

Practical Design Considerations for Lightweight Windshield Applications

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ABSTRACT

Automotive manufacturers are requiring lightweight materials, including glazing materials to improve vehicle fuel economy mandates. Since windshields are one of the largest glazing surface areas, reducing the thickness of the glass in its construction can significantly provide weight savings opportunities. Automotive glazing design considerations must include overall glass strength, rigidity, acoustical, and solar performance, which are affected by changes of glass thicknesses. This paper will evaluate those design considerations in the lightweighting of windshield glazings.

One important design consideration for the windshield position is the impact of debris from the environment. Lightweighting of glazings in this body position affects the way the construction reacts to an impact. Use of asymmetry in glass plies in a laminated construction can have a marked effect on the part's impact performance and surface damage creation. Various lightweight glazing constructions will be analyzed, and based upon basic strength and stiffness, the probability of failure from stone impact in parts per million is predicted from a statistical model. Further testing and analysis will be done to demonstrate lifetime effects in windshield glazings with respect to stone impacts will be discussed.

As a glazing part becomes thinner, the material choices have an impact on light transmission and solar performance. In order to maintain light transmission compliance (70%, with light illuminant "A" in the United States) and solar performance at comparable levels to standard products, enhanced material choices in glass composition, PVB composition, and coating technologies will be evaluated.

Additionally, as a glazing part becomes thinner, more exterior sound is transferred through the construction. This effect can be managed with acoustical interlayers at higher frequencies through constrained layer damping. Design considerations for the relative thickness of glass plies in the construction of the windshield will be evaluated and optimal construction options presented.

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IMPACT INTRODUCTION

The basic strength of glass under the expected impact conditions is required to predict the impact performance of a lightweight windshield construction. Since the rate of loading and area under load affect the performance strength of the glass under short duration impact conditions, the apparent performance strength of the glass can be greater than the basic strength as measured under long term loading. Under impact loading conditions the performance strength of the glass may increase from a nominal basic strength on the order of 10,000 psi to the range of 30 to 35,000 psi. In order to predict the increase in basic strength under stone impact loading conditions the time duration of the load and the area under load are used with the statistical strength of the glass to determine the total performance strength of a windshield construction.

Total Performance Strength of Windshield Constructions

The goal of quantifying the total performance strength of lightweight windshield constructions is to predict the probability of failure under expected in service loading conditions. There are three steps in the process for calculating the total performance strength of lightweight windshield constructions.

In the first step the basic strength of the glass surface is measured under standard loading conditions, typically 1,000 pounds per minute. The measurement is accomplished using ring on ring loading to failure using the ASTM C1499-15 test procedure. By using the ASTM test procedure on multiple samples both the glass strength and variation of strength are measured. This test method has been used to characterize glass basic strength as reported in several papers for both new and "used" windshields. [1, 2] Glass surface strength testing

from impact loading was performed for thin glass used in both symmetrical and asymmetrical windshield constructions, and is reported here for glass thicknesses from 0.7 to 2.1 mm including both thin aluminosilicate and soda lime silica glass compositions.

In the second step of the glass total performance strength calculation the time duration of the applied load is required. This time can be determined by measurement using simulated impact testing of twelve inch square samples fitted with strain gages using high speed data acquisition equipment. Using this test method the time duration of loading data was collected for a series of lightweight windshield constructions using a 0.375 inch diameter steel ball bearing for impacting the samples. Measured time under load for 95% of the maximum stress level varied from 8.6 to 16 microseconds.

The third component in the total performance strength calculation is the expected in service load. These expected loads can also be measured using the same test procedure described for measuring the time duration of the load. The measured strain data from testing lightweight windshield constructions was converted to stress and utilized to validate a finite element model of the impact test. Then, using the validated model, exact performance comparisons of proposed lightweight windshield constructions were made. The model load conditions can then be changed to simulate other load conditions that may be encountered in service.

