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Sound Insulation of Monolithic or Laminated Single- and Double-Glazing Panels

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ABSTRACT

Sound transmission characteristics of single or multiple panels as sound insulation components in buildings have been studied extensively, and numerous models have been developed over the past few decades. Though most of them have been validated individually with specific test results in their developing phases, evidence showed that considerable discrepancy exits from one model to another. By applying many existing models onto glazing panels such as windows, doors, or building facades, the authors found that most of them unable to accurately predict their sound insulation performance. Apparent discrepancy up to 3-5 dB in terms of OITC/STC index was even found between the predictions by commercial software and those well-recognized test results. More accurate theoretical models are highly demanded in the industry to guide the design of real practice. To address this need, revisits of most existing theoretical models were made by the authors, and extended models are accordingly developed and presented in this study to provide more accurate predictions on the acoustic performance of monolithic or laminated single- and double-glazing panels. Test results collected from literature as well as conducted by the authors are further provided to validate the proposed models.

Keywords: Sound radiation, Insulation, Sound Transmission Loss, glazing panel, laminated glass

1. INTRODUCTION

The acoustic performance of building facades such as window, door, and curtain wall in terms of their sound insulation is one of the critical calibers to the quality of Schüco products across the world. Architecture designer, general engineer or contractor are heavily relying on commercial software to estimate the acoustic performance of certain designed products. However, majority of them do not necessarily have the knowledge sensing whether the estimations provided by the software reflecting the reality of the product or will meet the need from customers. In this sense, the accuracy of the theoretical models behind any commercial software plays a considerable role in designing a product.

Over the past few decades, numerous models have been developed to predict the sound transmission characteristics of single or multiple layer panels. In many theoretical models, various constants or parameters were empirically determined by best matching the predictions with test results. As a consequence, a model might work well for a certain type of materials while not applicable to others. Moreover, evidence showed that considerable discrepancy exits from one model to another. By applying many existing models onto single or multiple glass panels, the authors found that most of them unable to accurately predict their sound insulation performance. Apparent discrepancy up to 3-5 dB in terms of OITC/STC index was found between the predictions by commercial software and those well-recognized test results, which is even higher for multiple layer laminated glass panels.

In this study, based on existing theoretical models of sound transmission loss on single and multiple panels, extended models are developed and summarized for a single layer of laminated glass and a double layer of insulating-laminated glass panels. Test results collected from literature as well as

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conducted by the authors are further provided to validate the extended models.

2. SINGLE LAYER GLAZING PANEL

2.1 Monolithic Glazing

2.1.1 Current models in the literature

From Davy's studies (1–3), the diffuse field sound transmission coefficient of a single rectangular homogeneous panel with dimensions of $a \times b$ can be calculated as

$$\tau = \begin{cases} \tau_l = \dfrac{2}{\alpha_0^2}\left(\ln\left(\dfrac{1+\sqrt{1+q^2}}{p+\sqrt{p^2+q^2}}\right)+\dfrac{1}{\lambda}ln\left(\dfrac{h+\sqrt{h^2+q^2}}{p+\sqrt{p^2+q^2}}\right)\right), & f \le fc \\ \tau_h = \dfrac{\sigma_0^2}{2\alpha_0 r_f(\sigma_0+\alpha_0\eta)}\left(arctan\left(\dfrac{2\alpha_0}{\sigma_0+\alpha_0\eta}\right)-arctan\left(\dfrac{2\alpha_0(1-r_f)}{\sigma_0+\alpha_0\eta}\right)\right), & f > fc \end{cases} \tag{1}$$

where the radiance efficiency σ_0 in high frequency ($f > fc$) is given by $\sigma_0 = \begin{cases} \frac{1}{\sqrt[n]{g^n+q^n}}, & if\ p \le g \le 1 \\ \frac{1}{\sqrt[n]{(h-\lambda\cdot g)^n+q^n}}, & if\ 0 \le g \le p \end{cases}$ with parameters summarized as $\alpha_0 = \pi f \frac{m}{\rho_0 c}$; $r_f = \frac{f}{f_c}$; $p = \min\left(\zeta_1\sqrt{\frac{\pi}{2ka_0}}, 1\right)$; $q = \frac{2\pi}{k^2 A_s}$; $g = \begin{cases} 0, & if\ f \le f_c \\ \sqrt{1-f_c/f} & if\ f \ge f_c \end{cases}$; $h = \frac{1}{\frac{2}{3}\sqrt{\frac{\pi}{2ka_0}}-\zeta_2}$; $\lambda = h/p - 1$, and m is the surface density of the panel, ρ_0 the ambient air density, c the sound speed traveling in the ambient air, η the total damping loss factor of the panel, wave number $k = 2\pi f/c$, A_s the area of the panel, $a_0 = \frac{A_s}{a+b}$ the dimension of the panel by considering it as an equivalent square panel; n, ζ_1 and ζ_2 are empirical constants which are suggested to take the value of $n = 2, \zeta_1 = 1.3$, and $\zeta_2 = 0.124$.

