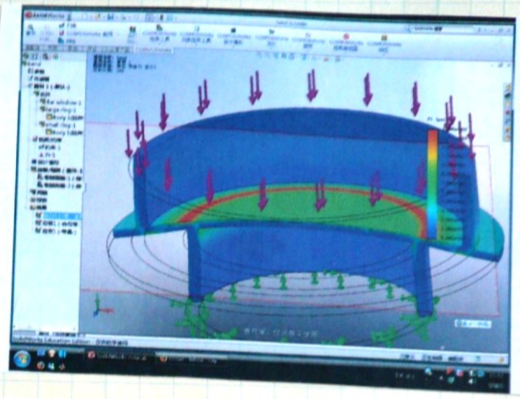
r_o/a	0.2	0.4	0.6	0.8
K_{y_c}	−0.02078	−0.02734	−0.02042	−0.00744
K_{M_c}	0.14683	0.12904	0.07442	0.02243
$K_{M_{ra}}$	−0.09600	−0.16800	−0.19200	−0.14400

(*Note:* If r_o approaches 0, see case 17)

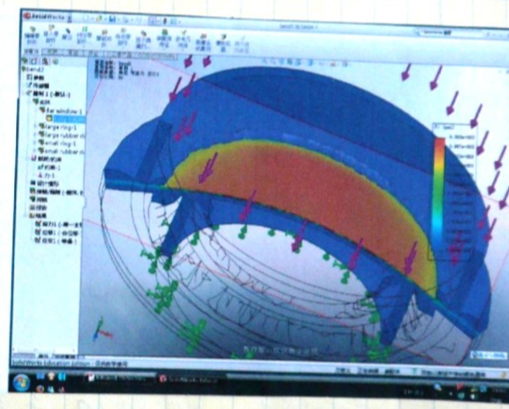
03-409

II Bend

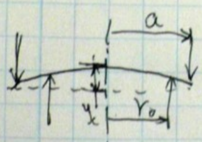
— Before adding rubber ring between metal ring and glass. tensile stresses are concentrate in some unwanted region.



— After apply rubber ring stress will nicely spread out uniformly in the middle. (this is a 30 lb Force) we got about **4000 Psi** tensile stress



☆ compare to calcalation using equations from **Roark's**



$a = \frac{ID_{Big}}{2} = \frac{1.62}{2} = \underline{0.81}''$

$r_0 = \frac{OD_{small}}{2} = \frac{1.25}{2} = 0.625''$

$M_c = W a L_9$

$= \frac{F}{2\pi r_0} a L_9$

$= \frac{30\,lb \times 0.81}{6.2831 \times 0.625} \times 0.2192 = 1.356\ lb\,in$

$\sigma = \frac{6M_c}{t^2} = \boxed{3970\ psi}$

$t = 1.15\,mm$ $(0.04528\ in)$

6450 Psi for $t = 0.9\,mm$ — 0.0358 in

$L_9 = \frac{r_0}{a}\left\{\frac{1+\nu}{2}\ln\frac{a}{r_0} + \frac{1-\nu}{4}\left[1-\left(\frac{r_0}{a}\right)^2\right]\right\} = 0.219198$

$L_3 = \frac{r_0}{4a}\left\{\left[\left(\frac{r_0}{a}\right)^2+1\right]\ln\frac{a}{r_0} + \left(\frac{r_0}{a}\right)^2 - 1\right\} = 1.7413 \times 10^{-3}$

