

# Retained Strength for AutoGrade™ Cover Glass

**Khaled Layouni, Timothy M. Gross, Matthew L. Black, Jason T. Harris,**

**JongSe Park, Yousef K. Qaroush**

Corning Incorporated, Corning, NY 14831

layounik@corning.com

**Abstract:** *Automakers are responding to consumers' demand for more connected and immersive driver experiences by deploying displays that are larger, longer, shaped, and more integrated. Because of this consumer pull, an auto-specific use-case for displays has emerged, challenging today's incumbent cover materials with different industry requirements. The spotlight is on the auto industry's headform-impact test (HIT), a regulatory test where cover glass performance and system-level architecture play important roles. Today, incumbent solutions frequently fail during these reliability tests, increasing supply chain costs.*

*In this article, the retained strength metric is considered when designing the industry's first cover glass optimized for auto interiors, Corning's AutoGrade™ Gorilla® Glass, while a methodology is proposed to consistently measure retained strength. Furthermore, two cover glasses are introduced based on these studies: one for two-dimensional (2D) display formats and one for three-dimensional (3D) display formats. The 2D cover glass is optimized to enable systems to pass industry reliability tests (using Corning's system-level design guidelines) while preserving its authentic feel, superior durability, and advantaged optics of glass for flat applications. The 3D glass was developed for shaped or curved applications, delivering the same reliability performance when bent to shape as the 2D cover glass. These cover glass solutions can enable connectivity for drivers with the sophistication they've come to expect from their smartphones.*

**Keywords:** Cover glass; Glass; HIT; Strength; Flaws; Headform; Impact

## Introduction

The incumbent cover glass used for auto interior applications was designed for consumer electronics (smartphone, tablet, etc.) to survive specific use-case damage events, such as phone drops. Auto interior cover glass must respond to the emerging automotive use case. This includes meeting the requirements of the auto

industry's headform-impact test (HIT), a regulatory test where cover glass performance and system-level architecture play important roles.

In this article, HIT has been investigated and the corresponding impact on glass attributes defined. Retained strength is proposed as the relevant metric for auto interior cover glass and the methodology is described.

## Supply Chain & Installation Flaws

Glass strength is not directly a material property. Instead, glass strength primarily depends on surface flaws and mechanical properties related to glass composition, e.g. Young's modulus and fracture toughness. In order to control glass strength, the use-case flaws from a supply chain (Fig. 1) were characterized. Thirty-nine commercially available auto interior display modules with known cover glasses, which had seen one to five years of use, were analyzed and characterized as described in figure 2. About half of the display modules had cover glass made of Aluminosilicate (AlSi) and one-third were ion-exchanged soda lime glasses (IOX-SLG). The authors would like to mention that this does not represent the whole auto-interior display market, but it is the distribution of displays that were analyzed during this study where the focus was on analyzing glass-based displays.

A methodology based on [1] was established to measure the critical flaws for these cover glasses. The modules were torn down (Fig. 3) and the cover glass was laser cut before being tested under ring-on-ring (ROR) biaxial loading. Because HIT stresses the backside surface (S2) of a display cover glass, these flaws were of interest and were characterized. Specifically, the origin flaw was identified, and its check depth was measured by fractography, with an example measurement visually described in figure 4.

The resulting flaw size distribution is described in figure 5. The number of display parts is equal to 28, where 42 samples were extracted. S2 Max flaw size ~ 3.8 μm and

extrapolated flaw size at 99.9% ~ 5 μm. In order to survive HIT without breakage, the cover glass must then withstand the applied stress in the presence of this flaw distribution. How stress is applied during HIT is described in the following section.

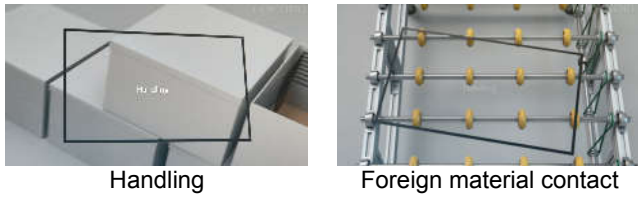


Figure 1. Example of supply chain sources of flaws.