The total damping loss factor is the sum of the internal damping loss factor η_0 and that due to the transmission of vibrational energy from the panel to its surrounding elements η_e. According to Annex C of ISO 12354-1:2017(E)(4), η_e can be evaluated for structural elements with a surface mass $m \le 800\ kg/m^2$ as $\eta_e = \frac{m}{485\sqrt{f}}$. The critical frequency can be determined by $f_{c=}\frac{c^2}{2\pi}\sqrt{\frac{M}{B}}$, where $B = \frac{Et^3}{12(1-v^2)}$ is the bending stiffness of the panel.

From the sound transmission coefficient determined in Eq. (1), the sound transmission loss (STL) of a single homogeneous panel can be calculated by $\text{STL} = -10\lg(\tau)$. To better match the prediction of STL with experimental results, it was proposed that the sound transmission coefficient below the critical frequency τ_l' is calculated as the sum of $\tau_l\ and\ \tau_h$ in Eq. (1) by accounting for the bending stiffness effect.

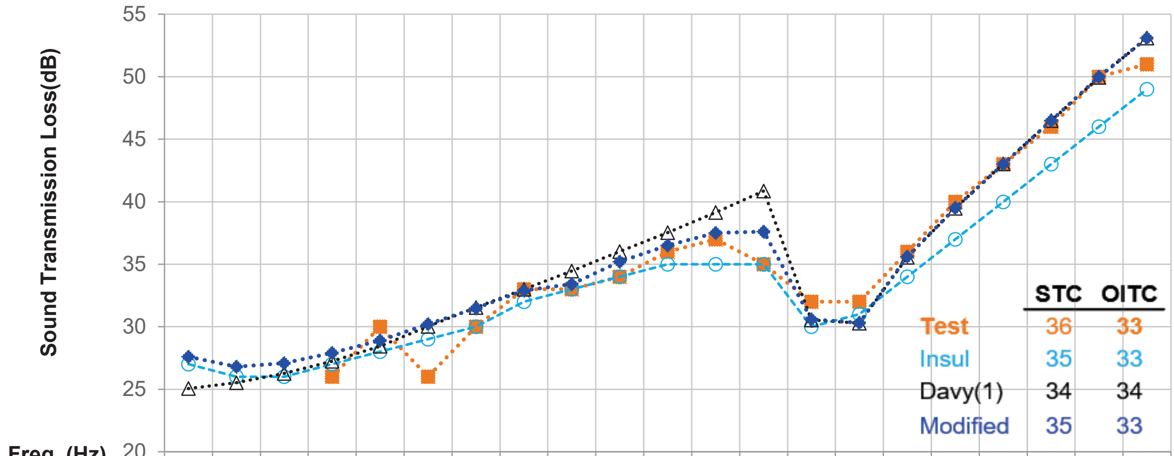
2.1.2 Modifications

Though it was identified that Davy's model provides closest evaluations of STL for single glazing panels in the current literature (5), the authors found that near the resonant and critical frequencies, considerable discrepancies exist between the prediction of the STL by Davy's model and the test results, often there is about 2 - 3 dB discrepancy in terms of STC/OITC index. To address this issue, certain revisions were made by the authors (5) by adding two more sections within the lower frequency range and adjusting the radiation efficiency to improve the predictions based on Davy's models. Accordingly, the revised sound transmission coefficient of the panel is given by

$$\tau = \begin{cases} \tau_{l1} = \dfrac{1}{\alpha_0^2}ln\left(\dfrac{1+\alpha_0^2}{1+\alpha_0^2 cos_b}\right), & f \le 2f_l/3 \\ \tau_{l2}, & 2f_l/3 \le f \le f_l \\ \tau_m = \tau_l', & f_l \le f \le f_c \\ \tau_h, & f > f_c \end{cases} \tag{2}$$

