Passive noise control measures for Transportation noise abatement

The chapter investigates the passive noise control measures for transportation noise abatement with a major objective of strengthening the sound insulation of facades especially the window glazing. The work focuses on experimental and analytical studies for design and development of highly sound insulative window glazing for traffic noise abatement as windows is one of the weakest part of building facades. The design considerations involved in development of highly insulative sandwich window glazing is discussed based on application of Taguchi method and experimental investigations conducted in Reverberation chambers. Finally, the parametric sensitivity analysis of various factors affecting the sound insulation of multi-layered sandwich gypsum constructions using Taguchi method is discussed for the design and development of highly insulative constructions. The chapter highlights the application of dry wall technology for noise abatement and control.

7.1 Background

The control strategies focussing on strengthening the sound insulation of receiver i.e. dwellings so as to reduce the noise exposure and provide acoustic comfort to the residents are the last resort when there is no control neither at the source nor any treatment can be done on the pathway of sound propagation. As windows and doors are usually the weakest part of facades and partition systems, their acoustic performance often determines the acoustic performance of the whole facade. Thus, the focus of present work is on experimental and analytical studies for design and development of highly sound insulative window glazing for traffic noise abatement. Laboratory investigations in specialized Reverberation chambers in conjunction with theoretical studies in this regard for developing best sandwich dry wall constructions of high sound transmission loss for their applications as partition panels and windows in dwellings shall be instrumental as field studies for verification can only be pursued once the particular partional panel (or wall) is erected in actual.

Sound Transmission Loss (TL) or sound reduction index, $R$ is a performance of sound
insulation measured in reverberation chambers. Sound Transmission Class (or \( STC \)) is an integer rating of how well a building partition attenuates airborne sound \[40\]. The better the \( STC \) of materials, better the sound insulation it provides. This integer rating is widely used to rate interior partitions, ceilings/floors, doors, windows and exterior wall configurations in USA \[200\].

Window properties in addition to glass thickness, inter-pane spacing and treatment of cavity either with absorptive materials or simply air can appreciably affect the sound transmission loss. At low frequencies, it is affected by panel resonances depending upon the dimensions of glass panes and the edge constraints. Below the co-incidence frequency, both edge constraints (rigidly mounted, simply supported, etc.) and damping affects the sound transmission. Near and above the co- incidence frequency, the \( TL \) is strongly dependent on damping. Changes in \( STC \) of double glazing with glass thickness are 6 dB/doubling of thickness \[201\]. Quirt proposed that both double and triple glazing have a pronounced dip at the frequency \( f_0 \) where the mass-air-mass resonance is predicted for the double glazing. Above this resonance, the \( TL \) of double and triple glazing are virtually identical. Below this resonance, the triple glazing provides slightly larger sound transmission loss. For typical spacing of the two panes, the \( STC \) of double-glazed windows increases at 3 dB/doubling of the separation \[201\]. Tadeu \[202\] investigations on glazed solutions without frame reveal that double glazing only exhibits better insulation behaviour than single panels if air chambers are close to or greater than 50 mm thick, or if air chambers are very small. Brekke \[203\] investigated that for a symmetrical mass-spring-mass-spring-mass system, there are two fundamental resonances; the higher frequency is normally well above the range of interest and lower frequency corresponds to that predicted by equation (7.1).
where \( \mu_i \) is the mass per unit area of the two panels 1 and 2 and \( d \) is sum of two panel separations. Brekke also proposed the validity of this equation for the unsymmetrical partitions as well. Apart from the mass-air-mass resonance frequency, co-incidence frequency also plays a pivotal role in controlling the sound transmission through partition panels. The concept of co-incidence theory is that mechanical impedance of the plate equals to the bending impedance, leading to large vibration at the resonance. The partition panels thus radiate the acoustic wave in phase of transmitted sound waves at frequency \( f_c \) [204].

\[
f_c = \sqrt{\frac{c^2}{2\pi} \left( \frac{2\rho(2t_f + 2t_c)}{E_f t_f (t_f + t_c)^2} \right)}
\]  

(7.2)

The amount of resonance dip has been found to depend upon the damping of the panel above the co-incidence zone; the sound reduction index is calculated as [205]:

\[
R = 20\log \left( \frac{\pi f_m}{\rho c} \right) + 10\log \left( \frac{2\pi f}{f_c} \right)
\]  

(7.3)

where \( \eta \) is the loss factor and \( f_c \) is the critical frequency. Above the critical frequency, the insulation curves exhibit slopes with an inclination close to 9 dB/octave, as predicted by equation (7.3). The sound reduction index for the plane waves assuming grazing incidence follows the mass law [206] described as

\[
R = 20 \log (Mf) - 47 \text{ dB}
\]  

(7.4)

where \( M \) is the mass per unit area of panel in kg/m\(^2\) and \( f \) is frequency in Hz. This equation predicts an increase in the sound reduction index of about 6 dB for each doubling of the mass per unit area. The mathematical description of sound transmission loss observed in laboratory is a complex phenomenon although many of
the theoretical formulations have been developed for prediction. This is attributed to
the various factors viz., size of the partition panel and reverberation room, extent of
diffusion, low frequency resonances and co-incidence dip introduced at higher
frequencies. Improving the sound insulation of double glazing without increasing its
thickness or weight is one of the major challenges faced by industry. Near and above
the co-incidence frequency, the $TL$ is strongly dependent on damping, that depends
not just on losses in glass but on sound energy dissipated within the seals around the
window or transmitted to the supporting structure [207]. The sound insulation
characteristics of sandwich constructions has been a focus of study since past three
decades and variety of solutions have been provided by engineers to combat traffic
noise. However, the mitigation of low frequency noise (50 Hz to 200 Hz) has been
still a challenge for the acousticians.

The various factors controlling the sound insulation of windows as investigated in previous investigations by various researchers have been summarized
in cause and effect analysis diagram as shown in Fig. 7.1. A critical element of
successful window design is integration with adjacent wall components and proper
sealing to minimize flanking transmission. Double seals should be used between sash
and frame ensuring adequate sealing. Permanently sealed double-glazed windows
often require an air pressure control system to maintain a constant air pressure and
minimal moisture in the airspace. The difference between neoprene and putty
mounting is as much as 15 dB reported in co-incidence dip region [208]. The double
glazing has been the prominent solution for controlling the traffic noise although they
suffer from decrement on sound insulation at low frequencies attributed to mass-air-
mass resonance, wherein they become even worst than the single plates. Installation
of optimally tuned Helmholtz resonators (HR) to increase the acoustical damping
level inside the cavity between double plates is a plausible alternative for enhancing the low frequency insulation. Mao [209] devised three sets of HR to be installed in cavity of windows and found considerable improvement of 4-6 dB in region 50 Hz to 120 Hz. However, the high frequency sound insulation is not benefited owing to the second resonance of HRs around 400 Hz. Li et al. [210] demonstrated the effectiveness of T-shaped acoustic resonators (TAR) embedded along edges in low frequency sound transmission control of finite double partitions. Thus, the measurement of sound insulation of the windows by laboratory method serves as a benchmark in design and development of appropriate configurations for a noisy environment. Schumacher and Mechel [211] state the differences between the laboratory (random incidence) and field measurements are in the ± 5 dB range. The present study provides a theoretical and experimental grounds for the development of highly insulative window glazing. A parametric study of factors affecting the sound insulation using Taguchi method and experimental results conducted in Reverberation chambers for different window configurations is presented to identify the prominent factors affecting the sound insulation of double window glazing. The present study focuses on the laboratory sound insulation properties of the double glazing as laboratory experiments serves as a benchmark in design of improved constructions. The study analyze the performance characteristics of double glazing in terms of $R_w$, $(C, C_{tr})$ and STC rating. The relative importance of all these parameters on single-number rating is evaluated using Taguchi method. The study also utilizes validated software ‘Insul’ version 7.0.4 [212] to analytically predict the sound transmission and single-number rating associated with various configurations as experimental results are sometimes practically cumbersome and expensive to perform.
Fig. 7.1. Cause and Effect analysis diagram for enhancing the sound transmission loss of window glazing.

7.2 Parametric study for Window glazing

7.2.1 Introduction

The sound transmission through double glazing has always been a grey area of research for its applications in facades and windows in dwellings for outside traffic.
noise abatement. Double glazing has been a preferred alternative for windows and also used widely in building facades. Although glass facades aesthetically prove to be the best alternative for facades, yet the sound insulation characteristics especially in noisy areas is a topic of concern. Triple glazing has been reported to have approximately the same performance as double window with the same total mass and thickness [213]. The complexity of triple glazing and economic constraints limits their applications in practical situations. It is imperative to analyze the relative influence of the parameters affecting the sound insulation properties of double glazing for design and applications for achieving the desired objectives. Although the sound transmission loss in entire frequency range from 50 Hz to 5 kHz is important, yet dependence upon the single-number ratings has been a contemporary approach followed by manufacturers, engineers and even the acousticians too. The choice of appropriate single-number rating is however very important. The present study focuses on the laboratory sound insulation properties of the double glazing as laboratory experiments serves as a benchmark in design of improved constructions. The study analyzes the performance characteristics of double glazing in terms of $R_w$, $(C, C_n)$ and $STC$ rating. The relative importance of all these parameters on single-number rating is evaluated using Taguchi method, which is a well known method widely used in industrial engineering for optimization of process parameters. As the experimental results are practically cumbersome and expensive to perform, so validated software ‘Insul’ version 7.0.4 [212] was used to analytically predict the sound transmission and single-number rating associated with various configurations. Insul is software programme for prediction of sound insulation performance of walls, floors, ceilings and windows. It models materials using mass law and co-incidence frequency approach and models complex partitions using empirical models of Sharp,
Cremer and others [212]. The transmission loss of double panels system is divided into four different frequency regions whereby the effect of shear waves at high frequency is accounted for masonry constructions. The size of the sample was taken as 2.7 m × 4 m. The recent investigations by Kurra [214] and development of a prediction model for multi-layered building elements confirms the compatibility of Insul model with experimental data. The standard deviation of difference of measured and Insul predicted data is observed to be 4.5 dB. Ballagh [215] investigations evidently reveals a mean difference in $STC/ R_w$ between measurement and theory less than 0.5 dB and 90% of results were found to lie within ± 2.5 dB. These evidences confirm the suitability of the Insul software for pursuing analytical studies pertaining to optimization of the performance characteristics of partition panels.

7.2.2 Taguchi method

The Taguchi method developed by Genuchi Taguchi is a statistical method used to improve the product quality and is commonly used in improving industrial product quality [216]. Taguchi designs experiments using specially constructed tables known as “orthogonal array” (OA). The use of these tables makes the design of experiments very easy and consistent [217] and it requires relatively lesser number of experimental trials to study the entire parameter space. As a result, considerable savings in time, cost, and labour is achieved using this innovative technique. The statistical analysis of variance (ANOVA) is performed to investigate which process parameters are statistically significant.

The Taguchi technique includes the following steps:

- determine the control factors and their respective levels,
- select an appropriate orthogonal array,
• conduct the experiments as dictated by orthogonal array,
• analyze data using ANOVA and determine the optimal levels of control factors,
• investigate the relative influence of all these parameters
• perform the confirmation experiments and obtain the confidence interval,
• improve the quality characteristics through optimization.

