The Control of Structure-Borne Noise from a Viaduct Using Floating Honeycomb Panel*

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This paper identifies the method to control the vibration responses of a concrete viaduct model under impulsive force excitation. The frequencies and mode shapes of resonances of the bending vibration across the section can control the magnitude of the structure-borne noise radiation. A plastic hammer is used to excite the cement viaduct model at the centre and at the supporting edge position of the cross-section separately. The results of analysis using a Finite Element Method are confirmed by the experimental findings of the cross-sectional modes. The findings showed that the local modes are of two types: (1) Centre mode — the centre of top panel can move but the edge is fixed. (2) Edge (web) mode — the centre of panel is fixed but the edge (supported by web) can move. It is found that by supporting the machines on the edge, the center mode will not be excited but the combined mode of edge and center mode can give rise to significant noise radiation. A honeycomb panel with high resonance frequency is used to reduce the vibration transmission from this combined mode. The design can be used as an alternative to floating slab for reducing noise.

***Key Words*:** Noise, Vibration Isolation, Honeycomb Panel

1. Introduction

In the previous paper by the authors(1), it was shown that there were structure-borne noise problems in Hong Kong due to shuttling trains passing on concrete viaducts and through tunnels. The dominant frequency range of such noise and vibration radiating from these concrete viaducts is between 20 Hz and 157 Hz. The previous analysis showed that the sound radiation is attributed mainly to the bending vibration mode of the concrete viaduct's cross-section. Thus it is necessary to investigate the detail bending vibration mode shape.

Heckl et al.(2) showed that the dominant frequency range of structure-borne noise excited by train traffic was in the range of 40 – 200 Hz. The vibration levels measured on the walls of a railway tunnel during train operation could be attributed to the wheel-track resonance. Floating slab with rubber isolator was used to reduce the vibration transmission(3) but it cannot be used for high speed trains due to excessive vibration of the train bodies. Thus, alternative method should be studied and it requires the knowledge of the vibration modes of the viaduct.

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Previous investigations(4) – (7) have been carried out on the measurement, prediction and control of the structure-borne noise. However, there is no prediction formula or experimental data for the vibration modes for viaduct.

Orikasa(8) and Kimura and Inoue(9) used the impedance approach leading to a direct estimation of floor impact sound. They used analytical plate equations to predict the vibration of the rectangular concrete floor between edges supported by beam or walls. The vibration mode shapes were assumed to be simply supported or clamped.

Lu et al.(10) constructed a scaled reinforced concrete frame model to study the structural response with generalized ground shock excitations. They noted the significance of the structural local modes at high frequency. The supported edge in the mode were fixed in vertical displacement but movable in rotation.

In the new rail viaduct in Hong Kong floating slab was required for the cross-sectional design in order to reduce structure-borne noise radiation(11), (12). The design was revised so that the section was made narrower so that the web on the edge can provide high impedance support to the slab. The design was found to decrease the structure-borne noise radiation but the vibration of train bodies due to isolator resonance of the floating slab prohibited its uses for faster and heavier trains.

In this study a cement viaduct model with no floating slab is excited at the centre and web positions and the corresponding vibrations are measured. The global mode (bending along the span only) and local modes (bending on cross-section elements) including centre and web modes are identified and analyzed.

2. Significance of Global and Local Modes in Structural Acoustics Analysis

In this study global vibration mode of the three-dimension viaduct is taken as the mode having bending motion along the span with no significant deformation on the cross-section. The resonant frequencies of global mode are usually in the low frequency range (in the case of rail viaduct it is always below 10 Hz). Many structural engineers focus their attention on the global modes mainly because of its importance as a determining factor for the structure safety, fatigue and comfort level assessment.

In the local vibration mode there is a bending mode in the cross-section of the viaduct (Fig. 1). It is noted that the edge section/ web face does not move. There are bending waves both along the structure span and in the cross-section. Figure 1 depicts the local bending mode of the viaduct. This local mode is usually at high frequency as compared to the global mode. It is more efficient in radiating structure-borne noise due to the vibration mode and frequency. No previous experimental results on the local mode of viaduct are found. The difficulty is the size of test specimen and thus only a short length of a viaduct section will be studied. The local modes can be found in this short test specimen.