where $f_l = \frac{\pi c_L t}{4\sqrt{3}}\left(\left(\frac{1}{a}\right)^2 + \left(\frac{1}{b}\right)^2\right)$ is the resonance frequencies of the panel, $c_L = \sqrt{\frac{E}{\rho(1-\upsilon^2)}}$ the propagation velocity of the quasi-longitudinal wave in the glazing panel; E, ρ, υ are Young's modulus, density and passion ratio of the panel, respectively, $cos_b\theta$ is an associate parameter to consider the practical limitation of sound radiation angle, which is given by (6) as $cos_b^2\theta = min\left(\frac{1}{k\sqrt{A_s}}, 0.9\right)$, τ_{l2} is determined by linear interpolation of τ_{l1} and τ_m. To better match the predictions with test results, the original radiation efficiency σ_0 of single glazing is replaced by $\sigma_1 = \begin{cases} \sigma_0, & f \le 0.9f_c \\ min(\sigma_0, \sigma_c), & f \ge f_c \end{cases}$, while between $0.9f_c$ *and* f_c, it is obtained by linear interpolation, and σ_c is a critical radiation efficiency to filter out the unrealistic high value at critical frequency.

Figure 1 provides an overall comparison of the STL for a ½ inch monolithic glass panel (with dimension of 36 in by 84 in) among Viracon test result (7), simulation by INSUL 9.0 (8), original prediction by (1), and the modified model (5). In comparison with measurements in the third-octave band, the theoretical values were averaged over the three frequencies which were 2−1/9, 1, and 21/9 times the center frequency of the third-octave band if the critical frequency locates within the measurement frequency (so does in the rest of the STL charts in this paper). Nearby the resonance frequencies of the panel, it shows 3~4 dB difference of sound transmission loss between the original model and the modified one.



Freq. (Hz)	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
Viracon				26	30	26	30	33	33	34	36	37	35	32	32	36	40	43	46	50	51
Insul	27	26	26	27	28	29	30	32	33	34	35	35	35	30	31	34	37	40	43	46	49
Davy (1)	25	26	26	27	28	30	32	33	34	36	38	39	41	31	30	36	39	43	47	50	53
Modified	28	27	27	28	29	30	32	33	33	35	37	38	38	31	30	36	40	43	47	50	53

Figure 1 - STL of ½ inch monolithic glass panel (36 in by 84 in)

2.2 Laminated Glazing

Laminated glass has been gaining more applications in industry as it provides better performance for structural, acoustical, and thermal performances. Laminated glass is achieved by bonding two or more glass plies with thermoplastic polymeric interlayers. The resulting laminated glass performs much safer than monothetic glass because the fragments remain attached to the interlayer even after breakage. To apply the extended model for the monolithic glass given in the previous section to laminated glasses, a laminated panel is considered as an equivalent single panel. The acoustic performance of a single laminated glass depends not only on individual layers but also on the interlayer and its dynamic performance. From this point of view, in addition to the effective properties of the laminated panel, the material properties of the interlayer must be included in the predicting model.

The effective thickness of the laminated panel is determined by following the procedures in ASTM E1300(9).

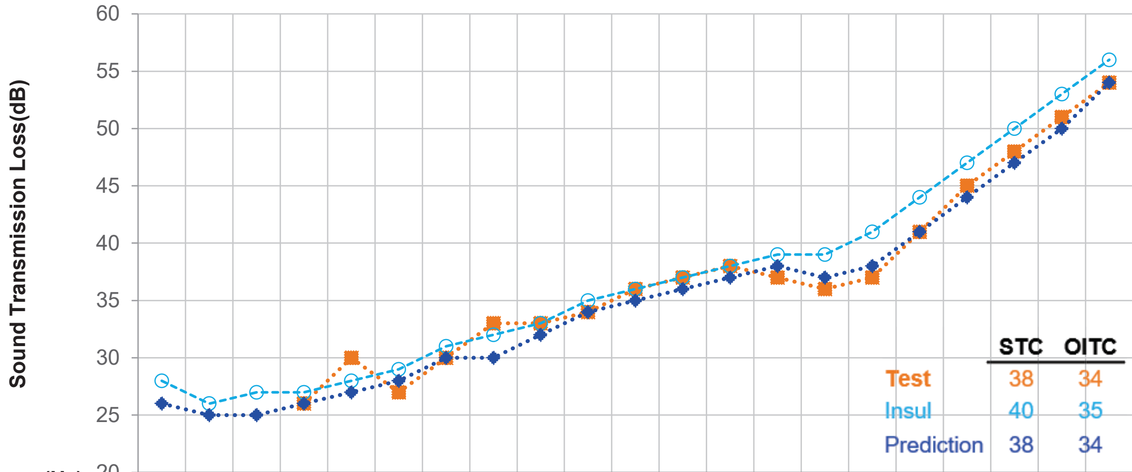
$$h_{ef,w} = \sqrt[3]{h_1^3 + h_2^3 + 12\Gamma I_s} \quad (3)$$

