

# **Fracture Mechanics Properties of Fused Silicas used for International Space Station Windowpanes**

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## **Summary**

The fracture toughness and slow crack growth (SCG) parameters of two silicas were measured as part of a program to review the reliability of the International Space Station windows. The materials exhibit the same fracture toughness ( $0.75\text{MPa}\sqrt{\text{m}}$  in  $\text{N}_2$ ) and very similar SCG parameters. The literature on fused silica indicates excellent agreement of fracture toughness, but a very wide range of slow crack growth parameters, even from the same institution, with strength-based methods usually yielding a lower power law exponent than direct crack velocity measurements. Use of the exponential function is shown to provide better agreement between test methods, with velocity curves derived from strength tests of bare fiber and polished or ground test specimens paralleling those from wide-range, direct crack velocity observations, implying that constant stress rate tests can predict long lifetime via the exponential function. However, much variation still exists. SCG parameters for soda-lime silicate are much less sensitive to the test method than fused silica. Static load tests and stress intensity measurements resulted in a fatigue threshold of  $0.3\text{MPa}\sqrt{\text{m}}$  for fused silica.

## **Introduction**

The windowpanes in the International Space Station (ISS) are subjected to a variety of loads, including micrometeoroid impacts. Because such loads and contaminant damage influence lifetime and reliability, the windowpanes are monitored and the findings reviewed to ensure system safety. As part of this process, the fracture toughness and slow crack growth (SCG) parameters were measured to compare the materials and derive parameters that can be used with life prediction codes such as NASGRO [1, 2] and CARES/Life [3]. This report summarizes the measured properties and compares them to results from the literature.

In the Russian manufactured segments of the ISS, the windowpanes are silica derived from natural quartz and supplied by The Research Institute of Technical Glass (NITS). In the US manufactured segments, the panes are Corning 7940, which is made by vapor phase oxidation.

Because damage dimensions on polished articles such windows tend to be small, strength-based approaches with grinding or indentation flaws were employed to measure crack growth parameters. Both ASTM International techniques and modifications thereof were employed [4-10]. Fused silica exhibits substantial crushing under contact loads such as indentation, however, under hypervelocity impact a wide variety of damage morphology is exhibited as shown in Figure 1.

Substantial crack growth research has been performed on Corning 7940 and 7980 [11-16]. Both macro-crack (Double Cantilever Beam (DCB), Applied Moment (AMDCB), Double-Cleaved Drilled Compression (DCDC)) and strength-based approaches (constant stress and stress rate loading) have been used as shown in Figure 2. These approaches use different length scales, stress intensity ranges, and crack size monitoring. The reported values of the power law crack growth exponent,  $n$ , typically range from the low-20's to the low 40's, with the reported velocity at a stress intensity above the threshold varying by more than four orders of magnitude. In some cases, parameter estimates from the same laboratory are vastly different. Some results are linear in log velocity vs. log stress intensity space, while others are clearly nonlinear. The large variation in published research implies substantial dependence of the estimated parameters on test technique, resultant velocity range, and the crack growth model assumed. Other factors influencing the exponent are the surface hydration and energy due to water adsorption [17] and volume expansion via water penetration [18].

Some trends with surface finish and preconditioning can be seen in Table 1 for strength-based data fit to the power law: polished  $n = 22$ ; as-ground,  $n = 24-29$ ; grit blasted, cold water soak,  $n = 29-45$ ; abraded, hot water soak,  $n = 59$ . For fracture mechanics tests,  $n = 36-42$  consistently except for one result wherein the 7940 was annealed;  $n = 23$ . For grit blasting followed by cold soaking,  $n$  correlates with soak time and initial flaw size. Generally, the data correlates with the flaw size used in testing, with exception of annealing and hot water soaking. Indentation results are more variable with  $n = 19-42$ ;

In this report, results from testing of two crack configurations at NASA GRC are compared with literature data. Although the purpose was to compare the two silicas, the investigation indicates a crack size and crack type dependence for power law crack growth parameters. In order to make comparisons or to generate component design data, similitude needs to be maximized and extrapolation minimized. Although the exponential crack growth model minimizes differences in parameter generated by different methods, substantial differences still exist. Some discrepancy might be attributed to a lack of similitude between the initial cracks used in inert strength testing and those evolving during crack growth testing.

## **Experimental Procedure and Results**

Russian ISS fused silica was supplied as 254 mm diameter by 14 mm thick disks. Silica representative of that in the US segment was taken from a retired window of Shuttle Orbiter OV-103.

### *(1) Elastic Constants*

Elastic constants were measured by using ASTM C1259 [4] with 32 mm diameter disks that were also used to determine strength and SCG parameters. Disk specimens from the surface of the quartz-based silica billet exhibited similar modulus to specimens removed

from the billet center ( $E = 72.7 \pm 0.2$  GPa and  $\nu = 0.18 \pm 0.001$ ), and similar to that of Corning 7940 ( $E = 71.8 \pm 0.2$  GPa and  $\nu = 0.18 \pm 0.005$ ) as shown in Table 1.

## *(2) Inert Strength*

Tests were performed in vacuum or silicone oil after a minimum soak time of one hour. The inert strength and Weibull parameters in Table 1 represent a ~400 grit diamond finish, which is commonly used when preparing strength specimens from polycrystalline ceramics. Higher values could be attained by polishing; however, strength typically is not an inherent property of very brittle materials, but instead represents the combination of surface damage (cracks) and fracture toughness.

## *(3) Fracture Toughness*

Fracture toughness was measured per ASTM C1421 [5, 6] by using the single-edged-precracked-beam (SEPB) and chevron-notched beam (VB). SEPB precracks were initiated from scratches scribed into the beam because indentations did not yield flat cracks. Results are given in Table 2. Fracture toughness of the quartz-based silica and Corning 7940 are very comparable. These results are also comparable to measurements on 7980 made at NIST (high purity N<sub>2</sub>:  $0.72 \pm 0.01$  MPa $\sqrt{m}$  [15]) and to measurements made at Sandia National Laboratories and NIST on Corning 7940 (1-2% RH N<sub>2</sub>: 0.76 MPa $\sqrt{m}$  [13]; vacuum: 0.74 MPa $\sqrt{m}$  [19]; vacuum and 0.02%RH N<sub>2</sub>: 0.73 to 0.76 MPa $\sqrt{m}$  [12]).

Measurements in air are lower than in high purity nitrogen, as would be expected for a material exhibiting stress corrosion. The VB exhibited higher results than the SEPB in dry nitrogen. This may reflect incomplete drying of the SEPB precracks as explained in the next paragraph.

On unloading of SEPB fracture toughness specimens after precracking, which was performed in air, it was noted that the precracks closed so tightly that they were not visible to the unaided eye, implying a crack opening of less than a wavelength of light. Upon loading of the specimens to induce failure, the crack opened and became visible at a stress intensity of ~0.3 MPa $\sqrt{m}$  (40% of  $K_{Ivb}$ ), as shown in Figure 3. The behavior was more pronounced in nitrogen. This tight closure may be the reason that the measured fracture toughness in N<sub>2</sub> is slightly lower (~4%) for the SEPB than the VB: a tightly shut crack may be difficult to completely dry, despite being placed in flowing high purity N<sub>2</sub> for times commensurate with that in the published literature. One specimen was held in dry N<sub>2</sub> for double the usual time (~8 minutes) to no avail. The VB grows the crack in situ, and thus forms a crack in a dry environment.

