F. Structural Reliability of Lightweight Glazing Alternatives

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Objectives

- Optimize glazing systems for cars of the future by decreasing sound transmission while maintaining structural rigidity.
  - Reduce sound transmitted through sidelights by 6 db by determining the effect of sidelight shape on sound transmittance, investigating sound-dampening materials for operating sidelight glazing, and quantifying the influence of alternate materials (e.g., laminated glass, bilayer glass) on sound attenuation.
  - Maintain the level of structural integrity while reducing glass thickness by validating the structural rigidity model for various types of urethane used in fixed glazing systems and by expanding/combining existing models to test various alternative constructions and glazing systems for side, rear, and roof windows.
- Reduce vehicle weight through alternate or thinner vision panels and/or by reducing the heat load transmitted through the glass. The goal is to improve the fuel economy of a car by requiring 30% less glass weight.
- Reduce side, rear, and potentially roof window glass weight while maintaining acoustics and minimizing price increases.
  - Consider several material options, including laminated glass, cast-in-place pseudo-laminated glass, and bi-layer materials.
  - Enhance fuel economy from reduced solar energy transmission.
  - Reduce solar energy transmission through glass by using absorbing substrates and reflective coatings.
  - Quantify gas mileage improvement opportunities from improvement in solar energy transmission.

Accomplishments

- Completed testing for demonstrating production compatibility using a resin injection method for side window laminations.
- Achieved 12-in. by 12-in. test panel interlayer fill times of 7–20 s, depending on viscosity.
- Fabricated 40 test windows with a new injection method for the cooperative research and development agreement (CRADA) partner to test interlayer material.
- Obtained preliminary test data from the CRADA partner showing successes and improvement areas.

- Completed and tested new tooling for ultraviolet (UV) and thermal curing of interlayer laminating resin.
- Characterized interlayer materials for accelerated curing for production.
- Demonstrated thermal and UV curing for continuous fill and cure laminating system.
- Demonstrated reduced infrared (IR) transmission up to 45% with alternative polymer systems.
- Characterized the sound transmission loss of the new lightweight laminated glass.
- Verified and extended the predictive sound transmission loss models to investigate the effect of the new polymeric materials.
- Completed the modeling of the acoustical response of glass.

Future Direction

- Develop lightweight side-door glass.
- Investigate the strength and thickness of new polymeric interlayer materials on overall side-door strength and performance.
- Investigate the overall thermal behavior based on the new interlayer materials, including the effect of laminated side-door glass.
- Fabricate newly designed tooling for complex automotive side window shapes and laminate with new interlayer materials.
- Investigate the use of nanomaterials for acoustic modification and UV resistance.
- Investigate multilayer interlayer for acoustic modifications.

Introduction

This project is a cooperative research and development agreement (CRADA) between the U.S. Department of Energy, Pacific Northwest National Laboratory (PNNL), Visteon Automotive Systems (Glass Division), and PPG, Inc. It started in June 2002.

The project will evaluate designs for optimized glazing systems to be used in cars of the future and will work to achieve the goals of FreedomCAR. The primary objective of the project is to reduce vehicle weight, improve fuel economy, and reduce vehicle emissions. However, to achieve these goals, it is necessary to consider the needs for high levels of structural reliability, competitive manufacturing costs, and passenger comfort from the standpoints of minimal acoustical noise levels and controlled interior temperatures. Energy savings will come from reducing weight by using thinner glazing; prior studies at PNNL have shown a potential for 30% reductions in weight from thinner glazing. Energy savings will also come from reducing interior heat loads; that, in turn, will reduce the demand for air conditioning. The evaluation of alternative glazing concepts will also seek means to improve acoustical characteristics that will minimize interior noise levels while maintaining glazing at minimal thickness and weight levels.

Lightweight Window Manufacturing

New lightweight window samples were fabricated using 1.6-mm and 2.3-mm glass plies (a conventional automotive glass ply has a thickness of between 2.4 and 2.6 mm. The new lightweight samples were formed and laminated at PNNL using several different types of polymer interlayers for comparison.

A new liquid control injection system was purchased for the scale-up effort for large windows. The new injection system allows for a continuous stream of mixed resin to be injected into the tooling for laminating. The fill rates and pressure can be controlled, and the system is flexible enough to be able to change resin systems that have significantly different resin ratios.