where Γ is the shear transfer coefficient which is a measure of the transfer of shear stresses across the interlayer $\frac{1}{1+\chi\frac{EI_s h_d}{G h_s^2 a^2}}$, where $I_s = h_1 h_{s2}^2 + h_2 h_{s1}^2$, $h_{s1} = \frac{h_s h_1}{h_1+h_2}$, $h_{s2} = \frac{h_s h_2}{h_1+h_2}$, $h_s = 0.5(h_1 + h_2) + h_f$, h_f is the interlayer thickness (mm), E the Young's modulus of glass, a the smallest in-plan dimension of the laminated panel, and G the interlayer storage shear modulus, χ is a coefficient governed by boundary and loading conditions of the composite. For a laminated glass under the very particular case of simply supported and uniformly distributed loading, a value of $\chi = 9.6$ was proposed by Wölfel (10).

For a laminated glass with fixed thickens of individual layers, it can be found from Eq. (5) That the effective thickness of the equivalent single glass keeps reducing as the thickness of the interlayer increases, which makes sense from a structural point of view but does not when the sound transmission is concerned. To better reflects the physics mentioned above, the equivalent thickness given in Eq. (5) is accordingly revised as $h_{ef,ac=}h_{ef,w} + h_f/3$

Because of the existence of the viscoelastic polymer layer, the radiance of sound transmitting through the laminated glass varies accordingly, which varies as the type of the interlayer varies. Generally, the radiance decreases as the thickness of the polymer interlayer increases, more specifically, its decaying rate is larger for softer interlayer compared with that of the stiffer one. To reflect these trends, the radiance in laminated glass is proposed by introducing a decay factor ψ for dthe ifferent interlayer, which is $\sigma_c' = \sigma_c - \psi t_f$, where ψ is determined by correlating the predictions with series of test results on laminated glass panel of different interlayers.

Figure 2 provides a comparison of the STL of a ½ single laminated glass panel (consists of two quarter inches monolithic glass combined with a 0.045 inch PVB thin layer, and dimension of 36 in by 84 in) among Viracon test result (7), simulation by INSUL 9.0 (8), and the present model. The comparison shows that the result predicted by Insul general overestimates the STL, especially at a frequency higher than the critical one, leading to an overestimated STC/OITC index. However, the present model can match the test result almost over the entire frequency range except those nearby the resonant one where a spike exhibit, which might result from collected error because of practical difficulties or uncontrollable boundary effects during a test at a lower frequency.



Freq. (Hz)	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
Viracon				26	30	27	30	33	33	34	36	37	38	37	36	37	41	45	48	51	54
Insul	28	26	27	27	28	29	31	32	33	35	36	37	38	39	39	41	44	47	50	53	56
Prediction	26	25	25	26	27	28	30	30	32	34	35	36	37	38	37	38	41	44	47	50	54

Figure 2 - STL of ½ inch single laminated glass panel (36 in by 84 in)

3. DOUBLE-LAYER GLAZING PANEL

3.1 Double-layer Monolithic Insulating Glazing

From Davy's studies (2,6,11,12), the diffuse field sound transmission coefficient of a double rectangular homogeneous panel with dimensions of $a \times b$ can be summarized as

$$\tau = \begin{cases} \tau_{l1} = \frac{1}{\alpha_d^2} ln\left(\frac{1+\alpha_d^2}{1+\alpha_d^2 cos_b^2\theta}\right), & f \le 2f_0/3 \\ \tau_{l2}, & 2f_0/3 \le f \le f_0 \\ \tau_m = \frac{1-cos_m^2\theta}{(q+pcos_m^2\theta)(q+p)}, & f_0 \le f \le k_0 min(f_{c1}, f_{c2}) \\ \tau_{mh}, & k_0 min(f_{c1}, f_{c2}) \le f \le max(f_{c1}, f_{c2}) \\ \tau_h = \frac{\pi(\sqrt{r_{f1}}+\sqrt{r_{f2}})\mu}{4\alpha_1^2\alpha_2^2\eta_1\eta_2\delta_d^2(\mu^2+v^2)}, & f > max(f_{c1}, f_{c2}) \end{cases} \quad (4)$$