The equations used here to predict the total performance strength of glass under load conditions were initially developed for predicting the probability of failure for flat glass panels under wind loading conditions. The formulas used in this paper to predict the total performance strength of glass under load were developed by PPG Industries. [3] Based upon the correlation between glass strength and loading, PPG Industries determined that the glass failure data followed the standard normal distribution. Other investigators agree with this conclusion. [4, 5, 6] Using the standard normal distribution the probability of glass failure under load can be calculated in parts per million, which, in the case of automotive windshield failure, is extremely useful for predicting occurrences from warranty breakage claims from proposed new lightweight windshield constructions.

Using the basic strength of the glass surface and its variation, the area under load, and the glass stress level produced by the expected loads experienced in service, the following equations can be used to predict the probability of failure using the standard normal distribution.

Probability of failure terms used in equations 1, 2, and 3:

- σ_{Max} = Maximum Measured Stress Level Applied. Supplied by strain gage measurement from the actual application.
- $\sigma_{Adjusted}$ = Total Performance Strength (TPS) of Glass. This is the glass basic strength adjusted by measured load time and area under load plus the measured residual stress level in the case of heat strengthened or tempered parts.
- $\sigma_{Std Dev TPS}$ = Standard Deviation of the TPS. This standard deviation of the TPS is calculated from the mean and coefficient of variation for both the basic strength and the residual stress.

- SNM = Standard Normal Multiplier (SNM). SNM determines probability from the standard probability curve.

$$\sigma_{Max} = \sigma_{Adjusted} + SNM(\sigma_{StdDevTPS}) \quad (1)$$

$$\sigma_{Adjusted} = \sigma_{BS} \left(\frac{t_s}{t_{Duration}} \right)^{\frac{1}{16}} \quad (2)$$

$$NormalDistribution(\sigma_{Max}, \sigma_{Adjusted}, \sigma_{StdDevTPS}) \quad (3)$$

The value of the standard normal distribution is calculated from the applied load, the adjusted basic strength, and the standard deviation of the total performance strength. Since the standard normal multiplier determines probability from the standard probability curve, the probability of failure can then be determined from a log plot of a load curve in PPM.

The procedure just described for predicting the probability of failure of a windshield ply from impact loading was used to predict and compare the probability of failure of both new and "used" windshields using the measured surface strength and standard deviation of the measured strength reported in reference 1. The windshield strength and standard deviation of strength for both new and "used" windshields from reference 1 are as shown in Table 1.

Table 1. Glass surface strength and strength standard deviation for new and "used" windshields.

Windshield Description	Measured Surface Strength (KPsi)	Strength Standard Deviation (KPsi)
New	15.0	6.0
"Used"	11.1	2.4

The service life for the "used" windshields in reference 1 ranged from 3,769 to 53,000 miles. The distribution of miles driven for the windshields shown in Table 1 are shown in the following Table 2, which is Table 1 in reference 1, SAE Paper No. 2000-01-2721.

Table 2. Description of Windshields Used for Ring-on-Ring Strength Measurement.

Windshield I.O.	No.	Service History	No. 8" X 8" Specimens
New	1	-	7
	2	-	11
	3	-	6
	4	-	9
	5	-	11
	6	-	3
Used	1	14,000 miles	5
	2	3,769 miles	7
	3	30,000 miles	6
	4	44,000 miles	5
	5	53,000 miles	4
Impact Damaged	1	60 mph impact	3
	2	60 mph impact	3

The calculated probability of failure versus applied load for the measured strength data in Table 1 was plotted, and is included here as Figure 1. The time duration of loading used in the total performance strength calculations was 16 and 8.6 microsecond, the range of ones measured during impact testing with strain gages when sampling at a data collection rate of 1,000,000 samples per second per channel. As can be seen from Figure 1, for a failure rate of 100 PPM under stone impact loading, which is considered zero for warranty claims purposes, the total performance strength difference between new and "used" windshield outer plies for 16 microseconds load duration is 30,000 psi - 26,000 psi = 4,000 psi. This difference in impact performance represents a reduction in strength of 13.3% for the "used" windshield.