Testing was performed with the new injection system to determine whether mixing was adequate with the commercial static mixer tubes. The tubes purchased with the machine were determined to be inadequate, and two alternative vendors were found to have better quality mixing tubes.

Several new lightweight laminated side glasses were fabricated using 2.3-mm plies. The new window glass samples that were constructed are 2.3-mm glass, 0.76-mm polymer interlayer, and 2.3-mm glass.

During FY 2004, researchers completed the demonstration of a production-compatible system. They conducted studies that demonstrated flow behavior, times to fill, curing studies, demold times, and material down-selection. The evaluation of optical properties was also addressed. Three of the commercially available materials were altered for specific characteristics in curing and hardness. Because the optical requirements for the sidelights are not as stringent as those for the windshield, other materials may prove to be more attractive and cost-effective.

Flow Behavior and Fill Time

A new aluminum fixture was designed and built to observe flow behavior in 12-in. by 12-in. glass panels working on UV curing of resins. Two new test fixture designs were used to hold the two glass plates against the fixture surface using vacuum and to control the separation for the interlayer to 0.5- and 0.75-mm gaps for resin filling. The gap is controllable with a spacer shim around the outside of the fixture.

The flow studies and measurements were performed using an 8-mm video camcorder with the clock on during taping. A ruler was laid across the glass plates before video taping, and the fill rate was determined based on the time to fill a particular length based on the flow front movement. The videos allowed for visualization changes in flow front profiles and time-to-fill measurements. Depending on the viscosity of the fluid, the flow front profile would vary from a parabolic flow front to a horizontal flow front. The low-viscosity materials demonstrated a horizontal flow, while the higher viscosity materials represented a parabolic shape. The shape of the flow fronts based on the viscosity of the material will help in predicting flow behavior in irregular-shaped windows and will determine the injection point of the part.

Previous flow studies used 8-in. head pressure to flow different materials and viscosities the length of the plates and tooling. The fill rates for this pressure and with viscosities as low as 123 cps had a fill rate of 14 in./min, while a viscosity of up to 3000 cps had a fill rate of 1.4 in./min.

Further testing with increased pressure shows that a 200-cps viscous material injected at 10 psi (70 kPa) fills the same areas and flows the same distance as the previously measured data in less than 5 s, which is equivalent to 3000-cps viscous material fills in 15 s. Table 1 illustrates the difference in pressure and viscosity affecting the fill rates.

Based on these fill rates, to fill a side window on an sports utility vehicle (SUV) of roughly 4200 cm^2 would take 25 to 70 s, depending on their viscosities.

Table 1. Fill rate comparisons with different viscosity resins and 0.60-mm interlayer thickness

Injection pressure	Viscosity (cps)	Time to fill (s)	Fill rate/length (mm/s)	Fill rate/area (mm^2/s)
8-in. head	123	49	5.96	1896
8-in. head	3000	492	0.59	189
70 kPa	123	5	58.40	18581
70 kPa	3000	15	19.47	6194

Material Curing Studies and Window Demold Times

With the validation of the injection process fill times, the focus changed on the cure times of resin. The cure times were evaluated on temperature and UV curing. The cure rates for thermal curing were based on temperature-controlled studies in a convection oven. The studies looked at demold times based on degree of cure. Further studies included Differential Scanning Calorimetry (DSC) that evaluated the resin mixtures at different isothermal temperatures. Figure 1 illustrates the reduction in cure times and increased temperatures. Even though the cure time can be significantly reduced, thermal oxidation of the material starts to occur and increases the yellowing of the cured material (which is undesirable) and reduces the light transmission. Demold times have been as low as 10 and 15 min, and additional curing took place at room temperature. The objective is to get the material to cure enough for handling and then allow the material to continue to cure after demolding. Cycle times of 20 min per fixture have been achieved.

