Acoustic Research Group
Department of Mechanical Engineering
University of Canterbury
Christchurch

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Noise Attenuation by Roof Cladding Systems

Laboratory Testing Part 2 Results: Roof Systems

Prepared by: Jeffrey Mahn

For: Peter Atkinson
Executive Officer
New Zealand Metal Roofing Manufacturers Inc.
Private Bag 92-066
Auckland 1142

Issued by: Dr J. Pearse
Mechanical Engineering Department
University of Canterbury
Private Bag 4800
Christchurch 8140
Ph: (+64) (3) 364-2987 ext 7252
Fax: (+64) (3) 364-2078
Email: jeffrey.mahn@canterbury.ac.nz

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Summary

The purpose of this study was to evaluate the effects of changes to the sound insulation of a typical roof system due to modifications to the components of the roof system. The measurements were intended to show the relative differences between the different roof systems in a carefully controlled laboratory environment. Although measurements made on dwellings in the field are expected to show similar relative differences when modifications are made to the roof system components, the single number ratings for the sound insulation of the roof systems reported in this study may not be indicative of the performance of identical roof constructions installed on dwellings. Therefore, it is important to emphasise the relative differences between the roof systems evaluated in this study and not the absolute sound insulation values when quoting the results of this study.

The modifications to the roof system components which were evaluated are shown in the table below.

Cladding	Ceiling	Sarking	Fibreglass Insulation
Corrugate 0.4	13 mm Standard GIB	17.5 mm Plywood	Pink Batt Classic R3.6 180 mm
Metal Chip Tile	13 mm Noiseline GIB	No Sarking	Two Layers of Pink Batt Classic R3.6 180 mm
Concrete Tile without Underlay	10 mm + 13 mm Standard GIB		
Concrete Tile with Underlay			

Four different claddings were included in the evaluation as well as three ceiling constructions, two variations of the plywood sarking and two variations of the thermal insulation.

Of the modifications evaluated, the most effective means of improving the sound insulation of a roof system was to double the thickness of the fibreglass insulation installed above the ceiling. Doubling the thickness of the fibreglass insulation would be less expensive and more effective than adding plywood sarking under the cladding and also has other benefits associated with the thermal insulation of the dwelling.

The choice of cladding had less of an effect on the single number ratings of the roof systems than modifications to the ceiling, doubling the thickness of the thermal insulation or the use of plywood sarking. The choice of cladding typically affected the STC rating and the weighted sound reduction index by 1 dB. However, the effect of the choice of cladding was more apparent when the data was presented in 1/3 octave bands with different claddings offering better sound insulation at frequencies, especially above the 630 Hz 1/3 octave band.

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1. Introduction

It would be beneficial to architects, builders, acoustic consultants and local authorities to have access to information about the sound insulation of roof systems. Knowledge of the possible improvements in the sound insulation due to changes to the components of typical roof constructions would be especially beneficial in cases where dwellings are to be built in areas with potentially high outdoor noise levels. However, there is little information published in the literature about the sound insulation of the roof systems typically used in New Zealand [1]. The last major Australasian study published in the past several decades was that conducted by Cook in Melbourne in 1980 [2-4]. The lack of published information has led to confusion and misinformation about the effect of the cladding and the most effective means of increasing the sound insulation of roof systems.

In order to provide the industry with the information needed to make informed decisions about the design of roof systems, the New Zealand Metal Roofing Manufacturers Inc. commissioned this study to evaluate the effect of modifications to the components of a typical roof system on the sound insulation of the roof system. The study was conducted in the acoustic rooms at the University of Canterbury. The measurements were made in the laboratory under carefully controlled conditions rather than in the field so that outside factors such as variations in the roof system design or outside noise would not affect the results. The materials were supplied by the Metal Roofing Manufacturers Association and the claddings were installed by professional roofers.

The laboratory measurements conducted as part of this study were designed to show the relative differences in the sound insulation of the roof systems due to changes in the components. The relative differences between the sound insulation of the roof systems are expected to be indicative of the differences which would be measured in actual dwellings. However, the single number ratings presented in this report may not be indicative of the performance of identical roof systems installed on dwellings. Therefore, any reference to this report must emphasize the changes to the sound insulation of the roof system which were achieved by modifying the roof system components and not the absolute values of the sound insulation.

This study included an evaluation of the effect of changing the cladding on the sound insulation of the roof system. The results presented in this study are different than those presented in Part 1 of the study [5] which evaluated the sound insulation of only the claddings without any other components attached. However, claddings are never installed on dwellings without other components of the roof system including the support structure. Therefore, the results of the Part 1 study can not be directly compared to the results from this Part 2 study.

2. Transmission Paths through the Roof System

The most common roof design in New Zealand includes a cladding, trusses, a layer of thermal insulating material above the ceiling in compliance with Clause H1 of the New Zealand Building Code [6] and the ceiling as shown in Figure 1.

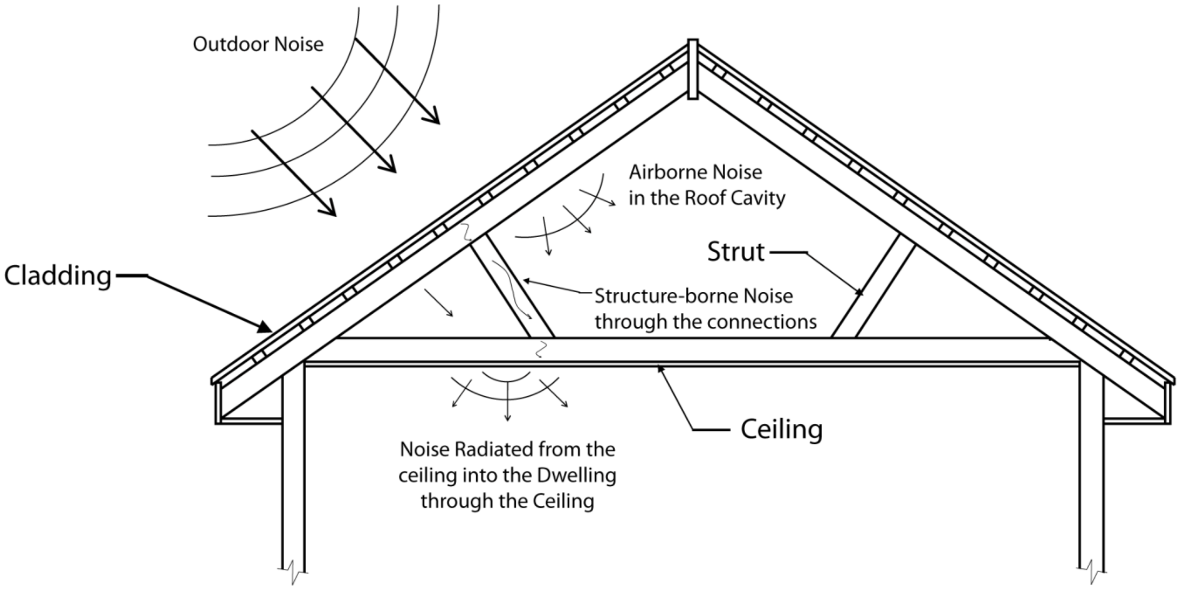

Figure 1: Rough sketch of a pitched roof system to demonstrate the transmission of outdoor noise into a dwelling through the roof system. The sketch does not show all of the possible roof components involved in the transmission of structure-borne noise.

There are two primary paths for outdoor noise (for example aircraft noise) to be transmitted through the roof system and into the dwelling. Both transmission paths begin with outdoor noise which is incident on the cladding exciting bending waves in the cladding. The bending waves can then reradiate noise into the roof cavity as shown in Figure 2.

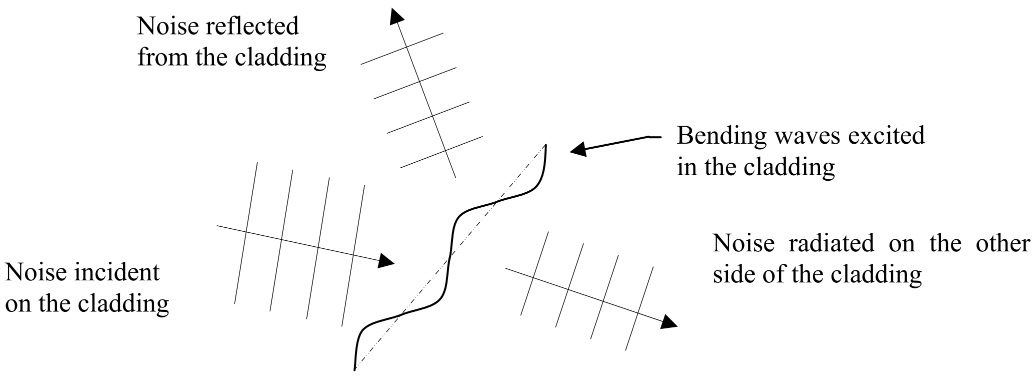

Figure 2: Transmission of airborne noise through the cladding and into the roof cavity.

The noise that is radiated into the roof cavity can in turn excite bending waves in the ceiling that result in noise that is radiated into the dwelling as shown in Figure 1.

The efficiency of the airborne noise to excite bending waves in the cladding and the efficiency with which the noise is reradiated into the roof cavity depends on the material properties of the cladding (such as mass and damping), the shape of the cladding and the structural connections between the cladding and the other roof system elements. The same factors apply to the efficiency of the ceiling to transmit noise into the dwelling.

Furthermore, if there are sound leaks in the cladding such as the gaps between concrete tiles, then outdoor noise can be transmitted directly into the roof cavity through the gap. Even a small sound leak could decrease the total sound reduction index of the cladding significantly [7]. It was found in Part 1 of the laboratory study that although underlay itself does not have a very high sound insulation, the use of underlay is effective at improving the sound insulation of claddings by preventing noise leaks though the gaps between tiles [5].

Modifications to the cladding to reduce the transmission of noise through the roof system can include improving the sound reduction of the cladding. Attempts to improve the sound reduction index of the cladding have included the addition of a layer of plywood sarking under the cladding. In this study, both the use of plywood sarking and the use of underlay under concrete tiles were evaluated.

If the magnitude of the airborne noise in the roof cavity can be decreased, then less noise will be incident on the ceiling, resulting in less noise transmitted into the dwelling. The attenuation of the airborne noise can be achieved by adding sound insulating materials into the roof cavity such as fibreglass insulation. If a layer of fibreglass insulation already exists to satisfy thermal requirements for the roof system, then additional layers of the insulation may improve the attenuation of airborne noise in the cavity and this modification to the roof system was evaluated in this study.

The second primary transmission path through the roof system includes the structural connections between the cladding and the ceiling. The bending waves which are excited in the cladding are transmitted as structure-borne noise through the connections such as the struts and into the ceiling as shown in Figure 1. The structure-borne noise excites bending waves in the ceiling which are in turn radiated as airborne noise into the dwelling. The efficiency of the transmission of the structure-borne noise into the ceiling can be changed by modifying the connections between the cladding and the trusses and the trusses and the ceiling. An example of changing the structural connections would be attaching the ceiling plasterboard to properly installed resilient rails rather than directly attaching the plasterboard to the joists.

Since noise is transmitted into the dwelling through the ceiling, another method of improving the sound insulation of the roof system could be to reduce the efficiency with which airborne and structure-borne noise to excite bending waves in the ceiling. One method of reducing the efficiency, particularly at the lower frequencies would be to increase the mass of the ceiling. Products such as Noiseline GIB have a higher mass per unit area than Standard GIB for this reason. In this study, roof systems with ceilings constructed of plasterboards with different mass per unit areas were evaluated.

3. Configurations Evaluated

3.1. Claddings

In Part 1 of this study, the sound reduction indices of different profiled metal claddings and of metal tiles with different finishes were evaluated. The results of the Part 1 study showed that the profiled metal claddings had sound reduction indices which showed similar trends across the frequency range of interest and therefore, it was concluded that one profiled metal cladding could be used in this Part 2 of the study to represent the family of profiled metal claddings. Likewise, the sound reduction indices of the metal tiles all showed similar trends across the frequency range and therefore only one metal tile was included in this study.

Concrete tiles with and without underlay were included in this Part 2 of the study since there are cases where underlay is not required to be used [8]. It was found in Part 1 of this study that the use of underlay improved the sound insulation of the concrete tiles.

The claddings included in this evaluation are listed in Table 1. All four of the claddings shown in Table 1 were evaluated for each of the roof systems considered.