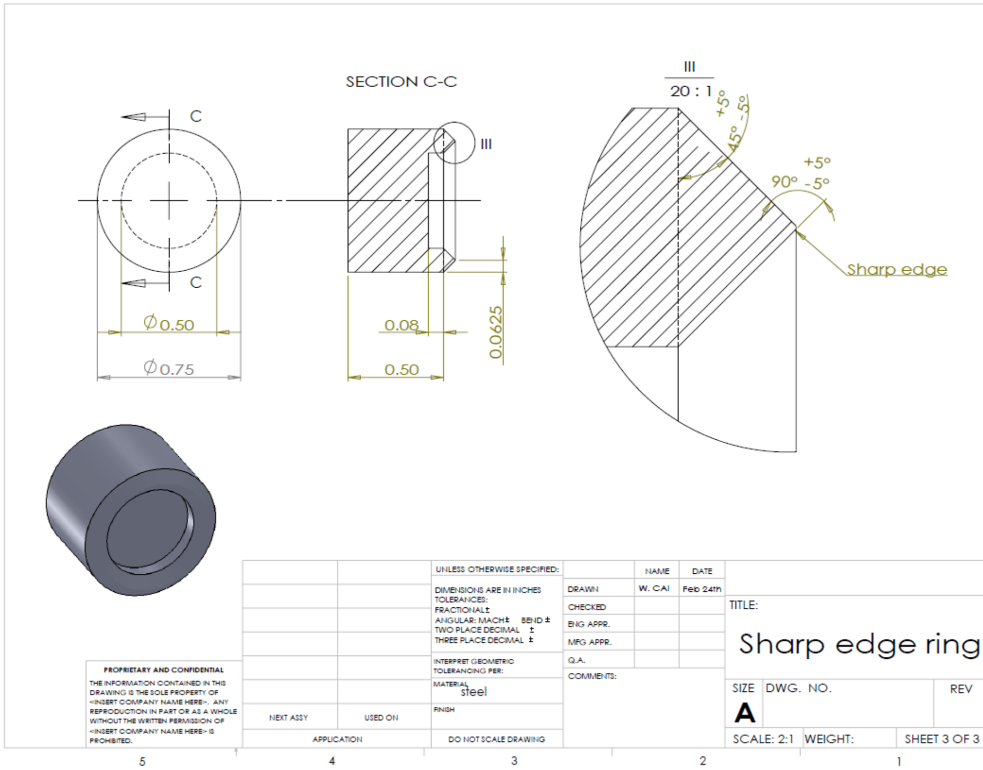
$y_c = \frac{-Wa^3}{2D}\left(\frac{L_9}{1+\nu} - 2L_3\right)$

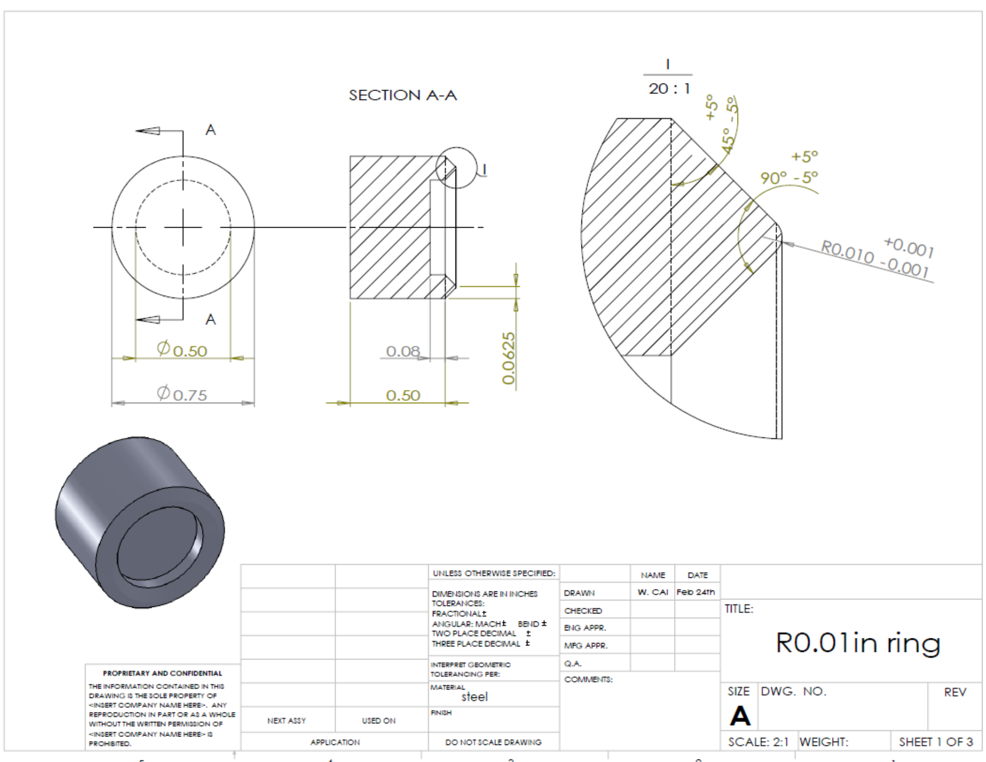
where $D = \frac{Et^3}{12(1-\nu^2)} = 87.088$