The effect of the difference in the time duration of loading from testing of the lightweight windshield constructions was also evaluated and plotted, and is included in Figure 1. As can be noted from the second set of dashed curves in Figure 1 for new and "used" windshields, the difference in stress level for the same failure rate is nominally four percent.

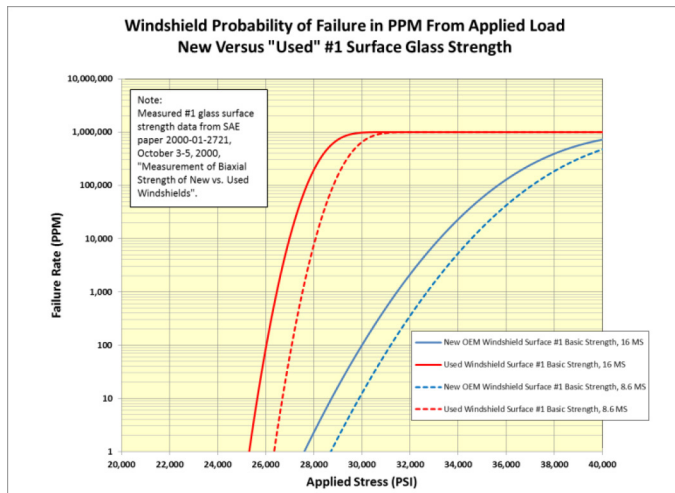


Figure 1. Windshield probability of failure versus applied load on surface #1 in PPM for both new and "used" windshields with two load durations.

Lightweight Windshield Performance Prediction

Lightweight windshield impact performance was predicted using finite element modeling techniques and simulations of lightweight windshield constructions with a model that was validated using measured glass strain data from impact testing. The model of the test consists of a twelve inch square laminated sample clamped in a test frame and impacted in the center with a 0.375 inch diameter steel ball bearing weighing 3.54 grams.

Following, in Figures 2 and 3, are the outputs from a typical impact simulation showing the ANSYS finite element calculated stress and deformation results for one of the lightweight windshield constructions

tested, which, in this case consists of a 1.8 mm soda lime silica (SLS) glass outer ply, a 0.76 mm polyvinyl butyral (PVB) interlayer ply, and a 1.4 mm SLS glass inner ply. A drop height of twenty feet (impact velocity of 24.5 MPH) is simulated in Figures 2 and 3.

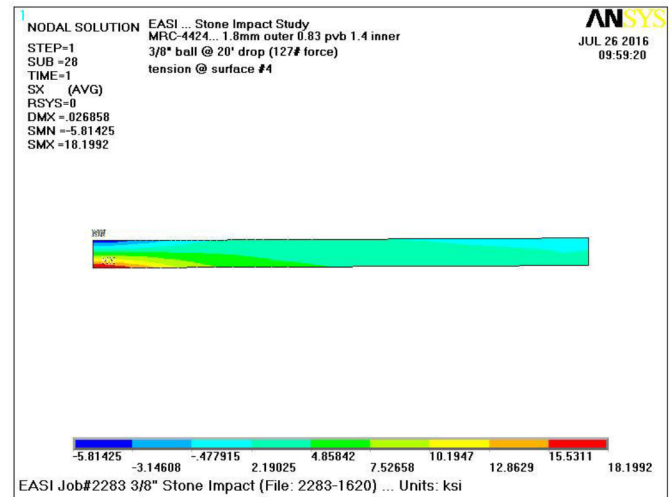


Figure 2. Glass tensile stress on surface #4 resulting from impact of a 0.375 inch diameter steel ball bearing at a velocity of 24.5 MPH.