3. Experimental Set-Up

Figure 2 shows the layout, dimensions and physical properties of an open-end concrete box model. The external dimensions of the concrete box are 500 mm (L) × 1 500 mm (W) × 750 mm (H), with 100 mm thickness. The size is typical for light rail viaduct and vertical elevator shaft.

Isolation pads were placed close to the edges of concrete box. This will isolate the floor vibration intrusion. In order to secure more low frequency force component the contact time was extended. To achieve this, a resilient pad was used to be a contact plat. A plastic hammer was employed to vibrate the concrete box mode.

For the vibration response measurement, an HBM force transducer S9 was used to log the input force via BAM-1B bridge amplifier. A PCB ICP accelerometer was placed at the input point for logging the acceleration signal

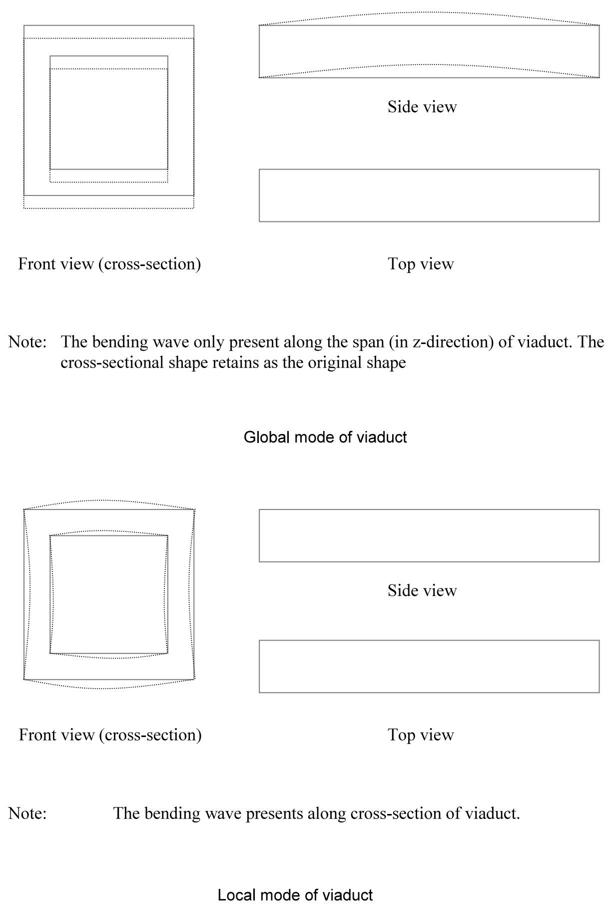


Fig. 1 Difference between global and local bending modes of viaduct

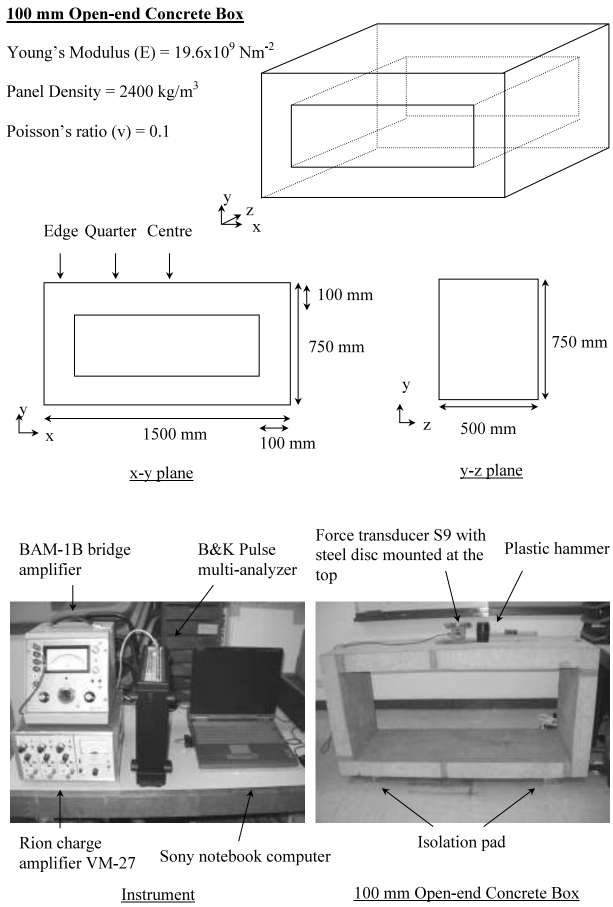


Fig. 2 The layout, dimensions and physical properties of the open-end concrete box