7.2.3 Application of Taguchi method

Selection of control factors and their levels were made on the basis of preliminary experimental investigations conducted in Reverberation chambers at CSIR-National Physical Laboratory and also from the literature review on the subject. Four control factors viz., front pane thickness, back pane thickness, air-gap and type of lamination are selected for the investigation. Each of the four factors were considered at three levels as shown in table 7.1. The choice of three levels have been made because the effect of these factors on the performance characteristics may vary non linearly. The front pane thickness and back pane thickness was varied from 3 mm to 9 mm although for large thickness, co-incidence dip may have its impact on the high frequency sound transmission loss of double glazing. The range of air-gap selected was 30 mm to 90 mm. The choice of lamination was challenging as there has been various commercial products developed. The PVB glazing is currently manufactured and marketed by a number of companies in various brands viz., ‘S-Lec’ ‘Butacite’, ‘Solutia’, ‘Saflex’, ‘Trosifol’ etc. The present study considers ‘Trosifol’ lamination as one of the parameters. The experiments were designed based on the orthogonal array technique. Application of an orthogonal array interestingly felicitates the minimum number of test runs required to reach a conclusion with a particular
level of confidence, whereby effects of multiple process variables on performance characteristics can be estimated simultaneously.

**Table 7.1 Selected parameters at different levels.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Front pane thickness</td>
<td>9 mm</td>
<td>6 mm</td>
</tr>
<tr>
<td>B</td>
<td>Back pane thickness</td>
<td>3 mm</td>
<td>6 mm</td>
</tr>
<tr>
<td>C</td>
<td>Air-gap</td>
<td>90 mm</td>
<td>60 mm</td>
</tr>
<tr>
<td>D</td>
<td>Lamination type</td>
<td>PVB 0.38 mm</td>
<td>PVB 0.76 mm</td>
</tr>
</tbody>
</table>

An $L_9$ ($3^4$) standard orthogonal array [218] as shown in table 7.2 was used in present work. The array is most suitable to provide the minimum degrees of freedom as $9 \left[1+4\times(3-1)\right]$ required for an experimental investigation. Four control factors each identified at three levels can be investigated using $L_9$ orthogonal array, while the intersections are considered to be negligible. The array has 9 rows and 4 columns and each row represents an experimental run, while each column accommodates a specific process parameter. The factors investigated were identified as A, B, C and D and while conducting the experiment, all intersections amongst parameters A, B, C and D are ignored. The goal of the present work was to investigate about the double glazing configuration having maximum $R_w+C_r$ (or $R_w+C$, $STC$, $R_w$) value. So, larger-the-better quality characteristic was implemented in this study.
Table 7.2 $L_9 (3^4)$ standard orthogonal array.

<table>
<thead>
<tr>
<th>Experiment No.</th>
<th>Front pane thickness in mm (A)</th>
<th>Back pane thickness in mm (B)</th>
<th>Cavity depth in mm (C)</th>
<th>Lamination Type (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9</td>
<td>3</td>
<td>90</td>
<td>PVB 0.38</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>6</td>
<td>60</td>
<td>PVB 0.76</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>9</td>
<td>30</td>
<td>Trosifol SC interlayer</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>9</td>
<td>30</td>
<td>Trosifol SC interlayer</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>6</td>
<td>30</td>
<td>PVB 0.38</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>9</td>
<td>90</td>
<td>PVB 0.76</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>3</td>
<td>30</td>
<td>PVB 0.76</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>6</td>
<td>90</td>
<td>Trosifol SC interlayer</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>9</td>
<td>60</td>
<td>PVB 0.38</td>
</tr>
</tbody>
</table>

7.2.4 Analysis and Discussion

The analysis of variance (ANOVA) was also performed to investigate the relative influence of significant parameter. Table 7.3 shows the computed results for ANOVA analysis with 95% confidence level. The $F$-ratio and percentage contribution of the various single-number rating $R_w$ is quantified in table 7.3 at 95% confidence level. ANOVA usage in Taguchi methods can be seen as a two step procedure [219]. In the first stage, the variance due to the individual factors and all possible combinations of factors that were studied is computed. In the second stage, the variance due to any pair of factors (or combination) is compared. The analysis thus reveals the significant factors affecting the design output. The measure of relative significance is ascertained by an $F$-test, whereby the factors having high probability typically higher than 95% are confirmed as significant factors. The inactive and smaller effects are added together to obtain a non-zero estimate of the error variance called ‘pooling up’ which can be used to combine factors or interaction effects with low magnitude of sum of squares [216, 219].
Table 7.3 Results of Analysis of Variance (ANOVA) for $R_w$ of double glazing.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Degree of Freedom (DOF)</th>
<th>Sum of Squares ($S$)</th>
<th>Variance ($V_e$)</th>
<th>$F$-Ratio</th>
<th>Pure Sum of Squares ($S'$)</th>
<th>Percentage Contribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Front pane thickness</td>
<td>2</td>
<td>24.00</td>
<td>12.00</td>
<td>35.77*</td>
<td>23.333</td>
<td>15.98</td>
</tr>
<tr>
<td>B Back Pane thickness</td>
<td>2</td>
<td>28.667</td>
<td>14.334</td>
<td>42.73*</td>
<td>28.00</td>
<td>19.18</td>
</tr>
<tr>
<td>C Air-gap</td>
<td>2</td>
<td>92.667</td>
<td>46.334</td>
<td>138.11</td>
<td>92.00</td>
<td>63.01</td>
</tr>
<tr>
<td>Pooled error</td>
<td>2</td>
<td>0.667</td>
<td>0.336</td>
<td>2.67</td>
<td>1.83</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>8</td>
<td>146</td>
<td>146</td>
<td>146</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

From $F$-Table, $F_{0.05;1,2} = 18.5$

* Factors are significant at 95 % confidence level.

These analysis thus ascertained the more robust design configuration. The ANOVA analysis for $R_w$ value in table 7.3 reveals the type of lamination doesn’t play a significant role and thus contributes to the pooled error. Air-gap and back pane thickness evidently have a greater impact on the sound insulation performance of double glazing. A similar analysis was conducted for single-number rating $R_w+C_{tr}$ as shown in table 7.4. The type of lamination was also observed to be insignificant for $R_w+C_{tr}$ rating. However, the ANOVA analysis shows that the front pane thickness has slightly higher impact on the sound insulation performance for $R_w+C_{tr}$ rating. It may be noted here that these results don’t contradict with the principle of reciprocity. The higher impact of backpane thickness in controlling $R_w$ value and vice-versa in case of $R_w+C_{tr}$ rating needs further subtle investigations for analysis. There have been some experimental investigations reported [204] that confirm the prominent role of back pane thickness in controlling the co-incidence dip. It has been observed that co-
incidence dip shifts towards low frequency as back pane thickness increases, while it is independent of inter-pane distance [201,204]. The slightly higher significance of front pane thickness in $R_w+C_{tr}$ value may be attributed to the seriously affected low frequency sound insulation properties of front pane directly exposed to outside traffic noise.

**Table 7.4 Results of Analysis of Variance (ANOVA) for $R_w+C_{tr}$ of double glazing.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Degree of Freedom (DOF)</th>
<th>Sum of Squares (S)</th>
<th>Variance ($V_e$)</th>
<th>F-Ratio</th>
<th>Pure Sum of Squares ($S'$)</th>
<th>Percentage Contribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Front pane thickness</td>
<td>2</td>
<td>66.889</td>
<td>33.4445</td>
<td>65.333</td>
<td>26.75</td>
</tr>
<tr>
<td>B</td>
<td>Back Pane thickness</td>
<td>2</td>
<td>62.889</td>
<td>31.4445</td>
<td>61.333</td>
<td>25.11</td>
</tr>
<tr>
<td>C</td>
<td>Air-gap</td>
<td>2</td>
<td>112.889</td>
<td>56.4445</td>
<td>111.333</td>
<td>45.59</td>
</tr>
<tr>
<td></td>
<td>Pooled error</td>
<td>2</td>
<td>1.556</td>
<td>0.778</td>
<td>6.223</td>
<td>2.55</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>8</td>
<td>244.222</td>
<td>244.222</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

From $F$-Table, $F_{0.05;1,2} = 18.5$

* Factors are significant at 95 % confidence level

The percentage analysis observed in ANOVA analysis has been shown in Fig. 7.2 for various single-number rating $R_w+C_{tr}$, $R_w+C$, STC and $R_w$. It is evident that air-gap is the most significant factor followed by front pane thickness and back pane thickness. Only in case of $R_w+C_{tr}$ rating, front pane is slightly more prominent, while in case of STC, $R_w$ and $R_w+C$, back pane thickness has more significance. The type of lamination has not statistical significance except in case of STC rating (5.3 %). This may be attributed to the fact that laminated glass provide better sound control than
regular glass, but the improvement occurs only in frequency range of co-incidence effect [220].

Fig. 7.2. Evaluation of percentage effect using ANOVA of various parameters on single-number rating of double glazing.
These conclusions thus invite further analysis on the effect of these single-number ratings with changing the air gap. Consequently, an analysis was done on Insul software for predicting the $R_w$ value and $R_w+C_{tr}$ value for air-gap ranging from 10 mm to 100 mm and with identical glasses in double glazing. Fig. 7.3 shows the effect of changing the air-gap on $R_w$ value for various thicknesses. While designing the suitable glazing, the design factors are concentrated on shifting the mass-air-mass resonance frequency ($m.a.m$) less than 50 Hz. The analytical predictions reveal that the design target for achieving the $m.a.m$ resonance less than 50 Hz could be achieved with a double glazing with identical glasses of 9 mm thickness separated with 100 mm air-gap. The $m.a.m$ frequency analytically predicted for identical 3 mm glazing on both sides and 100 mm air gap is 84 Hz. For glazing with thickness ratio 1:2, the $m.a.m$ is calculated to be 73 Hz in case of double glazing comprising of 3 mm and 6 mm glass and 100 mm air gap, and 63 Hz in case of double glazing comprising of 4 mm and 8 mm glass and 100 mm air gap. The $m.a.m$ is analytically predicted to be 56 Hz for double glazing with 5 mm and 10 mm glass separated with an air gap of 100 mm.

![Fig. 7.3. Effect of air-gap on $R_w$ of double glazing.](image-url)
The regression fit for the single-number rating and variables air-gap ($d$) and thickness ($t$) of identical glass in a non laminated double glazing is modelled as:

$$R_w = 0.75t + 0.0836d + 31.41; \quad R^2 = 0.89$$  \hfill (7.5)

$$R_w + C_{tr} = 1.595t + 0.1107d + 18.29; \quad R^2 = 0.90$$  \hfill (7.6)

$$R_w + C = 1.027t + 0.093d + 27.17; \quad R^2 = 0.88$$  \hfill (7.7)

$$STC = 0.768t + 0.0949d + 30.60; \quad R^2 = 0.81$$  \hfill (7.8)

The regression for the single-number rating and variables air-gap ($d$) and thickness ($t$) of identical glass in a laminated (PVB 0.76 mm) double glazing is modelled as:

$$R_w = 1.146t + 0.092d + 30.169; \quad R^2 = 0.92$$  \hfill (7.9)

$$R_w + C_{tr} = 1.878t + 0.121d + 16.827; \quad R^2 = 0.92$$  \hfill (7.10)

$$R_w + C = 1.458t + 0.105d + 25.31; \quad R^2 = 0.91$$  \hfill (7.11)

$$STC = 1.182t + 0.101d + 29.57; \quad R^2 = 0.83$$  \hfill (7.12)

It may be noted that these empirical formulations are valid for range $30 \text{ mm} \leq d \leq 100 \text{ mm}$ and $3 \text{ mm} \leq t \leq 10 \text{ mm}$ with coefficient of determination ($R^2$) in each case is greater than 0.80.