Metal Tile: Chip
Profiled Metal: Corrugate 0.4
Concrete Tile without Underlay
Concrete Tile with Underlay

Table 1: Claddings included in the evaluation.

Underlay was used under each of the claddings with the exception of the concrete tiles without underlay. The underlay which was used was Thermakraft 215 Bituminous Self Supporting Roofing Underlay. The underlay had a mass per unit area of approximately 0.37 kg/m^2. Further information about the underlay can be found in Appendix C.

3.2. Roof System Configurations

A base roof configuration was chosen to be representative of a typical pitched roof construction in New Zealand. The base system included a cladding, trusses located 900 mm on centre which is the standard practice for approximately 80% of the houses built in New Zealand, fibreglass insulation above the ceiling to comply with Clause H1 of the New Zealand Building Code [6] and a ceiling constructed of 13 mm Standard GIB plasterboard.

Four modified roof configurations were evaluated for comparison with the base roof system as shown in Table 2.

Roof System Configuration	Base System	Modify the Ceiling	Modify the Ceiling	Add Plywood Sarking	Double the Thickness of the Fibreglass Insulation
Sarking	No	No	No	17.5 mm CD Treated Plywood	No
Trusses	75 x 50 Pinus Radiata H 1.2 Trusses Dressed, 27^{o} Pitch, 900 mm Centres	75 x 50 Pinus Radiata H 1.2 Trusses Dressed, 27^{o} Pitch, 900 mm Centres	75 x 50 Pinus Radiata H 1.2 Trusses Dressed, 27^{o} Pitch, 900 mm Centres	75 x 50 Pinus Radiata H 1.2 Trusses Dressed, 27^{o} Pitch, 900 mm Centres	75 x 50 Pinus Radiata H 1.2 Trusses Dressed, 27^{o} Pitch, 900 mm Centres
Sound Absorbing Material	Pink Batt Classic R3.6 180 mm Thick	Pink Batt Classic R3.6 180 mm Thick	Pink Batt Classic R3.6 180 mm Thick	Pink Batt Classic R3.6 180 mm Thick	2 Layers of Pink Batt Classic R3.6 Each 180 mm Thick
Ceiling	13 mm Standard GIB (8.5 kg/m^2)	13 mm Noiseline GIB (12.4 kg/m^2)	10 mm + 13 mm Standard GIB (15.3 kg/m^2)	13 mm Standard GIB (8.5 kg/m^2)	13 mm Standard GIB (8.5 kg/m^2)

Table 2: Roof system configurations evaluated as part of this study. The shaded cells of the table highlight the changes from the base roof system. All of the four claddings were evaluated for each of the roof system evaluated. The values of the mass per unit area listed for the plasterboard were measured in the laboratory.

The modified roof system configurations were chosen to determine the effect on the sound insulation of the roof system due to a change in one of the components by comparing the sound insulation of the modified roof system to that of the base system. For each of the modified roof systems, only the ceiling, the sound absorbing material in the roof cavity and the cladding were changed and the rest of the system remained unchanged. Therefore the effects of the changes to the roof systems could be evaluated without changing the structure-borne transmission through the trusses.

In addition to the configurations listed in Table 2, the effect of increasing the volume of the roof cavity was evaluated by increasing the pitch of the roof. The increase in the pitch of the roof was achieved by replacing the original trusses which had a 27^{o} pitch with new trusses which had a 35^{o} pitch. However, replacing the trusses changed the system too greatly to allow for accurate comparisons with the other roof system configurations. Therefore, the sound reduction indices measured for each of the configuration with the new trusses could not be compared to the sound reduction indices measured for the base system to determine the effect of the modifications.

4. Method

4.1. Acoustic Measurements

The sound reduction indices of the roof systems were measured using the sound intensity method, following the standard ISO 15186-1:2000 [9]. The method involved the construction of the roof system in an 11.5 m^2 opening between a reverberation room and a semi-anechoic room. A diffuse sound field was generated in the 217 m^3 reverberation room using two JPB CBT70J loudspeakers which driven together with a pink noise signal generated by a Brüel & Kjær PULSE analyzer and amplified with a bridged QSC PLX2502 2500 Watt amplifier. The sound pressure level in the reverberation room was measured using five Brüel & Kjær Type 4189 1/2 inch, free field microphones which were also connected to the PULSE analyzer.

The transmitted sound intensity was measured using a Brüel and Kjær 2260 sound analyzer with Brüel and Kjær BZ7205 sound intensity software and a Brüel and Kjær Type 3595 sound intensity probe kit. The sound intensity probe kit was calibrated using a Brüel & Kjær acoustic calibrator, Type 4231 and a Brüel & Kjær adaptor, Type DP0888. All of the microphones were calibrated with a Brüel & Kjær Type 4231 acoustic calibrator.

The details of the equipment including model and serial numbers are listed in Appendix A.

For each of the roof systems, the measurement surface was qualified in accordance with Clause 6.4 of ISO 15816-1:2000. The sound intensity was measured using scans in two scanning patterns which were 90 degrees from each other as required by ISO 15186-1:2000. A minimum of 8 measurements which included two scanning patterns each were made for each roof system and the standard deviation between the measurements was determined.

The intensity sound reduction index was calculated according to the equation:

$$R = L_{ps} - L_{it} - 6 \text{ (dB)}$$

where L_{ps} is the sound pressure measured in the reverberation room (dB re 2 x 10^{-5} Pa) and L_{it} is the sound intensity level measured in the semi anechoic room (dB re 1 x 10^{-12} W/m^2). The sound pressure level in the reverberation room was determined from an average of three measurements in five positions in the reverberation room. The intensity sound reduction index was calculated in the 1/3 octave bands between 100 Hz and 4000 Hz.

4.2. Sample Installation

4.2.1. Trusses, Sound Absorbing Materials and Ceiling

The use of sound intensity allowed for the ceiling side of the roof system construction to extend into the receiving room so that the cladding side of the construction was parallel to the wall of the reverberation room as shown in Figure 3.

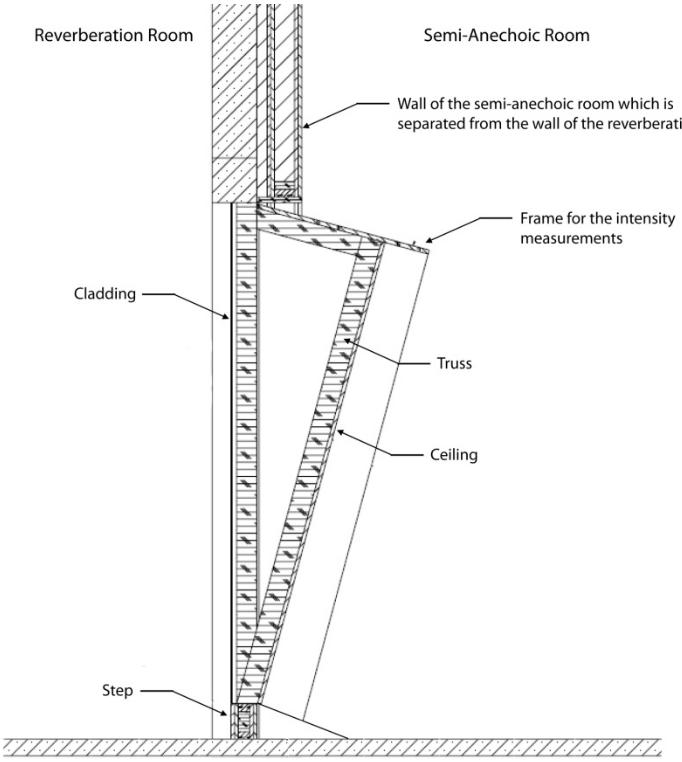

Figure 3: Rough cross-section of the roof system installed in the opening between a reverberation room and a semi-anechoic room.

The trusses used were dressed 75 mm x 50 mm Pinus Radiata H 1.2 as shown in Figure 4.

Figure 4: Installation of the trusses.

The trusses were located 900 mm on centre which is the standard practice for approximately 80% of the houses built in New Zealand. The trusses were fixed to the concrete wall of the reverberation room and extended into the semi-anechoic room. The trusses were installed on a step as shown in Figure 3 to allow enough room for the intensity measurements to be made on the semi-anechoic room side of the structure. The step also formed the bottom of a frame around the ceiling which was required for the sound intensity measurements. The step was a double leaf construction with timber studs and two layers of 13 mm plaster board on the reverberation room side as shown in Figure 5.

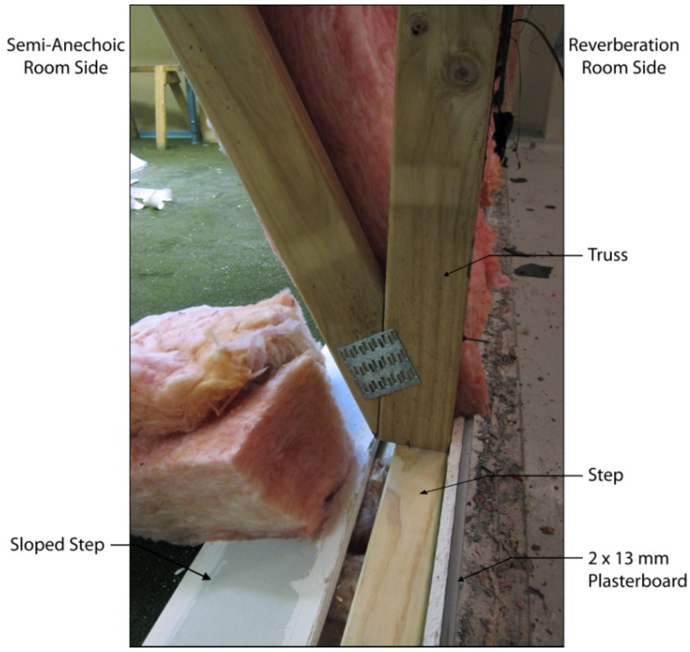

Figure 5: Step on which the trusses were installed. Note that the photo was taken when the wall system was being removed at the conclusion of the measurements. Missing from the photo is the layer of plasterboard on the ceiling which would fill the gap between the sloped step and the timber.

The cavity of the step was packed with sound absorbing material. On the semi-anechoic room side, the step sloped at an angle that was normal to the ceiling.

A plywood frame was installed around the roof system to seal the cavity between the trusses and to complete the frame for the intensity measurements as shown in Figure 6.

Figure 6: Semi-anechoic side of the roof system construction showing the plywood frame around the ceiling for the sound intensity measurements. The ceiling was made of plasterboard and the seams were sealed with paper and plaster.

All of the joints between the sheets of plywood were sealed with caulking and the seams between the sheets of plasterboard were sealed with paper and plaster as shown in Figure 6.

The fibreglass insulation was installed between the trusses and in contact with the ceiling as shown in Figure 7.

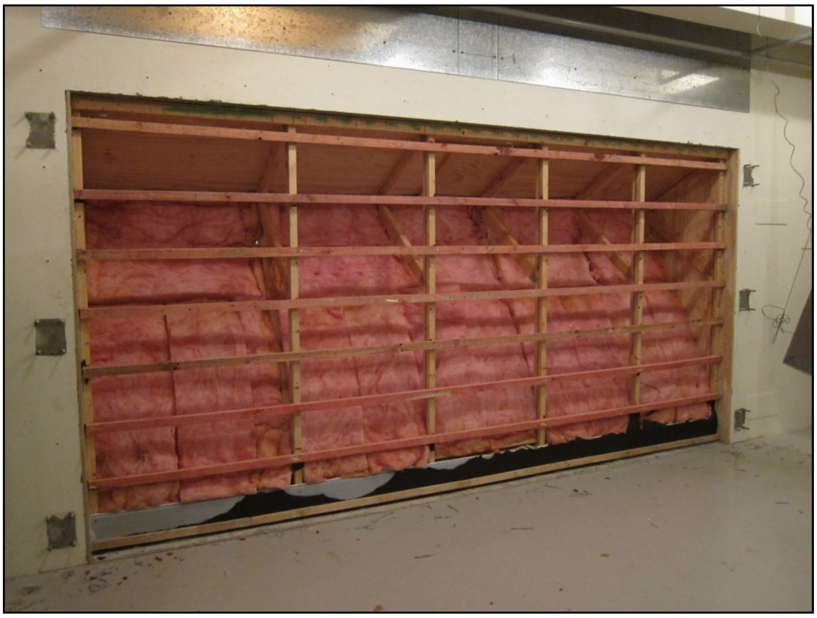

Figure 7: View from the reverberation room of the sound absorbing materials installed above the ceiling.