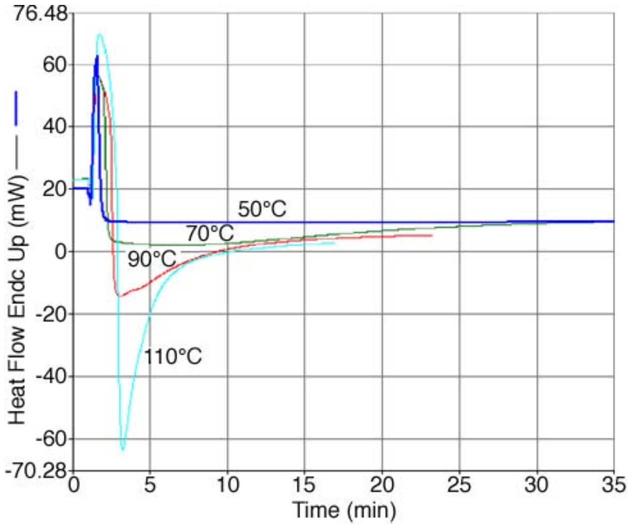

Figure 1. Epoxy isothermal DSC runs for cure times on mixed-resin system.

A new tool was fabricated for testing cure times using UV curing for polyester and acrylic resins. The UV testing shows promise, but some resin modifications are being worked on to help reduce masking affects. UV resins still look promising for production.

The UV-cured resin was modified with an accelerator and catalyst to partially cross-link the resin for demolding and then final cure with UV light. Figure 2 illustrates the reaction time for the resin at 93°C. The accelerators did not actually

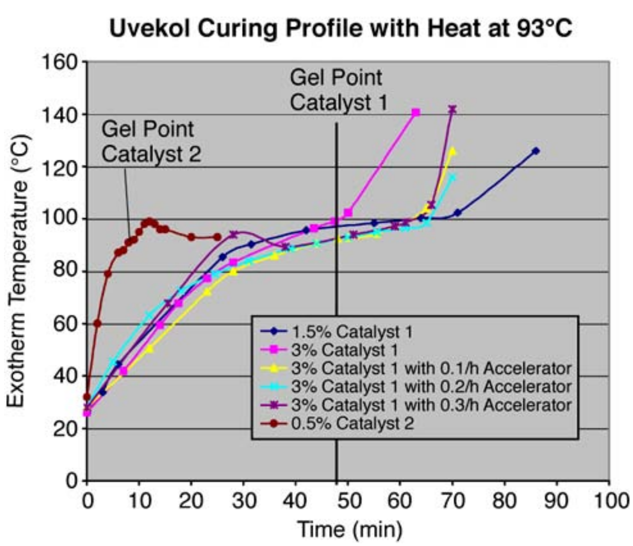

Figure 2. UV-cured resins with different ratios of catalyst and accelerators.

decrease the cure time; a reduction in the peak exotherm was reduced by 20°C. The reduction in exotherm helps reduce the overall shrinkage of the resin, which can impart temporary strain at the interface of the glass. Higher exotherms can also create resin boil because of the lower boiling point of the monomers, which can cause bubbles to form in the interlayer. Controlling the exothermic temperature can be just as important as decreasing the cure time.

Experiments on a second catalyst were conducted based on lessons learned from the first experiments. As indicated in Figure 2, a significant reduction in cure time and a significant reduction in peak exotherm were achieved. Further testing will be performed with this resin system.

Material Down-Selection

The materials down-selection led to polyurethane, acrylic, polyester, and epoxy. Testing conducted at PPG to further reduce the material down-selected was completed. The material has been down-selected to two final candidates that need further evaluation and optimization. Continued studies on the catalyst effects on the resin properties as well as the Society of Automotive Engineers (SAE) standards will assist in the final optimized material. Sound transmission loss is one of the important criteria, but it is difficult to find data on commercially available materials. Stress relaxation data are continuing to be collected on the two selected materials for use in the acoustic modeling of the sound transmission loss equipment. Furthermore, materials optimization for sound transmission loss is also being investigated. Several tests have been conducted based on the SAE Z26.1 criteria for side window laminations. PPG has done more total light transmission testing, UV and infrared (IR) testing, boiling water testing, humidity testing, and thermal cycling.