![Fig. 7.4. Effect of air-gap on $R_w + C_{tr}$ of double glazing.](image-url)
Thus from the regression equations developed, a consideration on design target of $R_w+C_{tr}$ value of 35 for window glazing, reveals that this value can be achieved with a double glazing having identical 4 mm glass with an 85 mm air-gap, while for an average gap of 50 mm, a double glazing having 6 mm identical glass on each side can accomplish the desired objective. Fig. 7.4 shows the effect of air-gap on $R_w+C_{tr}$ value of different double glazing of varied thickness. A 7 dB increment in $R_w$ value is observed for 50 mm air-gap, while for an 100 mm air-gap, the increment observed is 5 dB. The increase in $R_w+C_{tr}$ is 12 dB for 100 mm air-gap, while this increment is 13 dB for 50 mm air-gap. The predicted mean for quality characteristic ($R_w+C_{tr}$ and $R_w$) is computed as [216]:

$$ (R_w+C_{tr})_{mp} = \bar{Y} + (A - \bar{Y}) + (B - \bar{Y}) + (C - \bar{Y}) + (D - \bar{Y}) $$  \hfill (7.13)

A 95 % confidence interval (CI) for the predicted means of optimum quality characteristic ($R_w+C_{tr}$ and $R_w$) is estimated using the following equations [216]:

$$ CI = \sqrt{F(\alpha,1,f_e)\bar{V}_e \left(\frac{1}{N_{eff}} + \frac{1}{R}\right)} $$  \hfill (7.14)

$$ where \quad N_{eff} = \frac{N}{1 + T_{DOF}} $$  \hfill (7.15)

where $F(\alpha,1,f_e)$ is F-ratio required for 100 (1-$\alpha$) percent confidence interval, $f_e$ is DOF for error, $\bar{V}_e$ is error variance, $R$ is number of repetitions for confirmation experiments (=1) and $N_{eff}$ is effective number of replications, $N$ is total number of experiments (=9) and $T_{DOF}$ is total degrees of freedom (=8) associated with estimate of mean optimum. From the table 3 and 4, the values are: $\bar{V}_e = 0.336$ for $R_w$ and $\bar{V}_e = 0.778$ for $R_w+C_{tr}$, $f_e=2$ and from standard statistical table, the required F-ratio for $\alpha = 0.05$ is $F_{0.05;1,2} = 18.5$. Substituting these values in equations (7.14) and (7.15), the calculated CI is ± 3.52 for $R_w$ and 5.37 for $R_w+C_{tr}$ rating. Thus 95 % confidence level of the predicted $(R_w+C_{tr})_{mp}$ value is $(46 \pm 5.4)$ dB and $R_{w,mp}$ is $(50 \pm 3.5)$ dB. The
confirmation experiment was performed by analytically predicting the single-number rating for optimal configuration \((A_1B_3C_1D_3)\). The optimum configuration has \(R_w\) value of 49 and \(R_w+C_r\) value of 44, which lies within the predicted range from Taguchi method.

7.3 Experimental Investigations on Window glazing

7.3.1 Measurement of Sound Transmission Loss

Sound transmission measurements in the present work were made in Reverberation chambers at CSIR-National Physical laboratory, India [221,222]. The source room has a volume of 257 m\(^3\) and receiving room of 271 m\(^3\). Test specimens were mounted in an opening 1 m\(^2\) between the source and receiving room. Both the source room and the receiving room of the Reverberation chambers are irregular in shape with no parallel surfaces and are equipped with stationary diffusers. The volume of the chamber is 257 m\(^3\) and dimensions are 6 m × 6.5 m × 7 m. The reverberation chamber is a room within another room, both rooms being reinforced concrete. The outer room has a floor slab 300 mm thick supported on folded RCC plates and wall and ceilings are 125 mm thick. The inner room is floated on a 150 mm thick bed of coarse dry sand washed free of mud and silt. The sand bed is initially covered with 50 mm thick fiberglass and 25 mm thick particle board. The walls of inner chamber are 125 mm thick RCC resting on the floated floor made of highly polished terrazzo concrete. Imparting high polish to the surfaces, the viscous drag and thereby energy loss is minimized. The measured value of reverberation time for empty room within a standard deviation of ± 0.1 seconds at all frequencies is shown in Fig. 7.5. The walls, floor and ceiling are non parallel, the average inclination between the walls being 6° and between floor and ceiling 2° to 3°. To prevent the
resonance modes, the 125 mm cavity between the inner and outer walls is partially filled with mineral wool blanket to cover 30 % of the area. The ceiling of inner chamber is made of polished stone slabs 50 mm thick resting on steel girders and the plenum between the inner ceiling and outer room roof slab is partially filled with mineral wool to damp out resonance modes in this space. The sound source installed in the room consists of twelve 100 mm × 150 mm elliptical speaker units mounted in a dodecahedral enclosure fed through a power amplifier delivering up to 20 W (rms) output. The distribution within the room of sound level of filtered band of white noise is within ± 0.5 dB at high frequencies and within ± 1 dB at low frequencies. Diffusing plates have also been additionally suspended from ceiling and oriented at random to enhance the state of diffusion in the room. The standard deviation of correlation coefficient \( \frac{\text{Sinkr}}{k_r} \) was measured to be within ± 0.06 in frequency range 100 Hz to 125 Hz [7]. A diffuse field can be established in a rectangular room if there is at least 20-30 modes in the measurement bandwidth, and there is at least one mode per Hz. In the present case, \( \Delta N \) (number of modes) has the value 21 for \( f = 100 \text{ Hz} \) and \( \Delta f = 13 \) Hz (1/6 octave bandwidth).

Fig. 7.5. Reverberation time (in seconds) measurements for empty room.
A steady sound source of white noise was produced from noise generator, the noise signal was fed into and enhanced by a power amplifier, and finally emitted through a loudspeaker to produce a reverberant sound field inside the source room as shown in Fig. 7.6 [223]. A random incidence microphone placed on a rotating boom measured the spatial averaged sound pressure level in both the rooms. The samples were carefully mounted and caulked with silicone sealant to avoid any acoustic leaks.

The sound pressure in both the rooms was measured using two condenser microphones (B&K 4165) and a real time analyzer (Norwegian, 830) traceable to the national standards realized at CSIR-NPL, India. Measurement of sound pressure and reverberation time are made for the standard 1/3rd-octave bands with center frequencies from 100 Hz to 4000 Hz. Adequate diffusion existed in chambers while conducting the measurements [7]. The measured sound pressure differences were corrected for the equivalent absorption of the receiving rooms and test specimen area to yield transmission loss for each frequency band as specified in ASTM E90. The transmission loss is calculated as:

\[ TL = L_1 - L_2 + 10 \log_{10} \left( \frac{S}{A} \right) \text{ dB} \quad (7.16) \]

where \( L_1 \) and \( L_2 \) are the average sound levels (dB) in the source and receiving room, \( S \) is area of panel and \( A \) is total absorption of the receiving room. The evaluated uncertainty in measurement of sound transmission loss is ± 3 dB for 100 Hz, ± 2.7 dB in frequency range 125 to 200 Hz, and ± 2.0 dB in frequency range 250 Hz to 3.15 kHz and ± 2.5 dB at 4 kHz lower at a coverage factor of \( k=2 \) and a coverage probability of 95 % confidence level for normal distribution [224]. A sound transmission class rating (STC) is obtained for each panel in accordance with ASTM standard classification E413 [40]. The weighted sound reduction index, \( R_w \) is determined in accordance with ISO 717-1 [5].
7.3.2 Sound transmission through different configurations of Window glazing

Different configurations of windows based on their applications were tested in laboratory. The alphabetical nomenclature was used to differentiate between the various configurations for clarity and to avoid any ambiguity. Window type A was fabricated with size 920 mm× 620 mm and aperture size 930 mm × 630 mm. This configuration was designed on basis of a slider two track two panel without bug screen with clear float glass of size 368 mm × 301 mm and varied thickness with damped edges in window frame. The type B configuration was an open design with window size 920 mm × 620 mm and aperture size 930 mm × 630 mm. Clear float glass of varied thickness and size 730 mm × 430 mm with edges damped in window frame was used in this design. Another configuration type D similar to type B, but in a fix position were fabricated and tested in laboratory for their performance with...
window size 920 mm × 620 mm and aperture size 930 mm × 630 mm. This configuration used clear float glass of various thickness and size 832 mm × 532 mm with edges damped in window frame.

Fig. 7.7. Window configurations A, B, D and E tested; Type E (Left), Type A (in middle), Type B (in RHS), Type D (not shown) resembles type B; with a difference that it’s a fix design.

Window type E with open design of size 890 mm × 590 mm and aperture size 930 mm × 630 mm and float glass of various thickness and size 700 mm × 400 mm with edges damped in window frame was also fabricated and tested for their performance. Each sash was held firmly in position and butted against a wooden positioning strip fastened to frame and cracks around the perimeter were sealed using silicone sealant. Fig. 7.7 shows the type A, B and E windows; type D resembles type B window with a difference that it’s a fix design. An experimental investigation was performed for the type B window configuration of size 920 mm× 620 mm and aperture size 930 mm × 630 mm with different thickness of clear float glass. Fig. 7.8 shows the sound transmission loss observed with different glass thickness. It could be observed that with the increase in thickness of the glass, the weighted sound reduction index, $R_w$
value increases in accordance with the mass law. The co-incidence frequency is observed to be shifted to a lower frequency region with the increase in thickness. The test on 8 mm clear float glass without window frame revealed loss in insulation attributed to no damping provided by glass edges causing pronounced effect of co-incidence.

![Graph showing sound transmission loss of clear float glass of Type B configuration and varied thickness.]

**Fig. 7.8.** Sound transmission loss of clear float glass of Type B configuration and varied thickness.

The co-incidence frequency is calculated from expression [225]:

\[
f_c \approx \frac{12}{t} \approx \frac{3.4 \times 10^4}{\mu}
\]  

(7.17)

where \( t \) is thickness and \( \mu \) is mass per unit area. The experimentally observed \( f_c \) is in good agreement with the above equation. Another test was performed in reverberation chamber for characterizing the sound insulation characteristics for laminated construction with an open design. It can be observed from Fig. 7.9 that coincidence dip in case of 8 mm thick glass (Fig. 7.8) is arrested in case of 4 mm + 0.76 mm PVB
+ 4 mm configurations although the $R_w$ value ($R_w = 34$ dB) is same. Lamination consists of bonding two or more lites of glass together with one or more layers of plastic material thus producing a damping effect. The most commonly used laminate material for acoustical glazing is Polyvinyl butyral (PVB).

