Facade Noise Control with Glass and Laminates

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2 = Laminated glass field performance
3 = Vibro acoustic simulation
4 = Transmission loss angle of incidence

Abstract

'Design by analysis' is premised to bridge the gap between current reliance on laboratory measurements versus actual field performance, and is illustrated by applying current technology for sound insulation to glazing elements. A paradigm shift is proposed toward reliance on calculated glazing transmission loss and use of this full noise reduction spectra to describe performance, at octave band – and preferably more intermediate – frequencies.

Performance modeling is demonstrated. The entire transmission loss spectra for glass products can be simulated by calculation and preserved to combine with either exterior or interior spectra, thereby controlling upper limit interior noise quality from glazing as facade elements. Certain issues such as low frequency response and angle of incidence can be calculated better than measured. Glass has peculiar noise control problems.

Glasses deserve unique standards or guides. Different glass types may have same indicated laboratory parameters, but does that relate to real world? Laminated glass appears to be the necessary and appropriate basic multiattribute choice for facade noise control.

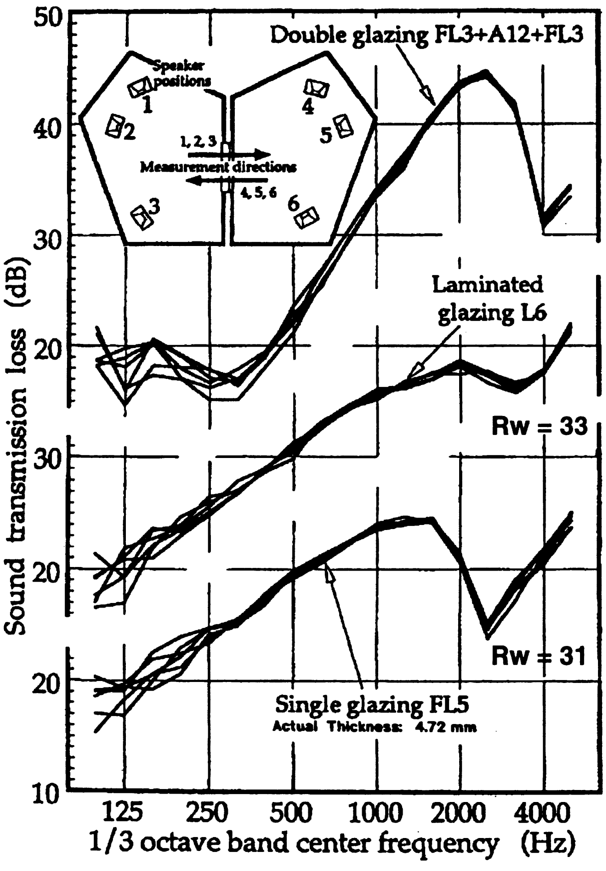

Figure 1. ISO 140 Glass Tests, FGMAJ.

Introduction (Figures 1 and 2)

Current limitations of facade glazing design for noise control include especially a reliance on laboratory measured 'performance parameters'. Recently, paradigms for noise control have been evolving toward standards and guides producing such single figure (single-valued) acoustic parameters which discount important field performance effects, if not the specific problems peculiar to glass. Limitations include representing size (finite versus infinite plates), variation in edge constraints (boundary condition), assumptions of diffuse noise source (non-specific plane wave angle of incidence), experimental limitations for laboratory measurements at low frequencies, and averaging TL across the frequency bands.