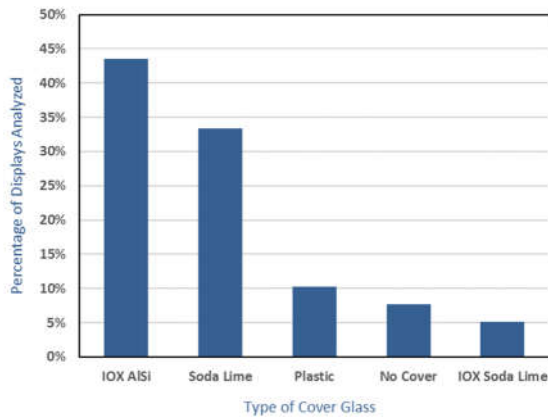


Figure 2. Distribution of cover glass analyzed from commercially available display modules (39 displays).

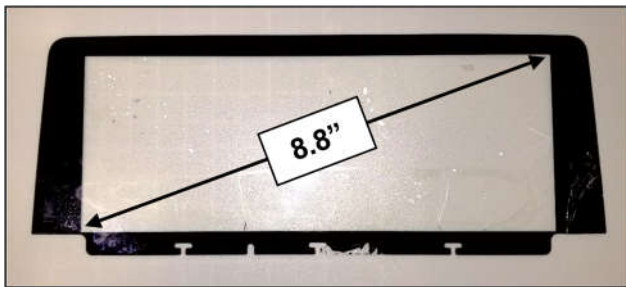


Figure 3. Example of an ion-exchanged AlSi cover glass analyzed during this study.

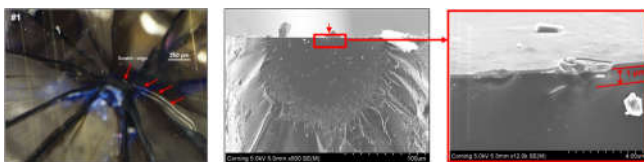


Figure 4. Example of check depth measurement after Ring-on-Ring testing.

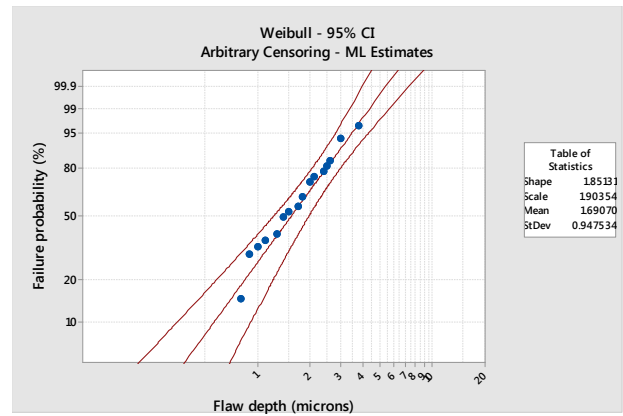


Figure 5. Flaw size distribution for backside surface, S2.

## Headform-Impact Test (HIT)

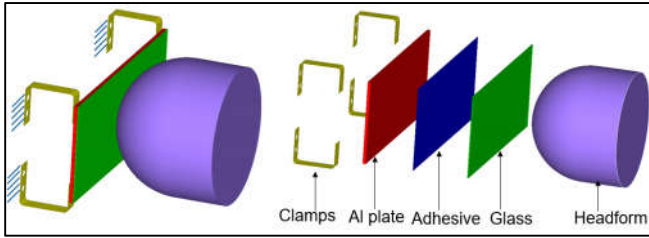
### Regulation

The HIT configurations are defined by government regulations such as FMVSS201 in the USA, GB 11552 in China and ECE R21 in EU/UN. Different geographic regions have their own regulations, but most test configurations and requirements are similar, where the total headform deceleration must not exceed 80G for longer than a 3ms duration. The head form, an impact object of the test, has a mass of 6.8kg and a diameter of 165mm, which represents a human head. The impact velocity is equal to 6.69m/s. The resulting kinetic energy at impact is 152J. None of these standards are specifically written for the use of glass in this application, where breakage behavior is regulated; however, in general the auto industry desires no glass breakage during HIT.

### Stress estimation during HIT from equivalent simplified modules

As described previously, HIT is a system-level test and it is important to have appropriate stiffness to meet regulation. To map out a design window of the stiffnesses for auto display modules and supporting structures, a concept of K1 and K2 was introduced. K1 refers to the linear spring constant of a display module at the impact location. K2 refers to the spring constant of the supporting structure including the instrument panel, car cross beam, etc. Since the actual response from an impact has geometry nonlinearity and time dependency, there are some limitations using the concept of K1 and K2 for an entire impact duration. However, it is effective and intuitive to predict an early stage response which can help customers design their display modules and supporting structure.