## *(4) Slow Crack Growth*

Slow crack growth properties of 7940 and quartz-based silica in distilled, de-ionized water were measured by constant stress rate loading or “dynamic fatigue” per ASTM C1368 [7], ASTM C1499 [8, 9] and ASTM C1161 [10] of as-ground disks and with

beams subjected to three, 5 N Vickers indentations, thereby allowing crack growth mechanisms to be exhibited on a scale commensurate with that typically encountered during grinding and handling. Constant stress rate testing results in relatively short failure times. In order to generate long failure time data, beams of the quartz-based silica with five, 5 N indentations were tested in water with static loads covering 43 to 52% of the inert strength. The narrow range was a result of a threshold stress and failures during loading. The effect of a vacuum on 7940 crack growth was determined by constant stress rate loading of indented beams at  $\sim 10^{-5}$  torr.

The measured fracture stress as a function of stress rate and the “static fatigue” curve are shown in Figures 4 and 5, and the corresponding crack velocity curves are shown in Figure 6. The static fatigue data runs-out at 40 MPa, or 44% of the inert strength, implying a stress intensity threshold of  $0.33 \text{ MPa}\sqrt{\text{m}}$ . The parameters are summarized in Tables 3 and 4 for the power law

$$v = \frac{da}{dt} = AK_I^n = A^* \left( \frac{K_I}{K_{Ic}} \right)^n \quad (1)$$

and Table 5 for the exponential law via Trantina’s approximation [20]

$$v = \frac{da}{dt} = A_e \exp(n_e K_I) = A_e \exp \left( n_e^* \frac{K_I}{K_{Ic}} \right) \quad (2)$$

where  $v$ ,  $a$ , and  $t$  are crack velocity, crack size, and time, respectively. Constants  $A$  and  $n$  are the material/environment dependent SCG parameters, and  $K_I$  and  $K_{Ic}$  are, respectively, the Mode I stress intensity factor and the critical stress intensity factor or fracture toughness. For estimation of the SCG parameters from the as-ground data, values of  $K_{Ic} = 0.75 \text{ MPa}\sqrt{\text{m}}$  (inert conditions) and coefficient  $Y = 1.95$  (long surface crack) were used. For indented specimens,  $Y = 1.28$  was used. The effect is small relative to that between as-ground and indented specimens, as shown in Figure 6. The effectiveness of Trantina’s approximation was investigated by comparison to results from a numerical grid search routine. Table 6 compares results for a range of parameters and indicates that the approximation is good for engineering purposes.

Although both silicas exhibit very similar crack growth exponents for a given flaw system, the quartz-based silica exhibits slightly greater strength levels, implying more resistance to grinding or indentation damage. However, limited data was taken on the quartz silica, the variances are large, and the two materials were not ground at the same time. For engineering purpose, the materials are equivalent.

No loss of measurable strength is exhibited by 7940 in vacuum as stress rate is reduced, implying little or no slow crack growth in the absence of water. Static load testing of indented quartz-base silica gave similar crack growth parameters ( $n = 32-41$ ) to constant stress rate testing ( $n = 39 - 42$ , see Table 3) depending on fit range and censoring, with the censoring of very short-term strengths driving the parameter to 40. The static load results are conservative relative to the constant stress rate results, as shown in Figure 6.

It is noteworthy that the two flaw systems produce different crack growth parameters and velocity curves despite operating at similar strength levels, implying an effect of flaw type. The estimated crack velocity at failure ( $K_{Ic}$ ) for indented specimens is very high, much higher than for ground specimens. Also noteworthy is the large difference between inert strength and the strength in water. Extrapolation of the water data even to very short failure time (0.1 s) is much lower than the inert value (70 vs 95 MPa) and the use of such an extrapolated value lowers velocity near the fracture toughness to that of ground disks. These discrepancies may result from morphological changes in the cracks during slow crack growth, as shown in Figure 7 for an impact crater held at constant load until failure. Initially, the crack is small relative to the crater but with SCG becomes a large semi-elliptical crack nearly encompassing the crater. Similitude is needed between the cracks used in inert strength testing and those growing over time. In this work, 5 N indentations gave SCG parameter similar to those of macro-cracks.

For comparison, data for soda-lime silicate glass was also generated with constant stress rate testing of ground disks and indented beams with and without post-indentation annealing. In the case of as-indented beams, the estimated parameters were corrected for residual stress [21]. Macrocrack data was generated with a compact tension specimen. Figure 8 shows the results along with published data [11, 22-23, 25]. The effect of various residual stress corrections on velocity parameters for glass can be seen in Table 7 and reference [22]. Because fused silica crushes, rather than forming a distinct median crack system, no residual stress corrections were made.

Much better agreement occurs between strength and fracture mechanics techniques for soda-lime silicate glass as shown in Table 7; however, fused silicas are more resistant to stress corrosion than soda-lime silicate glass. For fused silica, because different crack/damage types exhibiting the same strength level result in such different SCG parameters, the crack configuration, size, and any residual stresses in an application are particularly important.

## Discussion

Despite the similarity of independent fracture toughness measurements for 7940 and 7980, the range of reported crack velocity is substantially different, as shown in Figure 2 for various techniques with a power law (eq. 1) fit for strength data. Even when the same institution uses the same technique, the results are very different (e.g. [15], [13], [24]). Besides the large variation in velocity, it is apparent that macro-crack techniques that directly observe velocity, such as the double-cantilever beam (DCB), give large value of  $n$  while strength techniques give lower values of  $n$ . These variations result in a very wide range of predicted life.

The strength-based results for polished bulk, ground bulk and bare optical fiber are similar for slower rates with a range of  $n = 21 - 24$ , with the exception of two values ( $n = 45, 38$ ) [25, 26], for which 7980 and a quartz-based silica were grit blasted and soaked in water for 40 hours to one week prior to testing. These two values are similar to macro-crack measurement in the literature and those generated in this work by using

indentations. Evidently, abrasion and soaking alter the crack growth behavior of fused silica. In contrast, less effect can be seen for soda-lime silicate in Table 2 of [25], implying the need for similitude between applications and testing. The parameter  $A$  is sensitive to the measured inert strength and fracture toughness: a 10% change in measured fracture toughness or inert strength nominally results in an order of magnitude change in expected velocity. However, because values are so different, the difference in  $A$  are unrelated to inert strength and fracture toughness.

For parameters measured with the DCB and DCDC, the  $n$  values are in general agreement with  $n > 35$  for higher velocities with the exception of one value of  $n = 23$  [13] for annealed 7940. However, the velocities at lower  $K_I$  are very disparate with the spread in predicted velocity at a  $K_I$  value varying by four orders of magnitude (Figure 2), implying the need for a better metrology and standardization of the test methods.

These differences can be attributed to a variety of causes: the presence of grinding/polishing related residual stresses [21]; non-linearity of the  $v$ - $K_I$  curve and the model used [27, 29]; flaw development [32]; stress intensity range used in testing [29]; hydration and surface energy effects [17, 18]; averaging of the velocity regimes by the strength methods; or to different diffusion rates in large vs. small cracks.

The current residual stress corrections [21] do not make sense with the strength-based data in this work: For the indented beams,  $n$  is predicted to be unusually high with either point or line corrections, and for ground disks either correction places the curves at very high a stress intensities, as shown in Figure 9. Further, Muroka and Abé [27] demonstrated that annealing only shifted the velocity curve to slightly higher stress intensities rather than changing the slope. The type of indentation and loading also play a role with direct observations of Knoop indentations [27] giving different parameters ( $n = 22$  vs 29, Table 4) from direct observation of Vickers indentation induced cone cracks [30].

For directly observed crack growth, the low-velocity regions do vary from virtually linear to very non-linear in log-log space (e.g., compare the data of [14-15] in Figure 10), implying the need for low velocity ( $10^{-10}$  m/s) data and the exponential function. Constant stress rate data captures both the low and high velocity regions inherently because a crack is grown from threshold to failure. It is noteworthy that when wide range velocity data is available [e.g., ref. 27], both the exponential and power forms represent the data reasonably.

