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The acoustical influence of balcony depth and parapet form: experiments and simulations.

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Abstract

The influence of balcony depth and parapet form on the acoustical performance of building facades close to roadways have been investigated. Various depths and two inclinations of parapet have been modelled on an 8 floor building. Pyramid ray-tracing simulations and scale model measurements have been carried out. The predicted and measured A-weighted sound pressure level reductions over the balcony back wall and in free field conditions have been compared. The results have been used to derive empirical equations for predicting protection as a function of geometrical parameters. The protection obtained by various parapet depths ranges between 4 and 8 dB(A), while an additional protection of between 0.5 and 4 dB(A) can be obtained by inclining the parapets.

Keywords: Environmental noise; Balcony; Pyramid tracing; Traffic noise

1. Introduction

It is known that surrounding landscape, natural or artificial barriers and soil composition can reduce the sound propagation when the distance between the sound source and the observer is in the vicinity of approximately a hundred meters [1]. When that distance is between 5-50 meters (as is the case in high density cities), the building envelope influences the noise levels from the nearby roadway,

A balcony is one of building envelope elements that can provide acoustic protection. A previous paper [2] discussed the benefits gained from the balcony ceiling. In this paper of the sound level reduction due to various balcony forms is investigated.

Previous studies have investigated sound levels reductions due to balcony depth by experimental and numerical models, and field measurements. Mohsen and Oldham [3] concluded that a first floor open balcony with 1m depth, without a ceiling, could provide L_{10} insulation of approximately 6 dB(A). Field measurements by May [4] did not give any information about the reduction obtained by isolating balcony's parapet surface. The numerical study of Hothersall [5] discussed the effect of treating parapet

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surfaces with absorbing materials for 1m-balcony depth and for 4 floors. It was found that these treatments can provide 3.9 dB(A) of reduction at the first floor and between 1 and 1.9 dB(A) reduction for the other floors. Hammad [6] evaluated the effect of four depths and two types of parapet forms (splitter and thnadner), for a five floor building with closed balconies. It was found that the protection increase by 2 dB(A) per floor level for lower levels, and the protection obtained by parapet forms range between 2 and 6 dB(A). Hossam El-dien and Woloszyn [2, 7, 8, 9, 10], have investigated the use of an inclined form to increase the shielding effect to protect the balcony back wall from the traffic noise nuisance in a free field conditions.

In this study, the effects of three balcony depths and two parapet inclinations on an 8-floor building near to a road are investigated by means of model experiments and numerical simulations. As in many references [2, 3, 5, 6, 7, 8, 9, 10] the general screening effects are expressed in terms of A-weighted sound levels.

2. Prediction Methodology and geometric parameters

The model experiments have used an equivalent to an infinite coherent line source parallel to the building facade. All the surfaces in the model are initially defined as quasi-specular surfaces (painted concrete block and varnished wood with absorption coefficient $\alpha=0.07$ at 1KHz).

Frequency	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz
Painted concrete block	0.1	0.05	0.06	0.07	0.09	0.08
Varnished wood	0.15	0.1	0.1	0.07	0.06	0.07

Table 1. Sound absorption coefficient in octave bands.

Reverberation has not been taken into account in either the simulations or the experiments. Moreover the effects of atmospheric absorption have not been scaled in the experiments since they have been carried out in the same atmospheric conditions (20°C temperature and 60% humidity). The corresponding Atmospheric attenuation A_{atm} values are presented in Tables 2 and 3 [11].

Frequency	1250Hz	2500Hz	5000Hz	10kHz	20kHz
A_{atm} (dB/1m)	0.007309	0.012712	0.030384	0.098938	0.359031

Table 2. Atmospheric attenuation on dB/1m for the scale model measurements.

Frequency	125Hz	250Hz	500Hz	1kHz	2kHz
A_{atm} (dB/10m)	0.00292	0.01056	0.03069	0.06186	0.10399

Table 3. Atmospheric attenuation on dB/10m for full-size simulation.

The atmospheric attenuation reduction has been calculated for various reception points (Table 4). Its effect is between 0.3 and 0.7 dB(A).

Distance (m)	Attenuation dB (A)
1.5	4.8
2.25	5.2
3	5.7

(a)

Distance (m)	Attenuation dB (A)
15	4.5
22.5	4.7
30	5.0

(b)

Table 4. Atmospheric attenuation in dB (A) at various distances, (a) scale model and (b) full-size simulation.

The basic idea of increasing balcony's depth and inclining balcony's parapet is to decrease the contributions of the reflected and diffuse energy components by increasing the shielding zones as shown in Fig. 1. The inclined parapet increases the shielding zone over the balcony back wall in comparison with the classical parapet form. This is due to the screening of that surface from direct rays and the increasing of the path between the source and the reception points.

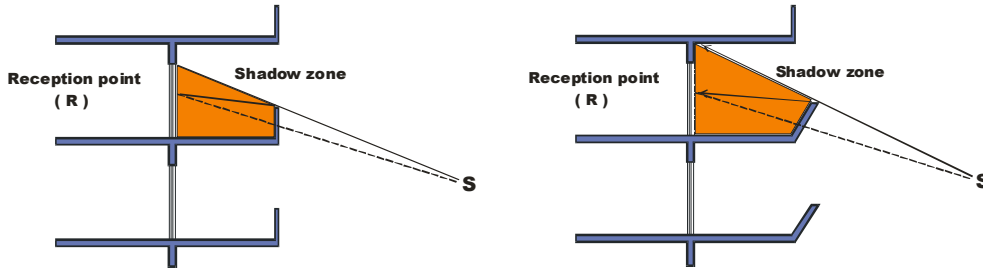


Fig. 1. Schematic representation the shielding effect before and after changing balcony parapet form.

The protection provided by these configurations are calculated by the following steps:

Firstly, the sound pressure reference level (SPL_f), in A-weighted scale, was calculated in free condition over the surface of the facade. The protection level due to the balcony depth is defined as the difference in noise level at an assessment point with and without balcony and calculated by the following relation:

$$L_w = SPL_f - SPL_w \text{ dB(A)}, \quad (1)$$

, while the protection level obtained by the inclined parapet is calculated according to:

$$L_\beta = SPL_w - SPL_\beta \text{ dB(A)} \quad (2)$$

, where SPL_β is the sound pressure level obtained by a balcony with inclined parapet at the same reception point, SPL_w is the sound pressure level after the insertion of a balcony with different depths.

As shown in Fig. 2, the simulation has been carried out with the following variables:

1. The horizontal projection depth ($W = 1, 2, \text{ and } 3 \text{ meters}$).
 2. The balcony's parapet inclined angle ($\beta = 15^\circ \text{ and } 30^\circ$).
- Including the fixed parameters:

1. Sound source (infinite).
2. Distance to road (8.00 m).
3. Front wall height (1.00m).
4. Balcony's length ($L = 5.00\text{m}$).
5. Number of floors (8 floors).