Realistic K1 and K2 ranges were defined based on Corning’s experience including auto display module tear down analyses, numerical simulations and actual experiments. A simple surrogate module was designed to cover a wide range of K1 and K2 values, as shown in Figure 6. Dynamic HIT simulations were conducted for all cases to calculate decelerations and stresses during impact. A typical size of display panel (13 inches as diagonal size) is used and the K1 and K2 values were varied by changing the thickness of the aluminum plate and stainless-steel clamps, respectively.



**Figure 6.** Example schematic diagram for the HIT surrogate model

An explicit dynamic finite element model is developed in LS-Dyna to model the rigid headform impact against the surrogate. Material properties used in the dynamic impact models are shown in Table 1.

**Table 1.** Cover material properties used in the headform impact against surrogate

Part	Material	Density [ton/mm <sup>3</sup> ]	Young's Modulus [MPa]	Yield Stress [MPa]	Tan Modulus [MPa]	Poisson's Ratio
Cover glass	Autograde™ glass	2.43E-09	76,700	-	-	0.21
Adhesive	Adhesive	1.30E-09	5	-	-	0.47
Al Plate	Al 6061	2.70E-09	69,000	276	690	0.33
Clamps	Steel 304	7.80E-09	205,000	215	2,050	0.3
Headform	Rigid	2.70E-09	69,000	276	690	0.33

Since the regulation requires that headform deceleration not exceed 80G for more than 3ms, Table 2 presents the model predictions, for typical K1 and K2 values, of the maximum decelerations for 3ms. All deceleration values higher than 80G indicate that the corresponding (K1, K2) should be outside the design window in order to comply with the regulation. Thus, this implies that the safe zone of display module and supporting structure stiffness directly depends on the panel stiffness (K1) and the back support (K2). This safe operating window is consistent with Corning’s HIT experimental results. The corresponding glass backside surface stress due to the biaxial flexure induced by the impact could be as high as 850 MPa depending on cover glass thickness.

**Table 2.** Model predictions for the 3 ms deceleration (G) of various K1 and K2 values

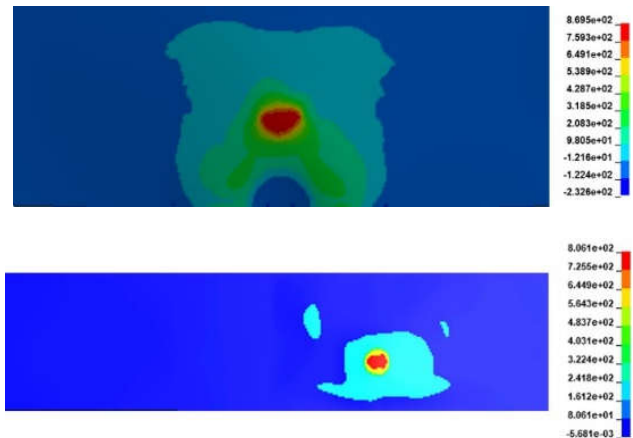
		K2 (N/mm)			
		368	696	1100	4152
K1 (N/mm)	1000	99	90	105	182
	500	80	62	109	133
	300	66	59	97	104
	100	42	54	64	68

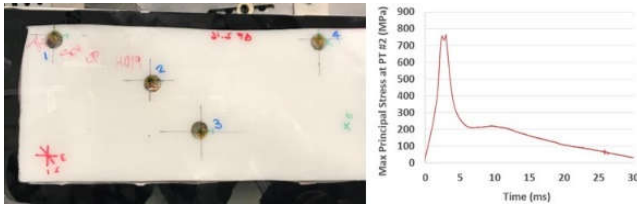
The headform impact reliability depends on several factors related to display module boundary conditions, impact energy, localized features under the cover glass (air gaps, supporting local features, etc.), panel stiffness and mounting bracket stiffnesses. Thus, it is expected the impact-induced cover glass stresses will be even higher in commercially available auto display modules, reaching values of 900 MPa, which will be discussed in the next section.

*Stress estimation during HIT from real modules*

The actual stress magnitudes of cover glasses in in-use auto display modules were measured by a strain gauge and calculated through numerical dynamic simulations, using customer designs. Figure 7 indicates some examples which pass HIT requirements where the approximated maximum principal stress on S2 was found to be close to 900MPa.

Both equivalent simplified display modules and commercially available auto display modules indicate that biaxial stresses can reach 900 MPa. In order to survive HIT, even under aggressive conditions, the cover glass must withstand a stress of 900 MPa.