A flaw threshold investigation by Dabbs and Lawn demonstrated that subthreshold indentation ( $\leq 0.5\text{N}$ ), which produces blunt flaws without radial cracks, resulted in low  $n = 19$  while larger, post threshold indentations ( $\geq 10\text{N}$ ) result in  $n = 31$  for stress rates between 0.1 and 1000 MPa/s. In contrast, similar testing in this work using 5 N indentations (between subthreshold and post threshold) at slower rates between 0.0001 and 1 MPa/s resulted in  $n > 39$  (see Table 4) like that of macrocracks. Parameters from pressurized indentation [32] is more akin to subthreshold values despite being generated with post threshold load. The indentation results are inconsistent. Blunt, undeveloped

flaws may develop into crack like configurations with sufficient time (Figure 7), lowering strength more so at lower rates, so that parameters exhibit a rate dependency. This effect is also seen for grit blasting followed by cold soaking:  $n$  correlates with soak time and initial flaw size. Soaking in order to develop cracks prior to testing may be good practice.

Based on the optical fiber data of Muraoka and Abé [27] and Armstrong [28], the difference in  $n$  between strength and direct observation data is due to the nonlinearity of the velocity curve and the tendency of strength test methods to operate at one end of the velocity curve [29]. However, when the exponential model is used with the dynamic strength-based measurements of Armstrong (optical fiber data) [28] and this study (indented and ground), the predictions intersect bulk silica data and parallel the 65% RH wide-range fiber data of Muraoka and Abé [27] (directly observed, small post threshold Knoop crack in a fiber), as shown in Figure 10. Further, Armstrong et al [28] demonstrated that the exponential form better accounts for humidity changes. The data of Braun and Fuller [15], which only employed two stress rates, exhibits lower slope but also agrees reasonably with macro-crack data when fit to the exponential function. Thus, the exponential model unites the shape of the curves derived from strength testing and direct crack observation. Table 4 gives fits to the exponential function ordered by flaw size for a crack type. Although some trends can be seen with flaw size, the effect is less pronounced than for the power law for a given flaw type, with smooth surfaces (ground, abraded or polished) consistently giving low parameters and macro-cracks consistently giving high parameters. Vickers indentations cracks are the most variable, with sensitivity to bluntness and stress rate.

In this work, the effects of stress rate and velocity regime averaging were minimized by testing at very low stress rates and preloads. The use of rapid rates can be seen to flatten the strength – stress rate curve and increase the parameter  $n$  for fused silicas and low expansion glass, as show in Figure 11. This implies that dynamic fatigue captures the whole velocity curve if a sufficient range of stress rates is used with an appropriate velocity model. Noteworthy is that the inclusion of the highest stress rate has little effect on the predicted velocity for either law compared to the large variation exhibited in Figure 10, implying that metrology is an issue for macro-crack measurements.

Finally, the use of water and lower stress rates should have helped mitigate diffusion rate effects.

Considering the nonlinearity observed for strength vs stress rate in this work (Figure 11) and that typically observed in direct  $v - K_I$  measurements along with the better agreement between strength and direct observations over a wide  $K_I$  range, the exponential model should be used, and similitude (flaw type and size) should be employed. With the exponential function, constant stress rate data is applicable to long life design because it covers stress intensities from the threshold to the fracture toughness, albeit on average. Figure 12 gives best estimate SCG parameters for small- and macro-cracks. Only one order of magnitude difference occurs between crack types at low velocities and two orders at high velocity ( $10^{-3}$  m/s).

Also noteworthy is the presence of a threshold stress intensity of  $0.3 \text{ MPa}\sqrt{\text{m}}$  in water for both large and small cracks, in agreement with prior measurements [30].

## Conclusions

Fused silica 7940 and quartz-based silica exhibit the same fracture toughness, and very similar slow crack growth parameters. Fused silicas exhibit a slow crack growth threshold at  $0.3 \text{ MPa}\sqrt{\text{m}}$ , 40% of the inert fracture toughness. Slow crack growth in vacuum was not detected using constant stress rate testing.

The published literature on fused silica implies that fracture mechanics and strength-based methods result in different parameters for fused silica when the power law is used: high values of  $n$  result from large-crack velocity measurements while strength methods tend to give low values of  $n$ , particularly for small, blunt cracks. The results for both methods depend somewhat on the range of data taken.

When fit with the exponential function via Trantina's approximation [20], SCG parameters from constant stress rate data for bulk polished [15] and ground specimens (this work) are in good agreement with those from bare optical fiber [28]. Further, the resultant velocity curves parallel those from direct crack growth observations of sharp cracks on fibers [27] and bulk silica [11-13], demonstrating that wide range stress rate data describes well the crack velocity of fused silica in both forms. Indentation derived parameters are more variable due to blunt vs sharp regimes ([32] and this work). The current residual stress corrections [21] are not effective.

Although use of the exponential model brings strength-based velocity predictions and direct velocity data into better agreement, the data groups into macro crack and strength-based regimes. Further, substantial variation between laboratories still exists. Better metrology is needed. Strength-based data generated in this work with more than four orders of stress rate do describe a wide range of growth velocity well via the exponential function, however, surface preparation (grit blasting, soaking, or annealing) does influence the results and similitude in crack sharpness and size with the actual application should be employed.

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Table 1 – Strength and elastic constants.

|                   | Silicone Oil               |                    |                                     | Elastic Modulus (GPa);<br>Poisson's Ratio |
|-------------------|----------------------------|--------------------|-------------------------------------|-------------------------------------------|
|                   | Inert<br>Strength<br>(GPa) | Weibull<br>Modulus | Characteristic<br>Strength<br>(GPa) | Surface                                   |
| Quartz-<br>silica | $98.9 \pm 4$               | 14                 | 101                                 | $72.7 \pm 0.2$ ; 0.18                     |
| 7940              | $92.9 \pm 10$              | 11                 | 95                                  | $71.8 \pm 0.2$ ; 0.18                     |

Table 2 – Fracture toughness of International Space Station silicas.

| Quartz-based Silica         |                       |                                | 7940 Fused Silica     |                   |
|-----------------------------|-----------------------|--------------------------------|-----------------------|-------------------|
| Method<br>(MPa $\sqrt{m}$ ) | Air<br>(75°F, 45% RH) | HP <sup>1</sup> N <sub>2</sub> | Air<br>(75°F, 45% RH) | HP N <sub>2</sub> |
| SEPB                        | $0.71 \pm 0.05$       | $0.73 \pm 0.02$                | $0.71 \pm 0.04$       | $0.73 \pm 0.03$   |
| VB                          | $0.71 \pm 0.04$       | $0.77 \pm 0.01$                | $0.73 \pm 0.04$       | $0.77 \pm 0.02$   |

1. 99.98% N<sub>2</sub>.