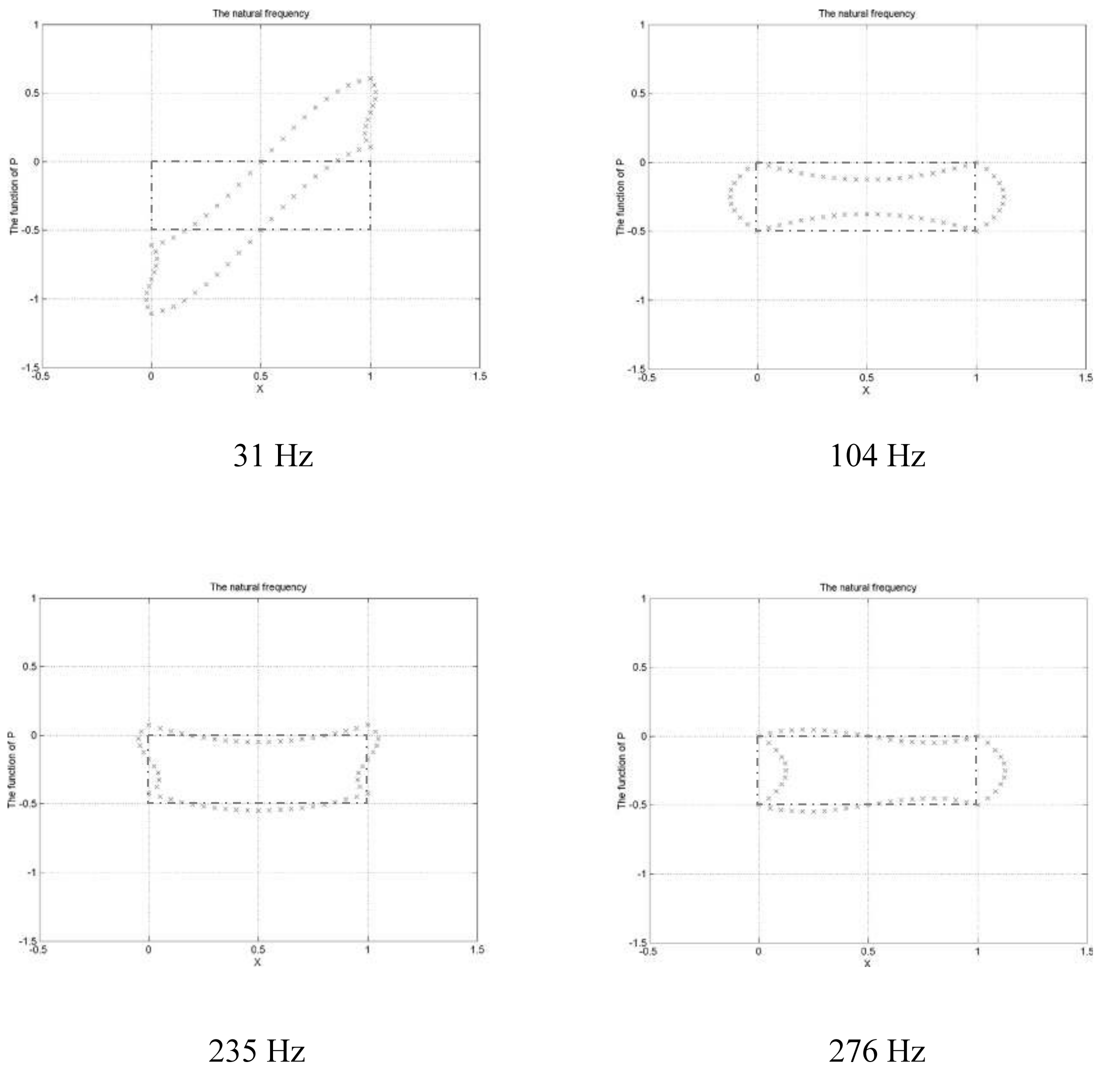


Fig. 3 Prediction results (frequency and mode shape) of the concrete box using FE model(12).
······ Original shape, ×××××× Resonant mode shape

via the Rion charge amplifier VM-27.

The input force and velocity signals were fed into the B&K Pulse multi-analyzer 3560c and Sony notebook computer for data logging and processing. The B&K Pulse multi-analyzer worked in real-time mode at a frequency resolution of 1 600-lines from 0 Hz to 1 kHz (0.6 Hz). The B&K Pulse multi-analyzer was set to record data at slice mode every 0.02 s. The slice having the maximum data was selected for data analysis. To ensure the repeatability of the measurement for point impedance data, the process was repeated in 10 times for each excitation position.

The centre, quarter and edge excitation location was at (x, y, z: 750 mm, 750 mm, 250 mm), (375 mm, 750 mm, 250 mm) and (50 mm, 750 mm, 250 mm) respectively. The point impedance data at these excitation positions were recorded in such locations.

For the mode shape measurement, three Rion PV-85 & PV-44A accelerometers and a PCB ICP accelerometer were used to register the vibration motion along the cross-section of concrete box structure. The ICP accelerometer was used as the reference. The other was moved along the surface of model. The acceleration signals were amplified by the Rion charge amplifier VM-27 and logged by the B&K Pulse multi-analyzer. A single impact response was measured in real-time during the data acquisition process.

4. Theoretical Analysis