where τ_{l2} and τ_{mh} are obtained from linear interpolations from their corresponding regions; $\alpha_d = \alpha_1 + \alpha_2$ with $\alpha_i = \pi f \frac{m_i}{\rho_0 c}$ and m_i is the surface density of the panel i, respectively; double panel resonant frequency (also known as the mass-air-mass frequency) $f_0 = \frac{c}{2\pi}\sqrt{\frac{\rho_0}{d}\left(\frac{1}{m_1+m_2}\right)}$ with d of the cavity gap between two panels,; $q = \frac{1}{2}\left(\frac{\xi_1}{\xi_2} + \frac{\xi_2}{\xi_1}\right)$, $\xi_i = \alpha_i(1 - r_{fi}^2)$, $p = \xi_1\xi_2\delta_d$, $k_0 = 0.8$ is a constant, sound absorption coefficient of the wall cavity of the double leaf wall $\delta_d = \delta_d(t_i, d)$ is determined by best matching a series of predictions and Viracon test results, $cos_m^2\theta = min\left(0.9, max\left(\frac{1}{k\sqrt{A_s}}, 0.24\right)\right)$; $r_{fi} = \frac{f}{f_{ci}}$, $\mu = \eta_1\sqrt{r_{f1}} + \eta_2\sqrt{r_{f2}}$, and $v = 4(\sqrt{r_{f1}} - \sqrt{r_{f2}})$.

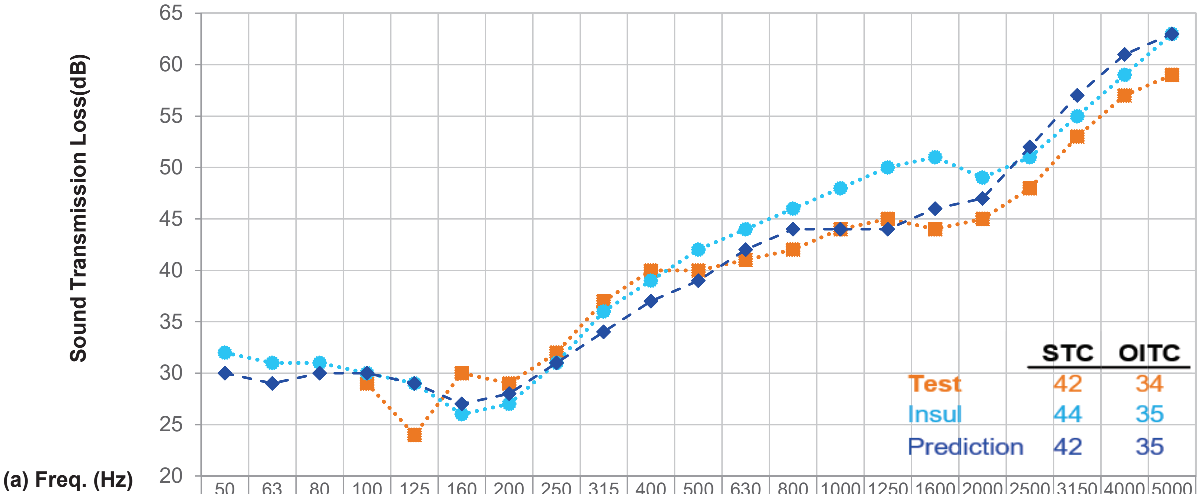
To account for the stud born transmission effect between the two panels, the STL has been accordingly revised as

$$\tau = \begin{cases} \tau_{L1} = \tau_{l1}, & f \le 2f_0/3 \\ \tau_{L2} = \tau_{l2}, & 2f_0/3 \le f \le f_0 \\ \tau_M = \tau_m + \tau_H + \tau_{SD}, & f_0 \le f \le k_0 min(f_{c1}, f_{c2}) \\ \tau_{MH} + +\tau_{SD}, & k_0 min(f_{c1}, f_{c2}) \le f \le max(f_{c1}, f_{c2}) \\ \tau_H = \frac{\int_0^1 \frac{dx}{(q_1^2+(x-p_1)^2)(q_2^2+(x-p_2)^2)}}{S_1^2 S_2^2 \delta_d^2} + \tau_{SD}, f > max(f_{c1}, f_{c2}) \end{cases} \quad (5)$$