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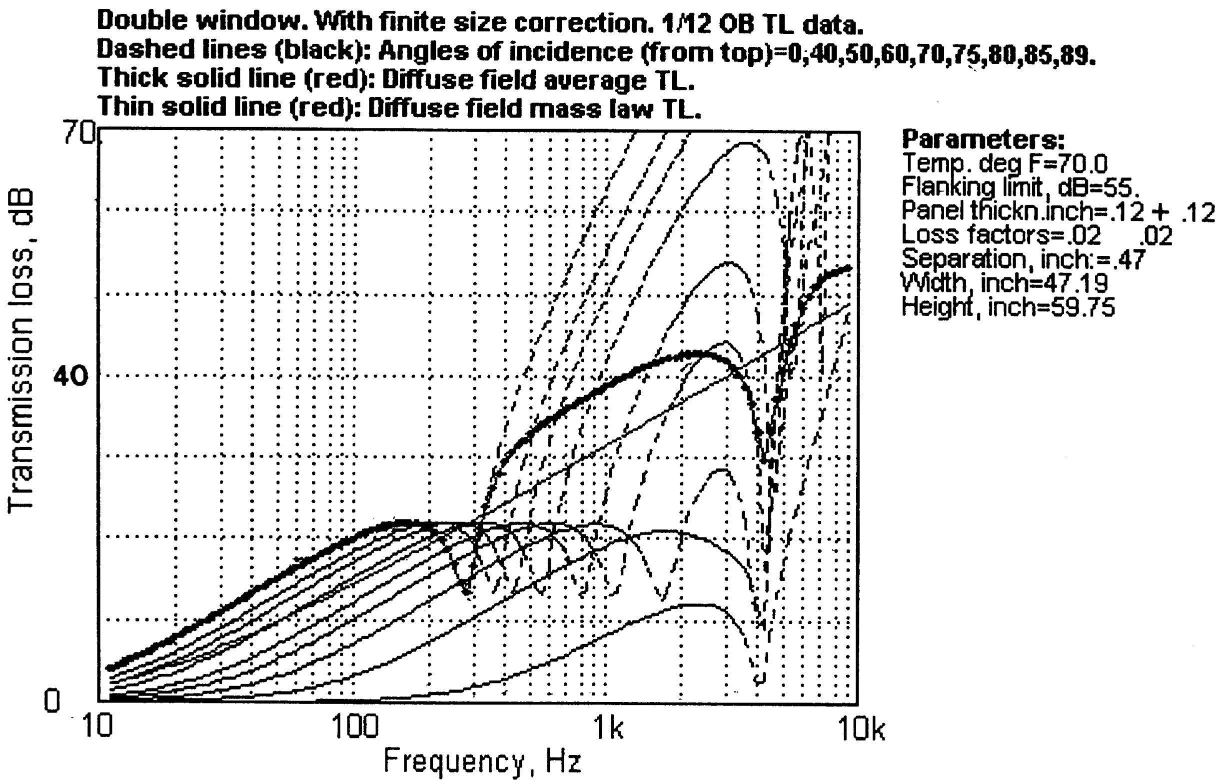

Figure 2. Simulation of 3+A12+3 Insulated Glass Unit.

The purpose of this work is to analyze and illustrate the theoretical differences between laminated and monolithic glasses, and identify some very strong effects of glass design choices on facade noise control i.e. basic principles.

Glazing systems chosen for facade vision panels are often prime determinants of day-to-day interior noise quality. Physics of noise transmission through glass exhibit coincidence and resonance effects. Monolithic glass has specific critical (and 'coincidence') frequencies where, simplistically, speed of bending waves in glass match the speed of sound in air. Near this particular frequency glass becomes more transparent to noise, having a lower transmission loss 'dip'. And resonance 'dips' affect lower frequency glass performance.

There is a gap between field performance for upper limit interior noise quality from windows as facade elements versus the current reliance on laboratory measurements for sound insulation of glazing. The evolving single-valued 'figures of merit' – when applied to glasses – have led to contradictory 'performance' assessments. Ideally facade glazing design choice results from an optimization based on utilization of the full spectra for external sources, internal noise environment target and glazing transmission loss. Multiattribute functionalities effect design in the 'systems triad' described here as: (1) the external query; (2) the internal response, an optimization process; (3) mutual perceptions, an acceptance review process for proposed design result. Some examples summarizing field experience illustrate state of the art in practice.

A 1998 presentation on basics of acoustical glazing was given from the perspective of satisfying clients on improved interior noise quality (field performance). J. Kwolkoski, David L. Adams & Associates Inc. (Denver) concluded, "both laminated glass and insulating glass units can provide significant acoustical benefits". While 6 to 7 dBa improvement is clearly noticeable, a 10 dBa improvement is usually targeted to satisfy clients; about 3 dB is discernible. From experience and analysis, "a change from a monolithic to a laminated unit tends to provide a 4 dBa improvement. An efficient option for increasing acoustical performance in insulating units is to utilize larger gas spaces in dual pane units." Retrofit can use an interior storm sash. Plain insulated glass can shift outdoor noise to irritatingly higher frequencies. So such combinations are of practical value.

However, present laboratory glazing test method assumptions for single-valued sound transmission parameters do not seem to adequately describe and quantify the acoustic performance of laminated glass units, especially field performance. For example, ISO 140 testing on laminated and monolithic glazings of required size (1.23x1.48 m) would indicate the ISO 717 parameter 'Rw' would increase to only 33 for 6 mm laminated glass, from 32 or 31 for monolithic 6 mm and 5 mm glasses respectively, with no difference

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when 'adapted' to 'traffic'. And the Rw=35 was the same for 10 mm laminated and monolithic. Are they the same? Figure 2 illustrates some complexities of Figure 1 IGU. Determining and utilizing the entire such TL spectra is the focus here, with performance assessment met EITHER by testing OR by calculation– **'design by analysis'.**

Distinctive and directional noise sources are particularly relevant to field performance. For instance, source noise from wet roadways is considerably higher in frequency than dry roads, and this exacerbates concerns about directly using reduced TL spectra. Variation of coincidence frequencies with angles of incidence becomes more important particularly for the most widely used monolithic glass barriers and higher frequency uses. Wet roadways should be 'worst case'. Extreme-vehicle noise is always directional. Traffic noise has relevance to higher frequencies.