**Figure 7.** Maximum principal stresses for commercially available auto display modules (from top to bottom): (a) 2D module from simulation (b) 3D shape with constant curvature radius from simulation (c) 3D module with bending at the center of the module from strain gauges.

### Retained Strength Requirement

Glass strength depends on the presence of surface flaws that act as stress concentrators. Glass failure almost always results from surface flaws associated with processing, finishing, handling, or service conditions. Glass strength is therefore not an intrinsic material property but is controlled by surface flaws. As described below by the simple fracture mechanics equation [2], fracture happens when the stress intensity factor ( $K_I$ ) reaches the fracture toughness ( $K_{IC}$ ), such that:

$$K_I = Y\sigma_a\sqrt{\pi a} \rightarrow K_{IC} = Y\sigma_c\sqrt{\pi a_c}$$

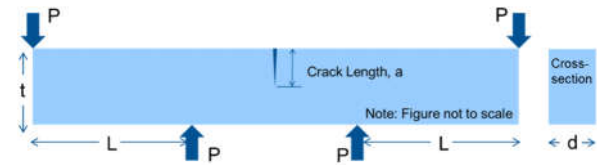
Where  $\sigma_a$  = Applied stress,  $Y$  = Geometry parameter,  $\sigma_c$  = Strength,  $a$  = Flaw depth

As mentioned above, the glass surface, during HIT, is subjected to stress that can reach 900 MPa. The flaw distribution generated by a supply chain can be described by a Weibull distribution where size = 5 micron at 99.9% level.

Corning's AutoGrade™ Gorilla Glass can survive stresses of up to 900 MPa with supply chain surface flaws present.

### Retained Strength Modeling

A finite element model was developed to study the effects of the interaction between the residual stress profile, crack length, and bending stresses. Plane strain geometry in four-point bending was analyzed and residual stresses from ion exchange processes were explicitly imposed before crack insertion and subsequent bending. All flaws were assumed to be perpendicular to the surface, originating at the tensile surface. The finite element geometry is shown in figure 8.



**Figure 8.** FEA model geometry for retained strength calculations.

Stress intensity factors were calculated by integrating along contours that surround the crack tip. Contours are comprised of special elements designed to capture the effects of the singularity. This method is one of the best available fracture mechanics tools for accurate calculations of stress intensity factors. The interaction integral method was used to calculate the J-contour integral, which was then converted to the stress intensity factor assuming linear elastic fracture mechanics principles. Additional information can be found in the Abaqus Theory Manual [3]. Because of the low amounts of deformation applied to the model, linear elastic fracture mechanics is a valid assumption. It should be noted that the above calculation has been done analytically by Green [4], but the analytical solutions neglect the impact of crack face self-contact, which can significantly affect the calculated stress intensity factor for cracks in residual stress fields.

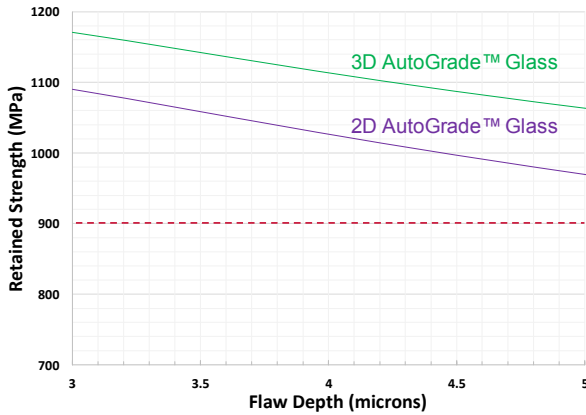
The primary output of the fracture mechanics simulations, which are described above, is a plot of the retained strength as a function of crack size for all cracks. The retained strength is the stress applied to the model via four-point bending at which the stress intensity factor reaches the material toughness. The stress is calculated according to Euler-Bernoulli beam theory, as shown below:

$$\sigma_{ret} = \frac{6PL}{dt^2}$$

The parameters are defined in figure 8. Retained strength is essentially the maximum bending stress that can be applied to the surface before the stress intensity factor at the crack tip reaches the fracture toughness of the material and will propagate catastrophically. The retained strength was calculated for the supply chain flaw range and glass composition was optimized to provide the required retained strength over the expected flaw range.