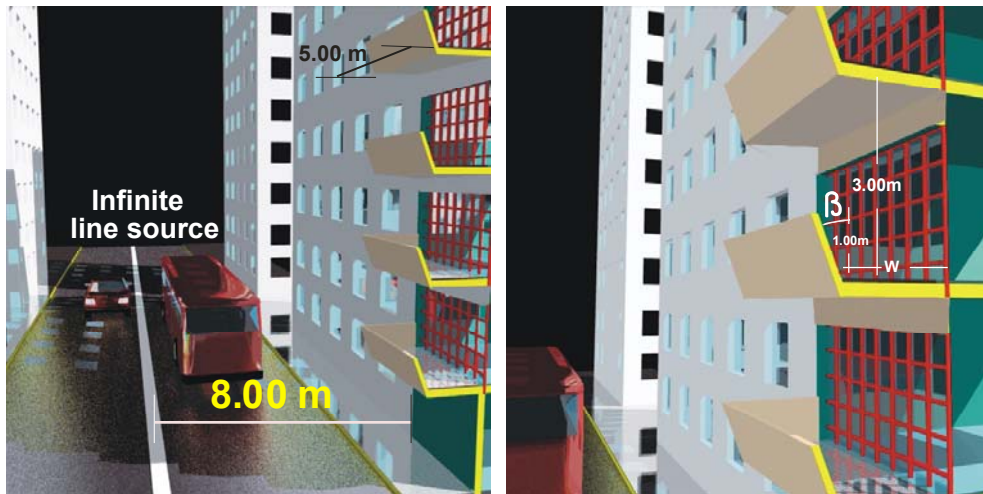


Fig. 2. Geometric parameters.

3. Numerical model

The simulation process is carried out through a pyramid tracing numerical modeling technique [12]. The main advantage of pyramid tracing over other diverging beam tracers (cone tracing [13], circular Gaussian beam tracing [14]) is the fact that pyramids perfectly cover the surface of a spherical source, while cones cause overlapping or uncovered zones (Fig.3).

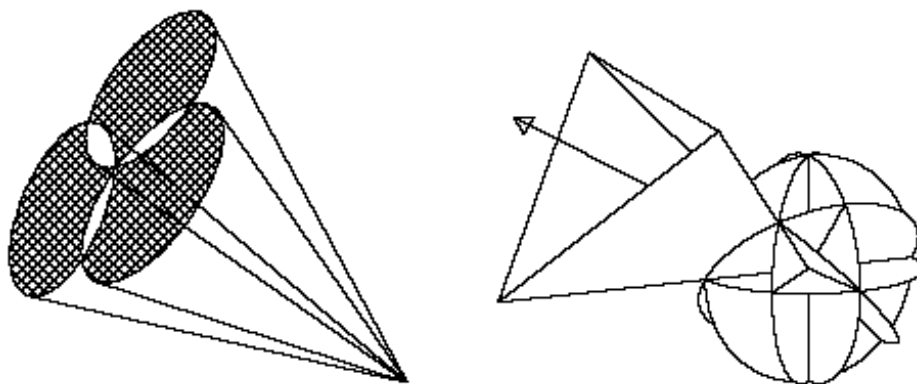


Fig. 3 Comparison between cone tracing and pyramid tracing [12].

In the pyramid tracing scheme, triangular beams are generated at the sound source, as shown in Fig. 3. The central axis of each pyramid is traced being specularly reflected when it hits on a surface. The three corners of the pyramid follow the axis, being reflected from the same plane where it hits.

One of pyramid tracing models, DISIAPYR[®], is used to simulate the acoustical environment. This algorithm allows the simulation of outdoor sound propagation with a complex urban form and the evaluation of sound passing through insulated panels, taking into account the edge diffraction over the boundaries, the shielding effects, the excess attenuation, the scattering of sound from the finite surfaces' edges, and the surface diffusion coefficient [15].

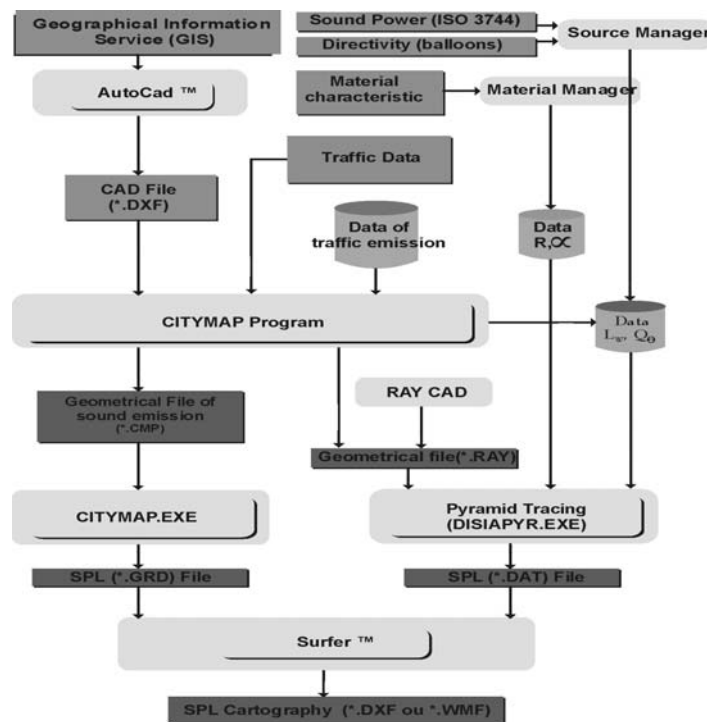


Fig. 4 Schematic representation of the pyramid tracing model (DISIAPYR[®]) [2].

Using the programs CITYMAP[®] and Source Manager[®] [14], an infinite line source was simulated with 2.00m between its point sources. The sound pressure level was calculated through 3000 reception points over the balcony back wall. The system of simulation is fully described in references [2] and [16].

4. Experimental model

4.1. Scale model

A 1:10 scale model of building façade with 2.50m height and 1.60m length (Fig. 5) was carried out. The building façade was simulated by varnished wood (absorption coefficient $\alpha=0.07$ at 1K.Hz) in order to satisfy the laws of acoustic similarity for the sound absorption by the building façade. The road is simulated by a reflecting surface (P.V.C. tiles over concrete floor)

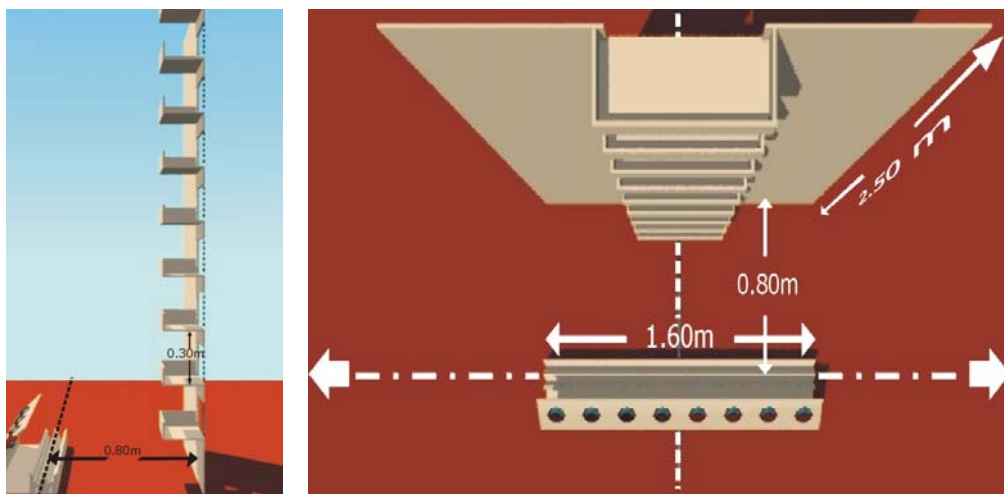


Fig. 5. Scale model dimensions.