Fig. 7.9. Sound transmission loss of single glazing with PVB lamination of Type B configuration (open design).

It has been reported that laminated glass provides better sound control than regular glass of same total thickness, but the improvement occurs only in the frequency range of the co-incidence effect [220]. A fix design with window size 920 mm $\times$ 620 mm and aperture size 930 mm $\times$ 630 mm was tested in laboratory to characterize the sound insulation. As is obvious, the sound insulation provided by the fix design was observed to be better than the open configuration. Fig. 7.10 shows the sound transmission loss observed in laboratory for type D configuration.
Fig. 7.10. Sound transmission loss of clear float glass of Type D configuration and varied thickness.

Fig. 7.11 shows the sound insulation characteristics of window type E with open design of size 890 mm × 590 mm and aperture size 930 mm × 630 mm and float glass of varied thickness and size 700 mm × 400 mm with edges damped in window frame.

Fig. 7.11. Sound transmission loss of clear float glass of Type E configuration (open design) and varied thickness.

In continuation with the various designs tested at laboratory, a slider window design widely used in dwellings due to aesthetic considerations in recent times was tested for
their performance. Window was fabricated with size 920 mm× 620 mm and aperture size 930 mm × 630 mm. This configuration was designed on basis of a slider two track two panel without bug screen with clear float glass of size 368 mm × 301 mm and varied thickness with damped edges in window frame.

It can be observed from Fig. 7.12 that the sound insulation is poor as compared to other designs attributed to the flanking transmission around the corners due to slider window panes in the frame. The $R_w$ value observed in each case was 22 ± 1 even with an introduction of air gap and laminated PVB glazing, which concludes that such type of configuration shouldn’t be preferred for noisy ambience.

Fig. 7.12. Sound transmission loss of clear float glass of Type A configuration with double and triple glazing.

7.3.3 Sound transmission through double & triple glazing

The sound insulation characteristics of double and triple glazing have been proven by various studies to be much better than the single configurations. A variety
of double and triple glazing were fabricated and tested to investigate the effect of widening the air gap, provision of lamination of thicker PVB layer and introduction of inert gas in cavity along with varied thickness of clear float glass. Fig. 7.13 shows the laboratory results for an open design double glazing. The 5 mm layer clear float glass with 1.52 mm PVB sandwich construction provided a better insulation as compared to the other attributed to the reduction in co-incidence dip introduced by thicker lamination of 1.52 mm PVB. The low frequency sound insulation is improved in this case to around 3 dB due to addition of damping layer leading to shifting of mass-air-mass resonance frequency to low frequency region below 100 Hz. However, the results were still not very optimistic in the low and medium frequency range in accordance with the mass law.

Fig. 7.13. Sound transmission loss of sandwich construction of clear float glass with PVB lamination and air gap of Type B configuration (open design).

The trend of approximately 3 dB per doubling of air chamber thickness has been pointed out in many previous studies. So, different sandwich constructions were fabricated and tested to ascertain their performance and substantiate theoretical
predictions. The effect of widening the air gap was analyzed by testing different 6 mm clear float glass double leaf construction with varied air gap of 12 mm, 30 mm and 85 mm. The narrow air space between the panes doesn’t provide improved insulation although increase in sound insulation with increased air gap is evident. At low frequencies, mass-air-mass resonance has most influence as can be seen in Fig. 7.14.

![Sound transmission loss comparison of triple & double glazing constructions of clear float glass with air gap of Type D configuration.](image)

An interesting observation could be noticed about the addition of laminated layer reduces the resonance dip, but couldn’t virtually eliminate it. The insulated glazing shows a low frequency dip due to mass-air-mass resonance, but the depth of the dip is much reduced, presumably due to added damping of inner layer. The lowest frequency of mass-air-mass resonance occurs for normal incident sound is calculated as [226]:

```
0 5 10 15 20 25 30 35 40 45 50 55 60
100 125 160 200 250 315 400 500 630 800 1000 1250 1600 2000 2500 3150 4000
```

Frequency (Hz)
\[ f_0 = 1150 \sqrt{\frac{t_1 + t_2}{t_1 t_2 d}} \]  

(7.18)

where \( t_1 \) and \( t_2 \) are thickness of the two glass layers and \( d \) is their separation, all in mm. The resonance frequency \( f_0 \) calculated from equation (7.18) gives value of \( f_0 \) to be approximately 200 Hz for 12 mm air gap and 120 Hz for an air gap of 30 mm consistent with the laboratory results. Both flexural resonances and mass-air-mass resonances contribute to decrease in \( TL \) at low frequencies. Theory predicts that for the frequencies immediately following the mass-air-mass resonance, the \( TL \) increases at 18 dB/octave.

With the widening of air gap to a considerable extent, the low frequency resonance is virtually gone, and there exists an improvement in sound transmission loss in the whole frequency range. It can be observed that with an air gap of 85 mm, the value of \( f_0 \) comes out to be 72 Hz, which lies beyond the region of experimentation. Thus, it can be inferred that the widening of air gap is more prominent than the damping provided by laminated layer in affecting the sound transmission characteristics of the glazing.

![Graph showing sound transmission loss](image)

Fig. 7.15. Sound transmission loss of sandwich construction of clear float glass with Argon and vacuum in air gap of Type D configuration (fix design).
An experimental investigation was carried out with cavity filled with inert gas like Argon and another with vacuum created in the cavity. The cavity was filled with inert gas like argon to reduce heat loss by slowing down convection in the air space as argon has 34\% lower thermal conductivity than air. However, there was no substantial change in sound insulation observed as shown in Fig. 7.15. The low frequency resonances at 160 Hz, 250 Hz and 400 Hz and co-incidence dip at 2 kHz leads to degradation in insulation characteristics of this configuration with presence of argon although the resonance dip is more pronounced in case of air in the cavity. In case of vacuum in the cavity, an unambiguous behaviour of pronounced mass–air–mass resonance at 160 Hz was observed, which leads to conclusion that vacuum in the small window cavity doesn’t seem to sustain.

Another test was performed to evaluate the extent of reduction in the resonance dip inculcated by the damping layer introduced in the glazing as shown in Fig. 7.16, whereby both resonance and co-incidence dips are arrested.

![Figure 7.16](image)

**Fig. 7.16.** Sound transmission loss of sandwich construction of clear float glass with PVB lamination and air gap of Type D configuration (fix design).
It can be noticed (Fig 7.16) that both the resonance and co-incidence dip are significantly arrested by the damping layer provided causing an overall increase in the sound transmission loss in the whole frequency range.

Experimental investigations carried out on different double glazing with air gap less than 30 mm revealed a pronounced dip attribute to mass-air-mass resonance at lower frequencies. These laboratory results (Fig. 7.17) are in consistent with the theoretical formulations proposed for empirically calculating the mass-air-mass resonance. Thus, the design considerations should be focused to choose an air gap between 30 mm and 100 mm. Widening the air gap above 100 mm, however has a negative impact on high frequency sound insulation observed in many studies attributed to the standing wave resonances induced in the cavity.

![Fig. 7.17. Sound transmission loss of double window glazing with air gap less than 30 mm.](image)
The effect of widening the air gap was further investigated by introducing an average air gap of 85 mm between two glazing of varied thickness installed in separate frames, and two glazing not exactly parallel to each other as shown in Fig. 7.18. This unexpected saturation observed in case of 8 mm + 8 mm configuration may be attributed to the pronounced co-incidence dip introduced by the two 8 mm thick glass in front and back panes at 1.6 kHz and 3.15 kHz, leading to lowering of the sound transmission loss in vicinity of co-incidence dip. The critical frequency marks the beginning of co-incidence phenomenon and as such in this case it starts at 1.6 kHz causing an unexpected loss of high frequency insulation of the double glazing. An unexpected reduction of 7 dB is observed due to pronounced co-incidence dip introduced by two 8 mm glass panes.

Fig. 7.18. Sound transmission loss of double glazing construction of Type D configuration (fix design) with 85 mm air gap in each case.

The benefit of widening the air gap introduced in double leaf construction evident from the experimentation was utilized in construction of a sandwich window system with either one double glazing or both double glazing. A window configuration of 5
mm clear float glass with an 85 mm air gap and 10 mm clear float glass with 6 mm air gap and 8 mm clear float glass (size 832 mm ×532 mm) with damped edges in window frame was fabricated and tested. Another sandwich construction of 10 mm and 8 mm double glazing separated with an air gap of 6 mm and attached with 85 mm air gap to a single glazing of 5 mm thickness was tested in laboratory. The experimental results as shown in Fig. 7.19 show a significant increase in the transmission loss of these configurations. An interesting observation was noticed that with the thicker pane on front side, the higher frequency insulation was enhanced by maximum 2 dB, while in case of thinner 5 mm pane kept on front side; the low frequency insulation was slightly improved although it registered a resonance dip at 160 Hz.

Fig. 7.19. Sound transmission loss of improved sandwich constructions of Type D configuration (fix design) with high $R_w$.

Another window with two double glazing in separate frame viz. 6mm clear float glass with 12 mm air gap and 6 mm clear float glass with 85 mm air gap and 10 mm clear
float glass with 6 mm air gap and 8 mm clear float glass (size 832mm × 532 mm) with damped edges in window frame was tested. A resonance dip at 160 Hz could also be observed in this case.

It can be concluded that a significant increase in sound insulation is observed at higher frequencies when either one glazing is double or both are double. The average sound insulation is however same in both the cases. Such a combination could be the best possible solutions for applications in exteriors of building facades in noisy environment and where the honking noise component is dominant in road traffic noise.

7.3.4 Results and Discussion

The mass law predicts a 6 dB increase in sound insulation when the mass of the panels is doubled. However, this much increment couldn’t be realized in practice due to the resonance and co-incidence effects. In case damping is provided at the edges, it can reduce the reflection of waves at its boundaries and can lead to better results. It is evident from the experimental results that with the increase in air gap, the sound insulation performance increases. Thus, for achieving a higher sound transmission loss, it is advisable to use an air gap of 100 mm as reported in many studies. The increase is air gap is limited by the reflections of waves in the cavity giving rise to stationary waves formation for frequencies above \( f = c/2d \) and cavity in that case can be regarded as a reverberant space. The present work shows a sufficiently higher transmission loss in whole frequency range could be achieved by an air gap of 85 mm. In case of cavity not filled with absorptive material, the sound transmission depends not only on inter-pane spacing but also on width and height of cavity relative to wavelength. For frequencies below \( f = c/2d \), Brekke proposed that the analogy between cavity and reverberant room can’t be justified and sound field is
treated theoretically as two dimensional standing wave system. The experimental results show a significant improvement of insulation close to 3 dB per doubling of air chamber thickness for frequencies $f > c/2d$. The experimental results of Quirt and Tadeu conclude that sound transmission loss is very similar when combined inter-pane spacing of triple window matched the double glazing. The triple glazing however exhibit consistently higher transmission loss both at frequencies below the mass-air-mass resonance and in vicinity of co-incidence dip. The TL of double glazing can be optimized by optimizing the thickness and depth of air space to bring the mass-air-mass resonance below 100 Hz. The laminated glazing is observed to be a better option than conventional ones as the co-incidence dip could be controlled by providing laminations of increasing thicknesses. Fig. 7.20 shows the co-incidence frequency variation with the back pane thickness for the experimental findings in comparison with the co-incidence frequency calculated from relationship proposed by Kim et al. 2002 [204].