Transmittance Testing

To date, more than a hundred laminated glass panels have been fabricated and tested. The initial panels were used on the ring-on-ring testing, which demonstrated the adhesion properties. There were also initial transmittance spectrums using a UV-Vis spectrometer, which helped to determine the transmittance of the laminate. The U.S. requirement for total transmittance for sidelight windows is 70%. PPG has done some initial total transmittance testing shown in Table 2. The total transmission test exceeds the 70% requirement for both tested materials. Material 1 has pretty much the same total transmission, and Material 2 is approximately 9% lower than the polyvinyl butyral (PVB). However, the UV transmission is lower in Material 1 and the same in Material 2 relative to the PVB standards. One of the most interesting results is the IR transmission. The PVB standards show a 71% IR transmission, and Material 2 is relatively close to that as well. However, there is almost a 50% drop in the IR transmission in Material 2. Finally, the total spectral transmission of Materials 1 and 2 shows a drop of less than 2% for the exposure. The glass substrates used for these test were all done on clear glass with no modifications for UV or IR. These differences are directly related to the interlayer materials.

The IR reductions in Material 2 can significantly reduce the heat load in the vehicle. This can further improve fuel economy by reducing the taxable horsepower from interior cooling and providing more comfort for the occupants.

Other Testing

Other testing being evaluated at PPG are boil, humidity, thermal cycling, and ball drop. The first round of boil testing was completed, and all specimens passed. The boil test submerges a 12-in. by 12-in. laminated glass panel in boiling water for 6 h.

The boil specimens were evaluated for delaminating, bubbles, and a cloud effect zone from the edge less than 12 mm. There were no issues from the boil test, and the material has passed that test.

The first humidity test results were marginal and needed further work to improve on the laminate. After some resin modification to optimize for the humidity, a significant reduction in the ESN total was observed; however, a total ESN number goal is zero. The initial ESN numbers were on the order of 2200, and we currently have ESN numbers around 100. This is a significant change, but further work will need to be accomplished to obtain a zero value.

The improved humidity-resistant resin also caused the material to fail the ball drop test. The initial ball drop testing passed with the previous formulations. It is now understood that a change as small as 5% in our resin formulation to improve humidity resistance had a detrimental effect on the ball drop. Ball drop testing properties are now being improved upon, and further testing is currently ongoing but has not been completed to date.

PNNL tested for stone impact and found some very unique differences compared to the PVB interlayer materials. The PVB had higher speed stone impact tolerance by about 10-15 mph; however, sidelight windows do not have criteria for stone impact. The evaluation was done to compare the difference between the materials being evaluated. Even though the speed was lower, the impact speeds were still satisfactory.

Acoustic Chamber Modeling and Testing

A coupled structural-acoustic modeling procedure was developed using commercial finite-element code ABAQUS to systematically study the structure vibration and acoustic behaviors of the injection-molded laminated glass. Our goal is to use the analytical modeling tool to examine the effects of resin properties on the acoustic performance of the laminated glass specimen.

To analyze the acoustic test chamber with an accurate-yet-efficient model, we initially assumed that the air layer 1 in. above the top glass surface (top microphone location) experiences incident waves of the same amplitude and frequency. An axisymmetric model was used for simplicity and the

Table 2. Spectral transmission average data

Material	Total transmission (%)	UV (%)	IR (%)	TSET (%)	Total transmission after UV exposure (%)
PVB Standard 1	88	NA	71	76	NA
PVG Standard 2	88	7	71	76	NA
Material 1	87	5	69	75	85
Material 2	79	7	38	53	78

foam supporting the glass boundary is modeled with two-dimensional (2-D) connector elements (see Figure 3). In Figure 3, the air layers are modeled with 4-node linear acoustic elements ACAX4R, and the glass and the resin layer are modeled with 4-node bilinear solid elements CAX4R with different materials properties. The interfaces between the air (acoustic elements) and glass (solid elements) are constrained at their abutting surfaces using the *TIE option. The thicknesses of both glass layers are set to be 2.3 mm, and the intermediate resin layer is 0.5 mm thick.

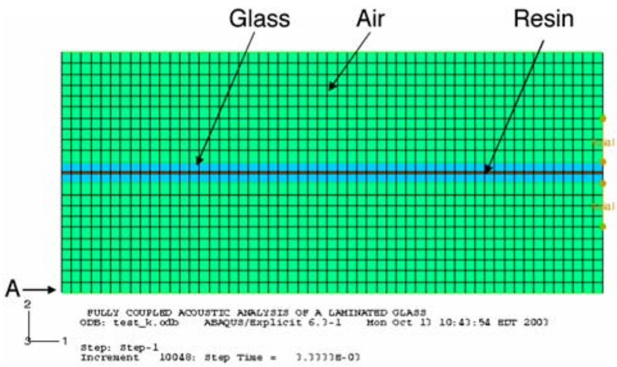

Figure 3. Coupled structural-acoustic finite-element model.