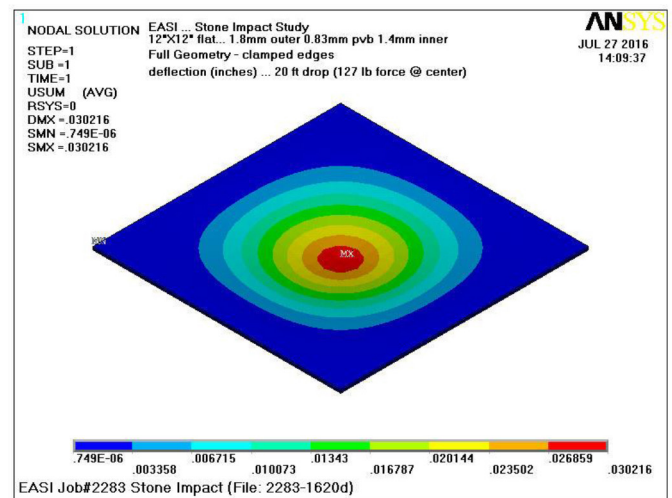


Figure 3. Glass deformation resulting from impact of a 0.375 inch diameter steel ball bearing at a velocity of 24.5 MPH.

Simulations were made with this model in which the laminated glass constructions shown in Table 3 were each impacted at three velocities with a steel ball bearing. The maximum calculated glass impact stress results for surfaces #2 and #4 for a series of lightweight windshield construction options are shown in Table 4.

As can be seen from the glass stress data in Table 2, as the impact velocity increases the glass stress level also increases, as expected. For symmetrical constructions, as the overall glass thickness decreases the stress level increases and the #4 surface always has a higher stress level than the #2 surface.

Table 3. Calculated maximum glass stress levels from impact loading of the outer ply (#1 surface) in lightweight windshield laminated constructions at three different impact velocities for surfaces #2 and #4.

Outer Ply Tensile Stress Levels (Surface #2)					Inner Ply Tensile Stress Levels (Surface #4)						
	Glass				Thickness (mm)		Glass				Thickness (mm)
	17.3 MPH	21.2 MPH	24.5 MPH	17.3 MPH			21.2 MPH	24.5 MPH			
	Glass Stress Level (Kpsi)			Glass Stress Level (Kpsi)							
2.1	17.1	20.9	24.0	2.1	2.1	34.2	41.8	48.0	2.1		
2.1/2.1	17.8	21.7	25.1	4.2	2.1/2.1	19.8	24.2	28.0	4.2		
1.8	18.5	22.5	25.8	1.8	1.8	37.0	45.0	51.6	1.8		
1.8/1.8	23.2	28.4	32.7	3.6	1.8/1.8	24.4	30.0	34.6	3.6		
1.6	19.9	24.1	27.6	1.6	1.6	39.8	48.2	55.2	1.6		
1.6/1.6	25.9	31.6	36.5	3.2	1.6/1.6	26.6	33.4	38.6	3.2		
2.1/2.1	17.8	21.7	25.1	4.2	2.1/2.1	34.2	41.8	48.0	4.2		
2.1/1.6	19.8	24.3	28.0	3.7	2.1/1.6	11.7	14.3	16.5	3.7		
1.8/1.8	23.2	28.4	32.7	3.6	1.8/1.8	24.4	30.0	34.6	3.6		
1.8/1.4	22.0	26.9	31.0	3.2	1.8/1.4	12.0	15.7	18.1	3.2		
1.8/0.7	18.8	23.0	26.6	2.5	1.8/0.7	12.0	14.8	17.1	2.5		
2.1/0.7	17.4	21.3	24.6	2.8	2.1/0.7	11.1	13.6	15.7	2.8		
1.8/1.4	22.0	26.9	31.0	3.2	1.8/1.4	12.0	15.7	18.1	3.2		
1.6/1.6	25.9	31.6	36.5	3.2	1.6/1.6	26.6	33.4	38.6	3.2		

The 2.1/1.6 mm asymmetrical construction exhibits the same maximum glass stress levels as the symmetrical construction that is the #2 surface stress level equals the #4 surface stress level for the asymmetrical versus symmetrical constructions, respectively. By contrast, the 1.8/1.4 mm asymmetrical construction exhibits a lower stress level than the symmetrical construction for both the #2 and #4 surfaces with the #4 surface stress levels significantly lower than the #2 surface stress levels. Since the 1.8/1.4 mm construction exhibits only a 9.7 percent higher glass stress level than the 2.1/1.6 mm construction, while providing a weight savings of 12.6 percent, this construction could be a candidate for implementation in a vehicle for weight savings.