Table 3 – Power law slow crack growth parameters for International Space Station silicas in water.

| Quartz-based Silica                        |        |                          |                         | 7940 Fused Silica |                          |                         |
|--------------------------------------------|--------|--------------------------|-------------------------|-------------------|--------------------------|-------------------------|
| Dynamic Loading of Ground Disks in Water   |        |                          |                         |                   |                          |                         |
| Fit Method                                 | $n$    | $A$<br>m/s·(MPa√m ) $^n$ | $A^*$<br>(m/s)          | $n$               | $A$<br>m/s·(MPa√m ) $^n$ | $A^*$<br>(m/s)          |
| Data points                                | 28 ± 4 | 10.7                     | 3.85 x 10 <sup>-3</sup> | 28 ± 3            | 242                      | 7.76 x 10 <sup>-2</sup> |
| Medians                                    | 30 ± 1 | 26.7                     | 5.43 x 10 <sup>-3</sup> | 27 ± 4            | 142                      | 5.74 x 10 <sup>-2</sup> |
| Dynamic Loading of Indented Beams in Water |        |                          |                         |                   |                          |                         |
| Data points                                | 42 ± 8 | 3.27 x 10 <sup>7</sup>   | 206                     | 39 ± 3            | 1.13 x 10 <sup>7</sup>   | 139                     |
| Medians                                    | 43     | 3.38 x 10 <sup>7</sup>   | 146                     | 42 ± 6            | 1.13 x 10 <sup>8</sup>   | 642                     |
| Static Loading of Indented Beams in Water  |        |                          |                         |                   |                          |                         |
| Data points                                | 34 ± 4 | 9.91 x 10 <sup>5</sup>   | 50.2                    |                   |                          |                         |
| Medians                                    | 36 ± 6 | 4.59 x 10 <sup>6</sup>   | 153                     |                   |                          |                         |

Table 4 – Power law slow crack growth parameters for fused silica and optical fiber ordered by initial crack size based on  $K_{Ic} = \sigma Y \sqrt{a}$ . The tests were run in water unless specified otherwise.

| Method                                      | $n$ | $A$<br>$m/s(MPa\sqrt{m})^{-n}$ | Material<br>Type | Inert<br>Strength<br>(MPa) | Crack<br>size,<br>$\mu m$ | Surface Condition                      | Reference             |
|---------------------------------------------|-----|--------------------------------|------------------|----------------------------|---------------------------|----------------------------------------|-----------------------|
| <b>Polished, Ground, or Abraded Surface</b> |     |                                |                  |                            |                           |                                        |                       |
| Stress Rate                                 | 21  | $8.0 \times 10^{-6}$           | Optical fiber    | 5,620                      | $\ll 1$                   | Coated Optical fiber                   | [31] (Ritter service) |
| “ “                                         | 21  | $1.5 \times 10^0$              | Optical fiber    | 12,000                     | $\ll 1$                   | Stripped Optical fiber                 | [28] (Armstrong)      |
| “ “                                         | 22  | $1.2 \times 10^0$              | 7980             | 142                        | 17                        | Polished disks                         | 15 (Braun)            |
| “ “                                         | 29  | $1.5 \times 10^4$              | 7900             | 134                        | 19                        | 600 grit abraded rods, 2-hr cold soak  | [17] (Ito)            |
| “ “                                         | 59  | $1.4 \times 10^{13}$           | 7900             | 142                        | 17                        | 600 grit abraded rods, 112-hr hot soak | [17] (Ito)            |
| “ “                                         | 28  | $1.1 \times 10^{-1}$           | Russian bulk     | 99                         | 35                        | 400 grit ground disks, 4 stress rates  | This work             |
| “ “                                         | 23  | $2.7 \times 10^0$              | 7940             | 93                         | 40                        | 400 grit ground disks, 4 stress rates  | This work             |
| “ “                                         | 27  | $1.4 \times 10^2$              | 7940             | 93                         | 40                        | 400 grit ground disks, 5 stress rates  | This work             |
| “ “                                         | 38  | $6.5 \times 10^6$              | GE fused quartz  | ~88                        | 44                        | Grit blasted rods, 38-hr cold soak     | [25] (Sherburne)      |
| “ “                                         | 45  | $1.2 \times 10^9$              | 7940             | 78                         | 56                        | Grit blasted, 168-hr cold soak         | [26] Gulati           |
| <b>Indentation Cracks</b>                   |     |                                |                  |                            |                           |                                        |                       |
| Stress Rate                                 | 16  | $5.5 \times 10^{-2}$           | Optical fiber    | 1,000                      | 0.5*                      | 0.25N indentation                      | [32] (Dabbs)          |
| Static load                                 | 29  | $1.2 \times 10^1$              | Optical fiber    | -----                      | 20 - 25                   | 0.5N Knoop, annealed 1150°C 60% RH     | [27] (Muraoka)        |
| Stress Rate                                 | 42  | $3.3 \times 10^7$              | Russian bulk     | 98                         | 36                        | 5N indented beams, data points         | This work             |
| “ “                                         | 39  | $1.1 \times 10^7$              | 7940             | 94                         | 39                        | 5N indented beams, data points         | This work             |
| “ “                                         | 42  | $1.1 \times 10^8$              | 7940             | 94                         | 39                        | 5N indented beams, medians             | This work             |
| Static load                                 | 34  | $9.9 \times 10^5$              | Russian bulk     | 91                         | 41                        | 5N indented beams, data points         | This work             |
| Stress Rate                                 | 33  | $1.21 \times 10^5$             | Bulk             | 70                         | 70                        | 20N indentation                        | [32] (Dabbs)          |
| Static on indenter                          | 22  | $7.8 \times 10^0$              | 99.7% bulk       | -----                      | 95 - 150                  | 10N indentation, held in place         | [30] (Sglavo)         |
| Static on indenter                          | 20  | $1.1 \times 10^0$              | 99.7% bulk       | -----                      | 200 - 300                 | 39N indentation, held in place         | [30] (Sglavo)         |
| <b>Macro-cracks</b>                         |     |                                |                  |                            |                           |                                        |                       |
| DCB                                         | 36  | $5.9 \times 10^4$              | 7940             | -----                      | -----                     | N/A                                    | 12 (Wiederhorn)       |
| AMDCB                                       | 39  | $6.9 \times 10^7$              | 7940/80          | -----                      | -----                     | N/A                                    | 15 (Braun)            |
| DCB                                         | 42  | $6.1 \times 10^6$              | Bulk             | -----                      | -----                     | N/A                                    | 11 (Wiederhorn)       |
| “ “                                         | 23  | $2.8 \times 10^2$              | 7940             | -----                      | -----                     | Annealed 1090°C                        | 13, 14 (Michalske)    |

\* report damage size was 3 – 6  $\mu m$ , implying a damage zone or very blunt flaw.

Table 5 – Exponential law slow crack growth parameters for silica via Trantina’s approximation [20] for fused silica and optical fiber ordered by initial crack size based on  $K_{Ic} = \sigma Y \sqrt{a}$ . The tests were run in water unless specified otherwise.