The modeled retained strength could be overestimated because of the assumption of zero volume flaws. The damage introduction event results in material removal and/or the creation of a micro ductile groove, which prevents the crack faces from maintaining contact and negates some of the benefit of the surface compression toward keeping the crack tip closed. Figure 9 indicates that Corning's AutoGrade™ Gorilla Glass for Automotive Interiors provide retained strength greater than 900 MPa for the considered flaw range. In addition, Corning's AutoGrade™ cover glasses were introduced based on these studies and specifically designed for use with two-dimensional

(2D) display formats and with three-dimensional (3D) display formats.



**Figure 9.** Predicted retained strength according to the fracture mechanics model as a function of flaw depth for the AutoGrade Gorilla Glass stress profile and a competitive cover glass stress profile.

## Retained Strength Measurement

### Flaws introduction Method

Retained strength for a cover glass, such as Corning’s AutoGrade™ Gorilla Glass for automotive interior, is the measure of failure stress with supply chain flaws present. This latter was estimated to be equivalent to 5 microns at 99.9%. To assess the glass performance against this distribution of flaws, a repeatable method for introducing such surface flaws needed to be developed.

There are many traditional techniques for introducing controlled damage to glass such as sliding cloth or paper across the glass, grit blasting the glass with sand or SiC, indentations on the glass with various diamond geometries, etc. One method familiar to the authors for introducing shallow damage to a glass surface is based on ASTM F735 [5] which uses a Taber Industries oscillating abrasion tester, model 6160 [6] to ‘shake’ sand across a specimen surface – typically this process is used for plastics, paints, and coatings. The media used for this abrasion technique is a graded 6/9 quartz silica sand. Both the Taber oscillating sand abrasion tester and a depiction of the 6/9 silica sand is shown in figure 10. The unit comes with a 100mm x 100mm specimen pocket within the specimen cradle, which can accommodate up to four 50mm x 50mm glass samples.



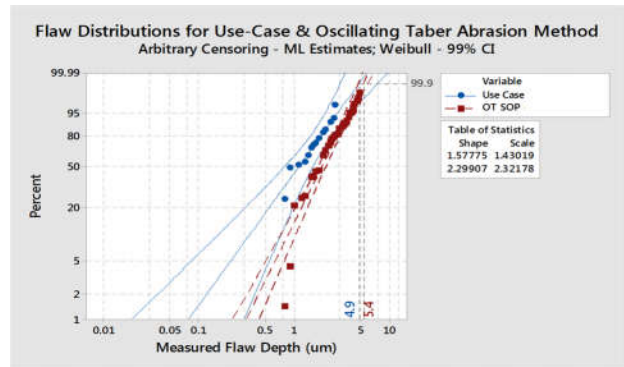
**Figure 10.** Model 6160 Taber oscillating sand abrasion tester & grade 6/9 silica sand in red box.

A standard operating procedure (SOP) was developed during this study to generate a well-controlled flaw distribution that could closely match the use-case distribution, especially at the 99.9% value. Both experimental distributions (use case and Oscillating Taber SOP) were comprised of 50mm x 50mm x 1.1mm thick ROR samples. The resulting SOP for the oscillating Taber (OT) abrasion method is described below:

- Additional sieving of silica sand with US No 7 and 8 mesh to further tighten the particle size distribution
- ‘Pre-aging’ of 1080g of sand using four ‘dummy’ soda lime glass samples having dimensions 50mm x 50mm x 1.1mm to a total cycle count of 9000 cycles at 150 cycles/min with a 4” stroke length
- With four coupons of glass to be tested, having dimensions 50mm x 50mm x 1.1mm thick glass, use 540g of pre-aged sand to abrade the glass at the same settings (150 cyc/min, 4” stroke) to a total of 600 cycles
- Continue using the 540g of sand for subsequent groups of four samples, up to a total ‘sand age’ of 27,000 cycles, which would equate to 30 individual runs

192 samples of Corning’s AutoGrade™ Gorilla Glass for Automotive Interiors were tested in ROR after the outlined OT abrasion method SOP. The resulting strength-limiting origin flaw is plotted against the original use-case flaw distribution and shown in figure 11.

As can be seen, the 99.9% flaw depth is approximately 5 microns, as measured by a fractographer looking through a microscope at 1000x magnification.