'Design by Analysis' – Examples Simulated and Tested

Glass transmission loss simulations were compared primarily to FGMAJ ISO 140 data, by Kobayashi Riken, Japan (Kobayashi Institute of Physical Research). [3] Installation and opening were per ISO 140-1 at a temperature of 20 $\pm$ 3^{o}C in a testing laboratory with two irregular reverberation rooms with volumes of 164 cubic meters in each sound source and receiving room. Each room was not rectangular but pentagonal (non-equilateral) shape with slanted ceiling, no baffles. (Figure 1) A diffuse field was simulated using 10 stationary microphones at once (5 in the sound source room and 5 in the receiving room). Each glazing specimen 1230x1480 mm was measured with three loudspeaker sound source positions in each room, then interchanging the sound source and sound receiving sides with each other, again measuring at three points with different loudspeaker locations. Six measurements were averaged at each frequency band.

Vibro-acoustic simulation results are presented numerically as narrow band and/or third-octave band plots of transmission loss for a monolithic and symmetric laminated glass rectangular flat plates of ISO 140 sizes (1.23x1.48 m). Monolithic glass is assumed 6 mm thick with ρ = 2530 kg/m^{3}, E= 70300 MPa, and nu= 0.23 used for mass density ρ, Young's modulus E and Poisson's ratio nu. Modal viscous damping factor of 1% (0.01) is used for monolithic glass. Laminated glass is bonded by a viscoelastic layer only 0.38 mm thick and two sheets of 3 mm thick glass. The WLF viscoelastic relation for DuPont PVB herein (BUTACITE®) was used for laminates, modeled at temperature of 20^{o}C. Results clearly demonstrate capability of RAYON-3D transmission solver to predict transmission loss curves for monolithic and laminated glasses, also otherwise validated for TL of insulated glass and other structures.

Theoretical background has been described by: Ben Mariem and Hamdi [1], and Guerich and Hamdi [4], among others. Glass plates were modeled by 180x140 = 25200 quadrangular plate finite elements. [6] Each element has four nodes and three degrees of freedom per node (lateral displacement, rotation/x_1 and rotation/x_2). Simply supported boundary conditions were applied at external edges of the rigid plate baffle. Natural frequencies and mode-shapes were computed up to 4000 Hz or within model limits, using I-DEAS Model Solution developed by Structural Dynamic Research Corporation (SDRC).

The modal acoustic radiation impedance matrix ***Z*** and the modal loading vector **p** were computed by RAYON-3D BEM Solver developed by STRACO, using 140x112 = 15680 quadrangular boundary elements. Each element has four nodes and one degree of freedom corresponding to the lateral displacement. To save CPU time, Boundary Element Mesh was coarser than the structural finite element mesh. This was also done to check capability of RAYON-3D for solving incompatible fluid-structure meshes. Diffuse sound field assumption was simulated by seven (7) non-correlated plane waves of unitary amplitude, arriving from first quadrant. Incident and azimuth angles (θ, ϕ in degree) values used: Normal (0, –); Oblique$_{1/2/3}$ (45,2); (45,45); (45,88); Parallel$_{1/2/3}$ (88,2); (88,45); (88,88).

Calculations were done in two steps: (1) Modal acoustic radiation impedance matrix ***Z*** (complex, non-diagonal, frequency dependent) and modal loading vector **p** (complex and frequency dependent) were computed by RAYON-3D every 35 Hz, from 20 to 4000 Hz; (2) Frequency response of plate including TL calculation was computed every 2.5 Hz, with a B-Spline interpolation technique of these acoustic vectors ***Z*** and **p**, each frequency step. Monolithic glass was computed in standard graphical environment of I-DEAS Vibro-Acoustics incorporating RAYON-3D transmission solver. Laminated glass used custom structural code developed by STRACO and coupled with RAYON-3D, featuring dedicated sandwich finite element with shear deformation and WLF correlations for the DuPont PVB layer modeled.