4.2. Line sound source

As shown in Fig. 6, a Line source was simulated with 8 tweeters AUDAX (TW 034X0), filtered to obtain a frequency response from 1.6 KHz to 25 KHz. The tweeters were directed towards a quadratic residue diffusor in order to provide a quasi quarter-cylindrical propagation in front of the building facade.

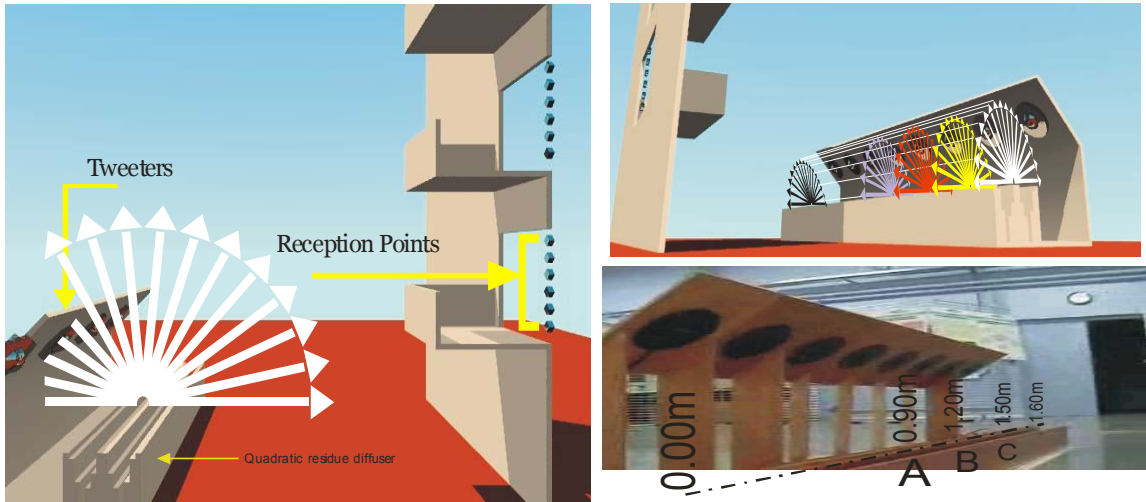


Fig. 6. Line source with a quadratic residue diffuser.

The tweeters were fixed in a varnished wooden frame with 1.60 m length and the distance between the tweeters centers is 0.20 m, corresponding to the full scale model (16.00 m line source with 2.00 m between its points).

By this diffusing system based upon Schröder's quadratic residue diffusor modeling [17], the line source directivity (Fig.7) is made quasi-uniform in the aperture angle of interest (from 40° to 80°). The line source directivity measurements were made using a ¼" microphone Larson Davis type 2530. The sequence of the quadratic residue diffusor is calculated following the Schröder's modulo formula [17] and with 1.60m length, 0.14m height, and 0.11m width.

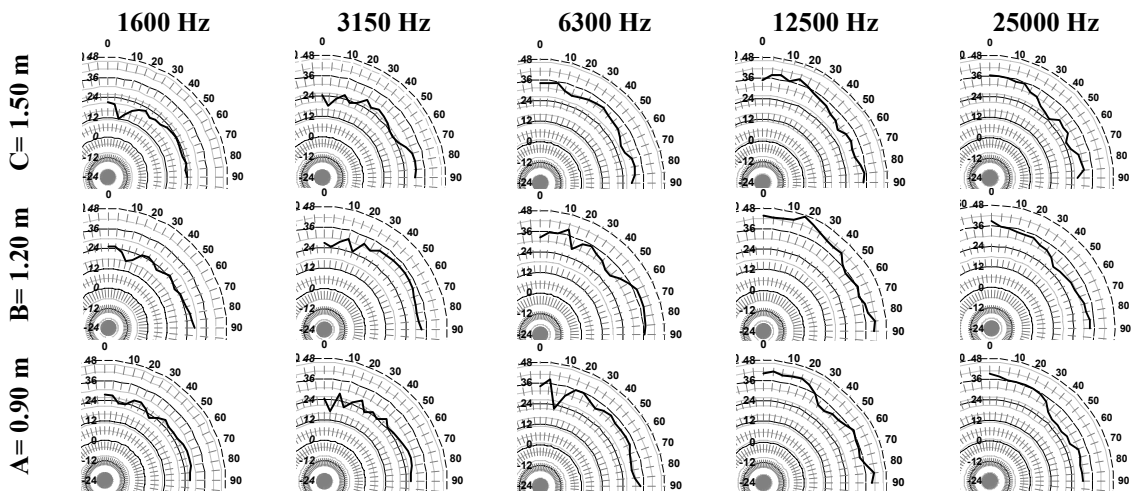


Fig. 7. Line source directivity measurements at A, B, and C sections.

4.3. Acquisition system

As shown in Fig.8, the experimental results were obtained using a measurement exploiting maximum-length sequence stimulus (MLS). The A-weighted sound pressure levels are measured with a 1/2 inch free field microphone (G.R.A.S – type 40 AE) connected to a MLSSA card via a preamplifier-conditioner (01dB - PRE12S). The sound pressure level in A-weighted scale was calculated through 18 reception points (Fig. 9) over the balcony back wall (6 points at the centre and 6 points at every side with a horizontal distance equal to $L/8$ from parapet side). The finite size of the microphone diaphragm means that, in the full scale every point covers 0.0156 m^2 area (microphone area in full scale) and represents the average of 5 measurements at the numerical model. The effects due to directivity of the microphone have not been considered in the analysis since the changes in the incidence angle due to balcony modifications were small.

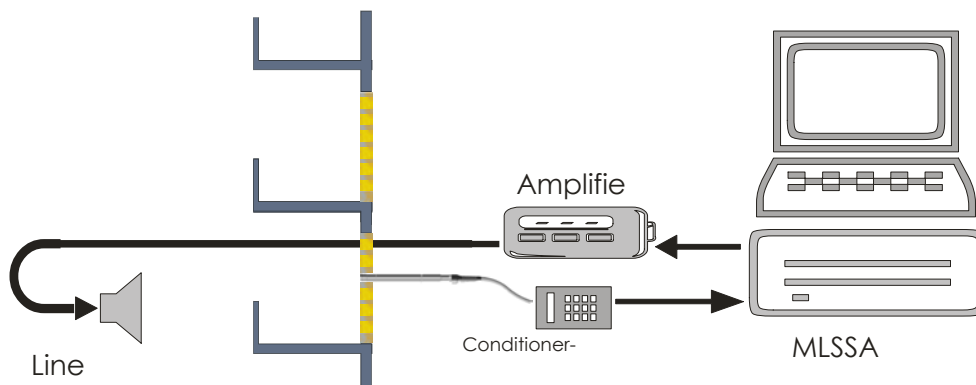


Fig. 8. Schematic representation of measurement system.