| Method                                      | $n_{e*}$ | $n_e$ | $A_e$<br>m/s           | Material<br>Type   | Inert<br>Strength<br>(MPa) | Crack size | Surface Condition                                          | Reference                            |
|---------------------------------------------|----------|-------|------------------------|--------------------|----------------------------|------------|------------------------------------------------------------|--------------------------------------|
| <b>Polished, Ground, or Abraded Surface</b> |          |       |                        |                    |                            |            |                                                            |                                      |
| Stress<br>Rate                              | 31.0     | 41.3  | $6.41 \times 10^{-21}$ | Optical<br>fiber   | 5620                       | $\ll 1$    | Coated Optical fiber                                       | [31] (Ritter<br>service)             |
| “ “                                         | 47.5     | 63.3  | $1.25 \times 10^{-19}$ | Optical<br>fiber   | 12,000                     | $\ll 1$    | Stripped optical fiber,<br>95%RH                           | [28] (Armstrong)                     |
| “ “                                         | 36.9     | 49.2  | $9.14 \times 10^{-18}$ | 7980               | 142                        | 17         | Polished disks                                             | 15 (Braun)                           |
| “ “                                         | 47.7     | 63.7  | $2.95 \times 10^{-19}$ | 7900               | 134                        | 19         | 600 grit abraded rods, 2-<br>hr cold soak                  | [17] (Ito)                           |
| “ “                                         | 45.5     | 60.6  | $8.25 \times 10^{-22}$ | Russian<br>bulk    | 99                         | 35         | 400 grit ground disks, 4<br>rates, 0.0001 – 1 MPa/s        | This work                            |
| “ “                                         | 41.3     | 55.1  | $2.82 \times 10^{-19}$ | 7940               | 93                         | 40         | 400 grit ground disks, 4<br>rates, 0.0001 – 1 MPa/s        | This work                            |
| “ “                                         | 46.9     | 62.5  | $1.81 \times 10^{-20}$ | 7940               | 93                         | 40         | 400 grit ground disks, 5<br>rates, 0.0001 – 10 MPa/s       | This work                            |
| “ “                                         | 41.0     | 54.7  | $2.28 \times 10^{-17}$ | GE fused<br>quartz | ~88                        | 44         | Grit blasted rods, 38-hr<br>cold soak                      | [25] (Sherburne)                     |
| “ “                                         | 75.6     | 100   | $6.00 \times 10^{-27}$ | 7940               | 78                         | 56         | Grit blasted, 168-hr cold<br>soak                          | [26] Gulati                          |
| Median                                      | 45.5     | 60.6  | $2.82 \times 10^{-19}$ | -----              | -----                      | -----      | Polished, ground or grit<br>blasted                        | 15, 17, 25, 26, 28,<br>and this work |
| <b>Indentation Cracks</b>                   |          |       |                        |                    |                            |            |                                                            |                                      |
| Stress<br>Rate                              | 26.0     | 34.7  | $1.72 \times 10^{-14}$ | Optical<br>fiber   | 1,000                      | 0.5*       | 0.25N indentation<br>0.1 – 1000 MPa/s                      | [32] (Dabbs)                         |
| Static                                      | 49.2     | 65.6  | $1.30 \times 10^{-22}$ | Optical<br>fiber   | -----                      | 20 - 25    | 0.5N Knoop, annealed<br>1150°C 60% RH                      | Muraoka [27]                         |
|                                             |          |       |                        |                    |                            |            | .5N Knoop, 60% RH                                          |                                      |
| Stress<br>Rate                              | 72.3     | 96.5  | $1.10 \times 10^{-26}$ | Russian<br>bulk    | 98                         | 36         | 5N indented beams, data<br>points                          | This work                            |
| “ “                                         | 64.3     | 88.3  | $3.70 \times 10^{-24}$ | 7940               | 94                         | 39         | 5N indented beams,<br>median fit                           | This work                            |
| Static                                      | 71.2     | 94.9  | $1.23 \times 10^{-25}$ | Russian<br>bulk    | 91                         | 41         | 5N indented beams, data<br>points, 10 – 10 <sup>6</sup> s  | This work                            |
| “ “                                         | 61.0     | 81.2  | $1.17 \times 10^{-23}$ | Russian<br>bulk    | 91                         | 41         | 5N indented beams, data<br>points, 100 – 10 <sup>6</sup> s | This work                            |
| Stress<br>Rate                              | 44.5     | 59.3  | $2.02 \times 10^{-18}$ | Bulk               | 70                         | 70         | 20N indentation<br>0.1 – 1000 MPa/s                        | [32] (Dabbs)                         |
| Static                                      | 36.3     | 48.4  | $1.18 \times 10^{-17}$ | 99.7% bulk         | -----                      | 95 - 150   | 10N Knoop, held in<br>place                                | 30 (Sglavo)                          |
| Static                                      | 32.8     | 43.8  | $1.99 \times 10^{-16}$ | 99.7% bulk         | -----                      | 200 - 300  | 39N Knoop, held in<br>place                                | 30 (Sglavo)                          |
| <b>Macro-cracks</b>                         |          |       |                        |                    |                            |            |                                                            |                                      |
| DCB                                         | 55.9     | 74.5  | $3.7 \times 10^{-23}$  | 7940               | -----                      | -----      | N/A                                                        | 12 (Wiederhorn)                      |
| AMDC<br>B                                   | 65.4     | 87.3  | $5.8 \times 10^{-24}$  | 7980               | -----                      | -----      | N/A                                                        | 15 (Braun)                           |
| DCB                                         | 65.4     | 87.2  | $1.1 \times 10^{-25}$  | Bulk               | -----                      | -----      | N/A                                                        | 11 (Wiederhorn)                      |
| “ “                                         | 37.1     | 49.4  | $5.4 \times 10^{-16}$  | 7940               | -----                      | -----      | Annealed 1090°C                                            | 13, 14<br>(Michalske)                |
| Median                                      | 65.4     | 87.4  | $5.80 \times 10^{-24}$ | -----              | -----                      | -----      | N/A                                                        | 11, 12, 15                           |

\* reported damage size was 3 – 6  $\mu\text{m}$ , implying a damage zone or very blunt flaw.

Table 6 – Exponential parameters derived from approximation [20] and a numerical grid search.

| Material            | $n_{e*}$      |           | $A_e$ (m/s)            |                        |
|---------------------|---------------|-----------|------------------------|------------------------|
|                     | Approximation | Numerical | Approximation          | Numerical              |
| Optical fiber       | 26.0          | 27.1      | $1.72 \times 10^{-14}$ | $1.21 \times 10^{-14}$ |
| S8070 glass-ceramic | 30.8          | 30.8      | $2.87 \times 10^{-16}$ | $2.87 \times 10^{-16}$ |
| S-TIH-1 Glass       | 33.1          | 34.7      | $2.62 \times 10^{-15}$ | $1.93 \times 10^{-15}$ |
| 7980                | 34.3          | 34.1      | $3.44 \times 10^{-17}$ | $4.55 \times 10^{-17}$ |
| Herasil-F           | 44.5          | 43.9      | $2.02 \times 10^{-18}$ | $4.43 \times 10^{-18}$ |
| 7940                | 81.1          | 81.1      | $3.94 \times 10^{-28}$ | $3.11 \times 10^{-28}$ |

Table 7 - Power law slow crack growth parameters for soda-lime silicate glass in water where  $n'$  and  $A'$  are the estimated parameters without residual stress correction and  $n$  and  $A$  are those with the point correction of reference [21].

| Test Set                       | $n'$           | $n$            | $A'$<br>$\text{m/s}(\text{MPa}\sqrt{\text{m}})^n$ | $A$<br>$\text{m/s}(\text{MPa}\sqrt{\text{m}})^n$ |
|--------------------------------|----------------|----------------|---------------------------------------------------|--------------------------------------------------|
| As indented slide plate ('09)  | $15.4 \pm 0.7$ | $19.8 \pm 0.8$ | 0.08                                              | 0.60                                             |
| As indented slide plate ('10)  | $15.4 \pm 0.3$ | $19.8 \pm 0.4$ | 0.12                                              | 0.87                                             |
| Ground disks                   | $17.9 \pm 1.5$ |                | 0.26                                              |                                                  |
| Indented, annealed slide plate | $20.0 \pm 2.1$ |                | 0.21                                              |                                                  |
| Indented, annealed slide plate | $16.7 \pm 0.4$ |                | 0.05                                              |                                                  |
| Compact Tension                | $18.9 \pm 0.7$ |                | 0.24                                              |                                                  |