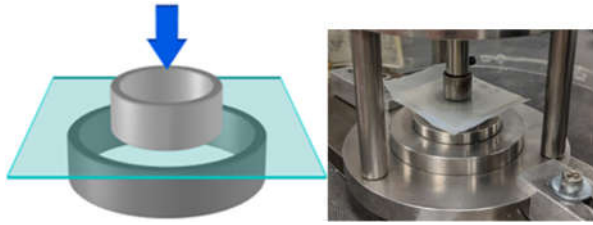


**Figure 11.** Measured origin flaw depths for use-case and OT SOP (from fractured ROR samples)

### Strength Measurement

A typical method to evaluate the surface strength of glass is the concentric ring on ring method, as detailed in ASTM

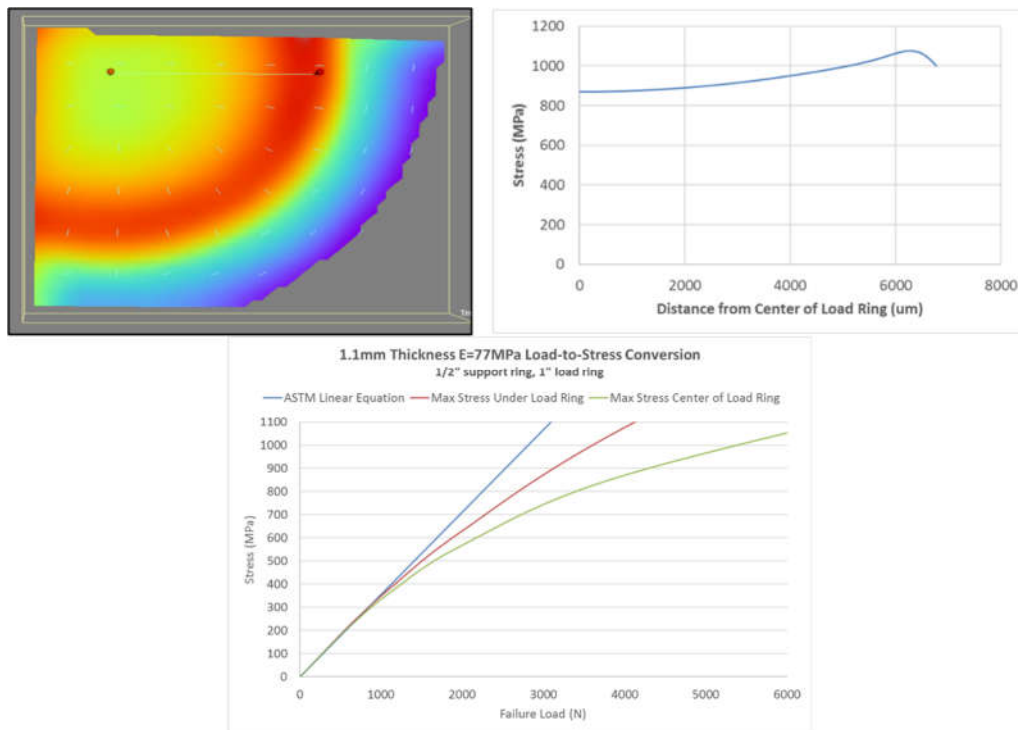
C1499 [7]. It is schematically shown in figure 12 where a lab setup also includes a Teflon sheet below a test sample. This is to reduce friction between the glass sample and the support ring, especially when high flexure occurs.



**Figure 12.** Schematic and lab fixture of the ASTM C1499 Ring on Ring biaxial flexure surface strength method

As a result of the high flexure of strengthened glass specimens during this test, the stress between the loading ring is not constant. As shown in figure 13, through modeling and digital image correlation (DIC), the ASTM linear load-to-stress conversion equation cannot be used. The maximum stresses are developed underneath the load ring because of the high deflection generated by high loads and relatively thin glass.

To accurately estimate the failure stress and ultimately the retained strength of each glass specimen, a three-dimensional FEA model was used to generate a load-to-stress curve for failures underneath the load ring.



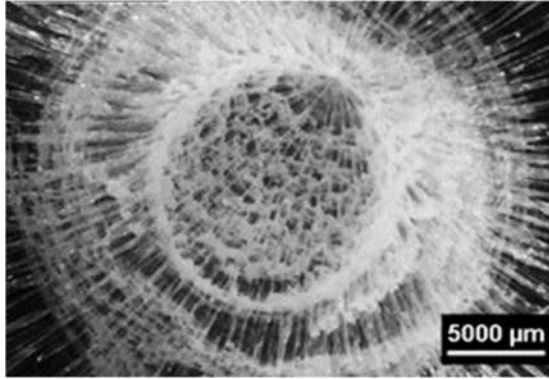
**Figure 13.** ROR induced stress by DIC with center-to-below load ring stress distribution (top) and modeling (bottom) show stress non-linearity and peak stress under load ring due to high deflection

Because of peak stresses occurring underneath the load ring during this testing, most glass failures originated under the ring. An example is shown in figure 14, where the outline of the load ring can be seen within the fractured glass specimen and its origin is directly on line with the load ring outline.