$y_c = \underline{0.0041\ in}$

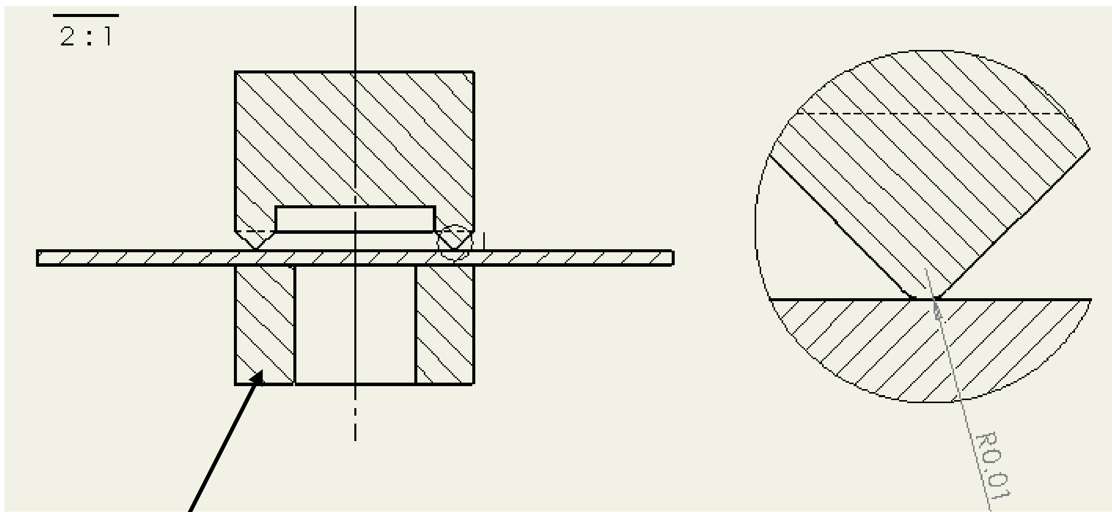
Appendix II

Drawing of indentors and double rings





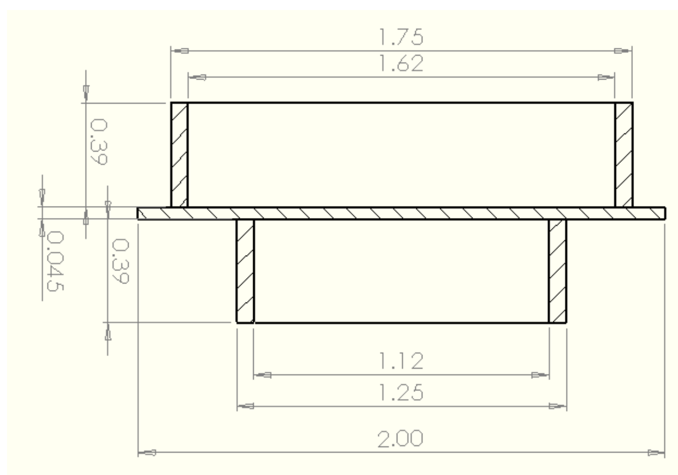
Sharp edge (about .0002in)
R=0.01 in;



Support metal rings
OD 0.75'' ID 0.38'' 3/8'' height

Aluminum tube (for double ring strength test)
OD 1.25'' ID 1.12''
OD 1.75'' ID 1.62''

There will be a layer of nature Latex rubber between Aluminum tube and the glass sample.



Appendix III

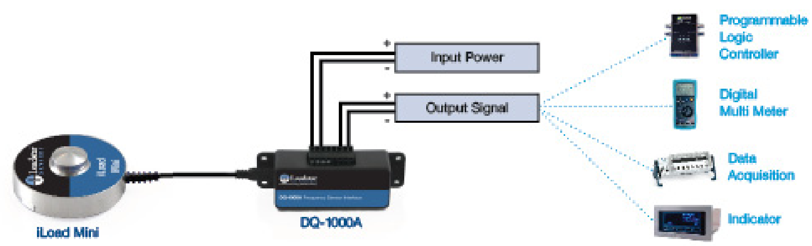
Load cell specs and software

http://www.loadstarsensors.com/iloadmini.html

Suggested Configuration

Frequency to Digital USB Output

Frequency to Analog Output



Unlike conventional resistive sensors based on either strain gauges or piezo-resistive techniques, Loadstar's breakthrough patented technology harnesses changes in capacitance to measure loads quickly and accurately. In the Mini, the change in capacitance is converted into a change in frequency of the output signal.