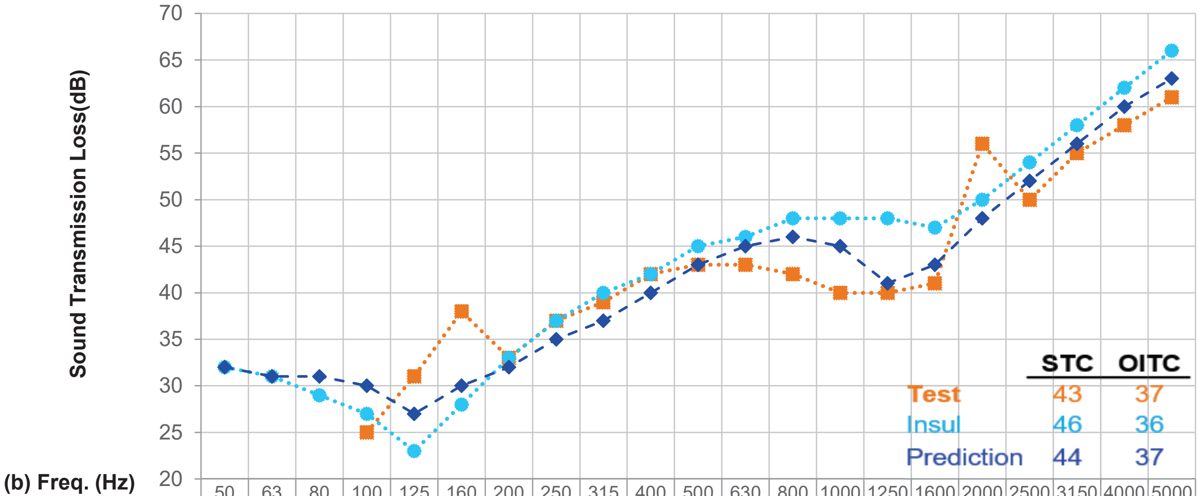
where the stud born transmission efficiency $\tau_{SD} = \frac{32\rho_0^2 c^3 D J_2}{G^2 b_0 (2\pi f)^2}$ with stud transmission ratio $J_2 = min\left(2/\left(1+\left(1-\frac{4\omega^{3/2}m_1 m_2 c C_M}{G}\right)^2\right), K\right)$, C_M stud mechanical compliance, and K the minimum stud transmission; the space between studs is approximated as one third of the panel width, i.e., $b_0 = b/3$, $G = m_1\sqrt{2\pi f_{c1}} + m_2\sqrt{2\pi f_{c2}}$, τ_{MH} is determined by linear interpolations from τ_M and τ_H without considering τ_{SD} ; $p_i = 1 - \frac{1}{r_{fi}}$, $q_i = \frac{1+\frac{\alpha_i \eta_i}{\sigma_i}}{S_i}$, $S_i = \frac{2\alpha_i r_{fi}}{\sigma_i}$, $\sigma_i = \begin{cases} \sigma\sigma_i & f \le 0.9fc \\ min(\sigma_c, \sigma\sigma_i) & f \ge fc \end{cases}$; $\sigma\sigma_i = \begin{cases} \frac{1}{\sqrt[n]{{g_i}^n + q^n}}, & if\ p \le g_i \le 1 \\ \frac{1}{\sqrt[n]{(h-\lambda \cdot g_i)^n + q^n}}, & if\ 0 \le g_i \le p \end{cases}$ and critical radiation efficiency σ_c is determined by the gap of the cavity between the two panels and their relative thickness as $\sigma_c = \sigma_c(t_i, d)$. Note that many inconsistencies exist in determining the parameters values in Eqs. (4) and (5) among Davy's studies on double panels (2,6,11,12), some of them have been accordingly reunified and modified in this study such that best agreement is achieved between the predictions and test results.

3.2 Double-layer Laminated Insulating Glazing

The STL of insulating-laminated (one layer monolithic and the other layer laminated) and double laminated insulating (both layers are laminated) are developed based on section 3.1. In this model, the laminated layers are firstly treated as an equivalent single layer by following the approach in section 2.2, sound absorption coefficient and critical radiation efficiency are then determined by regression analysis and reconstructed as a function of the thickness of individual layers and the cavity gap between them as $\delta_r'(t_i, t_f, d)$ and $\sigma_c'(t_i, t_f, d)$, where t_i is the equivalent thickens of laminated layers $(i = 1, 2)$ and t_f the thickness of the interlayer.



	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
Viracon				29	24	30	29	32	37	40	40	41	42	44	45	44	45	48	53	57	59
Insul	32	31	31	30	29	26	27	31	36	39	42	44	46	48	50	51	49	51	55	59	63
Prediction	30	29	30	30	29	27	28	31	34	37	39	42	44	44	44	46	47	52	57	61	63