$$f_c = \frac{c^2}{2\pi} \sqrt{\frac{12\rho}{E}} \quad (7.19)$$

where $\rho$ is volume density, $t$ is thickness and $E$ is modulus of elasticity of material. The co-incidence dip will move to lower frequency as the glass thickness is increased, more towards the region where the human ear will have increased perception. The co-incidence dip as reported by Kim et. al. 2002 [204] is dependent upon the back pane thickness in double glazing as the co-incidence dip shifts to a lower frequency with the increase in back pane thickness independent of inter-pane distance. The present experimental investigations shows concurrence with Kim et al. studies in validating the fact that with the increase in back pane thickness, the co-incidence dip shifts to a lower frequency.
The inter-pane distance has also been reported by Kim and Quirt to be non effective in controlling the co-incidence dip. The experimental and theoretical predictions differ sometimes from the actual results due to the baffle or niche effect and sealing loss [227]. The low frequency sound insulation is known to be worse for specimens placed at center than for specimens mounted at the edge of aperture. The difference in sound transmission loss for centre and edge locations of specimen describes the niche effect which depends upon the aperture dimensions and sound frequency. If aperture area is 1-2 m², the calculated niche effect can be 5-7 dB for $S = 1$ m² and 2-3 dB for $S = 2$ m². The sealing of the window has great importance in sound insulation provided by window. The higher the $STC$ of a sealed window, the more it is decreased by a given sound leak. The approximate reduction in the $STC$ is given by the expression [226].

$$10 \log_{10} \left[ 1 + .012 (L/S)10^{STC/10} \right]$$

(7.20)

where $L$ is air leakage at a pressure of 75 Pa, $S$ is the window area in m², and $STC$ is the rating for the sealed window. The frames and panes should be completely isolated.
from each other using neoprene type material to avoid sealing loss. The loss of sound insulation in type B window is over mid frequency range due to poor sealing. The difference between neoprene and putty mounting is as much as 15 dB reported in coincidence dip region [228]. The average sound insulation loss observed for type B window for single and double glazing is by causing approximate 0.1 % aperture and for triple glazing due to 0.1 % aperture at periphery with respect to an overall panel area.

7.4 Sound insulation provided by dry wall technology

A dry wall is a high performance light weight partition system consisting of GI steel frame, encased with gypsum plasterboards on either side attached through self-drilling drywall screws. The joints are then taped and finished with gypsum jointing compounds [229]. The dry wall technology has many advantages compared to the masonry constructions as follows:-

- Speed of installation is 3 to 4 times faster than masonry constructions,
- Lighter in weight than masonry constructions,
- Consumes less water than masonry constructions,
- Seamless and crack free surfaces, allowing ease of decoration via paint, tiles or wallpapers,
- Higher sound insulation and fire resistance, and
- Versatility, recyclable and less heat convection (0.16 W/m K) as compared to the brick wall (0.81 W/m K).

The sound insulation property of dry wall technology is excellent and thus sandwich constructions can be very helpful for noise abatement and control. Some of these sandwich constructions tested at Reverberation chambers at CSIR-National Physical
Laboratory, India (also named as CSIR-NPL) are enlisted in Appendix III. Fig. 7.21 shows the comparison of sound insulation properties of two such sandwich dry wall constructions tested by Halliwell [230] in comparison to that of concrete block of 90 mm and 190 mm thickness tested by Warnock [42]. G13-WS90(406)-GFB90-RC13(610)-G13 sandwich construction consists of one single layer of 13 mm gypsum board each side with 90 mm wood studs at 406 mm on centre and 90 mm glass fibre insulation with resilient channel at 610 mm on center. 2G16-SS90(610)-GFB90-2G16 sandwich construction consists of two layers of 16 mm gypsum board each side with 90 mm steel studs at 610 mm on center and 90 mm glass fibre insulation in cavity. It can be observed that sandwich constructions have good sound insulation properties in frequency range 125 Hz to 2 kHz; whereby in low frequency region, the sound insulation is degraded due to mass-air-mass resonances; while at high frequencies it is affected due to the coincidence effect. The sound insulation provided by the drywall constructions can be however significantly enhanced by combination with masonry constructions for its suitability for building facades.

![Graph showing comparison of sound transmission loss properties of dry wall constructions tested by Halliwell [230] with that of concrete block [42].](image_url)
7.5 Parametric study for Multi-layered building elements

7.5.1 Introduction

The sound transmission through masonry constructions has always been a grey area of research for its applications in facades and walls in dwellings for outside noise abatement. However, there are not many studies reported so far except those reported by National Research Council (NRC), Canada that focussed on the enhancement of sound transmission loss through masonry walls in conjunction with the dry wall technology. Warnock et al., 1990 [42] and National Concrete Masonry Association [231] reports in this regard provides a large data bank on sound transmission through concrete blocks attached with gypsum boards. The recent studies conducted by Rasmussen et al. [232,233] and Scholl et al., 2011 [234] pertaining to the sound regulation criteria in terms of Weighted Standardized Field Level Difference $D_{nT,w}$ and recommendation of fulfilling the criteria $D_{nT,w}+C_{50-3150} \geq 55$ dB thus essentially implicates the need of experimental investigations for measuring the sound transmission loss of masonry structures in conjunction with dry wall technology. These investigations are essentially required to ascertain their suitability of meeting the acoustic comfort criteria with an objective of strengthening the building facades. The importance of strengthening the facades is evident from Norwegian study (Amundsen et al., 2011) wherein for noise reduction of 7 dB inside the dwelling, the percentage highly annoyed respondents dropped from 42 to 16 percent [235]. The experimental investigations on massive concrete and plastered brick structures are practically cumbersome, expensive and time consuming. Thus, the theoretical validated prediction models can be utilized to fill this gap and investigate the pivotal factors affecting the sound transmission loss in terms of single number rating. The
method of attachment of gypsum boards via steel studs (staggered, with resilient channels or via double studs), stud spacing, thickness and density of absorptive material used etc are the pivotal factors to be investigated for ascertaining their significance in controlling the sound insulation. All these factors influencing the sound insulation characteristics of multi-layered building elements especially as reported in terms of widely used Sound transmission Class (STC) rating have been shown in a cause-and-effect analysis diagram (Fig. 7.22) based on exhaustive literature survey [42,236-244] and practical experiences gained in sound transmission loss testing. Influence of air-cavity on sound reduction index has been found to be dependent on frequency. Attachment via resilient channels and steel studs is instrumental in increasing sound transmission loss. Non-load-bearing steel studs are usually resilient enough to provide adequate mechanical decoupling between layers of gypsum board, while for load bearing steel studs; good results are obtained by use of resilient channels [239].

Addition of absorptive material in cavity is beneficial only if structural connections between the surfaces don’t transmit much vibrational energy. The stud spacing has been investigated to modify the low frequency resonance dips. Structural breaks are achieved by adding gypsum boards using resilient channels or staggered stud constructions. The addition of resilient channels although eliminates the primary structural resonance at 125 Hz, but also introduces a modified mass-air-mass resonance (Bradley et al., 2001 [237]). Stud spacing is however not so important in walls where there is a structural break. Increasing the number of gypsum board layers significantly improves the sound transmission loss characteristics due to increased mass resulting in increment of weighted sound reduction index, \( R_w \) value by 8-9 dB as

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observed experimentally in case of changing from one layer to two layers each side attached via steel studs 610 mm apart.

**Cavity depth**

- **Mass-air-mass resonance**
  
  \[
  m.a.m = \frac{m_1 + m_2}{dm_1m_2}
  \]

  - At low frequencies, better performance achieved for thicker layer, while at higher frequencies thinner air-gap is preferable

- **Doubling of cavity depth increases STC by 10 points**
  
  When filled with absorptive material

- **Air-space between a single layer of wall board & masonry concrete should be at least 60 mm for m.a.m < 80 Hz**

- **Staggered stud reduces direct connection & are more effective than constructions with resilient channels**

- **Double studs decouple the two sides of wall & provide better performance**

- **Increasing stud size lowers the frequency of primary structural resonance & increasing the stud spacing leads to even larger reduction in resonance frequency**

- **Adding resilient channels eliminates primary structural resonance but adds a much lower frequency m.a.m resonance**

**Sound Absorbing material in cavity**

- **Maximum increase in TL due to resilient channels is 15 dB for cavity depth > 75 mm & cavity filled with sound absorbing material**

- **Effective stiffness of resilient channel with 610 mm spacing is equivalent to stiffness of 160 mm air cavity**

- **STC increases by one or two points when going from 400 mm to 600 mm spacing**

- **Stud spacing is not important in walls with structural breaks**

- **Use of double studs, staggered studs (with or without resilient channels), Non-load-bearing steel studs, wood studs with resilient channels or load-bearing steel studs with resilient channels**

- **Adding sound absorbing material in cavity lowers m.a.m can’t be separated & TL is significantly high**

- **Double studs decouple the two sides of wall & provide better performance**

- **Maximize structural connections & all elements should be thoroughly caulked**

**Enhanced Sound Insulation performance of multi-layered Building Elements**

- **STC increments by one point on changing from 13 mm gypsum board to 16 mm, two layers each side connected via steel studs 610 mm apart**

- **STC increments by 6 points on changing from 13 mm gypsum board to 16 mm, two layers each side connected via steel studs 406 mm apart**

- **Coincidence dips control by damping material**

- **Use of two gypsum boards with different thickness & physical characteristics to control the coincidence dip**

- **Effective stiffness of resilient channel with 610 mm spacing is equivalent to stiffness of 160 mm air cavity**

- **Maximum increase in TL due to resilient channels is 15 dB for cavity depth > 75 mm & cavity filled with sound absorbing material**

- **Adding absorptive material in cavity lowers m.a.m resonance frequency**

  \[
  f_{m.a.m} = \frac{43}{\sqrt{Md}}
  \]

  - for cavity filled with absorptive material, \( d \) is depth of cavity (m) & \( M \) is mass of dry wall in kg/m²

- **Doubling of cavity depth increases STC by 4 points when not filled with absorptive material**

- **When airspace is filled with sound absorbing material, both cavity resonance of slotted concrete blocks & m.a.m can’t be separated & TL is significantly high**

- **Adding sound absorbing material in cavity lowers resonance**

- **Use of double studs, staggered studs (with or without resilient channels)**

- **Non-load-bearing steel studs, wood studs with resilient channels or load-bearing steel stud with resilient channels**

**Fig. 7.22. Cause-and-Effect analysis for enhancing sound transmission loss of multi-layered building elements.**
$R_w+C_{tr}$ rating is laboratory tested corresponding single-number quantity suitable for building facades for evaluating their sound insulation towards traffic noise. The prescriptive approach for walls between dwellings specified for deemed-to-satisfy provisions in Building Codes of Australia has been fixed to $R_w+C_{tr}$ not less than 50 when tested in laboratory and $D_{nt,w}+C_{tr}$ not less than 45 when tested on-site [245]. Masonry constructions have been shown to have good low frequency sound insulation characteristics and an $R_w+C_{tr}$ value of 69 ($STC=79$) has been experimentally tested for two-leaf concrete block walls [42]. The drywall technology alone suffers from poor low frequency sound insulation characteristics. Even addition of two layers of Oriented stranded boards with two gypsum board layers attached via 140 mm staggered wood studs and 65 mm glass fiber batt included in cavity shows an $R_w+C_{tr,50-5k}$ value of 35 dB [236]. Thus, a sandwich multi-layered massive construction with drywall attached is a good substitute although practically cumbersome and expensive. Guillen et al., 2008 [46] observations in this context have revealed that masonry-air cavity-gypsum walls have higher sound reduction index than masonry-air cavity-brick ones.