The load cell accepts a 5V DC input and outputs a TTL square wave whose frequency is proportional to the applied load. Most data acquisition systems, microprocessors and microcontrollers have the capability to measure the frequency of the signal.

The iLoad Mini load cell has 2 frequency outputs. When Control Input = logic '1', the Mini outputs the sensor frequency, F^{sensor}. When Control Input = logic '0', the Mini ouputs the reference frequency, F^{ref}. The compensated frequency F^{comp} = F^{sensor} - $K*^{Fref}$, where K is a constant provided by Loadstar. Loadstar provides the coefficients for the quadratic equation to translate F^{comp} to load.

Miniature Load Cell Dome: Aluminum

Load Cell - Standard	Part Number	Capacity	Accuracy (FS)	Output	Cable(included)	List Price
	MFD-010-200-A	10 lb	2%	250 - 150KHz	6' USB Mini B	Please Call or fill out form
	MFD-050-200-A	50 lb	2%	250 - 150KHz	6' USB Mini B	Please Call or fill out form
	MFD-100-200-A	100 lb	2%	250 - 150KHz	6' USB Mini B	Please Call or fill out form
	MFD-200-200-A	200 lb	2%	250 - 150KHz	6' USB Mini B	Please Call or fill out form

Appendix IV

Fit the Weibull distribution

5. Example from D. C. Harris

This example, [Harris 1999, p. 99] and repeated in [Yoder 2005, p. 741], concerns 13 disks of standard grade zinc sulfide, of a certain size, and processed similarly, subjected to stress in a ring-on-ring fixture. The observed stresses at fracture took the following values, in MPa.

62	89	110
69	90	125
73	93	126
76	100	
87	107	

To the *i*-th stress value, Harris assigns a failure probability $P_i = (i - \frac{1}{2})/13$. From equation (3-3), note that

$$\log\left(\log\frac{1}{1-P_f}\right) = m \log\sigma - m\log\sigma_0 \quad .$$

Harris fits a straight line to a plot of $\log\left(\log(1-P_f)^{-1}\right)$ *vs.* $\log\sigma$, obtaining $m = 5.4338$ as the slope, and then $\sigma_0 = 100.6$ MPa from the intercept.

This is a very *ad hoc* procedure. I will give a proper Bayesian analysis of this data, and demonstrate that the Harris analysis underestimates the failure probability at low stress.

The underlying assumption is that the ZnS disks possess a flaw length distribution leading to the Weibull distribution of equation (3-3). The hypothesis $H(\sigma_0, m)$ asserts that these disks, as prepared, are characterized by Weibull parameters σ_0 and m. The data D_i are the observed stresses σ_i at failure. The probability $P(\sigma|\sigma_0, m)\, d\sigma$ that failure occurs at stress between σ and $\sigma + d\sigma$ is given by

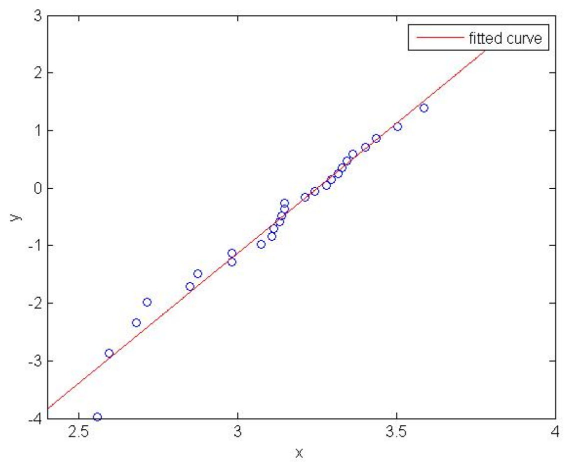
I used this method to fit load data in Matlab. (just show two of them to give you an idea)

Before indentation:

#	Peak load (lb)	tensile stress (ksi)
5	101.87	13.0
26	103.59	13.2
27	112.56	14.4
17	119.36	15.3
28	136.23	17.4
1	136.47	17.4
19	155.11	19.8
24	155.3	19.9
6	170.44	21.8
29	175.56	22.4
18	177.51	22.7
16	180.47	23.1
9	182.32	23.3
22	183.93	23.5
13	184.12	23.5
7	195.7	25.0
23	202.19	25.8
21	210.15	26.9
10	213.02	27.2
20	217.37	27.8
2	219.74	28.1
3	223.02	28.5
11	227.83	29.1
8	236.28	30.2
12	245.16	31.3
25	262.11	33.5
4	284.5	36.4