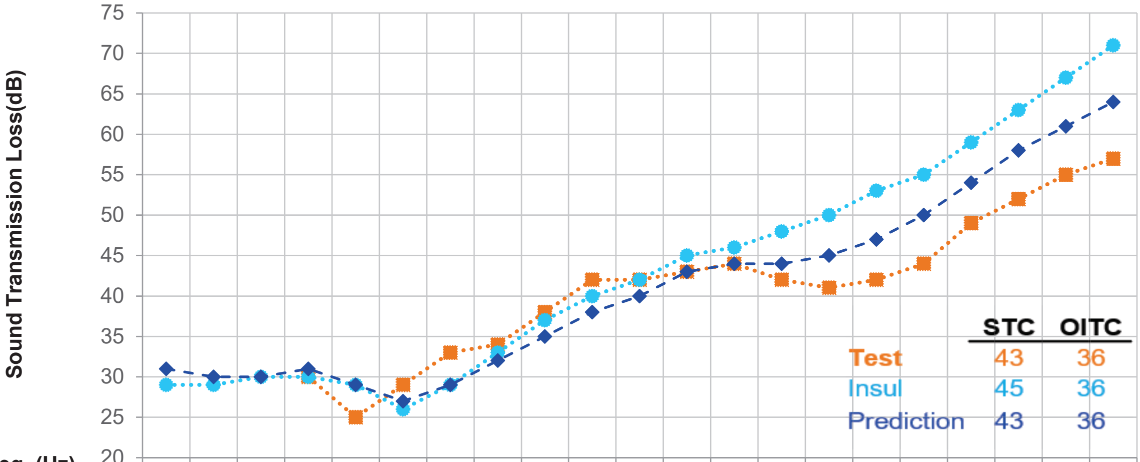


	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
Viracon				25	31	38	33	37	39	42	43	43	42	40	40	41	56	50	55	58	61
Insul	32	31	29	27	23	28	33	37	40	42	45	46	48	48	48	47	50	54	58	62	66
Prediction	32	31	31	30	27	30	32	35	37	40	43	45	46	45	41	43	48	52	56	60	63

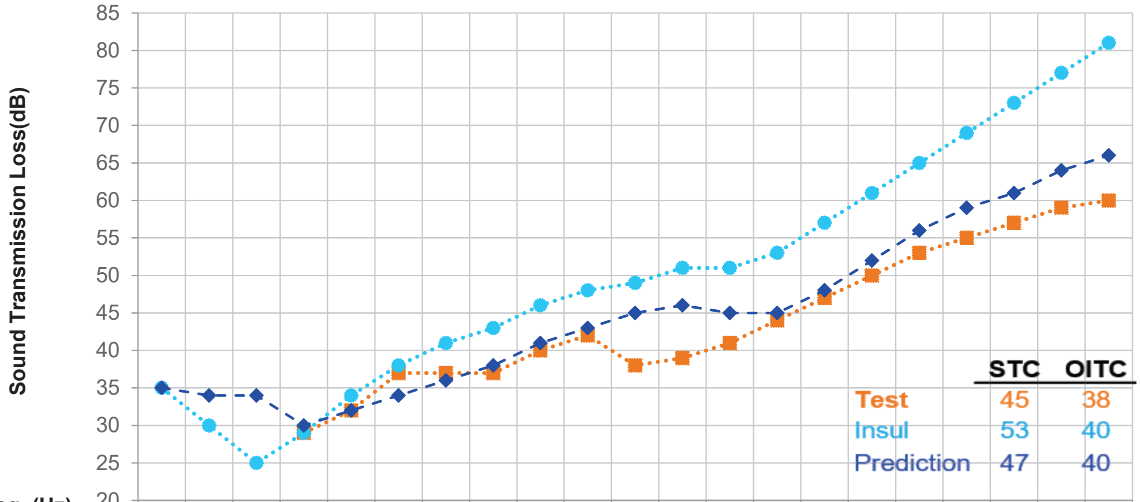
Figure 3 – STL of insulating-laminated double layer glass panel: (a) 1-3/16" overall - 1/4" glass, 1/2" airspace, 3/16" glass, 0.060" PVB, 3/16" glass; and (b) 1-11/16" overall - 3/8" glass, 3/4" airspace,1/4" glass, 0.060" PVB, 1/4" glass

Comparisons of the STL for two different insulating-laminated double layer glass panels among Viracon test, Insul simulation results, and the present model are provided in Figure 3(a) and (b). The overall thickness of these two panels are 1-3/16" and 1-11/16", respectively. The results show that in general both the present model and Insul agree with the test results and they can provide similar dips at the double panel resonant frequency and coincident frequency. However, nearby the coincide frequency Insul predicts much higher STL than the test results while the present model well aligns with the test result.