The present study focuses on evaluating the parametric sensitivity of all the factors affecting the sound insulation characteristics of multi-layered building elements consisting of concrete wall constructions attached with gypsum boards. The relative importance of all these parameters on single-number rating $R_w (C, C_{tr})$ in frequency range 100 Hz to 3150 Hz is evaluated in terms of percentage contribution using Analysis of variance (ANOVA). As the experimental results are practically cumbersome and expensive to perform, so validated software ‘Insul’ version 7.0.4 was used to analytically predict the sound transmission and single number rating associated with various configurations. Thus, the focus of the present work was to
utilize the numerical results predicted from the Insul software in conjunction with
application of well known technique of industrial engineering i.e. taguchi method for
optimization of sound transmission loss of multi-layered constructions.

The selection of an appropriate orthogonal array (OA) requires prior
estimation of degrees of freedom. The analysis of variance (ANOVA) was used to
investigate the significance of design parameters significantly affecting the quality
characteristic, which is accomplished by separating the total variability of the S/N
ratios, measured by the sum of the squared deviations from the total mean S/N ratio,
into contributions by each of the design parameters and the error. The total sum of
squared deviations from means (SS_T) can be calculated as [218]:

$$SS_T = \sum_{i=1}^{n} y_i^2 - \frac{1}{n} \left[ \sum_{i=1}^{n} y_i \right]^2$$  \hspace{1cm} (7.21)

where $n$ is number of experiments in the orthogonal array (e.g. 8 in $L_8$ OA) and $y_i$ is
resultant output ($R_w+C_{tr}$ & $R_w+C$) for $i^{th}$ experiment. The total sum of squared
deviations is decomposed into two sources: the sum of squared deviations due to each
design parameter and the sum of squared error. The sum of squared deviations due to
each process parameter (SS_p) is calculated as [218]:

$$SS_p = \sum_{j=1}^{t} \left( \overline{y}_{ij} \right)^2 - \frac{1}{n} \left[ \sum_{j=1}^{t} \sum_{i=1}^{n} y_{ij} \right]^2$$ \hspace{1cm} (7.22)

where $p$ represents one of the experimental parameters, $j$ is the level number of this
parameter $p$, $t$ is the repetition of each level of parameter, $\overline{y}_{ij}$ is sum of output
involving this parameter $p$ and level $j$. The sum of squares for each error parameter
(SS_e) is in $L_8$ OA considering seven parameters at two levels is then calculated as:

$$SS_e = SS_T - \sum_{i=1}^{7} SS_i$$ \hspace{1cm} (7.23)
where SS is sum of squared deviations due to each of the seven design parameters calculated using equation (7.22). The percentage contribution by each of the design parameters is a ratio of the sum of squared deviations due to each design parameter to the total sum of squared deviations [218,246]. The mean of squares deviation is calculated as ratio of sum of squared deviations due to each parameter to degree of freedom, wherein degree of freedom of each parameter is \((t-1)\). The methodology adopted for parametric sensitivity analysis using Taguchi method is shown in Fig. 7.23.

![Diagram](image_url)

**Fig. 7.23.** Methodology adopted for parametric sensitivity analysis of factors affecting sound insulation of multi-layered building elements.
Thus, the $F$-ratio for each design parameter is calculated as the ratio of the mean of squared deviation to the mean of squared error and is used to statistically ascertain the significance of design variable. The parametric sensitivity analysis was conducted using design of experiments based $ANOVA$ approach, wherein the significant parameters are analyzed in terms of main effects plot and relative importance of the parameters on single number ratings is evaluated in terms of percentage contributions using Analysis of Variance ($ANOVA$). The final step in Taguchi method is to predict and confirm the quality characteristic using the determined optimal design parameters.

### 7.5.2 Taguchi analysis for Multi-layered Concrete Constructions

The sound insulation of masonry constructions attached with gypsum boards is evident from experimental investigations reported by Guillen et al., 2008 [46]. It is imperative to analyze the significance of various parameters affecting the sound insulation characteristics for development of highly insulative facade constructions. The attachment of gypsum boards via non-load bearing steel studs to masonry constructions and cavity filled with absorptive material is considered to be the preferred configuration. Thus, the selection of control factors and their levels are made on the basis of experience gained in laboratory investigations conducted in Reverberation chambers at CSIR- National Physical Laboratory, New Delhi and from exhaustive literature review on the subject. Seven control factors, namely $A$ to $G$ identified at two levels were investigated using an $L_8$ orthogonal array, whereby the intersections are considered to be negligible. The array has 8 rows and 7 columns and each row represent an experimental run, while each column accommodates a specific process parameter. Table 7.5 represents the selected parameters at two levels. The
gypsum boards thickness is varied at two levels i.e. 13 mm and 16 mm. Thus, the study utilizes either one layer of thickness 13 mm, or two layers attached constituting a total thickness of 26 mm. The lightweight concrete thickness is varied from 90 mm (117 kg/m$^2$) to 190 mm (247 kg/m$^2$). The attachment of gypsum board can be done by various methods viz., wood studs creating cavity depth of 40 mm, resilient channels 13 mm, steel studs creating cavity depth of 65 mm, Z-bar channels creating cavity depth of 75 mm etc. [237,247].

Table 7.5 Selected parameters at different levels.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Level 1</th>
<th>Level 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Concrete Thickness</td>
<td>90 mm</td>
<td>190 mm</td>
</tr>
<tr>
<td>B Gypsum board Thickness</td>
<td>16 mm</td>
<td>13 mm</td>
</tr>
<tr>
<td>C No of Gypsum board layers</td>
<td>One</td>
<td>Two</td>
</tr>
<tr>
<td>Attached to concrete</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D Type of Studs</td>
<td>Steel</td>
<td>Wood</td>
</tr>
<tr>
<td>E Stud frame</td>
<td>Single</td>
<td>Studs with Resilient rail</td>
</tr>
<tr>
<td>F Density of Sound Absorbing Material (SAB) in Cavity</td>
<td>12.2 kg/m$^3$</td>
<td>11.7 kg/m$^3$</td>
</tr>
<tr>
<td>G Stud spacing</td>
<td>400 mm</td>
<td>600 mm</td>
</tr>
</tbody>
</table>

The present investigation utilizes two types of studs viz., steel and wood studs attached to concrete wall via single or studs with resilient rails. Resilient rails are usually steel channels fixed to the studs, with the wall or ceiling linings fixed to the resilient rail rather than directly to the stud so as to prevent direct vibration transmission via the stud by acting as a soft spring between linings and stud [212]. The selection of two levels for stud spacing is chosen on the basis of widely used configurations. Additionally, density of sound absorbing material is also considered for ascertaining its significance in affecting the sound insulation characteristics. The two options used for sound absorbing material are 65 mm glass fibre batt (GFB) of
density 11.7 kg/m$^3$ (flow resistivity = 3600 mks rayls/m) and 89 mm batt of density 12.2 kg/m$^3$ (flow resistivity = 4800 mks rayls/m).

Table 7.6. Experimental layout using an $L_8$ Orthogonal array.

<table>
<thead>
<tr>
<th>Experiment No.</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

The experiments are designed based on orthogonal array technique. An $L_8$ ($2^7$) orthogonal array is used in the present analysis as shown in table 7.6. Thus, 90 mm concrete attached with 16 mm gypsum board via single steel studs spaced 400 mm apart and $GFB$ 89 mm batt as absorptive material in cavity is first experiment as decided by $L_8$ orthogonal array. The physical parameters of materials used for calculation in Insul software are tabulated in table 7.7.

Table 7.7 Material physical parameters used in the calculation in Insul software.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density $kg/m^3$</th>
<th>Thickness (mm)</th>
<th>Surface Weight ($kg/m^2$)</th>
<th>Elastic Modulus ($10^9 N/m^2$, GPa)</th>
<th>Poisson Ratio ($\mu$)</th>
<th>Loss Factor ($\eta$)</th>
<th>$f_c$ (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum board</td>
<td>690</td>
<td>13</td>
<td>9</td>
<td>2.01</td>
<td>0.3</td>
<td>0.01</td>
<td>2923</td>
</tr>
<tr>
<td>Gypsum board</td>
<td>690</td>
<td>16</td>
<td>11</td>
<td>2.01</td>
<td>0.3</td>
<td>0.01</td>
<td>2375</td>
</tr>
<tr>
<td>Concrete</td>
<td>1300</td>
<td>90</td>
<td>117</td>
<td>3.697</td>
<td>0.3</td>
<td>0.015</td>
<td>427</td>
</tr>
<tr>
<td>Concrete</td>
<td>1300</td>
<td>190</td>
<td>247</td>
<td>3.697</td>
<td>0.3</td>
<td>0.015</td>
<td>202</td>
</tr>
</tbody>
</table>

These parameters are categorized at two levels e.g. $A_1$, $A_2$; $B_1$, $B_2$ to $G_1$ and $G_2$ etc. The goal of analysis was to investigate about the masonry-air cavity-gypsum configuration having maximum value of sound insulation. As such, the single-number
rating $R_w + C_{tr}$ is selected to be maximized as it correlates with the traffic noise reduction index for such constructions used as building facades. So, larger-the-better quality characteristic was implemented. The significant parameters are examined to have the highest variation between the average output value ($R_w + C_{tr}$) for two levels. It is evident from main effects plot in Fig. 7.24 that optimum levels are $A_2$ (190 mm Concrete), $B_1$ (16 mm), $C_2$ (two gypsum layers), $D_1$ (steel stud), $E_2$ (stud with resilient rail), $F_1$ (12.2 kg/m$^3$) and $G_2$ (600 mm stud spacing) respectively. The dotted line represents the mean value of $R_w + C_{tr}$ for two levels of parameters $A$ to $G$.

![Main effects plot of various parameters on $R_w + C_{tr}$ (dB) of concrete sandwich constructions with gypsum boards.](image)

**Fig. 7.24.** Main effects plot of various parameters on $R_w + C_{tr}$ (dB) of concrete sandwich constructions with gypsum boards.

ANOVA usage in Taguchi methods felicitates the computation of variance of all the factors affecting the output. The methodology reveals the significant factors affecting the design output. The measure of relative significance is ascertained by an $F$-test, whereby the factors having high $F$-ratio are confirmed as significant factors. Usually, when $F > 4$, it means that the change of the design parameter has a significant effect on the quality characteristic [246]. The in-active and smaller effects are added
together to obtain a non-zero estimate of the error variance called ‘pooling up’ which can be used to combine factors or interaction effects with low magnitude of sum of squares [246]. The ANOVA analysis reveals optimum parameters to be $A_2C_2D_1E_2G_2$ as shown in table 7.8. The type of studs and steel stud frame is observed to be the prominent factors affecting sound insulation followed by number of gypsum board layers and concrete thickness. Resilient channels used on one or both faces of single rows of stiff studs viz., wood studs or load bearing steel studs help to overcome the peripheral transmission through header and sole plates and thus improves the sound transmission loss considerably, allowing the sound absorptive material in cavity to be effective [242].