General model:
c(x) = a*(x-b)
Coefficients (with 95% confidence bounds):
a = 4.418 (4.082, 4.754)
b = 3.255 (3.232, 3.278)

sigma0 25.91961

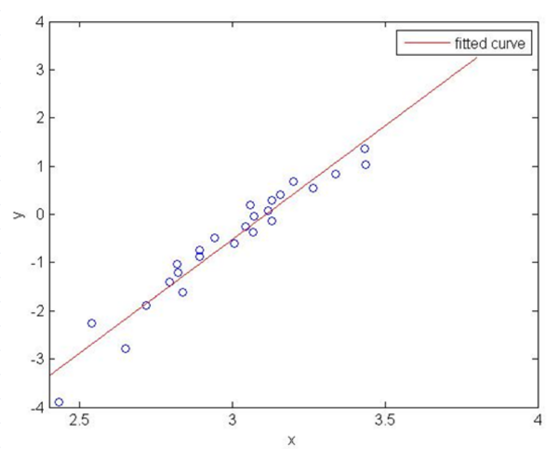


After 100 lb/in indentation

#	indentation load (lb)	bending load (lb)	tensile stress (ksi)
7	206.25	96.4	12.80
19	219.28	119.98	14.58
9	205.37	107.54	14.61
13	204.8	128.34	16.41
16	204.79	144.58	17.57
11	203.9	138.83	17.63
25	206.66	142.42	18.21
15	209.6	142.21	18.82
22	207.39	153.02	19.56
1	218.36	152.91	20.59
17	204.08	171.47	20.84
12	204.19	160.74	20.91
18	213.43	182.11	21.77
2	203.3	177.71	22.99
24	207.88	193.89	23.18
4	204.19	183.02	23.60
21	243.94	191.3	24.21
10	204.64	180.63	24.32
3	204.42	193.61	24.97
23	205.11	199.28	25.48
6	221.36	221.76	26.51
8	208.23	207.92	28.00
20	205.67	238.58	29.00
14	201.97	263.29	33.95
5	204.31	262.43	34.73

General model:
c(x) = a*(x-b)
Coefficients (with 95% confidence bounds):
a = 4.852 (4.403, 5.3)
b = 3.187 (3.162, 3.212)

sigma0 24.21567



Appendix V

Glass data sheet from Brian Cuerden.

Although there is no data for opti-plish BK7, but from the the scale between opti-polish Zerodur, D64 etched Zerdur, and D64 etched BK7, the strength I got from my experiment is in the proper range.

	A	B	C	D	E	F	G	H
3		Surface Damage, BK7 (Actual fracture data used)						
8	Equations:							
9		Sallowed=	Sigma/Ffos		Allowable Stress			
10		Ffos =	Fa*Fp*Ff		Factor of safety			
11		Fa =	(Sv/SL)^1/Lambda		Area Factor, Sv=stressed area			
12						SL=test stressed area		
13		Fp =	1/(ln(1/(1-Fv))^1/lambda)			Probability factor		
14						Fv=failure probability		
15		Ff =	(tv/tL)^1/n					
16					tv=stress load duration time, seconds			
17					tL=Lab stress duration time, seconds			
20	Strength Calculator							
22		Glass Parameters:						
23				Mpa				
24		Sigma, Lambda, n=		70.6	30.4	19.5		
25		Stressed Area =		4560	mm^2			
26		Failure Probability=		0.001				
27		Time at stress =		172800	sec			
29			Fa =	1.12934				
30			Fp =	1.2551				
31			Ff =	1.64934				
33		Allowable Stress =		30.2	Mpa			
34			=	4380	psi			