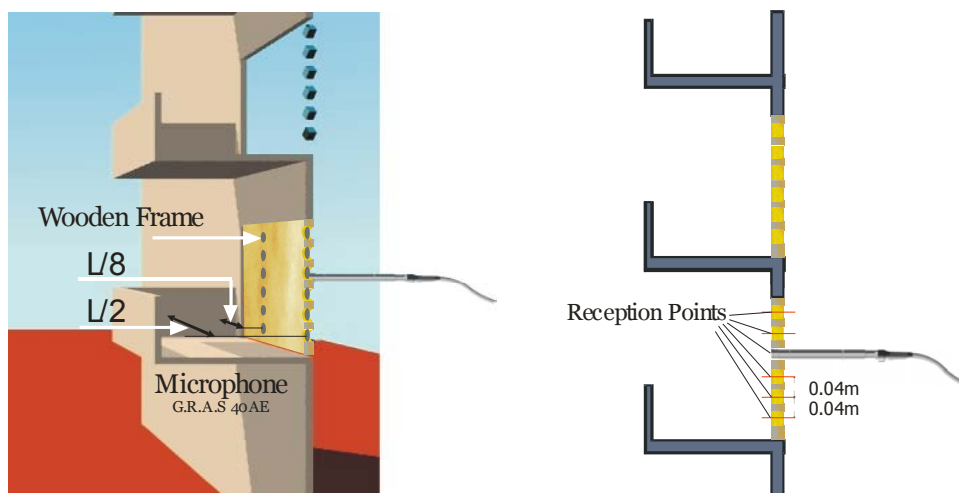


Fig. 9. Reception points and microphone position.

5. Results and discussion

5.1. Balcony width (W)

Firstly, the average of measured reduction are obtained (*by 3000 reception points*) and compared with the average of predicted reduction (*by 18 reception points*).

In Fig. 10 we present the reduction average in SPL as a function of building floor level for a 1m-balcony depth. It has been noted that predicted reduction average is often greater than the measured one, with differences range between 0.5 and 1.5 dB(A). Balconies at high floors can give better reduction than those at lower floors. This is due to the fact that receiver is subjected to strong direct and diffracted components at lower floors and the path deference of the diffracted and direct rays increases relatively with the balcony height. Generally, reduction average increases with floor level and can be calculated by the following empirical equation:

$$R_{1m} = \text{Ln}(N) + 5.4 \text{ dB (A)}. \quad (3)$$

Where N is floor level ($N= 2, 3 \dots 8$).

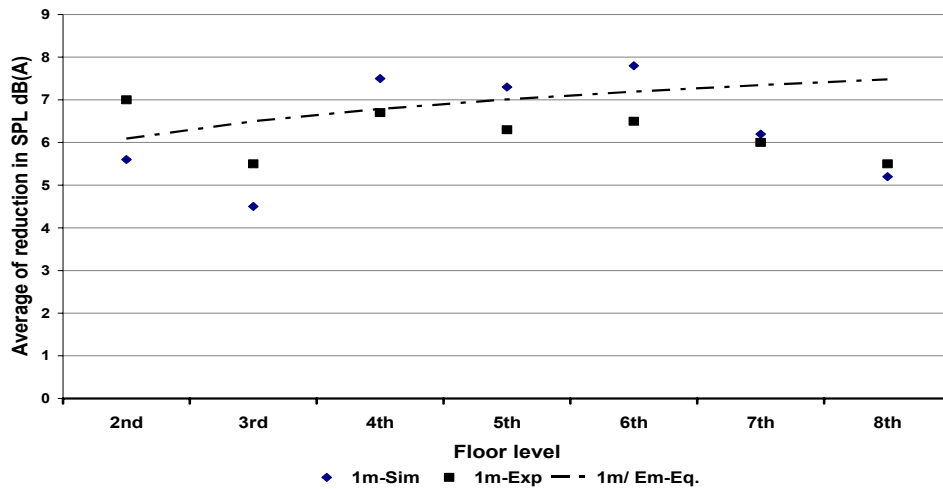


Fig. 10. Reduction Average for a 1m-balcony depth, \blacklozenge simulation results, \blacksquare measurements results, and $---$ empirical equation results.

At the second step, the measurements protection levels are obtained at the centre of a balcony back wall and compared with the predicted protection levels at the same assessment points.

Fig.11 displays the measured and the predicted protection results for a 1m-balcony depth at the centre of its back wall. These figures demonstrate that protection levels values at lower points are greater than those of higher points. This is due to the location of those points at the shadow zone and the sound reflection from balcony ceiling at the highest reception points.

From the prediction results and by using the least-square method (or regression model), we found that the protection level values obtained by these configurations can be calculated according to the following linear equation and with correlation coefficient $R=0.87$:

$$L_{1m}(h) = 0.50 N (h-1) - 6.80 h + 15 \text{ dB (A)}. \quad (4)$$

Where h represents the height of reception points above the balcony floor, and N is the floor level ($N= 2, 3 \dots 8$).

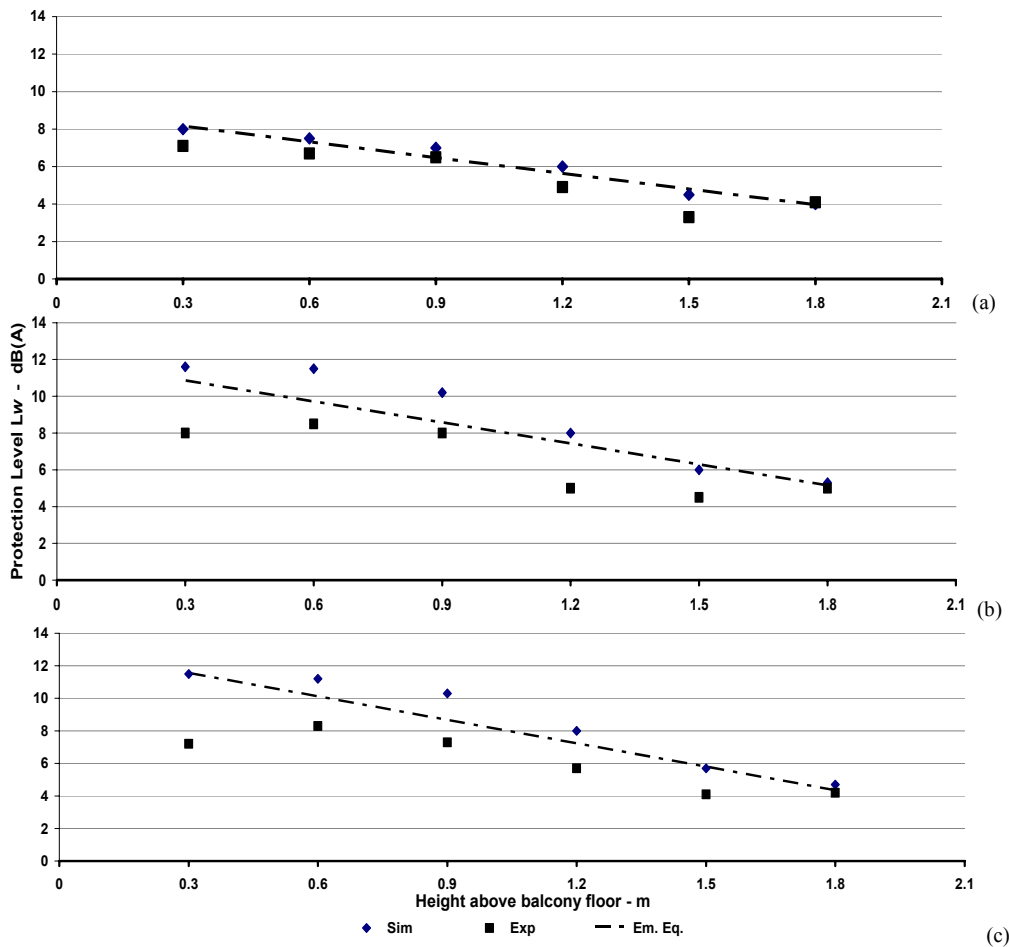


Fig. 11. Protection level for a 1m-balcony depth at the centre of its back wall, \blacklozenge simulation results, \blacksquare measurements results, and $- \cdot -$ empirical equation results for the (a) 8th, (b) 6th, and (c) 4th floors.