The Finite Element (FE) model with 8-degree of freedom stated in the previous paper was used to predict the local vibration mode of concrete box model.

The concrete viaduct has the following physical properties; the young's modulus (E) is 19.6×10^9 Nm^{-2}, panel density is 2 400 kg/m^3, poisson's ratio is 0.1 and the dimensions are shown in Fig. 2.

The FE model shows that the first four resonant modes of concrete box model are at 31 Hz, 104 Hz, 235 Hz and 276 Hz. The respective mode shape is shown in Fig. 3.

These four mode shapes are classified as the local vibration modes. The 31 Hz is the edge mode while 104 Hz is the centre mode. The 235 Hz should be the combined centre and edge mode as there are movement in the middle and at the edges. The 276 Hz is labelled as quarter mode as it only appears during the quarter excitation. It can be classified as special center mode since there is no movement at the edge and there is rotation in the center.

5. Experimental Results and Discussions

In the vibration and acoustic measurements, three excitation positions were conducted in the middle, at the quarter and edges of the top face (see Fig. 2). For the vibration measurement, the Frequency Response Function in terms of impedance (Force/ Velocity) and the respective mode shape were taken.

5.1 The centre excitation data

The resonant frequencies of concrete box model are identified in Fig. 4. The resonant frequencies due to the centre excitation are at 28.75 Hz, 104.38 Hz and 184.38 Hz and the corresponding mode shapes are shown in Fig. 4.