Monolithic Vibro-Acoustic Glass Simulation Cases (6 mm, Figures 4, 5, and 6)

Figure 6 compares 6 mm experimental third-octave tests with numerical simulation. It has been

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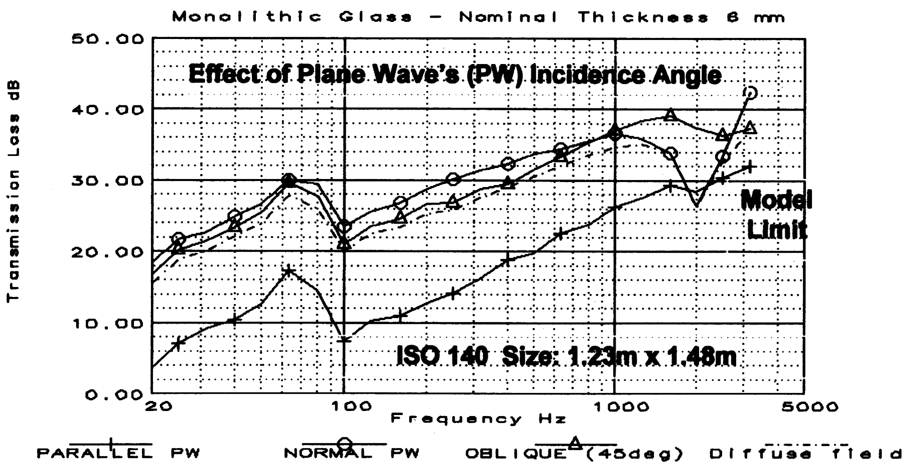