The photo was taken after a layer of tiles and underlay had been removed. The battens which were used when evaluating the roof systems with tiles can be seen nailed to the trusses.

4.2.2. Claddings

The profiled metal cladding was screwed to purlins which had been nailed to the trusses. Thermakraft 215 underlay was always installed under the profiled metal cladding. In the case where plywood sarking was installed under the profiled metal, the order of the components was: Truss - Sarking - Purlins - Profiled Metal.

The metal tiles were nailed to battens which had been nailed to the trusses. An example of the battens is shown in Figure 7. Thermakraft 215 underlay was always installed under the metal tiles. In the case where plywood sarking was installed under the metal tiles, the order of the components was: Truss - Sarking - Battens - Tiles.

The concrete tiles were screwed to battens which had been nailed to the trusses. Due to the pitch of the roof, each tile was screwed to the battens rather than the common practice of screwing only some of the tiles into place. In the case where plywood sarking was installed under the concrete tiles, the order of the components was: Truss - Sarking - Battens - Tiles.

The edges of the cladding were sealed against noise leaks using a sealing compound applied to the reverberation room side of the cladding as shown in Figure 8.

Figure 8: Sealing compound around the edges of the cladding to prevent sound leakage around the edges of the cladding.

The sealing compound was used around the entire perimeter of the cladding, except in the case of the metal tiles where a resilient material was inserted under the bottom row of tiles as shown in Figure 9.

Figure 9: Resilient material located between the bottom row of tiles and the concrete floor.

The purpose of the resilient material was to seal the large gaps between the metal tiles and the concrete floor.

4.3. Uncertainty

4.3.1. Measurement Uncertainty

The standard, ISO 15186-1:2000 does not include an estimate of the uncertainty of the measurements it describes. However it is not unreasonable to expect that the standard deviation of reproducibility of the measurements will not be greater than the standard deviation of reproducibility using two adjacent reverberation rooms as described in Annex A of ISO 140-2 [10] and listed in Appendix B of this report.

4.3.2. Uncertainty due to Workmanship

During the course of the study, changes to the roof system were made by different sets of builders and the claddings were installed by different roofers. The builders and roofers all had varying degrees of experience. The variation in experience of the roofers resulted in some cladding being installed very well and other which were not. This variation resulted in uncertainty in the measurements due to the workmanship as would be the case if the claddings had been installed on actual dwellings. Therefore, the total uncertainty of the measured data includes the uncertainty due to workmanship is included in the total uncertainty of the measurements, but has not been quantified in this study.

4.4. Single Number Descriptors Evaluated

Single number ratings are commonly used to quickly evaluate the noise attenuation of building elements. New Zealand currently uses the STC rating which is determined from the intensity sound reduction index measured between the 125 Hz to the 4000 Hz 1/3 octave bands according to ASTM E 413 - 10 [11].

The proposed revisions to Clause G6 of the New Zealand Building Code [12, 13] include the replacement of the STC rating by the weighted sound reduction index R_w which is calculated according to AS/NZS ISO 717-1:2004 [14]. Therefore, the calculation of the weighted intensity sound reduction index will also be included in the results presented in this report. The weighted intensity sound reduction index differs from the STC rating in that it is calculated using sound reduction index data in the 1/3 octave bands between the 100 Hz and the 3150 Hz 1/3 octave bands and the calculation does not include a limitation on the maximum deviation allowed from the reference curve. The maximum deviation from the reference curve allowed in the calculation of the STC rating is 8 dB in a single 1/3 octave band.

The proposed revisions to Clause G6 of the New Zealand Building Code also include the level difference. Therefore, the weighted intensity normalized level difference $D_{I,n,w}$ calculated according to ISO 15186-1:2000 and AS/NZS ISO 717-1:2004 is also included in the results of this study.

A summary of the single number ratings calculated in this study is shown in Table 3.

Calculation	Symbol	Reference Standard
STC Rating	STC	ASTM E 413 - 10
Weighted Intensity Sound Reduction Index	$R_{I,w}$	AS/NZS ISO 717-1:2004
Weighted Intensity Normalized Level Difference	$D_{I,n,w}$	AS/NZS ISO 717-1:2004

Table 3: Single number ratings evaluated in this study.

5. Results

5.1. Comparison between Claddings Installed on the Base Roof System

The intensity sound reduction indices of the claddings installed on the base roof system are compared in each 1/3 octave band in Figure 10. The figure also shows the STC ratings and the weighted intensity sound reduction indices.

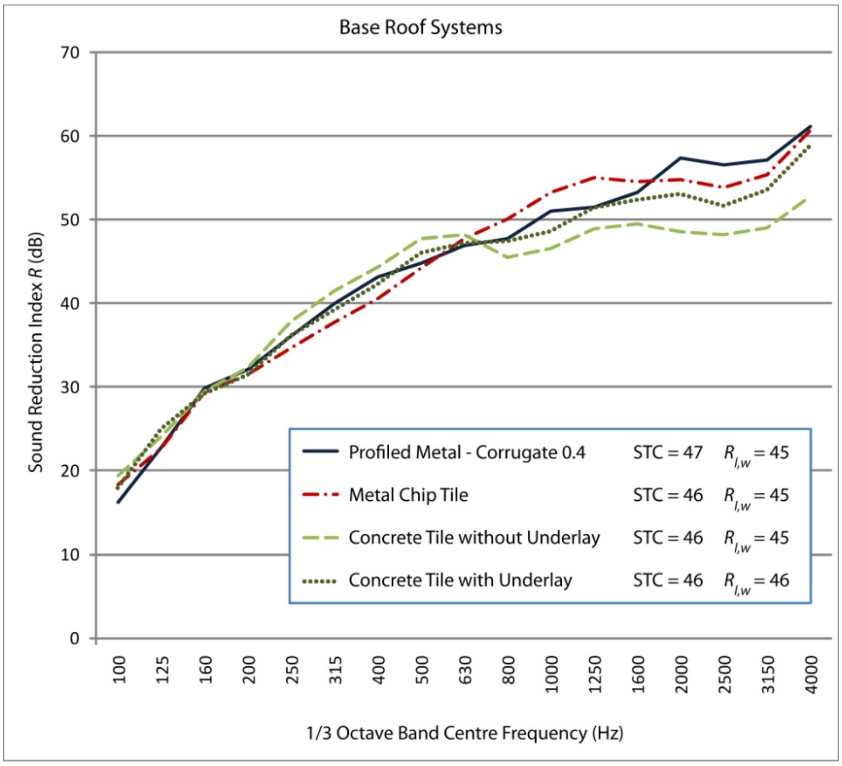

Figure 10: Sound reduction indices of the base roof system with the four claddings installed.

The 1/3 octave band data shows that in the 250 Hz 1/3 octave band and below, the sound reduction indices of the base systems with the different claddings differed by a maximum of 3.1 dB. Between the 250 and the 630 Hz 1/3 octave band, the sound reduction indices are within 4 dB of each other. Above the 630 Hz 1/3 octave band, the sound reduction indices differed by 4.6 to 8.8 dB. Therefore, the choice of cladding shows a significant effect on the sound insulation of the roof system above the 630 Hz 1/3 octave band. This is in agreement with the findings of Cook [4].

The installation of the concrete tiles with underlay resulted in the highest sound insulation below the 160 Hz 1/3 octave band which is in part why the concrete tile with underlay had the highest weighted intensity sound reduction index of the roof systems evaluated. The instalment of underlay under the concrete tile affected the sound reduction index predominantly above the 630 Hz 1/3 octave band. At the higher frequencies, the sound reduction indices of the concrete with and without underlay differed by as much as 6 dB.

The metal tile with underlay had a higher intensity sound reduction index than the concrete tile with underlay over most of the frequency range. However, in the 125, 250, 315, 400 and 500 Hz 1/3 octave bands the magnitude of the sound reduction index of the roof system with the concrete tiles with underlay was about 2 dB higher which gave the concrete tile with underlay a weighted intensity sound reduction index which was 1 dB higher than the metal tile.

The installation of the profiled metal and the metal tiles resulted in the highest sound insulation in the 1/3 octave bands above the 630 Hz 1/3 octave band. However, the difference between the sound reduction indices of the metal and the concrete claddings was not conveyed in the single number ratings due to the methods by which the single number ratings are calculated. The larger difference between the sound reduction indices at the lower frequencies had more of an effect on the single number ratings then the differences at the higher frequencies.

The difference between the values of the STC ratings and the weighted sound reduction indices for the different claddings installed on the base roof system was much less than the difference between the values for the claddings alone as measured in Part 1 [5] of this study. The single number ratings measured for the claddings in isolation are shown in Table 4.

Cladding	STC	$R_{I,w}$ (dB)
Concrete Tile with Underlay	21	21
Profiled Metal - Corrugate 0.4	19	19
Metal Tile - Chip with Underlay	18	18
Concrete Tile	15	16

Table 4: STC rating and the weighted intensity sound reduction index of the claddings when measured in isolation without the complete roof system. Claddings are never installed on residences without the accompanying roof system inclusive of the ceiling, trusses and possibly sound insulation in the ceiling cavity and therefore the numbers presented in the table should not be considered to be indicative of the performance to be expected for the claddings in the actual application.

The difference between the STC ratings of just the claddings was 6 and the difference between the weighted intensity sound reduction indices was 5 dB. The results indicate that once the claddings are installed on a roof system, the effect of the sound reduction index of the cladding on the single number ratings of the sound insulation of the roof system is negligible. For example, the difference between the concrete tiles with and without underlay was reduced from 5 dB to 1 dB in the case of the base roof system. This finding is in agreement with the data shown in Table 7 of the proposed revision to Clause G6 Appendix B [13] which shows approved solutions for improving the sound insulation of roof systems. The approved solutions in the proposed Clause G6 Appendix B do not distinguish between roof systems with different claddings.

5.2. Results of Modifications to the Roof System

The measured STC rating and weighted sound reduction indices of the base roof system and the modified roof systems with the different claddings installed are compared in Figure 11. The data is also presented in tabular form in Appendix E.

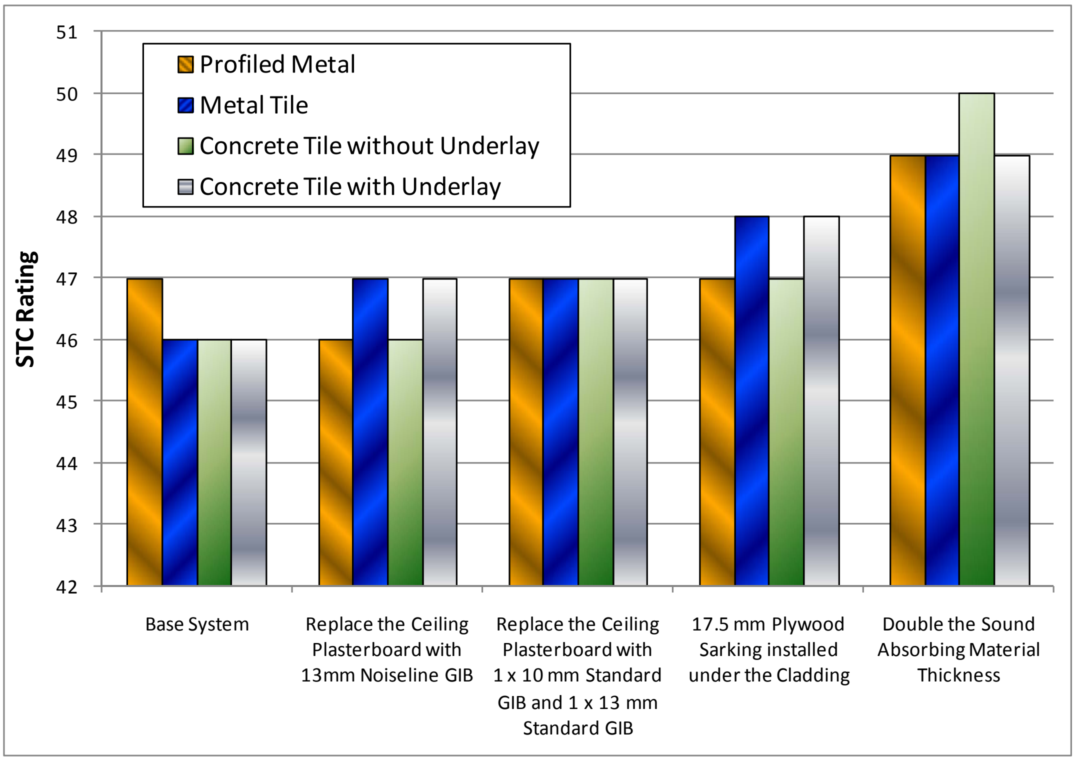

Figure 11: Comparison between the STC ratings of the roof system configurations with the different claddings. The STC rating is evaluated over the 1/3 octave bands between 125 Hz and 4000 Hz.