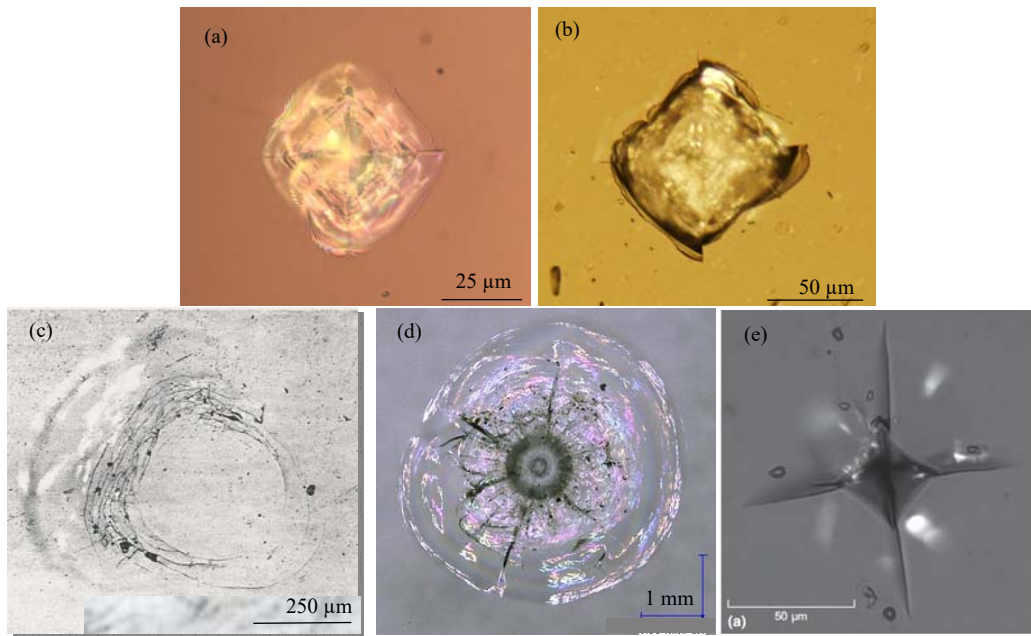


Figure 1 – Damage morphology in fused silica exhibited from (a) 5N quasi-static Vickers indentation (b) 20N quasi-static Vickers indentation (c) low velocity blunt impact and (d) hypervelocity impact on an STS-84 shuttle window. (e) 10N indentation in soda-lime glass.

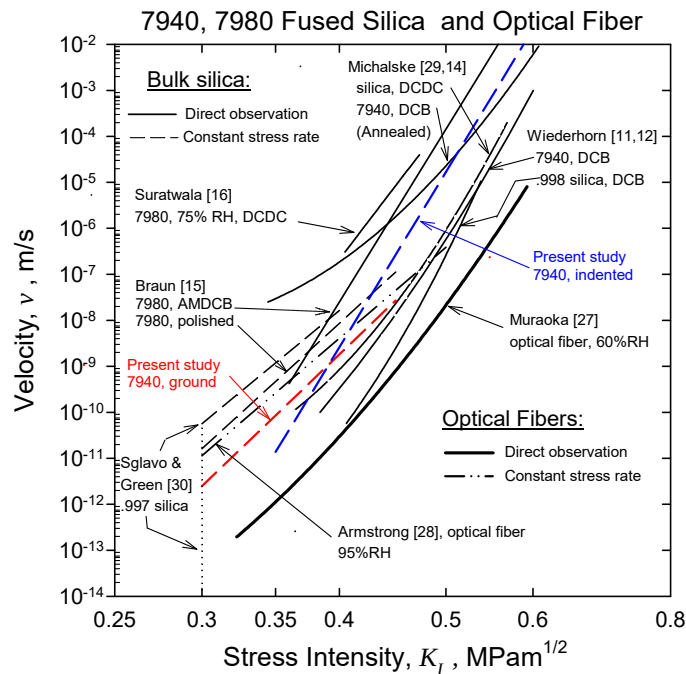


Figure 2 – Crack velocity of 7940, 7980, and optical fibers as a function of stress intensity as determined with direct crack observation and strength data fit to the power law.

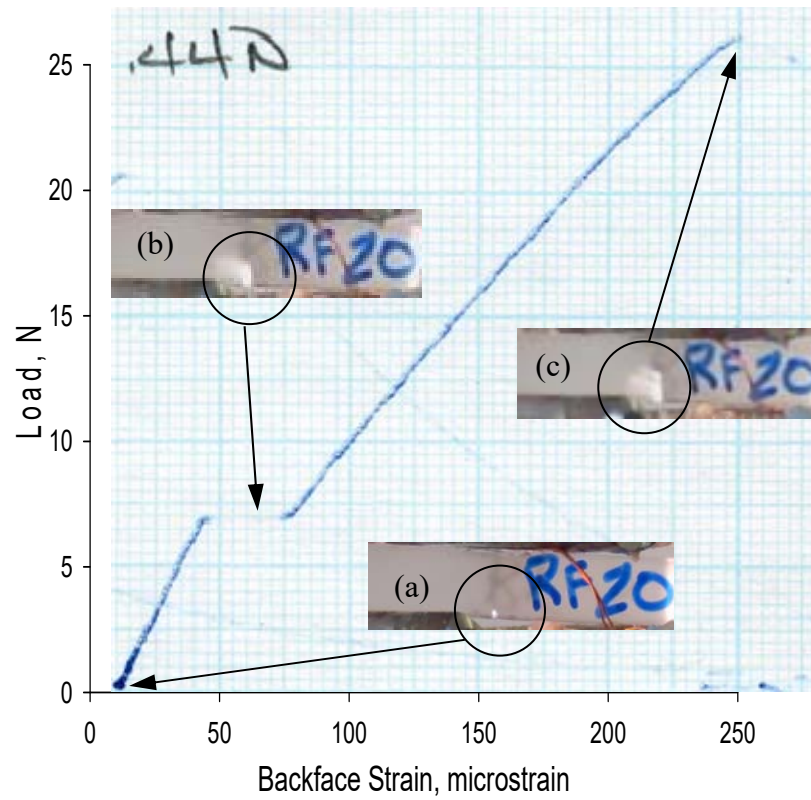


Figure 3 – Load–strain diagram for a precracked beam fracture toughness test. The strain jumps when the crack mouth opens at  $\sim 0.3 \text{ MPa}\sqrt{\text{m}}$ . Insets: (a) precrack before loading, (b) after opening, and (c) just before failure.

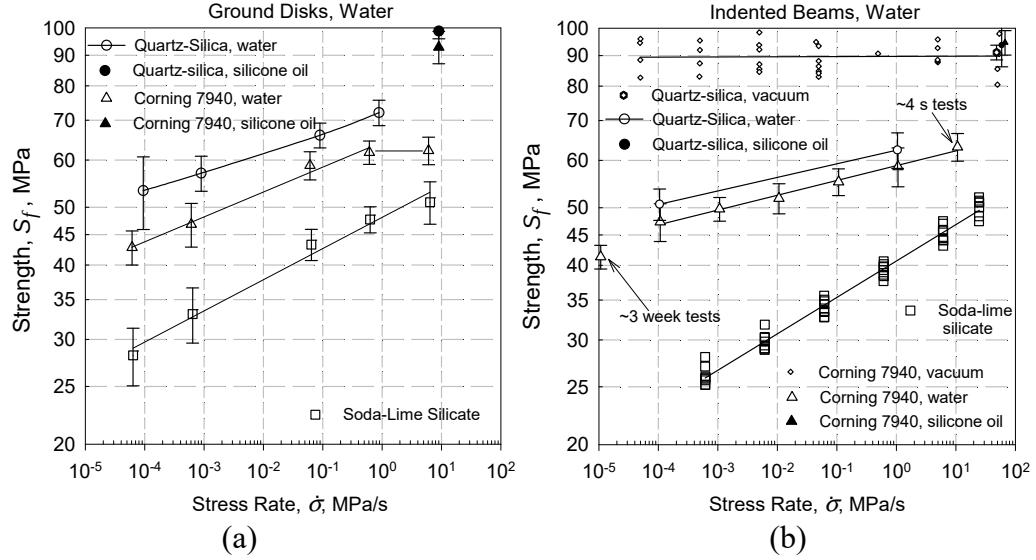


Figure 4 – Strength as a function of stress rate in distilled, de-ionized water for (a) as-ground disks and (b) as-indented beams. Data for soda-lime glass beams subjected to a 10 N indentation load are included.