Figure 4 shows the comparisons of the STL for two different double layer laminated glass panels among Viracon test, Insul simulation results, and the present model. At relatively low frequencies (below critical frequency of individual panels), the results predicted by Insul and the present model fairly agree with the test results. At higher frequency (above coincidence frequency), the present model still can reasonably match the test results. However, Insul significantly overestimates the STL, with a discrepancy up to 8 dB for the STC index. The theoretical model behind Insul is not able to provide a reliable prediction of STL for double layer laminated glass panels, especially when the overall thickness of the double laminated glass panel is large.



(a) Freq. (Hz)	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
Viracon				30	25	29	33	34	38	42	42	43	44	42	41	42	44	49	52	55	57
Insul	29	29	30	30	29	26	29	33	37	40	42	45	46	48	50	53	55	59	63	67	71
Prediction	31	30	30	31	29	27	29	32	35	38	40	43	44	44	45	47	50	54	58	61	64



(b) Freq. (Hz)	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000
Viracon				29	32	37	37	37	40	42	38	39	41	44	47	50	53	55	57	59	60
Insul	35	30	25	29	34	38	41	43	46	48	49	51	51	53	57	61	65	69	73	77	81
Prediction	35	34	34	30	32	34	36	38	41	43	45	46	45	45	48	52	56	59	61	64	66

Figure 4 – STL of double-laminated double layer glass panel: (a) 1-5/16" overall - 1/4" glass, 0.030" PVB, 1/4" glass, 1/2" airspace, 5/32" glass, 0.060" PVB, 5/32" glass, 3/16" glass; and (b) 2-5/8" overall - 3/8" glass, 0.060" PVB, 3/8" glass, 1" airspace, 3/8" glass, 0.090" PVB, 3/8" glass

4. CONCLUSIONS

Based on existing theoretical models of sound transmission loss on single and multiple panels, extended models have been developed for single and double insulating-laminated glass panels in this study. Various comparisons among test results and simulation predictions by Insul are provided to validate the extended models.

For single laminated glass panel, the comparison shows that the result predicted by Insul general overestimates the STL, especially at frequencies higher than the critical one, leading to an overestimated STC/OITC index. For double laminated glass panels, comparison results show that the predictions provided by Insul considerably overestimate the STL, with a discrepancy up to 8 dB in terms of the STC index for relatively thicker double laminated glass panel, indicating that the theoretical model behind Insul is not able to provide reliable prediction of STL for laminated glass panels. In other words, Insul usually considerably overestimates the STL for high performance double laminated glass panels.

Well agreements among the predictions by the present models and test results for various single or double laminated glass panels, however, demonstrate the viability of the present models. It is worthy to note that the presented models were calibrated by comparing test results only from various glass panels. The applicability of the presented models to other building materials such as gypsum board, brick or masonry wall has not been investigated yet.

REFERENCES

1. Davy JL. Predicting the sound insulation of single leaf walls: Extension of Cremer's model. The Journal of the Acoustical Society of America. 2009 Oct 1;126(4):1871–7.
2. Davy JL. The improvement of a simple theoretical model for the prediction of the sound insulation of double leaf walls. The Journal of the Acoustical Society of America. 2010 Feb 1;127(2):841–9.
3. Davy JL, Larner DJ, Wareing RR, Pearse JR. The acoustic radiation impedance of a rectangular panel. Building and Environment. 2015 Oct 1;92:743–55.
4. ISO 12354-1:2017(E). Building acoustics -- Estimation of the acoustic performance of buildings from the performance of elements -- Part 1: Airborne sound insulation between rooms.
5. Huang Y, Chen F, DeGanyar T. Sound insulation of a single finite panel—Comparison, validation, and parametric studies. The Journal of the Acoustical Society of America. 2018 Sep 1;144(3).
6. Davy JL. Predicting the Sound Insulation of Walls. Building Acoustics. 2009 Jan 1;16(1):1–20.
7. Viracon Acoustic Performance Data Tables. Available from: http://www.viracon.com/pdf/ViraconAcousticPerfDataTables.pdf
8. INSUL - Predicting Sound Insulation: A quick & accurate tool for predicting the sound insulation in walls, floors, and ceilings.
9. ASTM E1300-16. Standard Practice for Determining Load Resistance of Glass in Buildings. 2016.
10. Wölfel E. Nachgiebiger Verbund. Eine Näherungslösung und Deren Anwendungsmöglichkeiten. STAHLBAU, DER. 1987;56(6).
11. Davy J. Predicting the sound transmission of double leaf cavity walls due to point and line connections. Proceedings - European Conference on Noise Control. 2012 Jan 1;139–44.
12. Davy JL. Sound transmission of cavity walls due to structure-borne transmission via point and line connections. The Journal of the Acoustical Society of America. 2012;132(2):814–21.