As demonstrated in Fig. 12, the average reduction in sound pressure level for a 2m-balcony depth ranges between 5 and 8 dB(A), while the difference between the measured and predicted results is between 0.5 and 2 dB(A).

The average reduction obtained by this configuration is lower than that obtained by a 1m-balcony depth and this is due to the increase of ceilings reflected surfaces.

As the previous configuration, it is found that the average reduction increases with floor level and can be calculated by the following empirical equation:

$$R_{2m} = \text{Ln}(N) + 5.0 \text{ dB (A)}. \quad (5)$$

Where N is floor level ($N= 2, 3 \dots 8$).

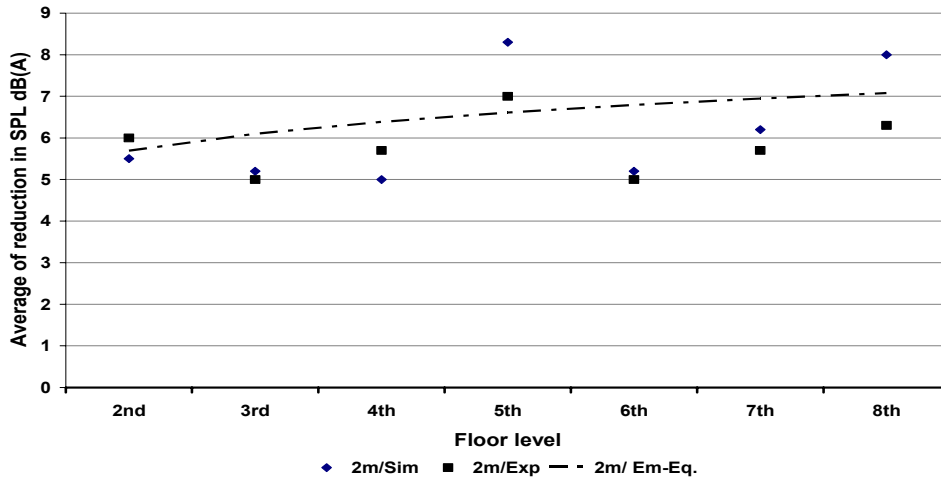


Fig. 12. Average reduction for a 2m-balcony depth, ◆ simulation results, ■ measurements results, and - - - empirical equation results.

In Fig. 13, we can notice that the difference between the measured and predicted protection levels provided by this configuration is almost negligible at the 4th floor (Fig. 13 (c)) while it is between 0.5 to 2 dB(A) at the 8th and the 6th floors (Fig. 13 (a) and (b)).

Generally, it is found that the protection is 1.5 dB(A) less than that offered by the previous type and can be calculated according to a linear empirical equation with correlation coefficient $R=0.81$:

$$L_{2m(h)} = 0.50 N (h-1) - 6.80 h + 13.5 \text{ dB (A)}. \quad (6)$$

Where h represents the height of reception points above the balcony floor, and N is the floor level ($N= 2, 3 \dots 8$).

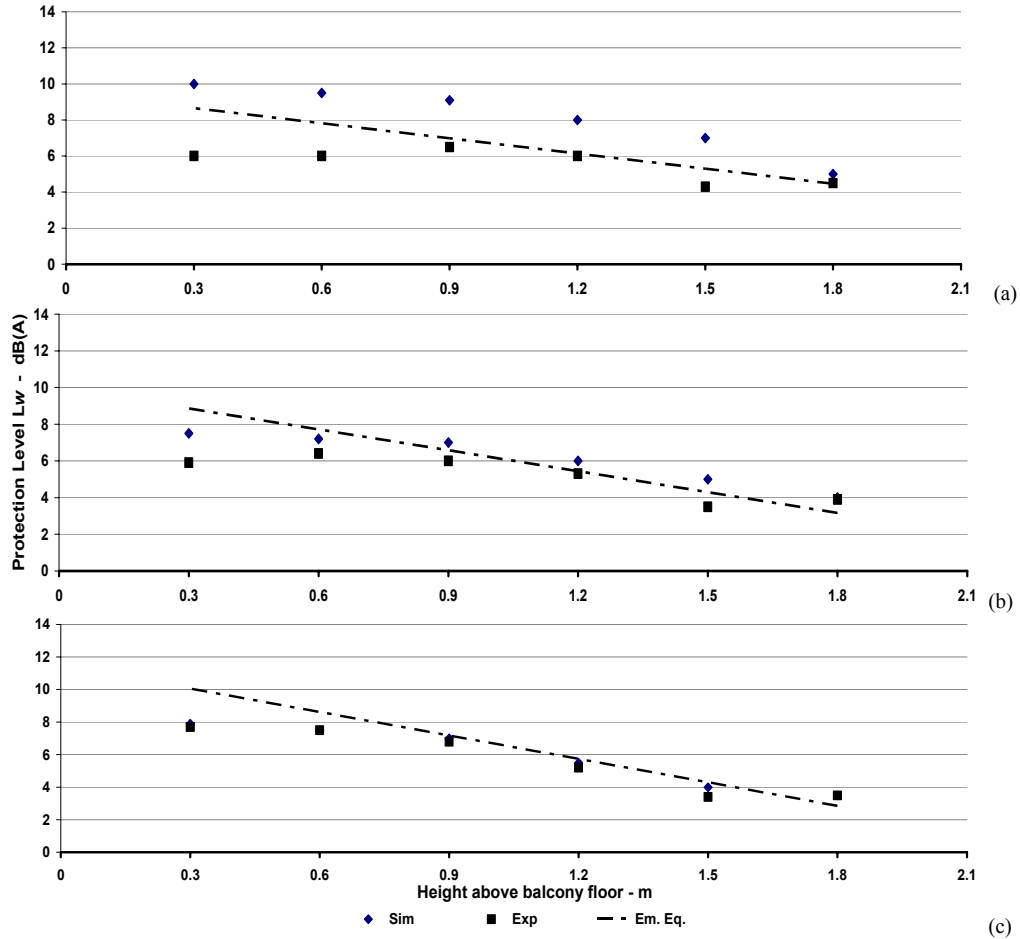


Fig. 13. Protection level for a 2m-balcony depth at the centre of its back wall, \blacklozenge simulation results, \blacksquare measurements results, and $- -$ empirical equation results for the (a) 8th, (b) 6th, and (c) 4th floors.