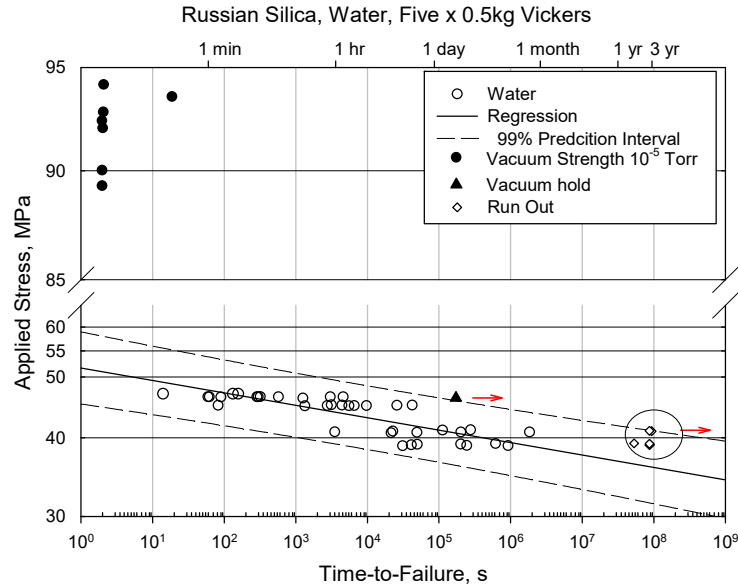
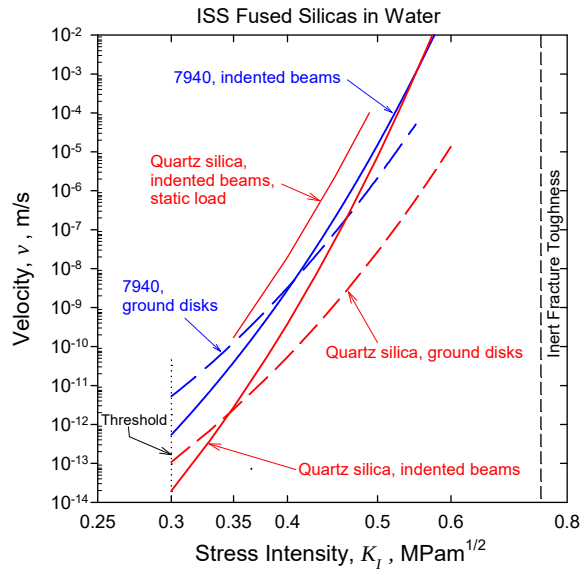
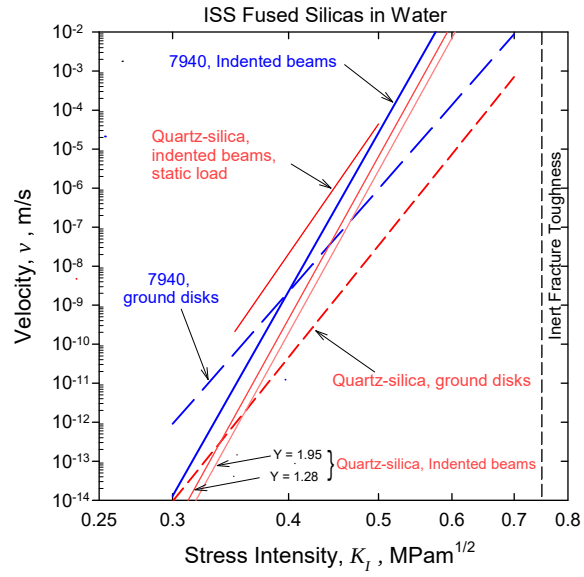


Figure 5 – Strength in vacuum and failure time at a stress in water for quartz-based silica.



(a)

(b)

Figure 6 – Crack velocity of fused silicas as a function of stress intensity: (a) power law and (b) exponential law.

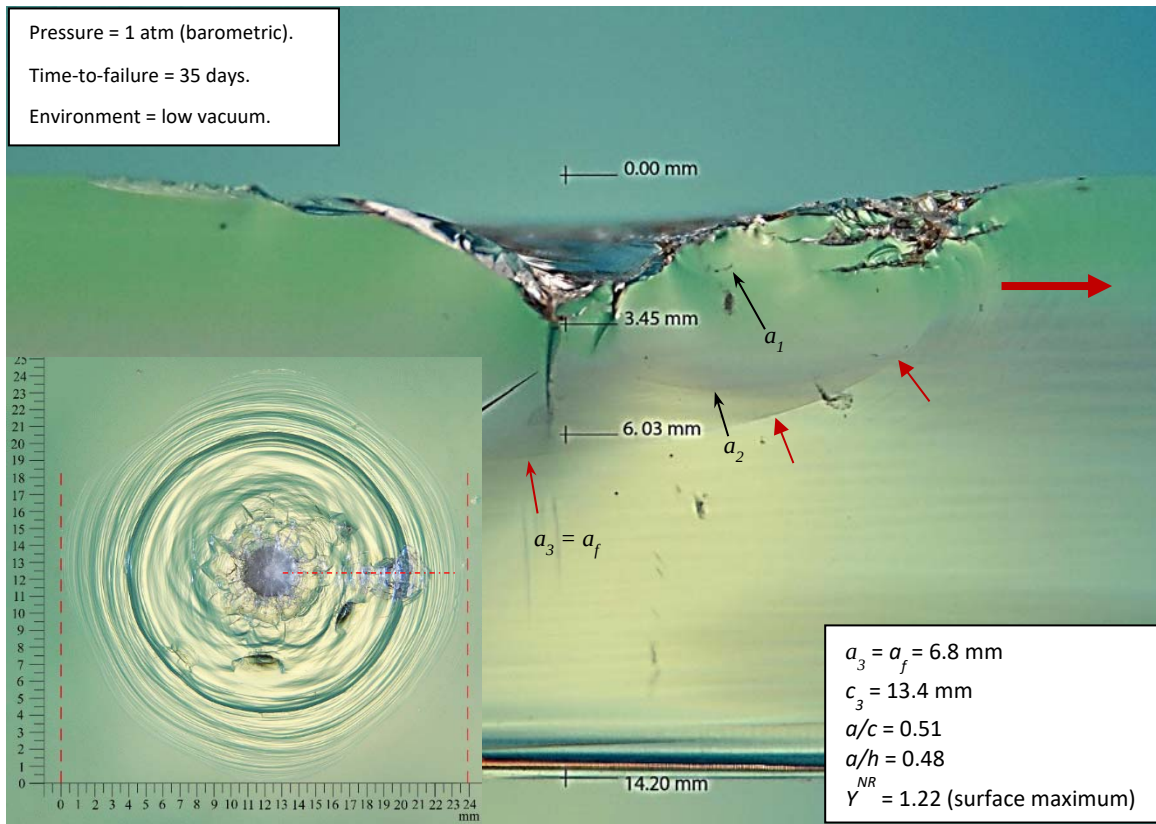


Figure 7 – Morphological changes as impact damage grows into a crack. The crack initiates from the crater edge and nearly encompasses it at fracture.

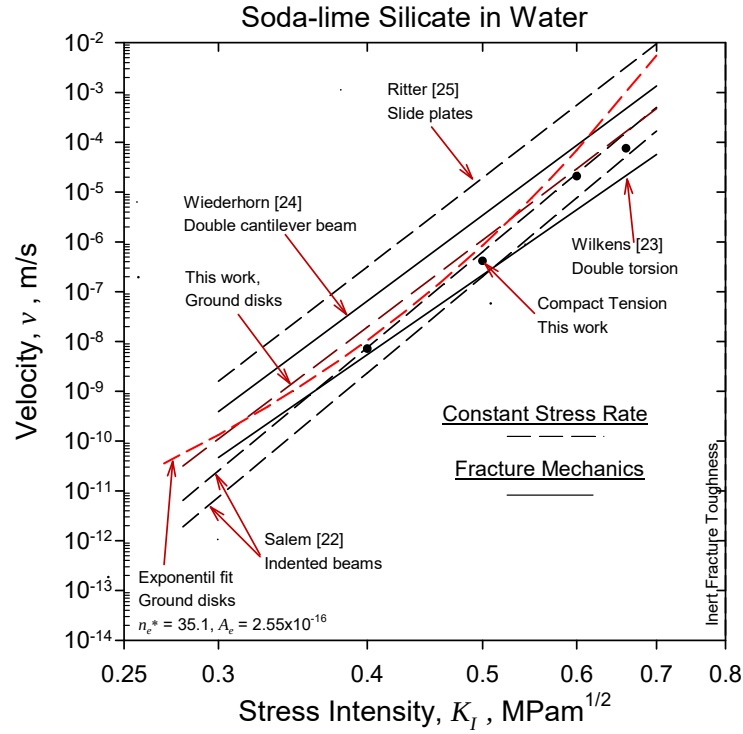


Figure 8 – Crack velocity of soda-lime silicate as a function of stress intensity.