When glass stress levels are compared for equal glass thickness constructions that are asymmetrical and symmetrical the same trend continues as with the asymmetrical constructions. For the 1.8/1.4 mm versus 1.6/1.6 mm construction comparison the asymmetrical construction has significantly lower stress levels on the #2 surface, and an even lower stress level for the #4 surface.

The two asymmetrical constructions with 0.7 mm aluminosilicate inner plies have the lowest weight per square foot of all of the constructions tested and are considerably more flexible. The maximum glass stress levels for these constructions are also the lowest of all the constructions tested. Therefore, the data for these constructions makes them strong candidates for weight reduction. These same phenomena were exhibited in the destructive testing discussed in the next section, when a thin float glass construction exhibited the same low stress behavior due to bending.

Deflections under impact loading were also calculated for each of the lightweight windshield constructions tested using the ANSYS model. A typical ANSYS finite element deformation output for a 1.8/1.4 mm asymmetric construction is shown in Figure 3. The results of the deflection calculations for all of the constructions tested are shown in Table 3.

Table 4. Calculated maximum glass deflection from impact loading of the outer ply (#1 surface) in lightweight windshield laminated constructions at three different impact velocities.

Construction	Deflection (Inches)		
	Impact Velocity		
	17.3 MPH	21.2 MPH	24.5 MPH
2.1/2.1	0.01363	0.01672	0.01924
1.8/1.8	0.01786	0.02198	0.02542
1.6/1.6	0.02096	0.02567	0.02967
2.1/2.1	0.01363	0.01672	0.01924
2.1/1.6	0.01712	0.02105	0.02435
1.8/1.8	0.01786	0.02198	0.02542
1.8/1.4	0.02141	0.02617	0.03022
1.8/1.4	0.02141	0.02617	0.03022
1.6/1.6	0.02096	0.02567	0.02967
2.1/0.7	0.02512	0.03082	0.03551
1.8/0.7	0.02784	0.03398	0.0393

The deflection data in Table 4 for symmetrical constructions indicates that as the total glass thickness decreases, the deflection increases. Comparisons between symmetrical and asymmetrical construction deflections, 2.1/2.1 mm versus 2.1/1.6 mm, and 1.8/1.8 mm versus 1.8/1.4 mm, indicate that there is a significant increase in deflection for the asymmetrical constructions; 27 percent and 19 percent, respectively. The highest overall deflections are for the thinnest constructions, 2.1/0.7 mm and 1.8/0.7 mm, as expected.

Lightweight Windshield Performance Testing

Performance measurements for lightweight windshield constructions were accomplished using stair step impact testing to failure of twelve inch square constructions clamped into a test frame using a 0.875 inch diameter steel ball bearing for impact from a 40 feet drop tower. To quantify the glass load at failure the kinetic energy from the average failure height was calculated. Ten samples were tested to failure for each construction to determine the average failure height. Asymmetric lightweight windshield constructions were tested using this method. A symmetric construction was also tested for comparison for each set of samples.

Three sets of asymmetrical construction samples were tested with a representative symmetrical construction, which represented the outer ply thickness of each set of samples. In each of the three sample groups the outer ply glass thickness was constant and the inner ply thickness was reduced to produce an asymmetrical construction. The constructions tested for each set of samples are shown in Table 4.

Table 5. Sets of lightweight windshield constructions impact tested to failure representing three families of asymmetric constructions.

Set 1 Constructions		Set 2 Constructions		Set 3 Constructions	
Outer Ply (mm)	Inner Ply (mm)	Outer Ply (mm)	Inner Ply (mm)	Outer Ply (mm)	Inner Ply (mm)
2.1	2.1	1.8	1.8	1.6	1.6
2.1	1.8	1.8	1.6	1.6	1.4
2.1	1.6	1.8	1.4	1.6	1.2
2.1	1.4	1.8	1.2	1.6	0.7
2.1	1.2	1.8	0.7		
2.1	0.7				