	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W
1					"CNTRLa" to update flaw depth estimates							Ki =	610	+	20
2													BK7 in air at 100% RH		
3				Stressed Area =		1130	mm^2	1.24	0.00	0.00	0.00				
4				Failure Probability=		0.5						Kic =	784	psi-sqrt(in)	
5				Time at stress =		10	sec	Note: flaw depth estimate is based on							
6								short term strength (no vrack growth					Estimated	Estimated	
7	Glass Strength Parameters		Test Area =		113	mm^2		over time).					Maximum	Maximum	
8			Test time =		10	sec					Allowable Stress		Flaw depth	Flaw depth	
9	Glass	Grit	Sigma	Lambda	n			Fa	Fp	Ff	Mpa	psi	inches	microns	
10			Mpa												
11	BK 7	SiC 600	70.6	30.4	19.5			1.079	1.012	1.000	10.045	1457	0.02378	604	
12	BK 7	D 64	50.3	13.3	19.5			1.189	1.028	1.000	41.15	5969	0.00309	78	
13	BK 7	D 64 etched	234.7	4.1	19.5			1.753	1.094	1.000	122.40	17752	0.00003	1	
14	ZKN 7	SiC 600	68.9	14.1	26.3			1.177	1.026	1.000	57.02	8269	0.00035	9	
15	BAK 1	SiC 600	58.9	8.2	18.2			1.324	1.046	1.000	42.54	6169	0.00053	13	
16	SK 16	SiC 600	62.3	19.3	21.6			1.127	1.019	1.000	54.25	7869	0.00045	11	
17	LaK 8	SiC 600	70	29.9	23.4			1.080	1.012	1.000	64.02	9285	0.00033	8	
18	LaK N9	SiC 600	64.8	9.3	21.6			1.281	1.040	1.000	48.63	7053	0.00043	11	
19	LaK 10	SiC 600	74.9	7.5	23.2			1.359	1.050	1.000	52.47	7610	0.00031	8	
20	LLF 2	SiC 600	64.7	17.9	17.5			1.137	1.021	1.000	55.74	8084	0.00040	10	
21	F 2	SiC 600	57.1	25	15.4			1.096	1.015	1.000	51.32	7443	0.00053	13	
22	BaSF 64	SiC 600	70.1	23.9	19			1.101	1.015	1.000	62.69	9092	0.00033	8	
23	LaF 2	SiC 600	56.6	20.1	16.9			1.121	1.018	1.000	49.56	7188	0.00054	14	
24	LaF N 21	SiC 600	75.9	28.6	21.9			1.084	1.013	1.000	69.14	10027	0.00028	7	
25	LaSF 8	SiC 600	50	13.1	22.7			1.192	1.028	1.000	40.78	5915	0.00075	19	
27			50.3	13.3	0							1457			
28											10.045	1457			
29					19.5	= estimated from CTE					10.04				
30	Grain Sizes														
32		Mean	Max	ASTM equiv											
33		u-m	u-m												
34	Bonded Diamond grains														
35	D 251	231	250	60/70											
36	D 151	138	150	100/120											
37	D 107	95	106	140/170											
38	D 64	58	63	230/270											
39	D 35	36	40												
40	D 15A	12.5	15												
42	Loose SiC grains														
43	SiC 100	116	149												
44	SiC 230	53	84												
45	SiC 320	29	49												
46	SiC 600	9	19												

Zerodur Crack Growth / Surface damage BK7 / E6 Crack Growth / Surface damage Zerodur

Appendix VI

Student distribution to determine the confidence of the result.

$t = \frac{|\bar{X}_1 - \bar{X}_2|}{S_D}$

enter table to find level of significance for t above.

ordinarily always use two tail test – one tail you have to know which sample has greater mean