Figure 4: 6_mm Monolithic Simulated With Angle of Incidence

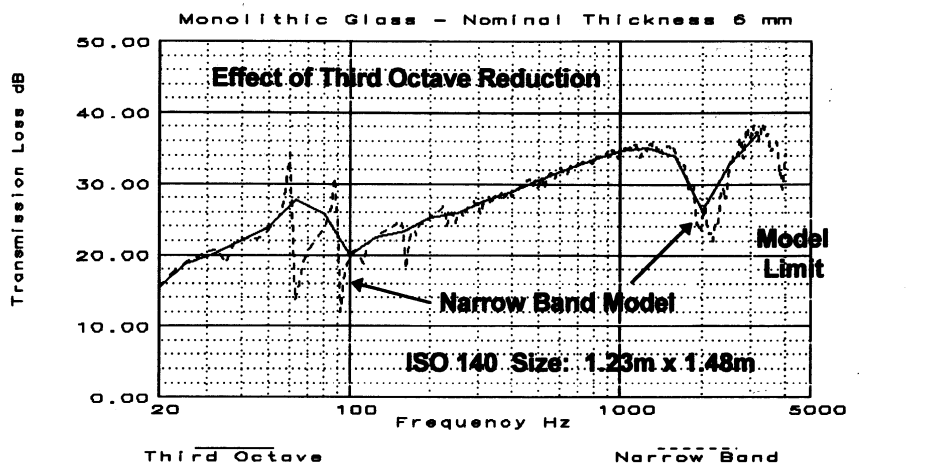

Figure 5: 6_mm Monolithic Simulated Narrow Band Frequency

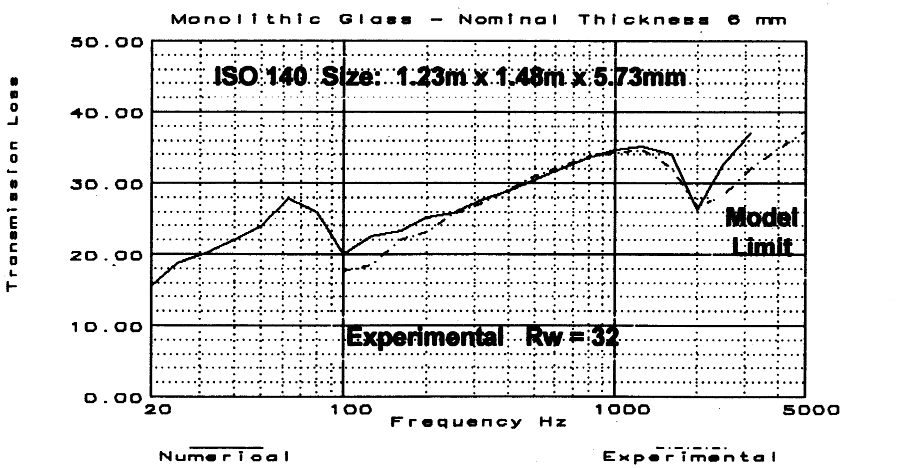

Figure 6: 6_mm Monolithic Simulation Compared to Test

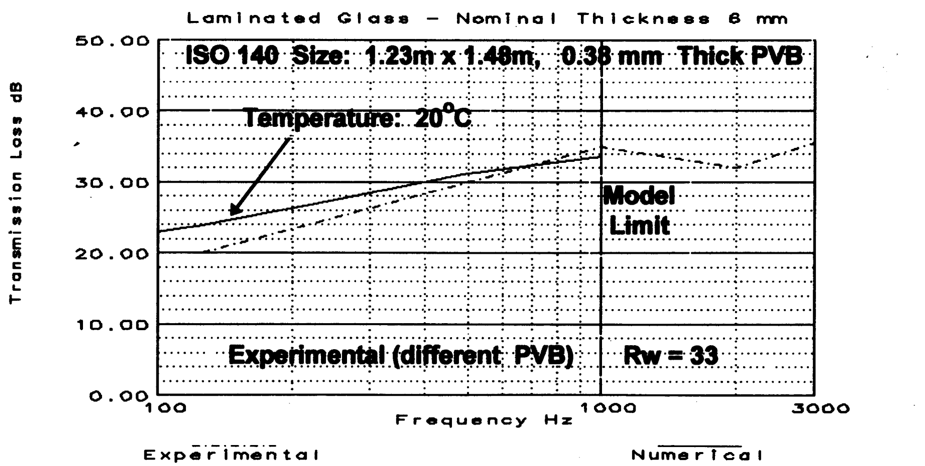

Figure 7: 6.38 mm Laminated Simulation Compared to Test

Numerical Vibro-Acoustic Simulations Comparing Monolithic and Laminated Glasses at 6 mm Nominal Thickness.

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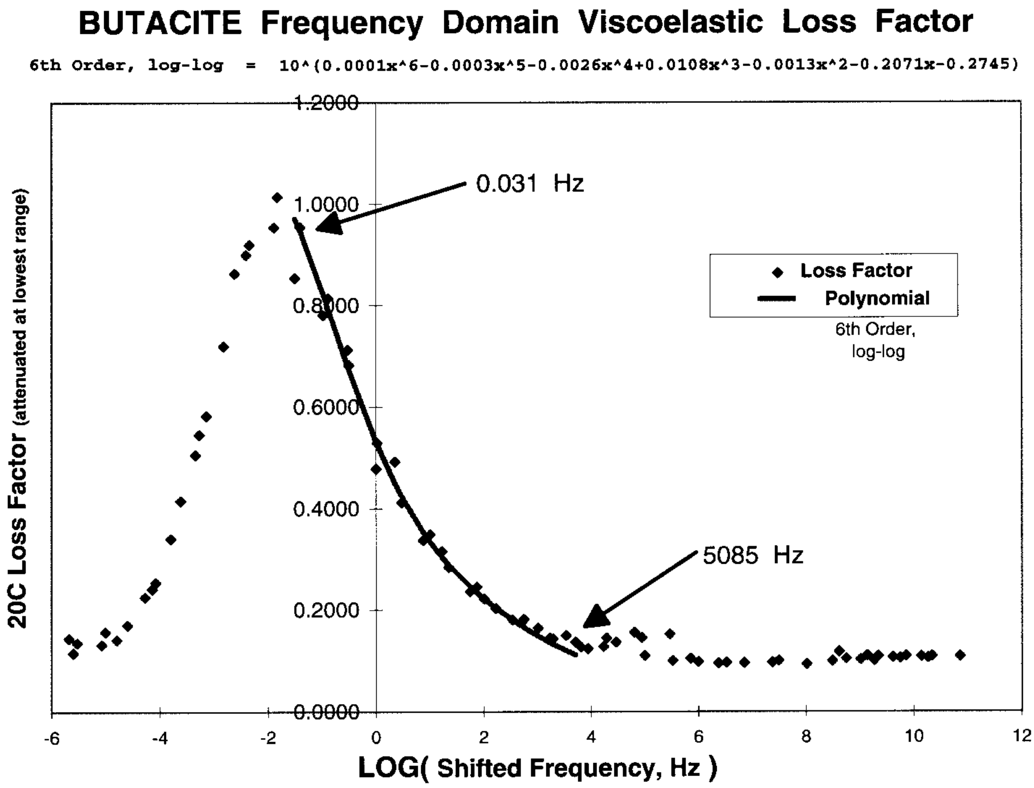

Figure 3. Acoustic Loss Factor Correlation.

known for monolithic glass TL the coincidence dip is expected around 2000 Hz and – as thickness increases – the dip shifts to lower frequencies and diminishes; resonance can occur at lower frequencies. And ISO 140 test size differs from usual size for ASTM E 90 and field sizes. Now and first, numerical simulation herein can give narrow band high-resolution spectra (Figure 5) near coincidence frequencies and below, showing the coincidence dip is actually 'worse' than previously thought. Narrow band calculations show larger coincidence deficiencies, which are 'washed out' even by third-octave band averaging. Secondly, those deficiencies around coincidence strongly depend on angle of incidence with parallel incidence giving much lower TL values. Thirdly for monolithic glasses at the lowest frequencies – for the octave band centered at 32 Hz – the TL values are calculated to drop off significantly. Therefor TL details are being lost both in the attenuation of spectral features by third-octave weighting and octave band representations, and especially by the even more attenuated reduction to single-value figures of merit. And this seems exacerbated by specimen details. So due to 'standardization', which is assumed related to 'performance' in the newer ISO and CEN 'criteria', Parmenen [5], some glazing types begin to 'sound' the same – except, perhaps, to the user's ears as interior noise.