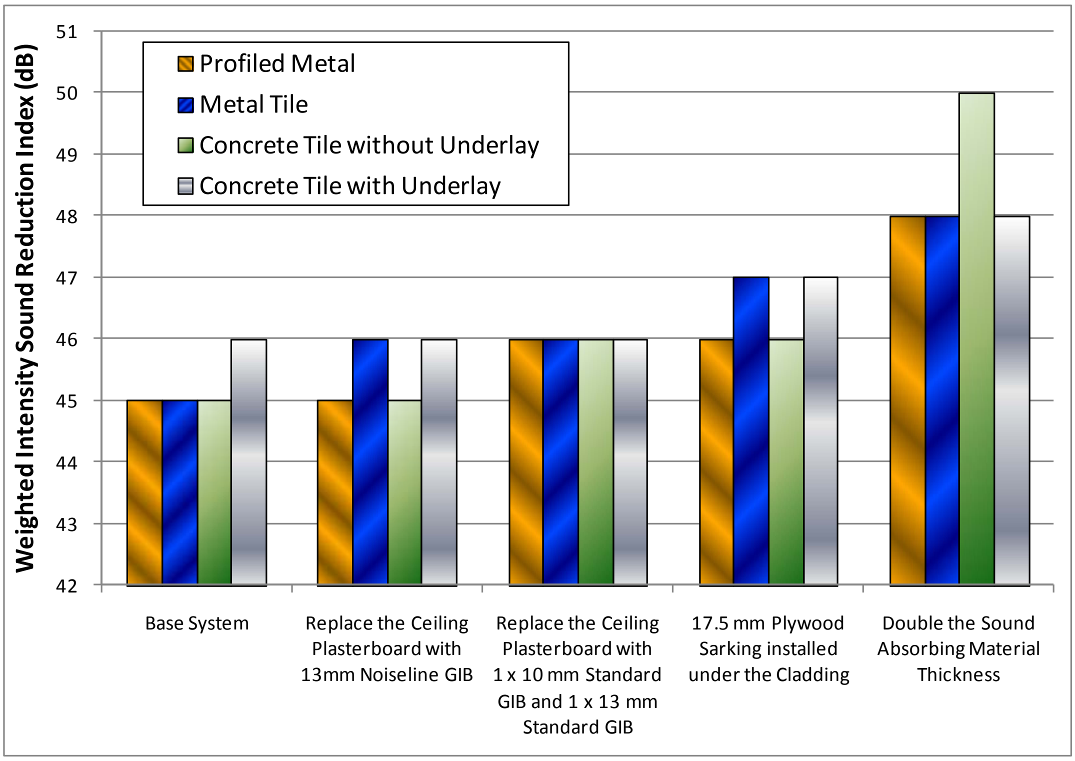

Figure 12: Comparison between the weighted intensity sound reduction indices of the roof system configurations with the different claddings. The weighted intensity sound reduction index is evaluated over the 1/3 octave bands between 100 Hz and 4000 Hz.

The modifications to the components of the roof systems resulted in a maximum improvement in the STC rating of only 4 and in the weighted intensity sound reduction index of only 5 dB. Doubling the thickness of the fibreglass insulation installed above the ceiling was the most effective method of increasing the sound insulation of the roof system. Modifications to the ceiling plasterboard were the least effective of the modifications at increasing the sound insulation of the roof systems. The installation of Noiseline GIB was less effective at increasing the sound insulation of the ceiling than the other modifications to the roof system. The installation of 17.5 mm plywood sarking under the cladding was only slightly more effective at increasing the single number ratings than adding an additional 10 mm Standard GIB to the ceiling.

The maximum variation between the claddings for each of the roof systems evaluated was 1 STC rating or 2 dB in terms of the weighed sound reduction index. Therefore, the choice of cladding had only a small influence on the sound reduction index of the roof systems evaluated.

The roof system with double the sound absorbing material above the ceiling with concrete tiles without underlay had a sound reduction index which was 2 dB higher than that measured for the same roof system with the other claddings including concrete with underlay. The difference between the concrete without underlay and the other claddings with underlay may have been due to the uncertainty due to workmanship.

5.3. Results Ordered by Cladding Type

5.3.1. Profiled Metal Cladding

The differences between the single number ratings of the base roof system and the single number ratings of the modified roof systems with the profiled metal cladding installed are compared in Figure 13.

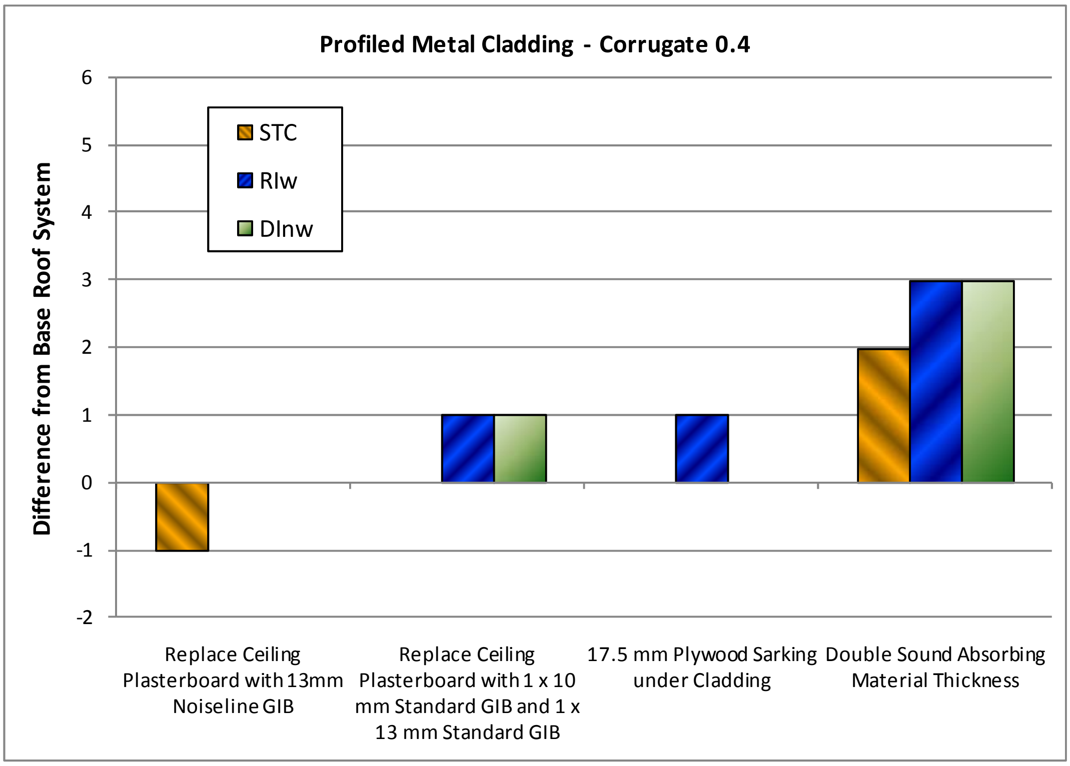

Figure 13: Change in the values of the STC rating, $R_{I,w}$ and $D_{I,n,w}$ due to modifications to the roof system with the profiled metal cladding.

The figure shows that modifications to the ceiling plasterboard or the addition of 17.5 mm thick plywood sarking under the cladding had little effect on the sound insulation of the roof system. Doubling the thickness of the sound absorbing material in the ceiling cavity resulted in the highest increases in the single number ratings with the STC rating increased by 2 and the $R_{I,w}$ and $D_{I,n,w}$ increased by 3dB.

The sound reduction indices of the different roof system configurations with the profiled metal cladding are compared in Figure 14.

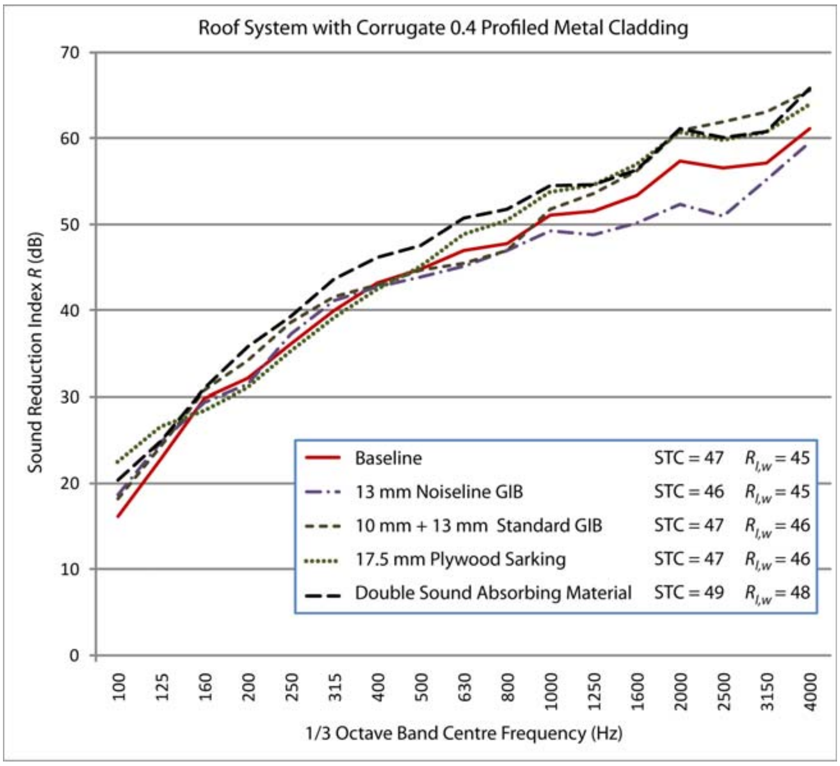

Figure 14: Comparison of the sound reduction indices of the roof system configurations with the profiled metal cladding.

Figure 14 shows that the roof system with the Noiseline GIB had a lower intensity sound reduction index than the base system in the 1/3 octave bands greater than 400 Hz. Although the use of the Noiseline GIB resulted in a higher sound reduction index than the use of the 13mm Standard GIB in the 1/3 octave bands lower than 400 Hz, the roof system with the Noiseline GIB had the lowest single number ratings of the roof systems evaluated. The low STC and $R_{I,w}$ ratings was primarily due to the large dip in the sound reduction index around the critical frequency in the 2500 Hz 1/3 octave band. As shown in Appendix D, measurements of the sound reduction index of 13 mm Noiseline GIB and 13 mm Standard GIB showed that there is a more pronounced dip in the sound reduction index for the Noiseline GIB than for the Standard GIB. The coincidence dip occurs when the speed of bending waves in the material equal the speed of sound in the air and the material becomes an efficient radiator of noise. The sound reduction indices of all of the claddings with the 13 mm Noiseline GIB installed on the ceiling showed similar, pronounced dips at the critical frequency.

The roof system with the ceiling of 10 mm + 13 mm Standard GIB had a higher sound reduction index than the base system with the exception of the 1/3 octave bands between 400 Hz and 1000 Hz. Therefore, adding an additional 10 mm of Standard GIB to the ceiling of the base system to result in a 23 mm thick ceiling of Standard GIB was more effective at improving the sound insulation of the roof system than using 13 mm Noiseline GIB.

The addition of the plywood sarking under the cladding increased the sound reduction index in the 100 Hz 1/3 octave band by 6 dB. The increase in this 1/3 octave band resulted in an increase in the weighted intensity sound reduction index, but not in the STC rating. Whereas the calculation of the weighted intensity sound reduction index includes the 100 Hz 1/3 octave band, the calculation of the STC rating uses the sound reduction index in the 1/3 octave bands between 125 Hz and 4000 Hz. The use of the plywood sarking also increased the sound reduction index in the 1/3 octave bands above 500 Hz. However, between the 160 and 500 Hz 1/3 octave bands, the roof system with the plywood sarking had the lowest sound reduction index of the roof systems shown in the figure.

The doubling of the sound insulation above the ceiling improved the intensity sound reduction index across the entire frequency range. The doubling of the sound insulation resulted in the highest increases in the magnitude of the intensity sound reduction index in the 1/3 octave bands between 125 and 1250 Hz compared to the other modifications to the roof systems. Therefore, unlike the addition of the plywood sarking which improved the sound reduction index of the base system at the low and high frequencies but only improved the $R_{I,w}$ by 1 dB, the doubling of the sound insulation resulted in the highest STC and $R_{I,w}$ values of all of the roof systems evaluated.