Appendix G **Table of Student's Distribution**

Values of *t*

n − 1 Degrees of Freedom	Level of Significance (α)													
	.45	.4	.35	.3	.25	.2	.15	.1	.05	.025	.01	.005	.0005	One-Tail Test
	.9	.8	.7	.6	.5	.4	.3	.2	.1	.05	.02	.01	.001	Two-Tail Test
1	.158	.325	.510	.727	1.000	1.376	1.963	3.078	6.314	12.706	31.821	63.657	636.619	
2	.142	.289	.445	.617	.816	1.061	1.386	1.886	2.910	4.303	6.965	9.925	31.598	
3	.137	.277	.424	.584	.765	.978	1.250	1.638	2.353	3.182	4.541	5.841	12.941	
4	.134	.271	.414	.569	.741	.941	1.190	1.533	2.132	2.776	3.747	4.604	8.610	
5	.132	.267	.408	.559	.727	.920	1.156	1.476	2.015	2.571	3.365	4.032	6.859	
6	.131	.265	.404	.553	.718	.906	1.134	1.440	1.943	2.447	3.143	3.707	5.959	
7	.130	.263	.402	.549	.711	.896	1.119	1.415	1.895	2.365	2.998	3.499	5.405	
8	.130	.262	.399	.546	.706	.889	1.108	1.397	1.860	2.306	2.896	3.355	5.041	
9	.129	.261	.398	.543	.703	.883	1.100	1.383	1.833	2.262	2.821	3.250	4.781	
10	.129	.260	.397	.542	.700	.879	1.093	1.372	1.812	2.228	2.764	3.169	4.587	
11	.129	.260	.396	.540	.697	.876	1.088	1.363	1.796	2.201	2.718	3.106	4.437	
12	.128	.259	.395	.539	.695	.873	1.083	1.356	1.782	2.179	2.681	3.055	4.318	
13	.128	.259	.394	.538	.694	.870	1.079	1.350	1.771	2.160	2.650	3.012	4.221	
14	.128	.258	.393	.537	.692	.868	1.076	1.345	1.761	2.145	2.624	2.977	4.140	
15	.128	.258	.393	.536	.691	.866	1.074	1.341	1.753	2.131	2.602	2.947	4.073	
16	.128	.258	.392	.535	.690	.865	1.071	1.337	1.746	2.120	2.583	2.921	4.015	
17	.128	.257	.392	.534	.689	.863	1.069	1.333	1.740	2.110	2.567	2.898	3.965	
18	.127	.257	.392	.534	.688	.862	1.067	1.330	1.734	2.101	2.552	2.878	3.922	
19	.127	.257	.391	.533	.688	.861	1.066	1.328	1.729	2.093	2.539	2.861	3.883	
20	.127	.257	.391	.533	.687	.860	1.064	1.325	1.725	2.086	2.528	2.845	3.850	
21	.127	.257	.391	.532	.686	.859	1.063	1.323	1.721	2.080	2.518	2.831	3.819	
22	.127	.256	.390	.532	.686	.858	1.061	1.321	1.717	2.074	2.508	2.819	3.792	
23	.127	.256	.390	.532	.685	.858	1.060	1.319	1.714	2.069	2.500	2.807	3.767	
24	.127	.256	.390	.531	.685	.857	1.059	1.318	1.711	2.064	2.492	2.797	3.745	
25	.127	.256	.390	.531	.684	.856	1.058	1.316	1.708	2.060	2.485	2.788	3.725	
26	.127	.256	.390	.531	.684	.856	1.058	1.315	1.706	2.056	2.479	2.779	3.707	
27	.127	.256	.389	.531	.684	.855	1.057	1.314	1.703	2.052	2.473	2.771	3.690	
28	.127	.256	.389	.530	.683	.855	1.056	1.313	1.701	2.048	2.467	2.763	3.674	
29	.127	.256	.389	.530	.683	.854	1.055	1.311	1.699	2.045	2.462	2.756	3.659	
30	.127	.256	.389	.530	.683	.854	1.055	1.310	1.697	2.042	2.457	2.750	3.646	
40	.126	.255	.388	.529	.681	.851	1.050	1.303	1.684	2.021	2.423	2.704	3.551	
60	.126	.254	.387	.527	.679	.848	1.046	1.296	1.671	2.000	2.390	2.660	3.460	
120	.126	.254	.386	.526	.677	.845	1.041	1.289	1.658	1.980	2.358	2.617	3.373	
∞	.126	.253	.385	.524	.674	.842	1.036	1.282	1.645	1.960	2.326	2.576	3.291	

# of samples − 1

z values (multiples of standard deviations)

Appendix G is taken from Table III of Fisher and Yates: *Statistical Tables for Biological, Agricultural and Medical Research,* published by Longman Group Ltd., London (previously published by Oliver & Boyd, Edinburgh), and by permission of the authors and publishers.

Example: With a sample size (*n*) of 20, using the .05 level of significance (α), the tabular value of *t* with 19 (*n* − 1) degrees of freedom is 1.729 for a one-tail test and 2.093 for a two-tail test.

thus for sample of 20 at .95% confidence given $\bar{x}$, s of sample

$S_D = \frac{s}{\sqrt{20}}$ (standard error of mean)

95% chance that mean is $\bar{x} \pm 2.093 \left(\frac{s}{\sqrt{20}}\right)$

Using the table above, to determine if the results of two sets of data are the same, except for statistical error.

For example,

The average stress sample suffered just before breaking in the double ring test.

Before indentation: <x1>; after 100 lb/in indentation: <x2>.

And their average standard deviation is Sd

Then t=|<x1>-<x2>|/Sd.

Find the t value in the table, for two-tail test. the number is the percentage confidence you can get for these two set of data.