Figure 4 shows in 1/3 octave bands, the TL curves of monolithic sample corresponding to three angles of incidences (normal, parallel$_2$, oblique$_3$), and assumed diffuse sound field. Clearly demonstrated is the influence of incidence angle on TL for the plate. Below 100 Hz, TL curves are derived by modal resonances of plate, from 100 Hz to 1000 Hz, the TL follows classic mass law; and near critical frequency of the plate (2000 Hz), a big TL dip is observed with a loss of attenuation of more than 10 dB – mainly from normal incidence.

Figure 5 shows superposition of two models corresponding to narrow and third octave bands analysis. This confirms third octave band analysis (weighting) is a poor indicator in low frequency region where TL is governed by the modal behavior of plate, but is well adapted for medium and high frequency regions. Averaging over the third octave band having the critical frequency reduces the depth of TL dip appearing at critical frequency.

Figure 6 shows in third octave bands the comparison between the numerical and experimental results. Excellent agreement is observed up to the critical frequency. Above critical frequency, numerical model overestimates measured TL; investigation is needed.

Viscoelastic Interlayer Properties for Laminated Glass (Figure 3)

Damping in laminated glass acoustics is theoretically founded upon the interlayer loss factor. Plasticized-PVB (DuPont Butacite® polyvinyl

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butyral) interlayer is modeled as a linear viscoelastic material (small strains). The storage (E') and loss modulii (E") have been determined using dynamic tensile measurements over ranges of frequency and temperature (5°C to 70°C). Loss factor (E"/E') is correlated with reduced frequency where actual frequency and shifted frequency are transposed through the Williams-Landell-Ferry (WLF) relation for time-temperature superposition. The WLF parameters of C1=20.7 and C2=91.1 at a reference temperature of 20°C were best fits to the E' data and were applied to E". Shifted frequency = actual*A_T. Shift factor: LOG(A_T) = -20.7*(T-20)/(91.1+T-20) was used for the master data set. Shear modulus (G') is related to storage modulus via Poisson's ratio determined (nu = 0.5) by non-contact optical method: G' = E'/(2*(1+nu)). Density is 1.075 g/cc. Polynomial correlations represent master data set of viscoelastic properties over the acoustic range (where G' is in Mpa and x is LOG of shifted frequency, constrained to the values correlated between 0.03 to 5000 Hz):

$$\mathrm{LOG}(G') = +0.0005322\,x^4 - 0.0002328\,x^3 - 0.057082\,x^2 + 0.376701\,x + 1.575709$$

$$\mathrm{LOG}(E''/E') = -0.0014304\,x^4 + 0.0117959\,x^3 - 0.012808\,x^2 - 0.202854\,x - 0.268857$$

Laminated Glass Vibro-Acoustic Simulation Case (6.38 mm, Figure 7)

A first-principles vibro-acoustic simulation from 100 to 1000 Hz was performed on 6.38 mm thick, ISO 140 size, laminated glass at 20°C using viscoelastic properties for DuPont PVB, as in Figure 3. Figure 7 compares the simulated third-octave bands to octave band TL reported for a 6 mm laminated glass construction tested by ISO 140 – probably using different, unknown source PVB. This laminate simulation also is directly comparable with 6 mm monolithic, per Figure 6. The theoretical response at 20°C closely matches the 32 dB TL value for monolithic at 1000 Hz. But importantly shows higher transmission loss than 6 mm monolithic glass at all lower frequencies down to 100 Hz, and probably down to 63 Hz. This is significant because first, this low frequency analysis demonstrates a theoretical basis for the improved sound transmission loss for laminated over monolithic. Secondly, the benefit is documented at the lower frequencies deemed important to traffic noise. Thirdly, this thinnest commercial PVB thickness, 0.38 mm, is thereby shown to have basic noise reduction benefit to users.

Figure 7 shows a laminated plate comparison between numerical and experimental TL curves; latter is given in octave bands analysis for a PVB composition different from DuPont's, but similar. Calculation was limited to 1000 Hz maximum. Again a relatively good agreement is observed, the deviation between the predicted and the measured results remains within 3 dB, even considering PVB differences. Comparison of TL curves for monolithic and laminated shows the acoustic frequency response of laminated glass is quite similar in-kind to monolithic glass except near the critical frequency where the depth of the dip in TL is drastically reduced in the case of laminated. This constitutes the principal advantage of the laminated glasses: depth of the transmission loss dips appearing at resonance and critical frequencies are significantly reduced by the damping added by the viscoelastic layer.

Examples Based on Laboratory Tests Alone

Benefit of increased TL for laminates can be illustrated using spectral averaging from multiple ASTM tests at Riverbank Acoustical Lab, measured in several different years.