Based on the FE model, the first local bending mode of concrete box model is at 31 Hz. The resonances below 31 Hz correspond to the rigid body mode (no deformation in box model) whereas above 31 Hz resonances are due to the local vibration mode. Figure 6 shows the mode shapes at 28.75 Hz, 104.38 Hz and 184.38 Hz. It is noted that the displacement along x- and y-directions at 28.75 Hz are quite uniform and are unlikely to have a bending motion in the beam elements. The 28.75 Hz can be regarded as rigid body mode. The 104.38 Hz is the local vibration mode being labelled as centre mode as there is no displacement at the edges. It agrees very well with the local vibration mode at 104 Hz (see Fig. 3) estimated with the FE model. For the mode shape at 184.38 Hz, there are displacements in the middle and at the edges. The 184.38 Hz (corrected frequency is 194 Hz) should be the combined centre and web mode. It should correspond to 235 Hz in the FE model (corrected frequency is 200 Hz).

It should be noted that the predicted values are relatively higher than the experimental data possibly due to the fewer degrees of freedom adopted. More degrees of freedom should be used in order to obtain a more precise vibration mode prediction.

5.2 The quarter excitation data

Figure 5 show the resonant frequencies for the quarter excitation are 29.38 Hz, 36.25 Hz, 94.38 Hz, 105 Hz, 185.63 Hz and 296.88 Hz and the corresponding mode shapes are shown.

It can be seen that 29.38 Hz, 104.38 Hz and 184.38 Hz for the quarter excitation has the same mode shape as 28.75 Hz, 104.38 Hz and 184.38 Hz for the centre excitation respectively.

These vibration modes should be the common cross-sectional modes. The vibration mode at 36.25 Hz, 94.38 Hz and 296.88 Hz do not appear at the centre excitation data. These vibration modes may have little or no displacement in the middle. And therefore the centre excitation does not contain this data.

The 36.25 Hz should correspond to the first local vibration mode at 31 Hz in the FE model. Based on the mode shape at 31 Hz and 94.38 Hz, there seems to have little displacement in the middle. The quarter and edges have more comparatively displacement level. Web excitation is more likely to produce these two modes. The 94.38 Hz should relate to the rigid body mode (rotational mode) as the rotational effect is clearly shown in Fig. 5.

The 296.88 Hz in Fig. 5 shows that there has maximum displacement at the quarter with fixed centre and edges. This vibration mode appears only at the quarter excitation but not during the centre and edge excitations. It agrees well with the FE model prediction of local vibration mode at 276 Hz (corrected frequency is 317.4 Hz) as shown in Fig. 3. The FE model using few degrees of freedom may cause the large deviation from the experimental data. More precise mode shape prediction can be obtained if more degrees of freedom are employed.

5.3 The edge excitation data

For the edge excitation, the resonant frequencies of concrete box model are 29.38 Hz, 36.25 Hz, 94.38 Hz and 185.38 Hz as shown in Fig. 6. These four resonant modes are also presented in the quarter excitation. The edge excitation cannot excite the centre mode at 105 Hz because there is no displacement at the edges.

It can be inferred that the 185.38 Hz is the combined centre and web mode as the 185.38 Hz is appeared at the centre, quarter and edge excitation positions.

5.4 Comparisons on point impedance

The results of analysis using the Finite Element Method are verified by the experimental findings of the cross-sectional modes. The findings showed that the local modes are of two types: (1) Centre mode — the centre of top panel can move but the edge is fixed. (2) Edge (web) mode — the centre of panel is fixed but the edge (supported by web) can move.

The impedance at excitation point of center, quarter and edge are shown in Fig. 7. Low impedance are found at the resonance frequencies in Table 1 as follows:

It can be seen that rigid body and edge modes give high impedance. The center excitation gives low impedance at 105 Hz and 185.8 Hz. The quarter excitation gives low impedance at 105 Hz and 296.9 Hz. The edge excitation in general gives higher impedance except at 185.8 Hz. This implies lesser energy entering the structure and thus a smaller vibration magnitude is resulted. The edge excitation is the most beneficial approach for reducing the vibration magnitude of box structure. However, there is significant response at the combined mode of