5.3.2. Metal Tile

The changes in the single number ratings for the roof system with the metal chip tile cladding installed are compared in Figure 15.

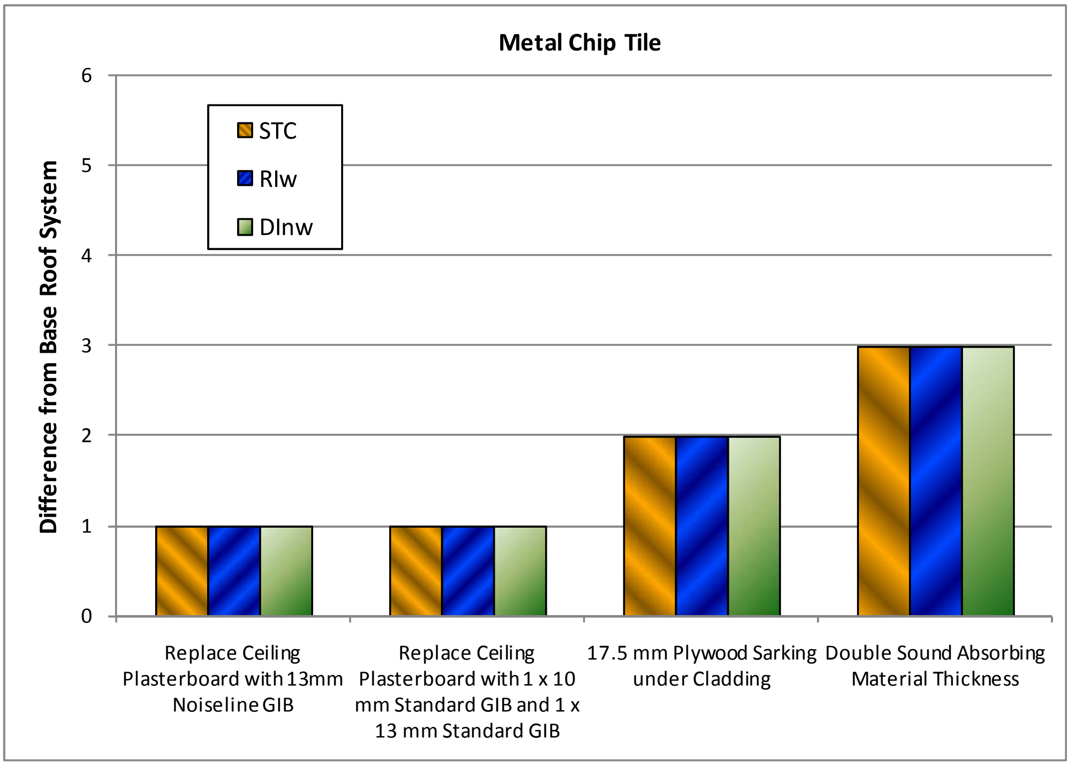

Figure 15: Change in the values of the STC rating, $R_{I,w}$ and $D_{I,n,w}$ due to modifications to the roof system with the metal chip tile cladding installed.

All of the modifications to the roof system with the metal chip tile cladding improved the sound insulation of the roof system. The greatest improvement in the single number ratings was achieved by doubling the thickness of the sound absorbing material in the ceiling cavity, resulting in an increase of 3 in the STC rating and an increase of 3 dB in both the $R_{I,w}$ and $D_{I,n,w}$.

The sound reduction indices of the different roof system configurations with the metal tiles installed are compared in Figure 16.

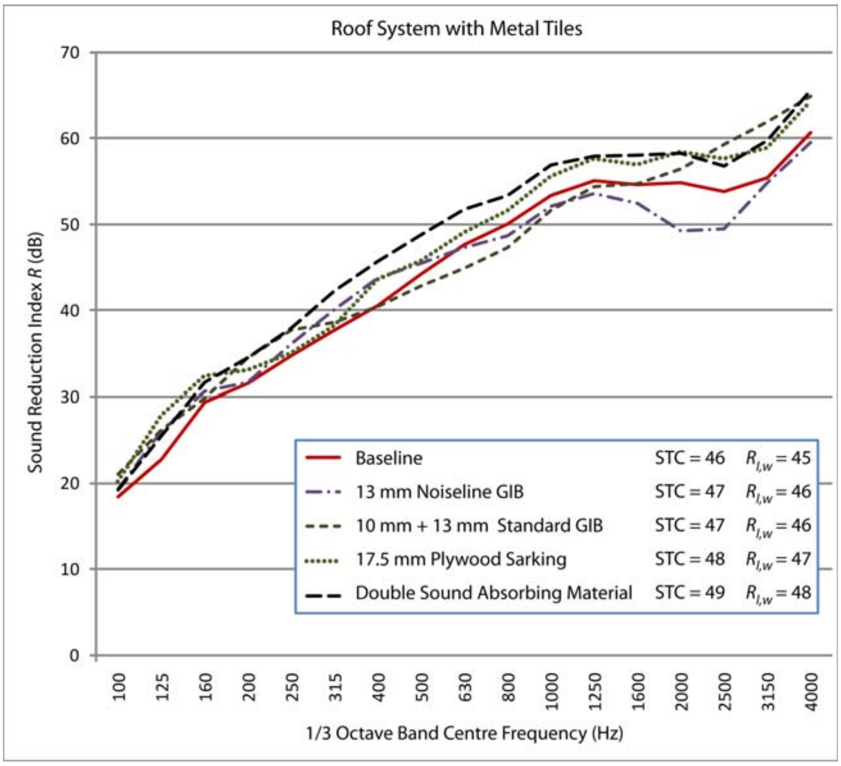

Figure 16: Comparison of the sound reduction indices of the roof system configurations with the profiled metal cladding.

All of the modifications to the roof system with the metal tiles improved the sound reduction index of the base system in the 1/3 octave bands below 400 Hz. As with the sound reduction index of the profiled metal cladding, the sound reduction index of the roof system with the 13 mm Noiseline GIB installed on the ceiling showed a coincidence dip around the 2500 Hz 1/3 octave band. Above the 400 Hz 1/3 octave band, modifications to the ceiling plasterboard were less effective at improving the sound insulation of the roof system than the addition of the plywood sarking or the doubling of the thickness of the sound absorbing material above the ceiling. Doubling the thickness of the sound absorbing material above the ceiling was the most effective method of improving the sound insulation of the ceiling over most of the frequency range with the exception of the 1/3 octave bands below 200 Hz and in the 2000 and 3150 Hz 1/3 octave bands.

5.3.3. Concrete Tile without Underlay

The changes in the single number ratings for the roof system with the concrete tile cladding without underlay are compared in Figure 17.

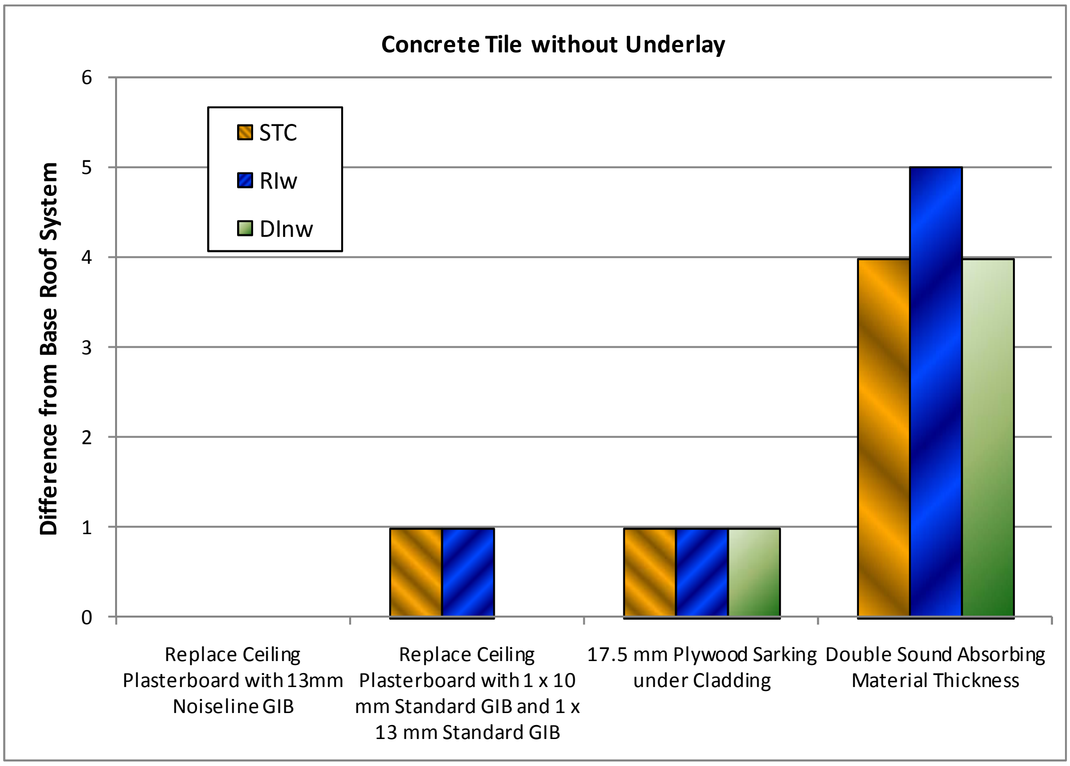

Figure 17: Change in the values of the STC rating, $R_{I,w}$ and $D_{I,n,w}$ due to modifications to the roof system with the concrete tile cladding without underlay.

The replacement of the 13 mm Standard GIB with the 13 mm Noiseline GIB had no effect on the single number ratings. The installation of the 23 mm Standard GIB or the use of the plywood sarking slightly improved the single number ratings. The greatest improvement in the sound insulation of the roof system with the concrete tiles without underlay was achieved by doubling the thickness of the sound absorbing material in the ceiling cavity.

The sound reduction indices of the different roof system configurations with the concrete tiles without underlay are compared in Figure 18.

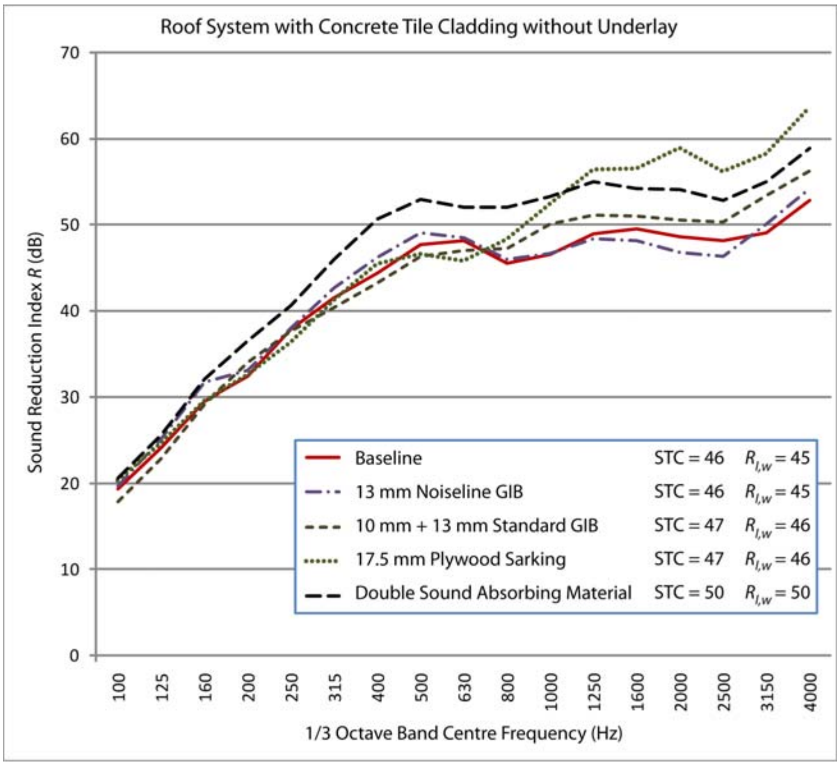

Figure 18: Comparison of the sound reduction indices of the roof system configurations with concrete tile cladding without underlay.