**Table 7.8 Results of Analysis of Variance (ANOVA) for $R_w+C_{tr}$ of concrete sandwich constructions with gypsum boards.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DOF</th>
<th>Sum of squares</th>
<th>Mean squares</th>
<th>F-ratio</th>
<th>Contribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$ Concrete Thickness</td>
<td>1</td>
<td>15.125</td>
<td>15.125</td>
<td>7.18$^*$</td>
<td>8.73</td>
</tr>
<tr>
<td>$D$ Type of Studs</td>
<td>1</td>
<td>66.125</td>
<td>66.125</td>
<td>31.12$^*$</td>
<td>42.99</td>
</tr>
<tr>
<td>$E$ Stud Frame</td>
<td>1</td>
<td>36.125</td>
<td>36.125</td>
<td>17.0$^*$</td>
<td>22.84</td>
</tr>
<tr>
<td>$G$ Stud Spacing</td>
<td>1</td>
<td>6.125</td>
<td>6.125</td>
<td>2.88$^{**}$</td>
<td>2.69</td>
</tr>
<tr>
<td>Pooled Error ($B, F$)</td>
<td>2</td>
<td>4.25</td>
<td>2.125</td>
<td></td>
<td>9.99</td>
</tr>
<tr>
<td>Total</td>
<td>7</td>
<td>148.875</td>
<td></td>
<td></td>
<td>100.00</td>
</tr>
</tbody>
</table>

$^*$Factors are significant at 90 % confidence level.

$^{**}$Factor is not significant at 90 % confidence level.

The use of 65 mm steel studs instead of wood furring strips would provide a bigger air space and wallboard would be decoupled from concrete block [240]. The density of sound absorbing material and gypsum board thickness are pooled up as these have been observed to be statistically insignificant; while stud spacing is statistically insignificant at 90 % confidence level as F-ratio is less than $F_{0.10;1:3} = 5.54$. 

243
Fig. 7.25. Percentage contribution of various parameters on $R_w (C, C_{tr})$ of sandwich concrete constructions.

Fig. 7.25 shows the percentage contribution of each parameter on $R_w (C, C_{tr})$ value as determined by ANOVA approach without pooling up the insignificant parameters. It can be observed that single-number rating, $R_w + C_{tr}$ is significantly affected by addition of gypsum layers as compared to $R_w + C$. The percentage contribution of concrete thickness (11.81 %) is significant as compared to the number of gypsum layers (5.62 %) for $R_w + C$ rating. The type of stud and stud frame are the vital parameters controlling the sound insulation characteristics. The attachment via resilient rails thus is a good solution for enhancing sound transmission loss provided all installation perspectives should be considered [248].

### 7.5.3 Sandwich Gypsum Constructions

The application of Taguchi method is extended to sandwich gypsum constructions for analyzing the pivotal factors affecting sound insulation characteristics. Six control factors viz., gypsum board thickness, no of layers, type of studs, type of steel stud frame, density of absorptive material and stud spacing were selected for the investigation. Each of the six factors is considered at two levels as shown in table 7.9 and identified as $A'$ to $F'$, whereby parameter $G'$ is zero in this case.
The gypsum boards thickness has been chosen to either one layer each side constituting a thickness of 26 mm, or using two layers each side constitutes a thickness of 52 mm. The selection of two levels for stud spacing is chosen on the basis of widely used configurations, while the sound absorbing material used is glass fibre 65 mm and 89 mm batt. The two options used for sound absorbing material are 65 mm glass fibre batt (GFB) of density 11.7 kg/m$^3$ (flow resistivity = 3600 mks rayls/m) and 89 mm batt of density 12.2 kg/m$^3$ (flow resistivity = 4800 mks rayls/m).

The main choices considered for steel stud frame are single non-load bearing steel stud and double studs configuration. Double studs are constructed by erecting two separate frames, usually 25 mm apart and lining the outside of each frame typically with 1 or 2 layers of plasterboard and as such there is no physical contact between each side of the wall, the only transmission path is via the air cavity. Thus, appreciably high sound insulation can be achieved with this configuration (Insul. co.nz). The experiments are designed based on orthogonal array technique. An $L_8(2^7)$ orthogonal array is also used in the present analysis.

Table 7.9 Selected parameters at different levels.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Level 1</th>
<th>Level 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A'$ Gypsum board thickness</td>
<td>13 mm</td>
<td>16 mm</td>
</tr>
<tr>
<td>$B'$ No of Gypsum board layers attached each side</td>
<td>Two</td>
<td>One</td>
</tr>
<tr>
<td>$C'$ Type of Studs</td>
<td>Wood</td>
<td>Steel</td>
</tr>
<tr>
<td>$D'$ Stud frame</td>
<td>Double</td>
<td>Single</td>
</tr>
<tr>
<td>$E'$ Density of Sound Absorbing Material in Cavity</td>
<td>11.7 kg/m$^3$</td>
<td>12.2 kg/m$^3$</td>
</tr>
<tr>
<td>$F'$ Stud spacing</td>
<td>600 mm</td>
<td>400 mm</td>
</tr>
</tbody>
</table>

$R_w+C$ is the preferred single-number rating for sound insulation between dwellings, the present investigations focus on optimizing $R_w+C$ value for sandwich gypsum partitions used as internal partitions in dwellings and other locations. The
objective of present analysis is to investigate about the sandwich drywall configuration having maximum value of $R_w+C$. So, larger-the-better quality characteristic was implemented. Fig. 7.26 shows the main effects plot for various parameters. It can be observed that $A'_2$ (16 mm gypsum board), $B'_1$ (two gypsum layers each side), $C'_2$ (steel stud), $D'_1$ (double steel stud), $E'_2$ (12.2 kg/m$^3$) and $F'_1$ (600 mm stud spacing) are the optimum parameters. The ANOVA analysis reveals that optimum levels are $A'_2B'_1C'_2D'_1$ as shown in table 7.10.

![Main effects plot of various parameters on $R_w$ of sandwich gypsum boards constructions.](image)

The stud frame and number of gypsum layers attached plays a prominent role in controlling the sound insulation characteristics. The type of stud viz., wood or steel is also an important factor. The density of sound absorbing material (or thickness) and stud spacing are statistically insignificant at 90 % confidence level and constitutes the pooled error. The benefits available from using sound absorbing materials with higher flow resistivity and density are evident at higher frequencies as compared to lower frequencies [243].
Table 7.10 Results of Analysis of Variance (ANOVA) for $R_w + C$ of sandwich gypsum boards constructions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DOF</th>
<th>Sum of squares</th>
<th>Mean squares</th>
<th>F-ratio</th>
<th>Contribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A'$ Gypsum board thickness</td>
<td>1</td>
<td>21.125</td>
<td>21.125</td>
<td>8.59</td>
<td>3.40</td>
</tr>
<tr>
<td>$B'$ No of Gypsum Layers</td>
<td>1</td>
<td>231.125</td>
<td>231.125</td>
<td>94.02</td>
<td>41.66</td>
</tr>
<tr>
<td>$C'$ Type of Studs</td>
<td>1</td>
<td>36.125</td>
<td>36.125</td>
<td>14.69</td>
<td>6.13</td>
</tr>
<tr>
<td>$D'$ Stud Frame</td>
<td>1</td>
<td>253.125</td>
<td>253.125</td>
<td>103.0</td>
<td>45.67</td>
</tr>
<tr>
<td>Pooled Error ($E', F' &amp; G'$)</td>
<td>3</td>
<td>7.375</td>
<td>2.458</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>7</td>
<td>548.875</td>
<td></td>
<td></td>
<td>100.00</td>
</tr>
</tbody>
</table>

* Factors are significant at 90% confidence level

ANOVA results indicates density or thickness of sound absorptive material to be statistically insignificant. Previous studies in this regard also seem to be inconclusive about definite relationship between density of sound absorbing material and sound reduction index. Uris (1999) observations shows that for frequencies below 1.25 kHz, the sound reduction index can be increased by reducing the rock wool density, while for higher frequencies this parameter does not greatly affect the acoustic insulation [249]. The ANOVA approach was repeated for different single-number ratings to ascertain the significance of these parameters. Fig. 7.27 shows the percentage contribution of various parameters on single number ratings, $R_w$, STC, $R_w + C_r$ and $R_w + C$ determined using ANOVA approach at 90% confidence level. It can be observed that the spectrum adaptation terms ($C$, $C_r$) are more sensitive to the number of gypsum layers attached, whereby stud frame is the most important factor in controlling the overall sound transmission loss characteristics. The percentage contribution due to type of stud is not so significant (6%) in this case as compared to the stud frame.
Fig. 7.27. Percentage contribution of various parameters on single-number ratings as determined from ANOVA method.

7.5.4 Confirmation Experiment

The predicted mean for quality characteristic \((R_w + C_{tr})_{mp}\) is computed as [216]:

\[
(R_w + C_{tr})_{mp} = \bar{y} + \frac{1}{n} \sum_{i=1}^{n} (y_i - \bar{y})
\]

(7.24)

where \(\bar{y}\) is the average of performance characteristic, \(R_w (C, C_{tr})\) corresponding to all eight experiments in table 7.6 and \(n\) is no of parameters considered that significantly affect the performance characteristic, \(y_i\) is mean value of individual parameters \((A_2C_2D_1E_2G_2)\) and \((A'_2B'_1C'_2D'_1)\) at optimum levels. The predicted \((R_w + C_{tr})_{mp}\) value for concrete block along with gypsum boards is calculated using equation (7.24) as 65.0 dB. Similarly, the predicted \((R_w + C)_{mp}\) value for sandwich gypsum construction is calculated using equation (7.24) as 63.6 dB. The confirmation experiment was performed by analytically predicting the single-number rating for optimal configuration. The optimum configuration as predicted from software has \(R_w + C_{tr}\) value of 65 dB in case of concrete sandwich constructions and \(R_w + C\) value of 64 dB in case of sandwich gypsum construction, which closely matches with that predicted from
Taguchi method. The close agreement of optimum value predicted from Taguchi method with the experimentally (or analytically) observed value also confirms that no important factor is missing in the present analysis [250]. It may be noted here that the confidence interval associated with mean value determined from equation (7.24) can also be calculated by simple mathematical formulation (equations (7.14) & (7.15)).

7.5.5 Results & Discussion

The parametric sensitivity of various factors controlling the sound insulation is instrumental in designing sandwich constructions for optimizing sound insulation characteristics. The addition of gypsum layers is helpful in accentuating the overall sound transmission loss due to increase in the mass. Theoretical simulation reveals an increment of $R_w$ value by 12 dB on changing double layers gypsum board each side to four layers each side when connected via double steel studs. The type of stud has been investigated in present study to be the critical parameter controlling the sound insulation characteristics in consistent with Warnock (1997) experimental observations [243]. Double studs stand to be the preferred frame owing to greater mechanical decoupling between two sides of partition achieved through two separate rows of studs. The staggered studs and resilient channels also show good performance. The primary structural resonance at low frequency is shifted to a lower frequency with addition of resilient channels along with steel studs. Analysis of experimental observations (reported in STC and average sound transmission loss) for some specific gypsum and masonry constructions [247] in terms of $R_w (C, C_t)$ reveals some of the major points helpful in understanding the effect of parameters discussed in table 7.5 and 7.9 as:
• Changing from steel studs to double steel studs increases $R_w+C$ value by 10 to 12 dB for studs spaced 610 mm apart.