In Fig.14, we show the reduction average provided by a 3m-balcony depth. It is obvious that the average reduction decreases (from 4 to 8 dB(A)). This is mainly due to the increase in reflecting and diffracting surfaces (Ceiling, floor, and parapet) than the previous types.

Following these results, we found that the average of reduction obtained by a 3m-balcony depth can be calculated by the following empirical equation:

$$R_{2m} = \ln(N) + 4.6 \text{ dB (A)}. \quad (7)$$

Where N is floor level ($N= 2, 3 \dots 8$).

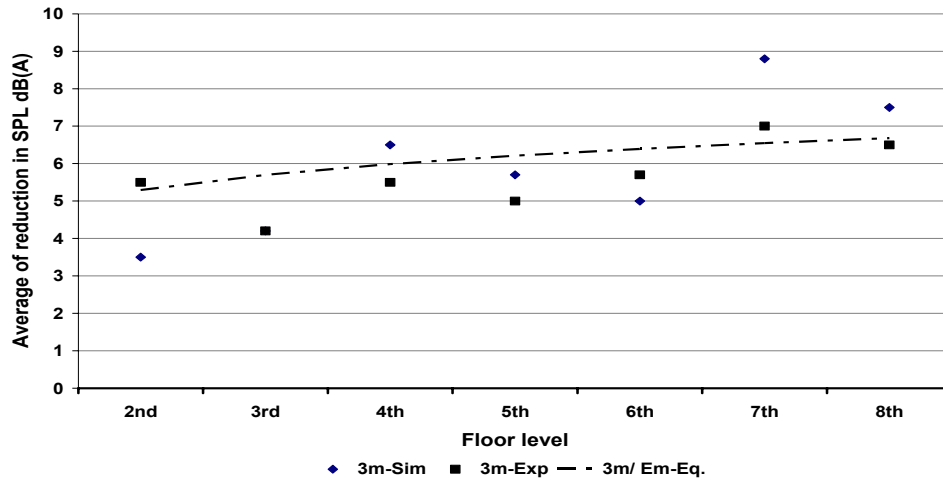


Fig. 14. Reduction Average for a 3m-balcony depth, ◆ simulation results, ■ measurements results, and --- empirical equation results.

Fig. 15 demonstrates that the differences between the measured and predicted protection levels provided by this type of balconies are approximately negligible for the most of reception points.

Generally, the protection level values is less than the 1 m balcony depth by 3 dB(A) and can be also calculated following a linear empirical equation with correlation coefficient $R=0.75$:

$$L_{3m(h)} = 0.50 N (h-1) - 6.80 h + 12 \text{ dB (A)}. \quad (8)$$

Where h represents the height of reception points above the balcony floor, and N is the floor level ($N= 2, 3 \dots 8$).

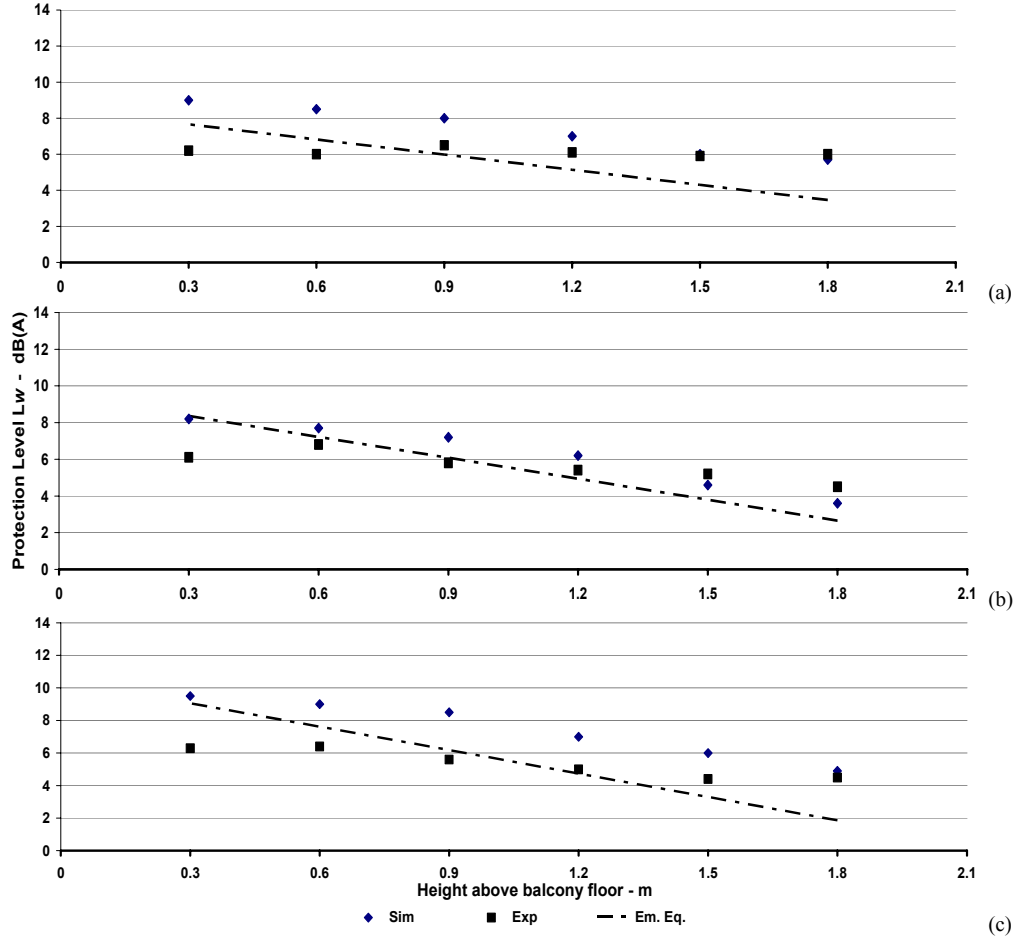


Fig. 15. Protection level for a 3m-balcony depth at the centre of its back wall, \blacklozenge simulation results, \blacksquare measurements results, and $- -$ empirical equation results for the (a) 8th, (b) 6th, and (c) 4th floors.

Equations 3, 5, and 7, show that the reduction average obtained by balconies with 1, 2, and 3m depths can be calculated by an empirical equation and as a function of geometrical parameters:

$$R_w = \text{Ln}(N) - 0.4W + 5.8 \text{ dB (A)}. \quad (9)$$

Where N is floor level ($N=2, 3 \dots 8$), and W is the balcony depth ($W=1, 2, \text{ and } 3\text{m}$).

Furthermore, equations 4, 6, and 8 leads to calculate the protection level at the centre of the balcony back wall by an empirical equation and also as a function of geometrical parameters:

$$L_{w(h)} = 0.50N(h-1) - 6.80h - 1.50W + 16.50 \text{ dB (A)}. \quad (10)$$

Where h represents the height of reception points above the balcony floor, and N is the floor level ($N=2, 3 \dots 8$).

5.2 Balcony inclined parapet (β)

The second set of results concerns the effect of a balcony with an inclined parapet. Two inclined angles are tested ($\beta = 15^\circ$ and 30°). Fig. 16 presents the reduction average obtained from that configuration and for a 1m-balcony depth. We can notice that the inclined parapet with 15° is more effective at higher floor levels where we can gain an additional reduction (from 0.5 to 2 dB(A)).