Load-to-stress conversion curves were used to quantify failure stresses under the ring. The equation below corresponds to an example for a sample having dimensions of 50 mm x 50 mm, load ring diameter of 1/2" (recommended range of 0.500-0.505"), a support ring diameter of 1" (recommended range of 0.995"-1.000"), a contact radius of each metal ring being 1/16", and 1.1mm thick glass with a

Young's Modulus value of 77 GPa, where F is the failure load in kilograms and  $\sigma$  is the stress in MPa. This equation is valid until a maximum failure load of 433kg.

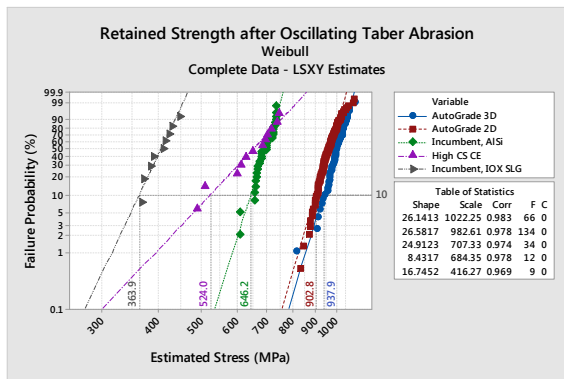
$$\sigma = -4.906 * 10^{-9} * F^4 + 7.303 * 10^{-6} * F^3 - 4.757 * 10^{-3} * F^2 + 3.687 * F - 5.520$$



**Figure 14.** Typical fracture of AutoGrade™ retained strength specimen with origin under load ring

### Retained Strength of Corning AutoGrade™ Gorilla Glass for Automotive Interiors

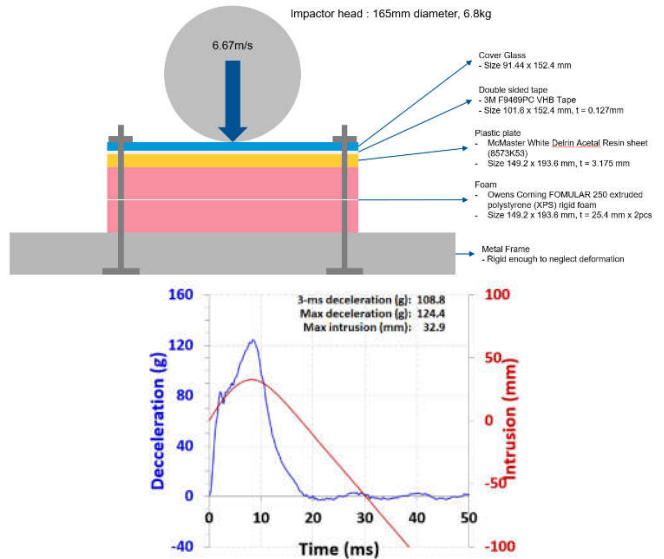
Both the 2D and 3D Corning AutoGrade™ Gorilla Glass solutions were developed to withstand the high-end stresses of HIT with knowledge of supply chain flaws that would be stressed during HIT. Experimentally generated retained strength for 1.1mm thick glass (after introducing simulated supply chain flaws) shows that both of Corning's 2D and 3D glasses exhibit a retained strength of 900 MPa or greater at the B10 level, as shown in figure 15. As for incumbent AISi cover glasses or other consumer electronics AISi cover glasses, the retained strength is much lower than 900 MPa. Even a high compressive stress composition (e.g., a compressive stress value >1100 MPa) results in low retained strength.



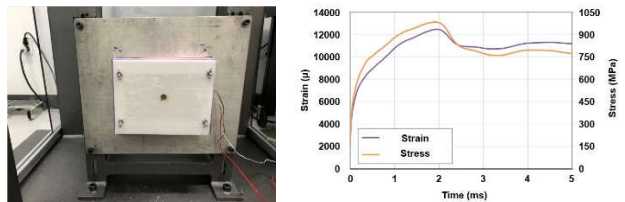
**Figure 15.** Retained strength after oscillating Taber abrasion SOP for Corning AutoGrade™ Gorilla Glass for 2D & 3D and other glasses

### HIT survivability

Since HIT is a system-level test including not only a cover glass but also supporting structures, a surrogate module was designed to accommodate the HIT conditions. Figure 16 shows the schematic of the module that was designed to represent aggressive biaxial bending cases during head impact. This surrogate setup has higher deceleration (3ms at 110G) than the regulation limit (3ms at 80G). Figure 17 shows the strain measured in the center of S2 during an impact and the maximum principle stress was calculated using three components of stresses. The maximum stress occurs in the early stage of impact (< 5ms), which is consistent with real modules and is above 900 MPa.