• Attachment of gypsum board (16 mm) via steel studs to 190 mm concrete significantly arrests the co-incidence dip encountered at 2.5 kHz in case of attachment of gypsum wall board to masonry concrete with wood studs and thus $R_w$ increases by 6 dB, while $R_w+C_{tr}$ increases by 7 dB. The sound transmission loss plot shows dip at 125 Hz in case of attachment of gypsum board via resilient channels alone that affects the low frequency sound insulation.

• $R_w+C$ value increments by 3-4 dB by changing 13 mm gypsum board to 16 mm gypsum board for 406 mm stud spacing, while there is no appreciable improvement for 610 mm stud spacing.

• The increase in stud spacing from 406 mm to 610 mm increases $R_w+C$ value by 1 dB for 16 mm gypsum layer each side attached via steel studs (SS65).

• The increase in stud size (or stud depth) from 65 mm to 90 mm modifies low frequency resonance and shifts to lower frequency and as such $R_w+C$ value for 16 mm gypsum layer each side increments by 2 dB for 406 mm stud spacing and by 4 dB for 610 mm stud spacing.

• On changing from single layer to two layers of gypsum board each side attached via single or double steel studs 610 mm spaced part, the increment in $R_w+C$ value by 8-10 dB is observed.

These observations are consistent with the Taguchi analysis, wherein the stud frame, type of studs (in case of masonry concrete with attached gypsum board constructions) and number of gypsum layers are investigated to be the prominent factors. ANOVA approach reveals stud spacing insignificant at 90 % confidence level in case of structural breaks present in the multi-layered walls consistent with Quirt
(1985) observations [239]. The sound insulation provided by the drywall constructions can be thus significantly enhanced by combination with masonry constructions for its suitability for building facades. The overall affect shall not only be the accentuated sound transmission loss, but also more strength, rigidity and durability. Attachment of a single gypsum board (16 mm) via steel stud to 190 mm concrete block and sound absorptive material (65 mm thick glass fibre batt) in cavity increases $R_w$ value by 9 dB and $R_w+C_{tr}$ value by 5 dB, when compared to 190 mm bare concrete block [42]. The $R_w+C_{tr}$ value is further enhanced by 14 dB by attaching 16 mm gypsum layers each side to 190 mm concrete through steel studs and sound absorptive material in cavity. As the primary structural resonances are shifted to lower frequencies with addition of double steel studs, the low frequency sound insulation is improved leading to improvement in the spectrum adaptation term for traffic noise, $C_{tr}$. The cavity depth has also to be taken care off for bringing the mass-air-mass resonance ($m.a.m$) less than 50 Hz for improving low frequency sound insulation. Thus, for 13 mm gypsum board attached to concrete wall and cavity filled with absorptive material, the optimum cavity depth for $m.a.m < 50$ Hz is calculated from equation, $f_{mam} = \frac{43}{\sqrt{Md}}$ (Warnock et al., IR586) as 82 mm. The optimum cavity depth in case of unfilled cavity is calculated as 160 mm from equation, $f_{mam} = \frac{60}{\sqrt{Md}}$ [42]. The maximum increase in sound transmission loss due to addition of resilient channels is about 15 dB and only occurs for cavity depths greater than 75 mm wherein cavity is filled with sound absorbing material (Bradley et al., 2001[237]). The $R_w+C_{tr}$ value increases by 12 dB on changing from single steel stud to double steel studs as shown (Fig. 7.28) in the analytical results predicted from the Insul software.
Fig. 7.28. Single-number rating for concrete constructions with different types of steel stud frame for attachment of two layers of Gypsum board (16 mm) to 90 mm concrete construction.

Staggered stud is also predicted to show an improved performance with $R_w+C_{tr}$ value incremented by 6 dB on changing from single steel stud to staggered steel stud. Thus, the attachment of gypsum layers via either of resilient channels, staggered studs, or double steel studs to concrete wall with sound absorptive material provides a higher sound insulation as compared to the bare concrete wall. The implementation of Mixed building technology [251] has to be thus brought in wide usage for protecting the dwellings from ever increasing traffic noise.

7.6 Conclusions and Discussion

The conclusions drawn from the analytical work done on Insul software utilizing Taguchi method and experimental study conducted in Reverberation chambers presented in this chapter is summarized as follows:-
• Air-gap plays a vital role in controlling the sound transmission of double glazing. The percentage contribution is 63% for $R_w$ value, while it is 45.6% for $R_w + C_{tr}$ value. It is observed experimentally that a mass-air-mass resonance of the windows is main culprit behind the decrement of transmission loss at low frequencies particularly. A double window provides a better insulation as compared to a single glazing and thus design considerations should be focused on choosing the thickness and depth of airspace to bring the mass air mass resonance frequency below 100 Hz. There has to be a trade-off in choosing the air gap as an air gap of less than 30 mm will lead to pronounced mass-air-mass resonance dip, while increasing the air space above 100 mm increases sound insulation at low frequencies more than at high frequencies as mass-air-mass resonance is lowered, but the standing wave resonances affects the high frequency insulation.

• A pronounced dip attributed to mass-air-mass resonance consistent with theoretical formulation is observed when air gap is less that 30 mm in double glazing. Significant increase in $(R_w + C_{tr})$ value is observed in a sandwich constructions with 85 mm air gap or in sandwich constructions with either one double glazing or both are double. The sandwich construction shown in Fig. 7.18 and 7.19 can be thus a probable solution for abatement towards road traffic noise. The sandwich construction shown in Fig. 7.19 could be the best possible solutions for applications in exteriors of building facades in noisy environment and where the honking noise component is dominant in road traffic noise.

• The back pane thickness has higher percentage in determination of single-number rating $R_w$, $R_w + C$ and $STC$ value as compared to front pane thickness, while front
pane thickness has slightly higher contribution in case of single number quantity $R_w+C_{tr}$. These investigations don’t contradict with the reciprocity law as back pane thickness has been experimentally observed to be more sensitive in controlling the co-incidence dip.

- The type of lamination has a very little role (< 3 %) which is statistically insignificant. However, in case of single-number quantity, $STC$; its percentage contribution is 5.3 %.

- The optimal levels of process parameters are observed to be $A_1$ (9 mm front pane thickness), $B_3$ (9 mm back pane thickness), $C_1$ (90 mm cavity depth) and $D_3$ (Trosifol lamination) respectively. The mean value of $R_w$ and $R_w+C_{tr}$ corresponding to optimum condition was obtained as $(50 \pm 3.5)$ dB and $(46 \pm 5.4)$ dB. The actual value calculated from Insul software was 49 and 44, which lies within the predicted range.

- A 5 dB increase in $R_w$ value is analytically predicted by changing the thickness from 3 mm identical glasses to 10 mm in a double glazing. The increase in $R_w$ value is 7 dB for 50 mm air-gap in case of changing the thickness from 3 mm identical glasses to 10 mm in a double glazing. The empirical formulations have been presented for various single-number ratings correlated with the air-gap and thickness of identical glass in non-laminated and laminated double glazing. The coefficient of multiple determination ($R^2$) in each case is greater than 0.80. These formulations can serve as an easy guide for design of appropriate glazing configurations based on the noise level reduction required.
A consideration on design target of $R_w+C_{tr}$ value of 35 for window glazing, reveals that this value can be achieved with a double glazing having identical 4 mm glass with an 85 mm air-gap, while for an average gap of 50 mm, a double glazing having 6 mm identical glass on each side can accomplish the desired objective.

The key factors controlling the sound insulation characteristics of concrete constructions along with gypsum board attached is the type of studs (43 %), type of steel stud frame (22.8 %), followed by number of gypsum layers attached (12.8 %) and concrete thickness (8.7 %). The steel stud frame plays a pivotal role in shifting the low frequency $m.a.m$ and flexural resonance. Addition of more gypsum layers can be instrumental in enhancing the sound insulation properties as well and bringing down the mass–air–mass resonance. This is evident from the experimental investigations as attaching 16 mm gypsum board to 190 mm concrete wall with 65 mm steel studs and glass fibre batt of 65 mm included increases $R_w$ by 9 dB and $R_w+C_{tr}$ by 5 dB.

The type of stud frame (45.7 %), number of gypsum layers attached (41.7 %) plays a significant role in affecting the $R_w+C$ value of sandwich gypsum constructions. The type of studs in this case viz., steel or wood has relatively less significance (6.1 %) as compared to these factors. The spectrum adaptation terms are however more sensitive to the number of gypsum layers attached.

Double studs are the best preferred attachment followed by staggered studs, steel studs with resilient railings. The stud spacing has also been analyzed to be non critical in controlling the overall sound insulation characteristics especially when structural breaks are provided in the walls consistent with Quirt (1985).
observations. Increasing the depth of cavity (deeper studs or greater separation between row of studs) is helpful in increasing the overall sound transmission loss characteristics provided standing wave resonances aren’t induced. An optimum depth of 160 mm in case of cavity unfilled and 82 mm in case of cavity filled with sound absorptive material is at least required for $m.a.m < 50$ Hz.

- The density and thickness of the sound absorbing material has no major role in deciding the sound insulation characteristics although it is evident that inclusion of sound absorbing material will shift the low frequency $m.a.m$ and also interrupt the standing wave resonances creeping in the cavity. The mean value of $R_w+C_{tr}$ and $R_w+C$ corresponding to optimum conditions is obtained as 65 dB and 63.6 dB. The value calculated from Insul software is 65 dB for sandwich concrete construction and 64 dB for sandwich gypsum construction. As the confirmation results are in close agreement with the experimental (or analytical) value, the fact rules out the omission of any other significant factor or interactions between the parameters shown in table 7.5 and 7.9.

The present work focuses on various design aspects related to single and double glazing for their applications towards reducing the traffic noise. The results obtained provide way for focusing further studies to achieve better sound insulation in low and high frequencies for windows which is a weakest link in building facade. The sound insulation of the windows by laboratory method serves as a benchmark in design and development of appropriate configurations for a noisy environment. Further investigations are to be concentrated on enhancing the sound insulation properties of double and triple glazing by filling the air gap with transparent fluids viz., evacuated monolithic silica aerogels and oils. The work also presents two case studies pertaining
to the optimization of sound insulation by application of Taguchi method for multi-layered building elements utilizing the analytical results predicted on Insul software.

Future work in this regard pertaining to the validation of these theoretical results by laboratory experiments can be very beneficial to the building industry for development of highly sound insulative configurations for their applications as building facades and partition walls. The present investigations stresses on the use of dry wall technology in conjunction with masonry constructions for applications in building facades in areas wherein high sound insulation is must for combating the outside traffic noise. Although the costs associated and practical complications involved are much higher, yet the use of both these can be instrumental in achieving the long term noise abatement objectives.