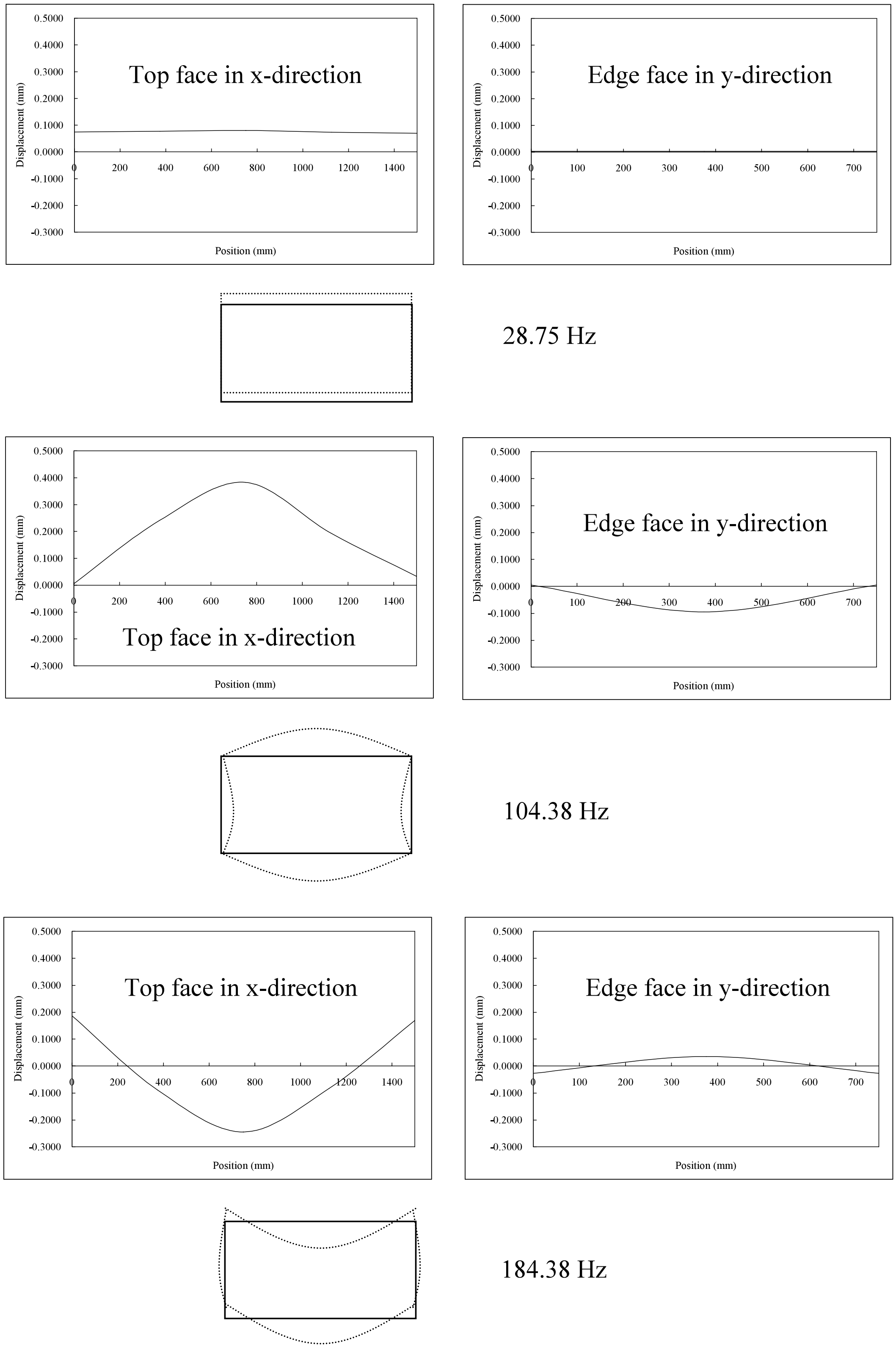
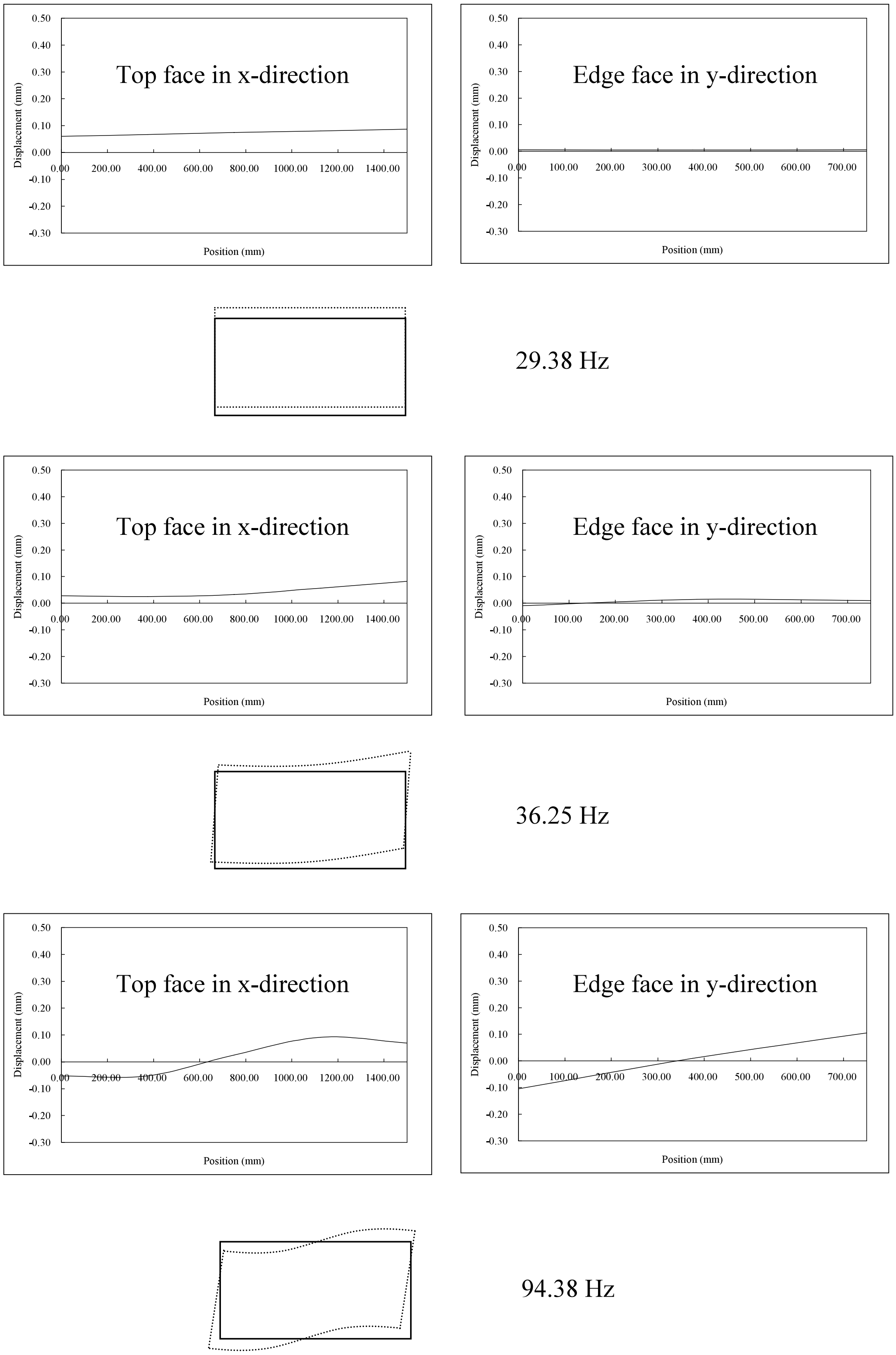