**Figure 16.** HIT configuration: (a) Schematic of experiment setup, (b) Typical deceleration and intrusion response

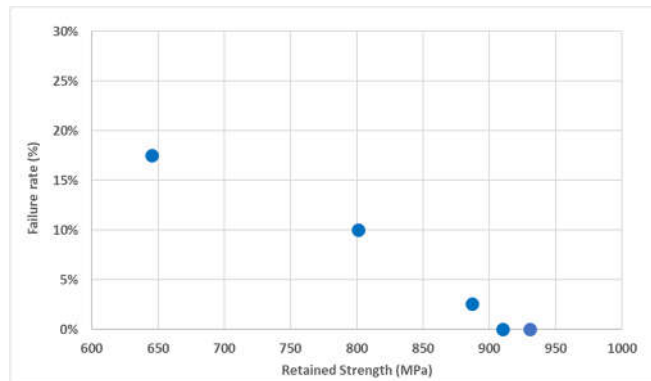


**Figure 17.** Test configuration and center S2 strain/stress measurement during HIT impact.

To validate experimentally the impact of retained strength on HIT, HIT experiments were performed using a foam surrogate for the supporting structure. Several glass samples

with variable retained strength values were tested. Figure 18 shows surface failure rate with respect to retained strength of the glasses. The glass with the retained strength of 646MPa indicates about 17.5% of surface failure rate. This rate decreases significantly and reaches 0% when retained strength is higher than 900MPa.

These results confirm the accuracy of using retained strength as a metric for HIT survivability (using system-level design guidelines).



**Figure 18.** HIT surface failure rate of glass with respect to retained strength

## Conclusions

During this study, retained strength was proposed as an accurate metric for HIT survivability in auto interior applications. Supply chain flaws were characterized and accurately reproduced in the lab. A methodology was proposed to experimentally measure retained strength on small samples. Both experimental investigation and modeling enabled defining a retained strength minimum value of 900 MPa for cover glasses for use in automotive interior application, as is exhibited by Corning AutoGrade™ Gorilla Glass for Automotive Interiors. Corning has developed two versions of this glass that provide retained strength higher than 900 MPa: one for two-dimensional (2D) display formats and one for three-dimensional (3D) display formats.

## Acknowledgements

Our thanks to Sean Coleman for assistance with flaw introduction methods and Fraaz Tahir for tear-down study. Also, the authors are thankful to fractography and mechanical testing groups in Corning who provided high-quality data.

## References

1. Quinn, G. D., 2007, *Fractography of Ceramics and Glasses*, National Institute of Standards and Technology.
2. J.C Newman and I.S. Raju, "Stress Intensity Factor Equations for Cracks in Three-Dimensional Finite Bodies," *Fracture Mechanics: Fourteenth Symposium—Volume I: Theory and Analysis*, ASTM STP 791, J. C. Lewis and G. Sines, Eds., American Society for Testing and Materials, pp. I-238 - I-265 (1983).
3. Smith, M. (2009). *ABAQUS/Standard User's Manual*, Version 6.9. Providence, RI: Simulia.
4. Green, D., *Compressive Surface Strengthening of Brittle Materials by a Residual Stress Distribution*. *Journal of the American Ceramic Society*, 1983. 66(11): p. 807-810.
5. ASTM International. *ASTM F735-17 Standard Test Method for Abrasion Resistance of Transparent Plastics and Coatings Using the Oscillating Sand Method*. West Conshohocken, PA; ASTM International, 2017. doi: <https://doi.org/10.1520/F735-17>.
6. *Oscillating Sand Abrasion Tester*, <https://www.taberindustries.com/oscillating-sand-abrasion-tester>.
7. ASTM International. *ASTM C1499-15 Standard Test Method for Monotonic Equibiaxial Flexural Strength of Advanced Ceramics at Ambient Temperature*. West Conshohocken, PA; ASTM International, 2015. doi: <https://doi.org/10.1520/C1499-15>