Single-Pane Laminated Glass Test Example (6 mm nominal, Figure 8)

Averages of three spectra each for monolithic 6 mm glass are compared to 1.52 mm thick interlayer in 2-plies of 3 mm glass. Single tests for other PVB thickness are also shown. Note coincidence and resonance. A substantial benefit is observed near the critical frequency. The thinnest commercial DuPont PVB thickness of 0.38 mm improves TL, and benefit seems fully developed at 1.52 mm thick. Even though this test seems affected by edge mounting at lower frequencies, some improvement seems apparent at 200 Hz. The effect of laminating PVB into 6mm nominal thick glass make-ups is strong enough to be observed experimentally.

Single Laminated IGU Test Example (12 mm of glass applied, Figure 9)

Three glass constructions with same surface mass density are compared, using DuPont average of three spectra each for insulated glass units 25 mm (1-inch) thick, with a non-laminated unit compared versus single-laminated IGU (6.76 mm nominal). Both coincidence and resonance dips are observed. In comparison at similar weight, monolithic 12 mm glass, shows IGU coincidence shifts to higher frequencies where

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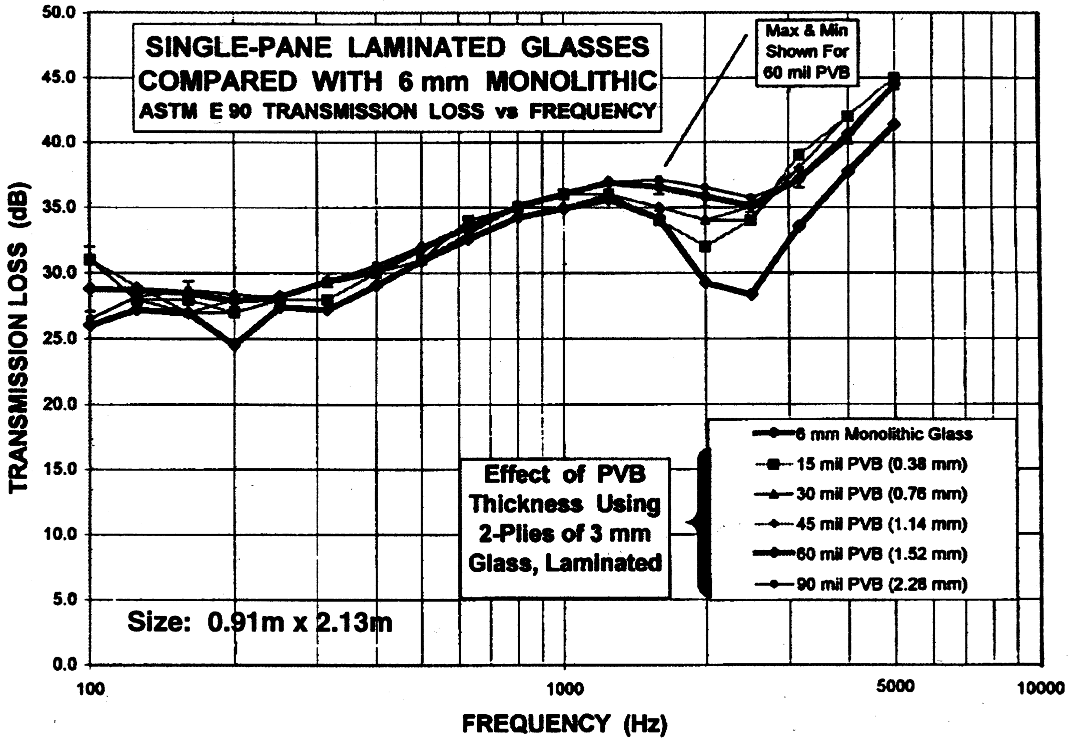

Figure 8. Effect of Lamination on 6_mm Transmission Loss.