Below the 1000 Hz 1/3 octave band, doubling the thickness of the sound insulating material had the greatest effect on the sound reduction index of the roof system. At the higher frequencies, the addition of the plywood sarking under the cladding resulted in the highest values of the sound reduction index. Figure 10 which compared the intensity sound reduction index of the claddings installed on the base roof showed that the concrete tile without underlay had the lowest sound reduction index above the 630 Hz 1/3 octave band of all of the claddings evaluated, most likely due to the air gaps between the tiles. The addition of the plywood sarking reduced the affect of the noise leaks, resulting in a large improvement in the sound reduction index at the higher frequencies as compared to the base system. However, the single number ratings do not reflect the improvement in the intensity sound reduction index above the 630 Hz 1/3 octave band with the addition of the plywood sarking due to the lack of significant improvement at the lower frequencies.

5.3.4. Concrete Tile with Underlay

The changes in the single number ratings for the roof system with the concrete tile cladding with underlay are compared in Figure 19.

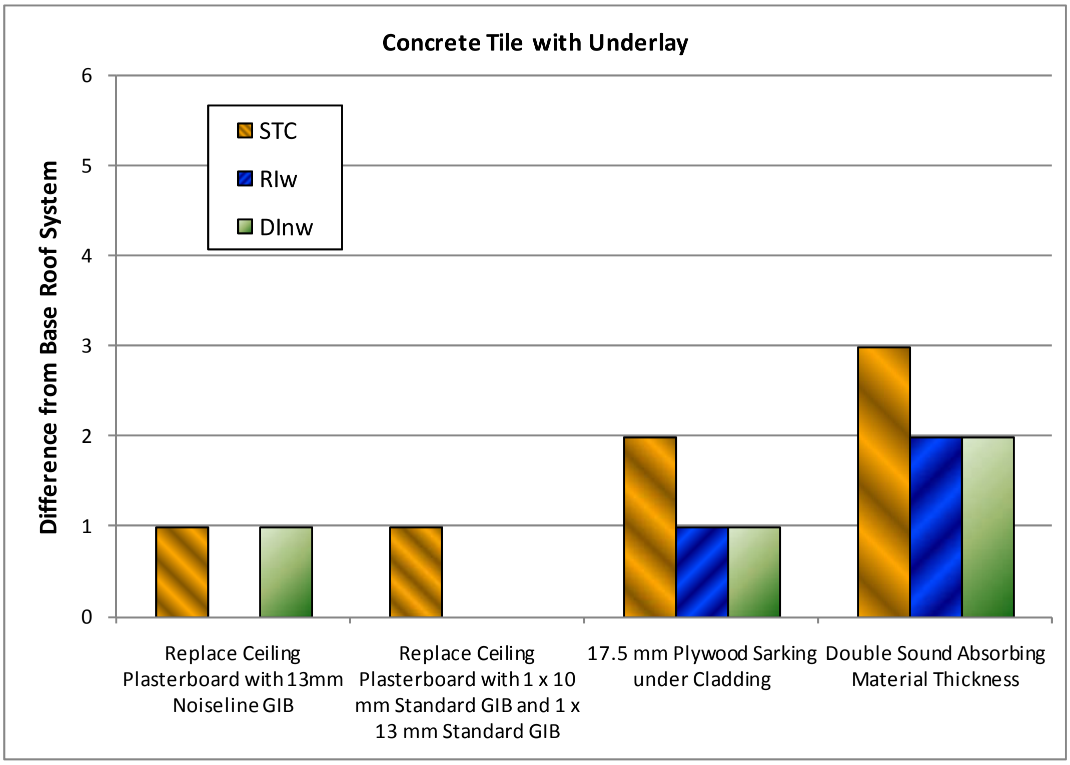

Figure 19: Change in the values of the STC rating, $R_{I,w}$ and $D_{I,n,w}$ due to modifications to the roof system with the concrete tile cladding with underlay.

The figure shows that the maximum improvement in the sound insulation of the roof system with the concrete tile with underlay was a gain of 3 in the STC rating or a gain of 2 dB in $R_{I,w}$ and $D_{I,n,w}$. As with the other claddings evaluated, the greatest gain in the sound insulation of the roof system was achieved by doubling the thickness of the sound absorbing material in the ceiling cavity.

The sound reduction indices of the different roof system configurations with the concrete tiles with underlay are compared in Figure 20.

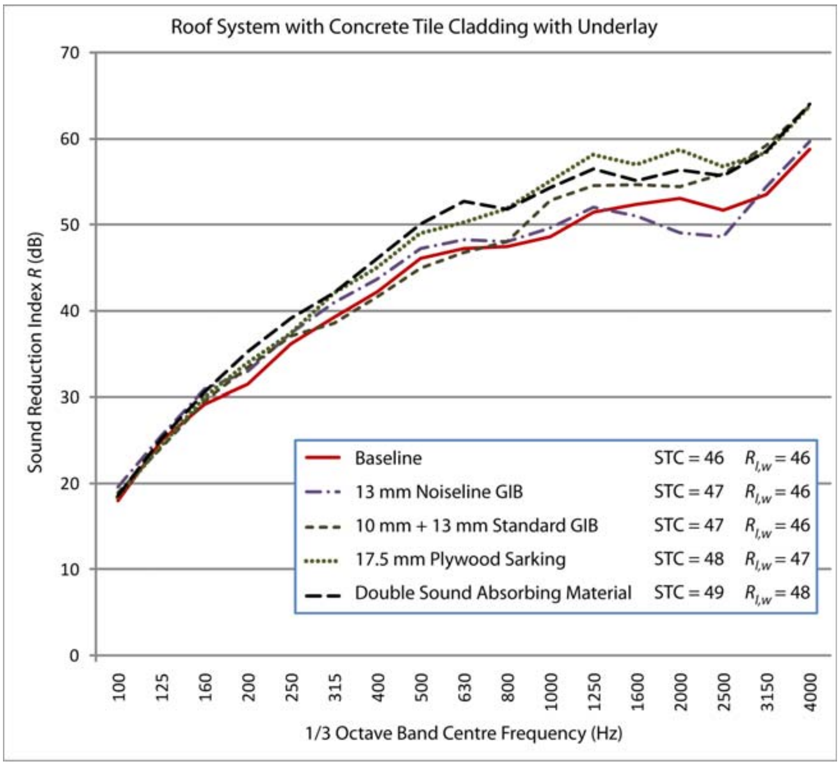

Figure 20: Comparison of the sound reduction indices of the roof system configurations with concrete tile cladding with underlay.

The figure shows the dip in the sound reduction index at the critical frequency of the 13 mm Noiseline GIB around the 2500 Hz 1/3 octave band. As with the other claddings, the addition of the plywood sarking or the doubling of the sound absorbing material above the ceiling were more effective at increasing the sound reduction index of the base system with the concrete tiles with underlay than modifications to the ceiling.

5.4. Results of Increasing the Roof Pitch

While the other modifications to the roof system required changes to only the ceiling, cladding or thermal insulation of the roof system, the modifications to the roof pitch required that the entire roof system be removed so that a new set of trusses could be installed. A different set of builders installed the new trusses and the builders attached the new trusses to the concrete opening in a different manner than the original builders had used. The replacement of the trusses represented a fundamental change in the system and required an assessment of the assumption that the sound reduction indices measured for the roof system with the new trusses were directly comparable to those for the base roof system.

In order to evaluate the effect of the new truss installation on the structure-borne noise, the velocity level difference between the Corrugate 0.4 cladding and the 13 mm Standard GIB was measured for the base system and the system with the new trusses according to ISO 10848-1 [15]. The velocity level difference is an indication of the attenuation of the structure-borne noise through the structural connections. The higher the velocity level difference, the less efficient the structure is at transmitting structure-borne noise.

The velocity level differences of the base roof system with Corrugate cladding and the identical roof system with the exception of the new trusses are compared in Figure 21.

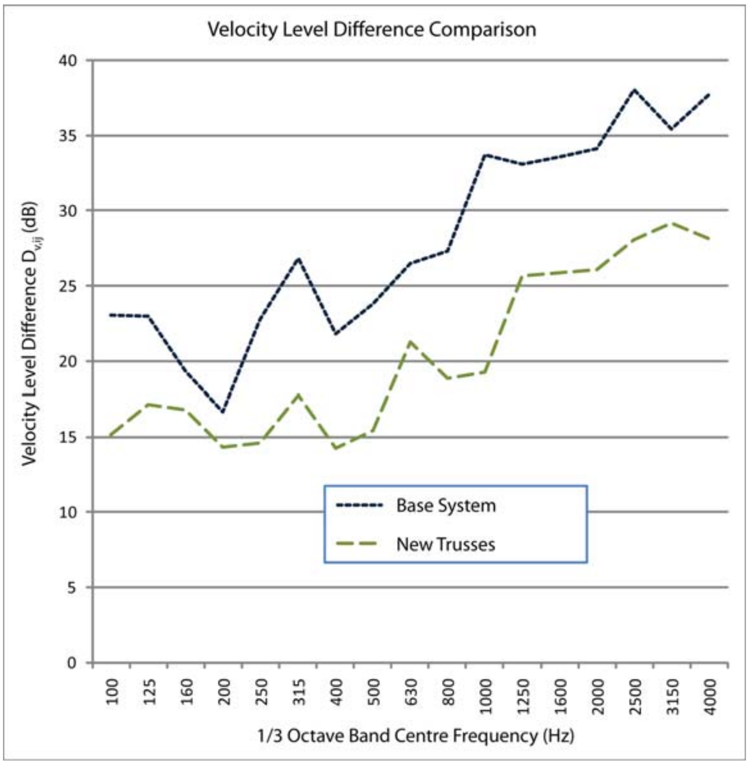

Figure 21: Comparison between the velocity level differences of the base system and the system with the increased roof pitch. The velocity level difference was measured between the Corrugate cladding and the 13 mm Standard GIB on the ceiling using three excitation positions and a total of forty five velocity measurements per side. The higher the magnitude of the velocity level difference, the less efficient the system is at transmitting structure-borne noise between the cladding and the ceiling.

The figure shows that the new trusses were more efficient at transmitting structure-borne noise than the base system. The difference between the velocity level differences was on average 8 dB but as high as 14 dB in the 1000 Hz 1/3 octave band. It was concluded that changing the trusses modified the system in terms of the structure-borne noise transmitted between the cladding and the ceiling. Therefore, the assumption that the measured sound reduction indices for the roof systems with the new trusses could be directly compared with the measurements for the base system no longer holds. However, several important points could be made about the measured data.

The sound reduction indices of the base roof system and the roof system with the new trusses with Corrugate and concrete tiles with underlay are compared in Figure 22.

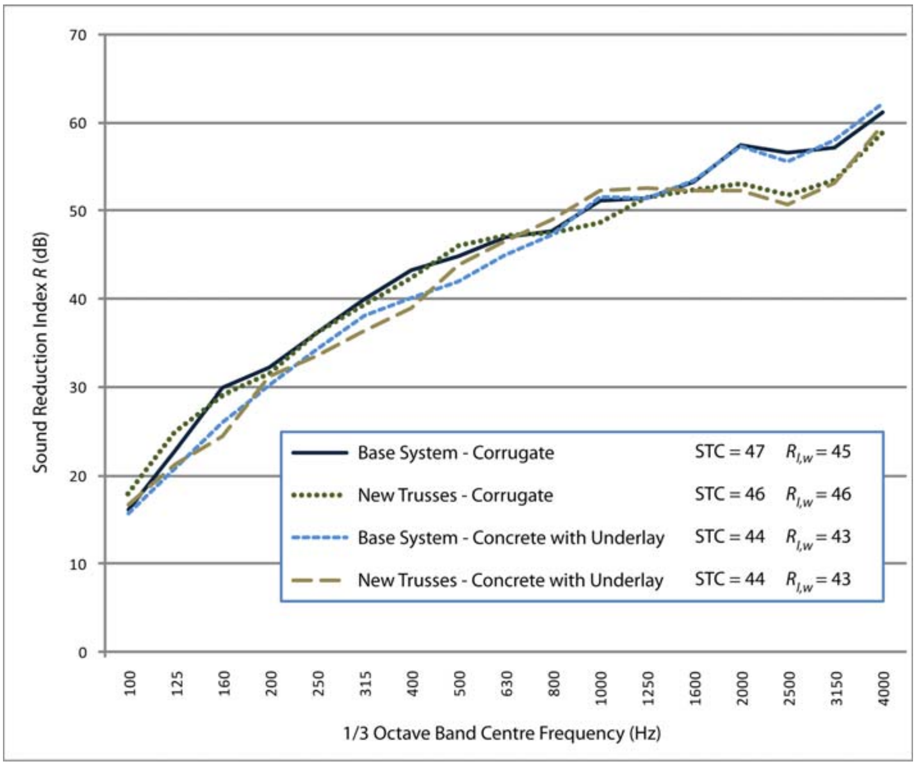

Figure 22: Comparison between the sound reduction indices of the base roof system and the system with the new trusses with Corrugate cladding and concrete tiles with underlay. The higher the value of the sound reduction index, the better the sound insulation of the roof system.