The incident wave comes from the top of the air layer with specified frequency and amplitude. The pressure response of the air at Point A, 1 in. below the glass center, is monitored as output of the analyses. Steady state dynamics procedures are used, and the final sound transmission loss values for different frequency levels were obtained through frequency sweep:

$$STL(dB) = 20\log(\frac{p_1}{p_{input}}) \quad , \qquad (1)$$

where p_1 is the response wave amplitude, and p_{input} is the input wave amplitude.

Figure 4 shows the predicted sound transmission loss (STL) values for the frequency sweep compared with discrete STL measurement from our experiments. Because the system has a natural frequency around 3500 Hz, we observe a dip in STL around 3440 Hz. This is very much consistent with our experimental findings in this study as well as other experimental findings reported in the open literature for architectural glass. In general, the predicted STL

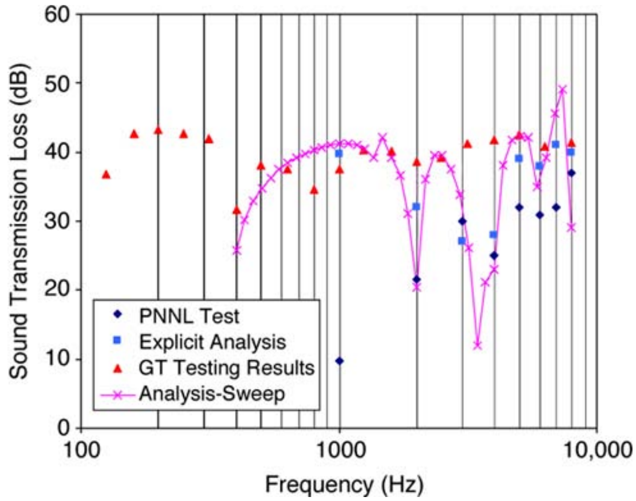

Figure 4. Predicted STL results compared with experimental results from different testing sources.

values compare reasonably well with the acoustic chamber measurement at frequencies higher than 2000 Hz. For frequencies lower than 2000 Hz, the prediction is higher than measurement.

To resolve the discrepancies between the predicted and measured STL values for low frequency levels and to better understand the sound transmission measurement, more acoustic measurements were carried out at the Georgia Institute of Technology (GT). Measurements of the sound noise reduction (in decibels) of four samples, 12-in. by 12-in., of laminated glass have been made in accordance to SAE J1400, in third-octave bands between 125 Hz and 8 kHz. The samples were mounted between the reverberant chamber and the semi-anechoic chamber of the Integrated Acoustics Laboratory (IAL) at GT. The results, together with the simulated results and the test results carried out at PNNL, are shown in Figure 4.

The measured STL values obtained at GT are generally higher than the ones obtained at PNNL. This is particularly true in frequency ranges lower than 1000 Hz. At frequencies higher than 400 Hz, the predicted STL values are in fairly good agreement with the GT measurements except for the fact that predicted results indicate more coincidence dips. It should be mentioned that very good repeatability has been found for both testing facilities at GT and PNNL. These results then indicate that caution should be exercised when comparing STL measurements from different experimental sources. More analytical work in this area will be pursued to characterize the STL of laminated glass plates with different resin layers.

Future Work

Future work is focused on fabricating larger automotive side windows along with further testing by the PPG. The new tooling will be more automated and will be ready to simulate production runs of surface areas at least four times the current area. Further, 12-in. by 12-in. testing plates will continue to be made with other interlayer materials and given to PPG for further testing. The overall mechanical, thermal, and acoustical behavior of the new light weight glass will be evaluated using both experimental and analytical procedures. New experimental data from the humidity and acoustic testing allows focusing on specific changes needed to modify the material formulations that will maximize the system performance. Modeling efforts are continuing to focus on the effects of polymer properties on sound transmission loss.

Furthermore, work is beginning in nanocomposites for the interlayer and multiplayer features in the interlayer, which could further improve the acoustic properties.