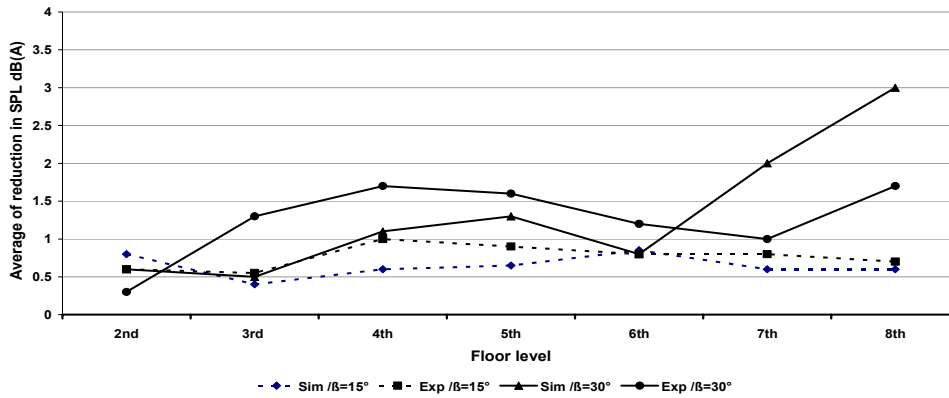


Fig. 16. Average Reduction provided by inclined parapets ($\beta = 15^\circ$ and 30°) for a 1m-balcony depth, (Sim) simulation results, and (Exp) measurements results.

Fig. 17 displays the protection level as a function of the reception point heights at the centre of balcony back wall at the 8th floor and for an angle ($\beta = 30^\circ$) corresponding to the maximum effect. It demonstrates that the protection levels at higher points are greater than those at the lower points. This is due to the increase of shadow zone as explained in section 2.

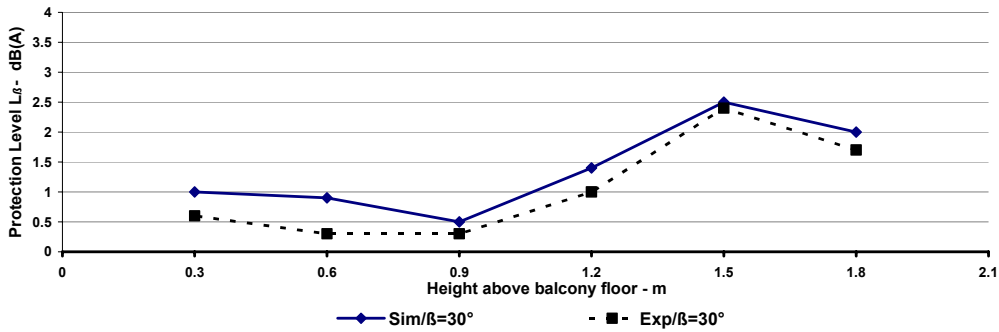


Fig. 17. Protection level provided by an inclined parapet ($\beta = 30^\circ$) for a balcony with 1m and at the centre of its back wall (8th floor), \blacklozenge straight line represents the simulation results, \blacksquare dashed line represents the measurements results.

For the 2m-balcony depth, the average reduction is greater than that obtained with 1m depth, and the inclined angle ($\beta = 30^\circ$) is more effective at the higher levels. In Fig.18, we can notice that of the average reductions are divided into two sequences: The first is located from the 2nd to the 5th floors, and the second is located from the 5th to the 8th floors.

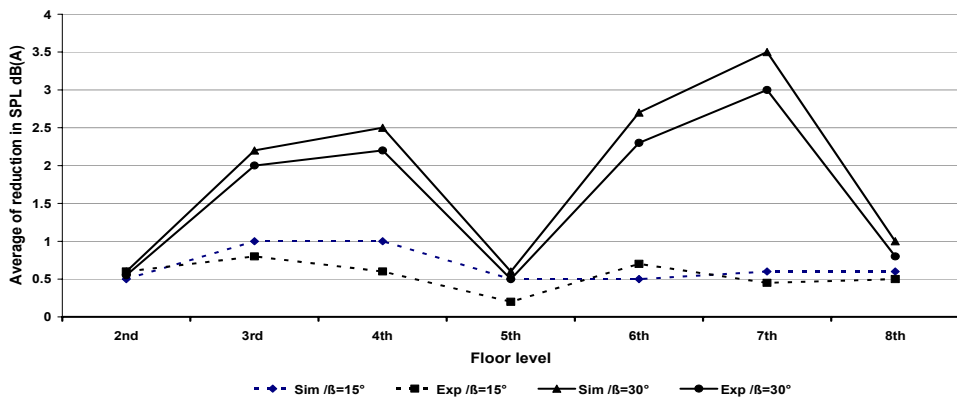


Fig. 18. Average reduction average provided by inclined parapets ($\beta = 15^\circ$ and 30°) for a 2m-balcony depth, (Sim) simulation results, and (Exp) measurements results.

As shown in Fig. 19, the negative effect of the balcony ceiling and balcony floor appears clearly at the 5th floor, where the ceiling and floor reflection surfaces are greater than those at the 4th and 6th floors. This effect causes a lower reduction at the lower reception points at the 4th floor, and at the majority of reception points at the 5th floor (this cause the dip in the average reduction at the 5th floor). On the other hand the reflected floor surfaces are negligible from the 6th floor because the ceiling surfaces are totally screened by the parapet form. This explains the dip in average reduction at the 5th floor.

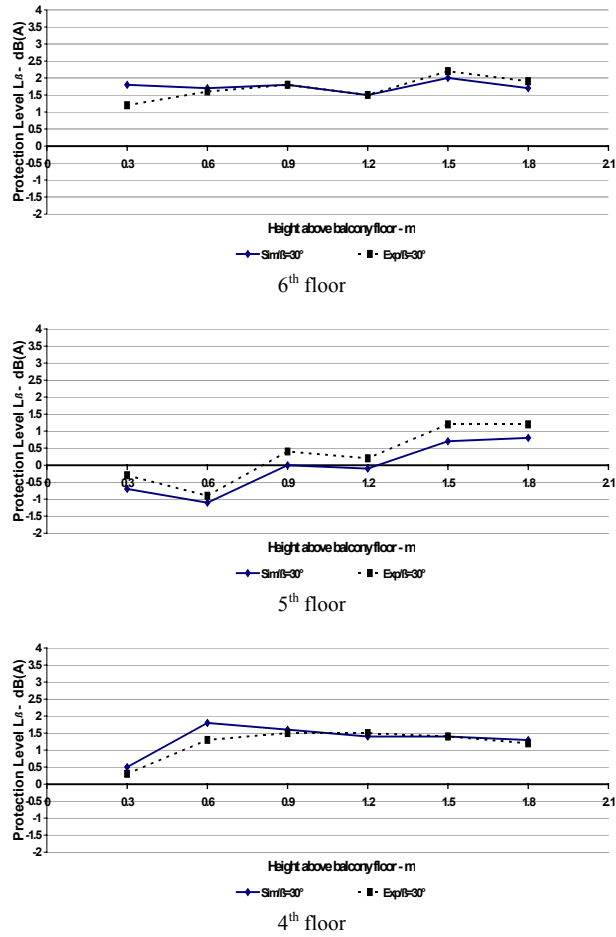
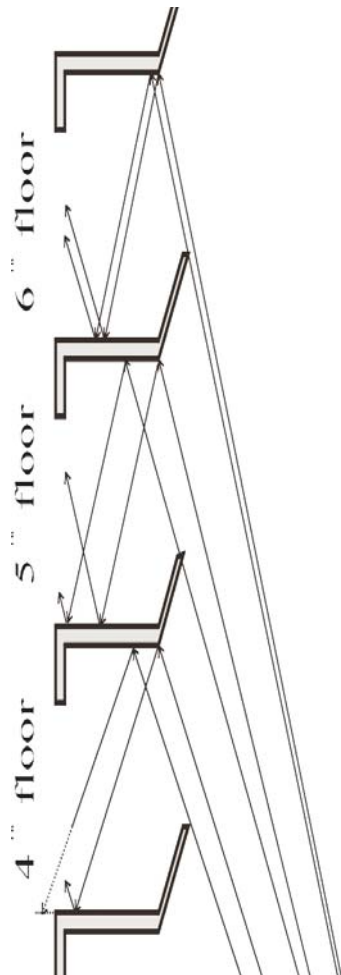