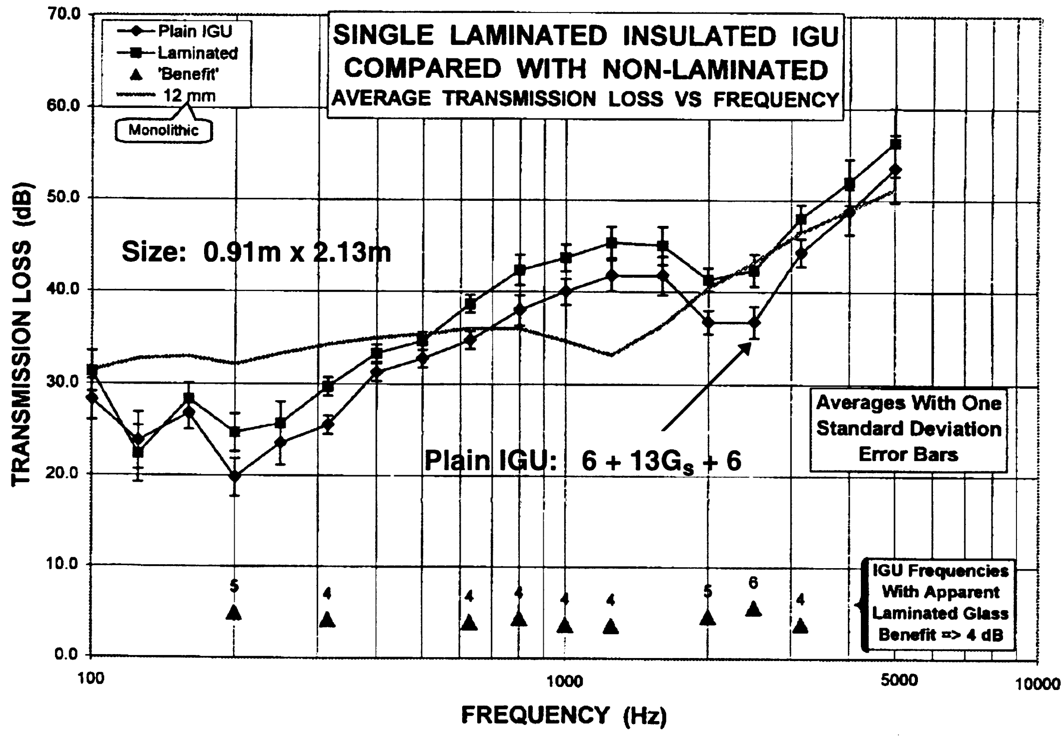

Figure 9. Effect of Lamination on 12_mm Insulated Glazing.

laminates are effective. For 6 mm thick panes with about 13.2 mm sealed gas space, the STC single valued parameter by ASTM E 413 (sensitive to coincidence dip near 2000 Hz) increased from 34 $\pm$ 3 dB for plain to 39 dB for single-laminated insulated. Nine frequencies showed improvement of 3.5 dB or more. The effect of adding a laminated pane to this IGU make-up is strong enough to be observed experimentally. Single-laminated IGU are particularly effective when laminates are used to create beneficially asymmetric pane thicknesses.

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Lab Tests Versus Expected Performance In Application

Laboratory test data – referring to TL (transmission loss) testing – are of value for comparison of products and ranking of expectations. Limitations for product TL testing and requirements thus limits – and to large extent prevents – direct application of such test results to facade performance [2], also note [8] and [7]:

- Equivalency assumptions between monolithic and laminated glass from tests seem inappropriate
- Such allegations of monolithic and laminated equivalency appear flawed for theoretical reasons
- Laminate "equivalency" to monolithic discounts theoretical narrow band damping differences
- Physics for plane wave angle of incidence affects such 'equivalency' assumptions in field-uses
- Single-value parameters are for rank-order classes, which are inappropriate to field performance
- Traffic noise has relevance to higher frequencies, especially for wet roadways as a "worst case".

Conclusions

Glass and insulated glass units have specific noise control issues. Thin interlayers provide substantial acoustic benefit in laminated glass. **B**asic **LAM**inates are thoroughly compatible with acoustic control as facade elements and provide multiattribute functionalities for safety, security and property protection. Laminated glass is always a multiattribute acoustic option. Benefits are quantifiable by calculational simulation. A PVB thickness of 0.38 mm (15 mil) provides a basic spectral acoustic TL benefit, increasing with thickness until fully developed at about 4-times this thickness. Laminates are premised here to represent the minimum essential advance in facade noise control performance over any monolithic or corresponding multi-glazed monolithic glass gas-spaced option, the necessary and appropriate 'default' choice for improvement. The reason is structural damping. Compatible noise barrier control is demonstrated by...

- Laminate benefits are quantifiable by calculational simulation OR testing;
- Single laminate simulation has confirmed its expected theoretical benefit;
- Single laminated IGU shows synergy, appearing quite effective based on test results;
- IGU simulation illustrates certain limitations and sensitivities, and thin gas spaces appear to increase transmission loss at low frequencies below 500 Hz experimentally.

'Design by analysis' appears feasible. Performance-based standards development to meet user's interior noise quality needs is proposed applying spectral TL control by direct use of – at a minimum – octave band transmission loss as the performance criteria. Appropriate glass product selection and application process must include design by analysis using available software to accomplish the performance objectives with improved scientific certainty, particularly if compliance is required.

Finally, it would seem to represent gross negligence on the part of the aware and responsible scientific community to perpetuate assumptions and conundrums that users are free to apply laboratory test data — which is, in itself, only a simulation — as field performance expectations, particularly where optimization of acoustical glass barrier construction against traffic noise is the objective. Focus must remain on interior noise quality and field experience.

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