The new trusses affected the sound reduction indices of the roof systems primarily below the 1250 Hz 1/3 octave band. The difference between the sound reduction indices is primarily due to the increase in the efficiency of the propagation of structure-borne noise through the trusses and not due to the increase in the volume of the air between the cladding and the ceiling. Above the 1250 Hz 1/3 octave band, the increase in the efficiency of the structure-borne noise through the trusses has less effect. Therefore, at the higher frequencies, the transmission of airborne noise through the cavity may be the primary transmission path through the roof system.

The comparison between the differences of the sound reduction indices of the claddings installed on the base system and on the system with the new trusses shown in Figure 23 shows that the differences follow similar trends.

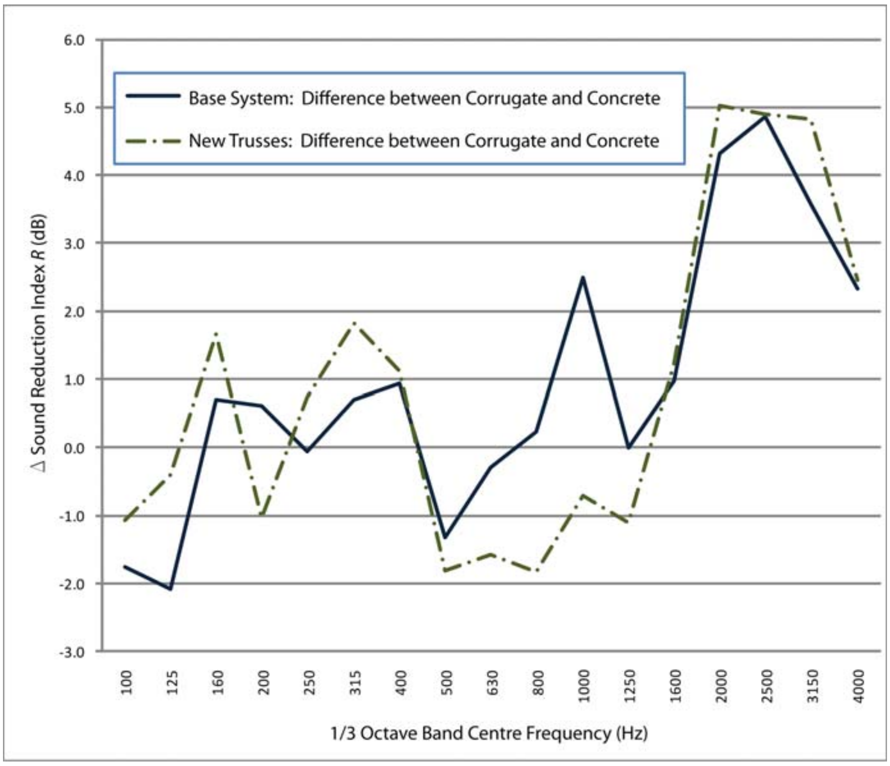

Figure 23: Difference between the sound reduction index of the Corrugate and concrete with underlay claddings for the base roof system and the roof system with the new trusses.

The differences are within 1 dB of each other over most of the frequency range with the exception of the 1/3 octave bands around 1250 Hz where the difference was 3 dB. The greatest difference between the velocity level differences of the base system and the system with the new trusses shown in Figure 21 also occurred in the 1/3 octave bands around 1250 Hz. The results suggest that the trends in the changes in the sound reduction indices of different roof systems due to changes in the components will be similar across different roof constructions.

6. Discussion

6.1. Benefits of Increasing the Fibreglass Insulation Thickness

The evaluation of the sound insulation of the modified roof systems has given an indication of the possible improvements in the sound insulation due to modifications of the roof system components. The measurements showed that adding additional sound absorbing material above the ceiling was the most effective method of increasing the sound insulation of the roof system for all of the claddings considered.

In addition to the advantage of increasing the sound insulation of the roof system, doubling the sound absorbing material above the ceiling has other advantages over the use of plywood sarking under the cladding, for example. The additional sound absorbing material improves the thermal insulation of the dwelling which has the advantage of additional comfort and energy savings for the inhabitants of the dwelling. Furthermore, the doubling of the thickness of the sound absorbing material above the ceiling is likely to be less expensive than the installation of plywood sarking under the cladding.

For example, consider a 110 m^2 dwelling with a gabled roof with 300 mm overhangs and a 35 degree roof pitch. Assuming that the roof system already has a 180 mm layer of R3.6 fibreglass insulation installed above the ceiling in compliance with Clause H1 of the New Zealand Building Code, if the thickness of the fibreglass were to be doubled, the area of the additional fibreglass required would be approximately 123 m^2. If instead, 17.5 mm plywood sarking was installed under the cladding, the area of the plywood sarking to be applied would be approximately 150 m^2 as shown in Table 5.

	Approximate Coverage Area (m2)	Coverage per Unit (m2)	Cost per Unit	Units Required	Total Cost
17.5 mm CD Treated Plywood	150.1	2.9	$86.09	53	$4,562.77
Pink Batt Classic R3.6 180 mm Thick	123.0	7.4	$82.98	17	$1,410.66

Table 5: Costs associated with adding 17.5 mm plywood sharking or layers of 180 mm thick R3.6 fibre glass insulation to a 110 m^2 dwelling with a gabled roof with 300 mm overhangs. The costs presented in the table do not include GST. It is assumed that one layer of 180mm thick R3.6 fibreglass insulation is already installed above the ceiling in compliance with Clause H1 of the New Zealand Building Code [6]. Therefore, only the costs of adding a second layer of the sound absorbing material above the ceiling is considered in the cost analysis.

The data in the table shows that the cost of the additional sound absorbing material in this case would be 60% less than the cost of installing the plywood sarking under the cladding. Furthermore the actual savings gained by doubling of the thickness of the fibreglass insulation would include the reduction in the cost of heating the dwelling due to the increased thermal performance of the roof system.

6.2. Comparison to Clause G6

The evaluation of the sound insulation of the modified roof systems showed that replacing the 13 mm plasterboard (ρ_s = 8.5 kg/m^2) with 13 mm plasterboard (ρ_s = 12.4 kg/m^2) or 23 mm plasterboard ($\rho_{s,total}$ = 15.3 kg/m^2) resulted in a maximum increase in the weighted intensity sound reduction index of only 2 dB. This result differs significantly from the increase suggested in Table 7 of the proposed Clause G6 Appendix B which showed a 10 dB increase in the sound insulation of the roof system was possible if a ceiling constructed of 10 mm plasterboard (ρ_s = 6.5 kg/m^2) was replaced with 13mm plasterboard (ρ_s = 8.5 kg/m^2). Note that Table 7 of the proposed Clause G6 does not include which single number descriptor is used to define the sound insulation which is a glaring omission. Based on the units, it is likely that the descriptor is the weighted sound reduction index.

Table 7 of the proposed Clause G6 also shows that replacing 10 mm plasterboard (ρ_s = 6.5 kg/m^2) with 2 x 13 mm plasterboard ($\rho_{s,total}$ ≈ 17 kg/m^2) and with 17.5 mm plywood sarking (ρ_s = 9.5 kg/m^2) installed under the cladding, the sound insulation would be increased by 20 dB. A system with both plywood sarking and 2 x 13mm plaster board was not evaluated in this study, but the findings in this study would suggest that a 20 dB increase in the sound insulation due to the combined modifications is unlikely.

The proposed Clause G6 does not include references for the basis of the proposed increases in the sound insulation. However, the Department of Building and Housing was contacted during the comment period for the proposed changes to advise of the study being conducted at the University of Canterbury and to challenge the numbers presented in Table 7.

6.3. Other Transmission Paths

Although this study concentrated on the direct transmission of noise through the roof system, it is important to note that the direct transmission of noise through the roof system is just one of the many possible transmission paths for external noise to enter a dwelling. The other transmission paths include the façade of the dwelling and most obviously, the windows [16]. By reviewing the sound reduction index values for various components of the external building envelope, Cook [4] found that the weakest link in the dwellings evaluated was the windows.

For example, according to the New Zealand Building Code, a bedroom in a dwelling with an external wall must have window area of no less than 10% of the floor area [17]. The net openable area of the windows must be no less than 5% of the floor area unless other forms of ventilation have been installed [18]. Consider a bedroom with a floor area of 10 m^2. The required window area would be 1 m^2, 0.5 m^2 of which must be openable unless other forms of ventilation have been installed. Cook [4] found that an openable window has an over-riding influence on the sound transmitted into a dwelling, even when of minimum regulatory area and kept closed. If the window was opened just 1/8, the noise level in the dwelling studied became unacceptably high. This effect was so pronounced that attempts to achieve a roofing system of high insulation properties was largely negated by the window component.

Therefore, other transmission paths, especially the windows must be addressed during the design of a dwelling. When comparing the sound reduction index of windows to that of other elements of the external building envelop, it is important to differentiate between measured data for glazing and measured data for windows. For example, Cook found that the STC rating of the metal roof that he tested was 34 without sarking or insulation between the ceiling joists. The 6 mm thick windows of the dwelling had a STC rating of 31 making them the primary source of noise in the dwelling. The sound reduction index of a window may be lower than that of the glazing since the performance of a window is affected by the window frame and the sealing as well as the glazing [19]. Steps to increase the sound reduction index of windows should include sealing the window to eliminate small gaps through which noise can penetrate and increasing the thickness of the glass.

7. Future Work

The next phase of the study proposed by the New Zealand Metal Roofing Manufacturers Inc. will be the evaluation of the sound insulation of roof systems installed in the field. The field testing will provide information about the absolute sound insulation of different roof constructions and will be used to validate the results of the laboratory testing.

8. Conclusions

Doubling the thickness of the 180 mm thick R3.6 Standard Pink Batts installed above the ceiling was the most effective method of increasing the sound insulation of the roof system. Doubling the thickness of the thermal insulation can cost significantly less than installing plywood sarking under the cladding and offers additional benefits such as increasing the thermal insulation of the dwelling.

Modifications to the ceiling, increasing the thickness of the sound absorbing material above the ceiling or adding plywood sarking under the cladding were found to improve the weighted intensity sound reduction index of the base roof system, but only by a maximum of 5 dB. This increase in the magnitude of the change in the sound insulation due to modifications to the roof system is significantly less than that suggested in the proposed revisions to Clause G6 of the New Zealand Building Code.

The choice of cladding installed on the roof system had a small effect on the sound insulation of the roof system. The maximum difference between the weighted intensity sound reduction indices of the claddings evaluated in this study was only 2 dB across all of the roof systems evaluated.

It was surprising how poorly the 13 mm Noiseline GIB performed in this study due to the coincidence dip in the 2500 Hz 1/3 octave band. Adding an additional 10 mm Standard GIB to the existing 13 mm Standard GIB already installed on the ceiling was more effective than the Noiseline GIB at improving the sound insulation of the roof system.

Appendix A: List of Equipment

Description	Manufacturer	Model	Serial Number
Analyzer	Brüel & Kjær	PULSE C Frame with 7539 5 Chanel Module	2483932
Acoustic Calibrator	Brüel & Kjær	4231	1934296
Dodecahedron Loudspeaker	Brüel & Kjær	OmniPower 4296	2071500
Dodecahedron Amplifier	Brüel & Kjær	2716	2301358
Loudspeakers	JBL	CBT70J	M912001409 M912001411
Amplifier for JBL Loudspeakers	QSC	PLX2502	050880990
Analyzer	Brüel & Kjær	2260	1894145
Sound Intensity Probe	Brüel & Kjær	4197	2225922
Microphones	Brüel & Kjær	4189-L	2573559
			2573560
			2573561
			2573562
			2573563

Table 6: List of equipment used during the measurements.

Appendix B: Standard Deviation of Reproducibility

The standard, ISO 15186-1 does not make note of the expected standard deviation of reproducibility of the measurement method the standard describes. However, it may be reasonable to expect that the standard deviation of reproducibility would not be great than that using the method described in the ISO 140 series of standards. ISO 140-2 [10] lists the standard deviation of reproducibility as determined from round robin testing and is reproduced in Table 7.