Fig. 19. Floors and ceiling reflection effects at the 4th, 5th, and 6th floors for a 2m-balcony depth with inclined parapet ($\beta = 30^\circ$).

The maximum protection from inclined balconies is at the 7th floor where 3.5 dB(A) additional protection is obtained. As shown in Fig. 20, the higher points are more protected, and there is a good agreement between the measured and the predicted protection level values.

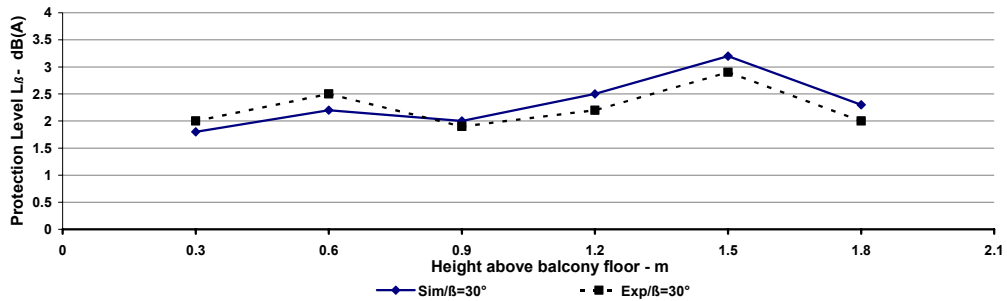


Fig. 20. Protection level provided by an inclined parapet ($\beta = 30^\circ$) for a balcony with 2m and at the centre of its back wall (7th floor), \blacklozenge straight line represents the simulation results, \blacksquare dashed line represents the measurements results.

For the 3m-balcony depth, the inclined angle ($\beta = 30^\circ$) is more effective than the inclined angle ($\beta = 15^\circ$).

As the previous type, the average reductions are divided into two sequences: The first is located from the 2nd to the 5th floors. The maximum reduction is at the 3rd floor and the minimum reduction is at the 4th and 5th floors. The second sequence of values is between the 5th and 8th floors.

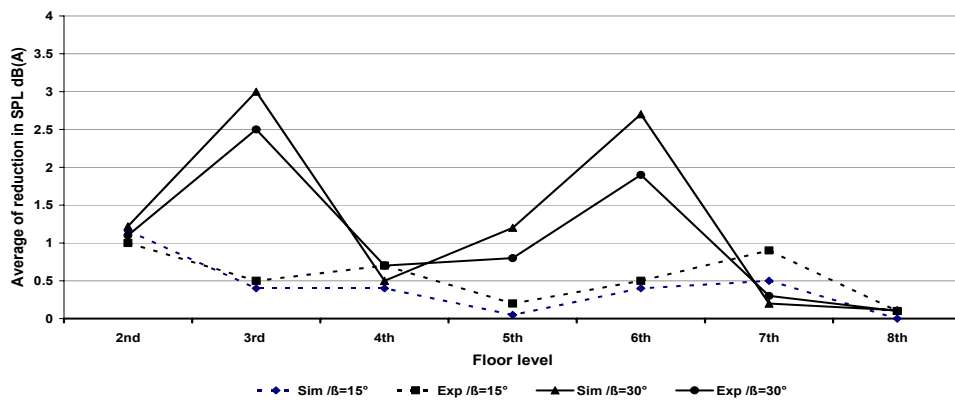


Fig. 21. Reduction average provided by inclined parapets ($\beta = 15^\circ$ and 30°) for a 3m balcony 3m depth, (Sim) simulation results, and (Exp) measurements results.

Fig. 22 demonstrates that the higher reception points are more protected at the 3rd floor corresponding to the maximum protection level for that configuration (3.0 dB(A)).

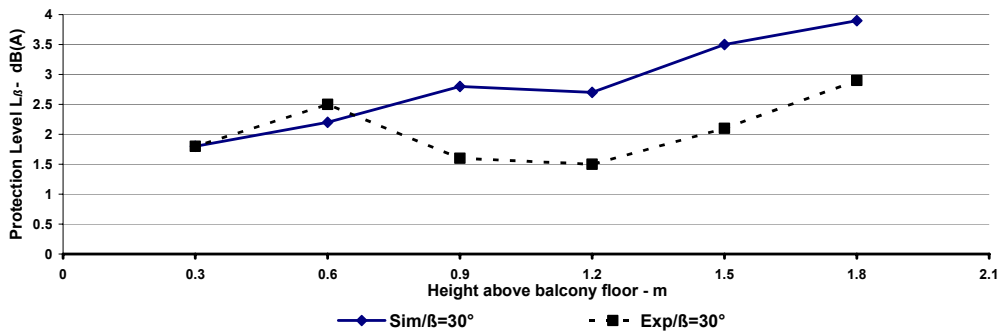


Fig. 22. Protection level provided by an inclined parapet ($\beta = 30^\circ$) for a balcony with 3m and at the centre of its back wall (3rd floor), \blacklozenge straight line represents the simulation results, \blacksquare dashed line represents the measurements results.

6. Conclusion

Experimental measurements and numerical simulations have been used to evaluate the acoustical influence of balcony projection depth and parapet. The concept of protection level has been used to quantify the noise reduction effect due to these configurations. Projection depths provide average reductions between 4 and 8 dB(A) and inclined parapets provide additional reduction values between 0.5 to 4 dB(A), with differences of between 0.5 and 2 dB(A) between the measured and predicted results.

Compared with the other results [4, 5 and 6], the reduction obtained by inclined parapets is approximately equivalent to that obtained by insulation treatments. Furthermore, the empirical equations have been derived to provide a simple prediction of protection level over the building façade for proposed conditions. Hence the results of this investigation will hopefully provide practical information to the architect who wishes to design self-protected facades with respect to the external acoustic environment. Furthermore, it will be seen that a slight modification of existing building envelope design can provide additional sound protection without compromising other environmental requirements.

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