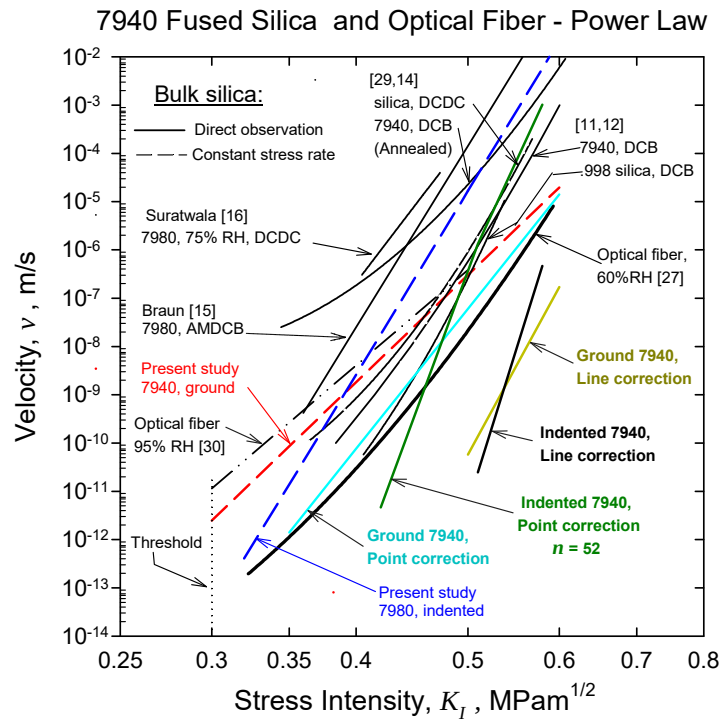


Figure 9 – Effect of residual stress corrections on crack velocity of 7940 as a function of stress intensity.

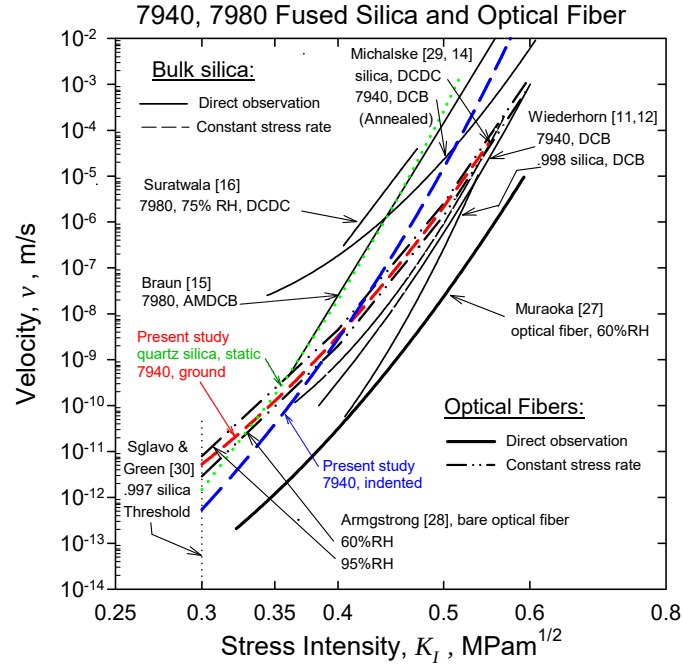


Figure 10 – Crack velocity of 7940, 7980, and optical fibers as a function of stress intensity as determined with direct observations and strength data fit to the exponential function.

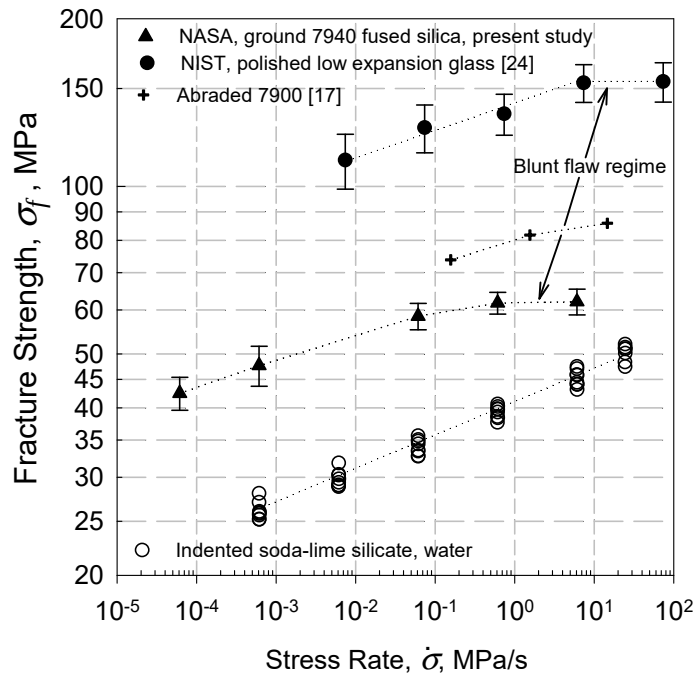


Figure 11 – Fracture strength of polished low expansion glass, ground or abraded fused silica, and indented soda-lime silicate as a function of stress rate.

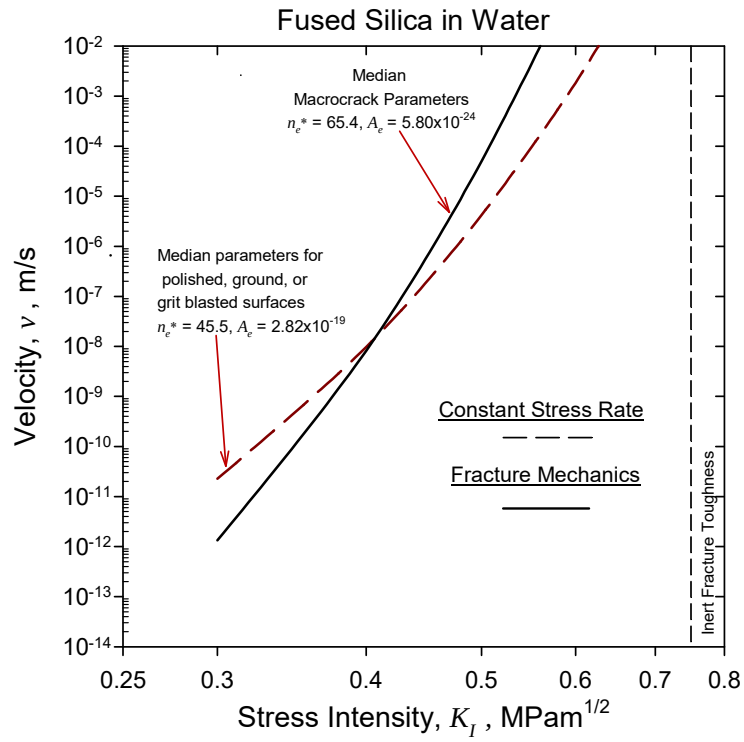


Figure 12 – Velocity curves for strength-based and fracture mechanics-based tests.