1/3 Octave Band Centre Frequency (Hz)	Standard Deviation of Reproducibility from ISO 140-2 (dB)
100	9.0
125	8.5
160	6.0
200	5.5
250	5.5
315	4.5
400	4.5
500	4.0
630	3.5
800	3.0
1000	2.5
1250	3.0
1600	3.5
2000	3.5
2500	3.5
3150	3.5
4000	3.5
5000	3.5

Table 7: Standard deviation of reproducibility from ISO 140-2.

Appendix C: Underlay Properties

The Thermakraft 215 Bituminous Self Supporting Roofing Underlay used in the study had the following properties [20]:

Nominal Weight	0.37 kg/m^2
Tensile Strength MD	15.57 kN/m
Tensile Strength CD	750 kN/m
Edge Tear	99.8 N
Ph Reaction	7.3 nominal
Permeability	197 g/m^2/day
Water Absorption	277 g/m^2 nominal

Appendix D: Sound Reduction Index of Plaster Board

The gypsum board used as part of the study included 10 mm and 13 mm Standard GIB and 13 mm Noiseline GIB. The sound reduction indices of 1.47 m^2 samples of the plaster boards were measured in the small transmission loss rig at the University of Canterbury. The results of the measurements are shown in Figure 24.

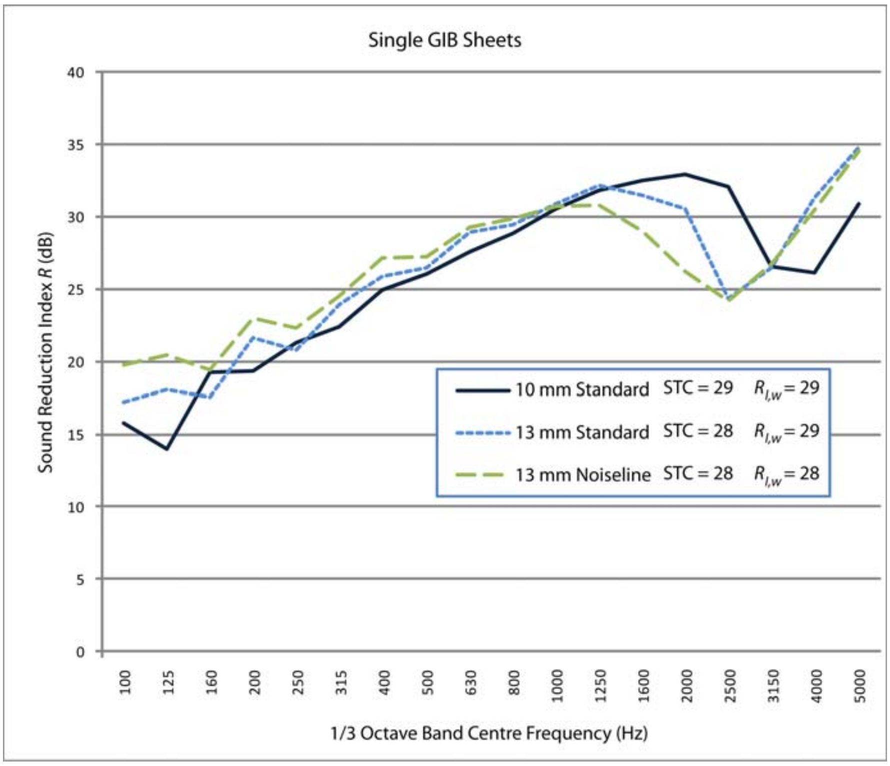

Figure 24: Comparison of the sound reduction indices of the different plaster boards used in the testing.

The mass per unit area of the different samples as measured in the laboratory are shown in Table 8.

Material	Mass per unit area ρ_s (kg/m^2)
10 mm Standard GIB	6.8
13 mm Standard GIB	8.5
13 mm Noiseline GIB	12.4

Table 8: Mass per unit area as measured in the laboratory.

Appendix E: Single Number Ratings

The single number ratings of the roof systems with the four claddings installed are shown in the following tables.

Roof System	Base System			
Cladding	Profiled Metal Cladding	Metal Tile	Concrete Tile without Underlay	Concrete Tile with Underlay
STC	47	46	46	46
$R_{I,w}$ (dB)	45	45	45	46
$D_{I,n,w}$ (dB)	45	44	45	45

Table 9: Single number ratings of the four claddings installed on the base roof system.

Roof System	Replace the Ceiling Plasterboard with 13mm Noiseline GIB			
Cladding	Profiled Metal Cladding	Metal Tile	Concrete Tile without Underlay	Concrete Tile with Underlay
STC	46	47	46	47
$R_{I,w}$ (dB)	45	46	45	46
$D_{I,n,w}$ (dB)	45	45	45	46

Table 10: Single number ratings of the four claddings installed on the roof system with the 13 mm Noiseline GIB ceiling.

Roof System	Replace Ceiling Plasterboard with 1 x 10 mm Standard GIB and 1 x 13 mm Standard GIB			
Cladding	Profiled Metal Cladding	Metal Tile	Concrete Tile without Underlay	Concrete Tile with Underlay
STC	47	47	47	47
$R_{I,w}$ (dB)	46	46	46	46
$D_{I,n,w}$ (dB)	46	45	45	45

Table 11: Single number ratings of the four claddings installed on the roof system with the 23 mm Standard GIB ceiling.

Roof System	Install 17.5 mm Plywood Sarking under the Cladding			
Cladding	Profiled Metal Cladding	Metal Tile	Concrete Tile without Underlay	Concrete Tile with Underlay
STC	47	48	47	48
$R_{I,w}$ (dB)	46	47	46	47
$D_{I,n,w}$ (dB)	45	46	46	46

Table 12: Single number ratings of the four claddings installed on the roof system with the 17.5 mm sarking.

Roof System	2 x 180 mm Pink Batt Classic R3.6			
Cladding	Profiled Metal Cladding	Metal Tile	Concrete Tile without Underlay	Concrete Tile with Underlay
STC	49	49	50	49
$R_{I,w}$ (dB)	48	48	50	48
$D_{I,n,w}$ (dB)	48	47	49	47

Table 13: Single number ratings of the four claddings installed on the roof system with double the thickness of the sound absorbing material above the ceiling.

Appendix F: Sound Reduction Index Data

The intensity sound reduction indices of each of the claddings installed on the base roof system are listed in Table 14.

1/3 Octave Band Centre Frequency (Hz)	R_I of Base Roof Systems (dB)			
	Profiled Metal - Corrugate 0.4	Metal Tile - Chip	Concrete Tile - without Underlay	Concrete Tile - with Underlay
100	7.6	9.0	6.5	12.6
125	6.5	9.3	6.1	15.5
160	9.8	10.4	9.1	17.3
200	10.1	12.8	9.9	19.0
250	13.5	14.5	12.3	18.3
315	14.4	16.5	13.4	18.9
400	15.0	17.0	14.7	17.9
500	16.1	18.0	14.8	20.1
630	15.9	17.6	16.0	22.7
800	15.2	16.1	17.7	25.1
1000	15.3	17.2	19.6	25.3
1250	14.3	17.5	19.8	25.3
1600	14.7	16.6	19.0	25.6
2000	21.6	15.9	25.5	29.9
2500	27.4	19.5	25.2	32.0
3150	30.0	28.9	25.5	34.2
4000	32.4	32.2	26.9	36.9

Table 14: Intensity sound reduction index in 1/3 octave bands of the claddings installed on the base system

The intensity sound reduction indices of each of the claddings on the roof system with the 13 mm Noiseline GIB installed on the ceiling are presented in Table 15.

1/3 Octave Band Centre Frequency (Hz)	R_I of Base Roof Systems (dB)			
	Profiled Metal - Corrugate 0.4	Metal Tile - Chip	Concrete Tile - without Underlay	Concrete Tile - with Underlay
100	7.6	9.0	6.5	12.6
125	6.5	9.3	6.1	15.5
160	9.8	10.4	9.1	17.3
200	10.1	12.8	9.9	19.0
250	13.5	14.5	12.3	18.3
315	14.4	16.5	13.4	18.9
400	15.0	17.0	14.7	17.9
500	16.1	18.0	14.8	20.1
630	15.9	17.6	16.0	22.7
800	15.2	16.1	17.7	25.1
1000	15.3	17.2	19.6	25.3
1250	14.3	17.5	19.8	25.3
1600	14.7	16.6	19.0	25.6
2000	21.6	15.9	25.5	29.9
2500	27.4	19.5	25.2	32.0
3150	30.0	28.9	25.5	34.2
4000	32.4	32.2	26.9	36.9

Table 15: Intensity sound reduction index in 1/3 octave bands of the claddings installed on the roof system with 13 mm Noiseline GIB installed on the ceiling.

The intensity sound reduction indices of each of the claddings installed on the roof system with 23 mm Standard GIB installed on the ceiling are listed in Table 16.

1/3 Octave Band Centre Frequency (Hz)	R_I of Base Roof Systems (dB)			
	Profiled Metal - Corrugate 0.4	Metal Tile - Chip	Concrete Tile - without Underlay	Concrete Tile - with Underlay
100	7.6	9.0	6.5	12.6
125	6.5	9.3	6.1	15.5
160	9.8	10.4	9.1	17.3
200	10.1	12.8	9.9	19.0
250	13.5	14.5	12.3	18.3
315	14.4	16.5	13.4	18.9
400	15.0	17.0	14.7	17.9
500	16.1	18.0	14.8	20.1
630	15.9	17.6	16.0	22.7
800	15.2	16.1	17.7	25.1
1000	15.3	17.2	19.6	25.3
1250	14.3	17.5	19.8	25.3
1600	14.7	16.6	19.0	25.6
2000	21.6	15.9	25.5	29.9
2500	27.4	19.5	25.2	32.0
3150	30.0	28.9	25.5	34.2
4000	32.4	32.2	26.9	36.9

Table 16: Intensity sound reduction index in 1/3 octave bands of the claddings installed on the roof system with 23 mm Standard GIB installed on the ceiling.

The intensity sound reduction indices of each of the claddings installed on the roof system with 17.5 mm plywood sarking installed under the cladding are listed in Table 17.

1/3 Octave Band Centre Frequency (Hz)	R_I of Base Roof Systems (dB)			
	Profiled Metal - Corrugate 0.4	Metal Tile - Chip	Concrete Tile - without Underlay	Concrete Tile - with Underlay
100	7.6	9.0	6.5	12.6
125	6.5	9.3	6.1	15.5
160	9.8	10.4	9.1	17.3
200	10.1	12.8	9.9	19.0
250	13.5	14.5	12.3	18.3
315	14.4	16.5	13.4	18.9
400	15.0	17.0	14.7	17.9
500	16.1	18.0	14.8	20.1
630	15.9	17.6	16.0	22.7
800	15.2	16.1	17.7	25.1
1000	15.3	17.2	19.6	25.3
1250	14.3	17.5	19.8	25.3
1600	14.7	16.6	19.0	25.6
2000	21.6	15.9	25.5	29.9
2500	27.4	19.5	25.2	32.0
3150	30.0	28.9	25.5	34.2
4000	32.4	32.2	26.9	36.9

Table 17: Intensity sound reduction index in 1/3 octave bands of the claddings installed on the roof system with 17.5 mm plywood sarking installed under the cladding.

The intensity sound reduction indices of each of the claddings installed on the roof system with double the sound absorbing material installed above the ceiling are listed in Table 18.

1/3 Octave Band Centre Frequency (Hz)	R_I of Base Roof Systems (dB)			
	Profiled Metal - Corrugate 0.4	Metal Tile - Chip	Concrete Tile - without Underlay	Concrete Tile - with Underlay
100	7.6	9.0	6.5	12.6
125	6.5	9.3	6.1	15.5
160	9.8	10.4	9.1	17.3
200	10.1	12.8	9.9	19.0
250	13.5	14.5	12.3	18.3
315	14.4	16.5	13.4	18.9
400	15.0	17.0	14.7	17.9
500	16.1	18.0	14.8	20.1
630	15.9	17.6	16.0	22.7
800	15.2	16.1	17.7	25.1
1000	15.3	17.2	19.6	25.3
1250	14.3	17.5	19.8	25.3
1600	14.7	16.6	19.0	25.6
2000	21.6	15.9	25.5	29.9
2500	27.4	19.5	25.2	32.0
3150	30.0	28.9	25.5	34.2
4000	32.4	32.2	26.9	36.9

Table 18: Intensity sound reduction index in 1/3 octave bands of the claddings installed on the roof system with 2 x 180 mm sound absorbing material installed above the ceiling.

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