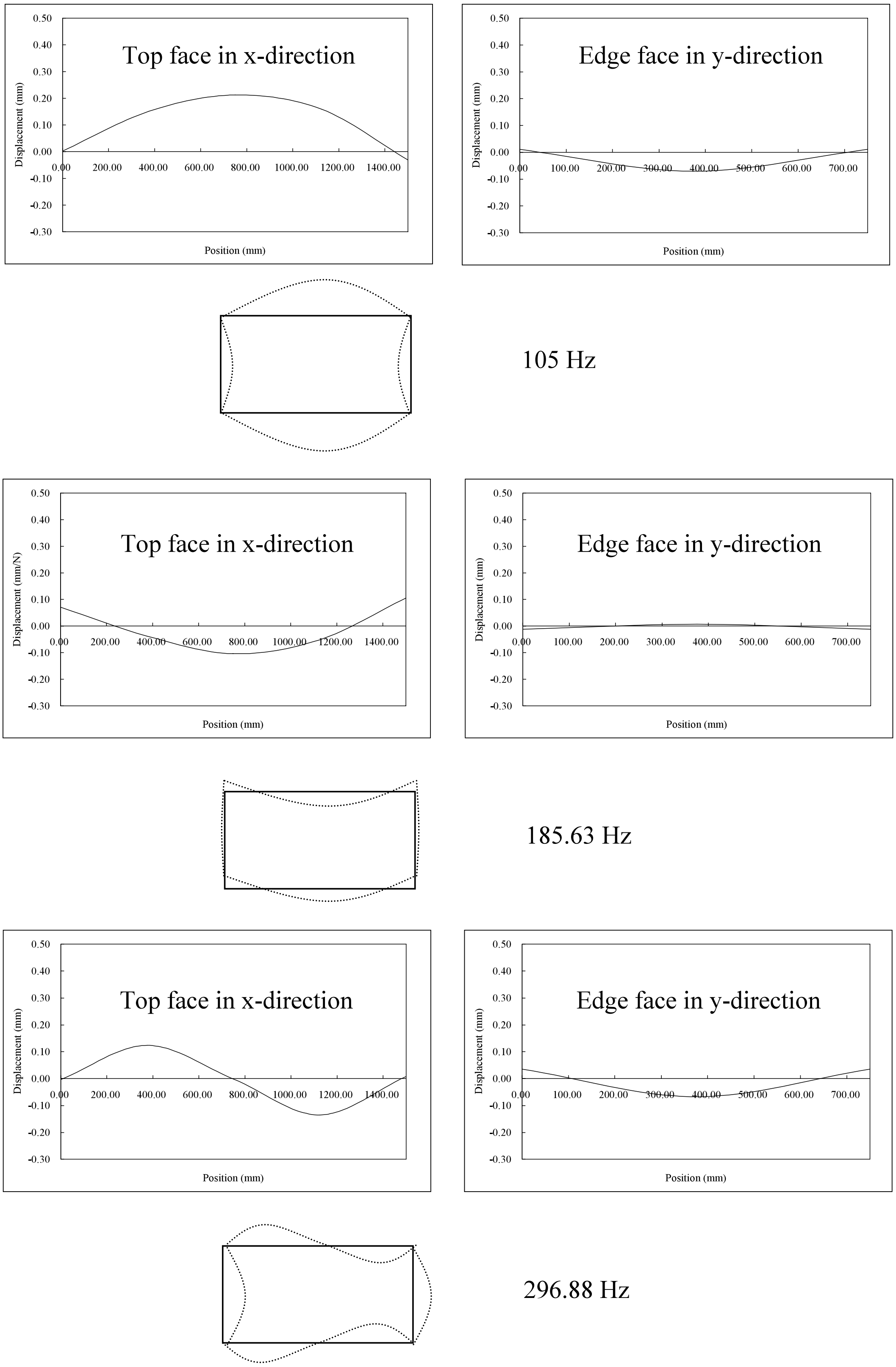


Fig. 4 Mode shapes at 28.75 Hz, 104.38 Hz and 184.38 Hz of concrete box model for centre excitation —— Original shape ······ Resonant mode shape

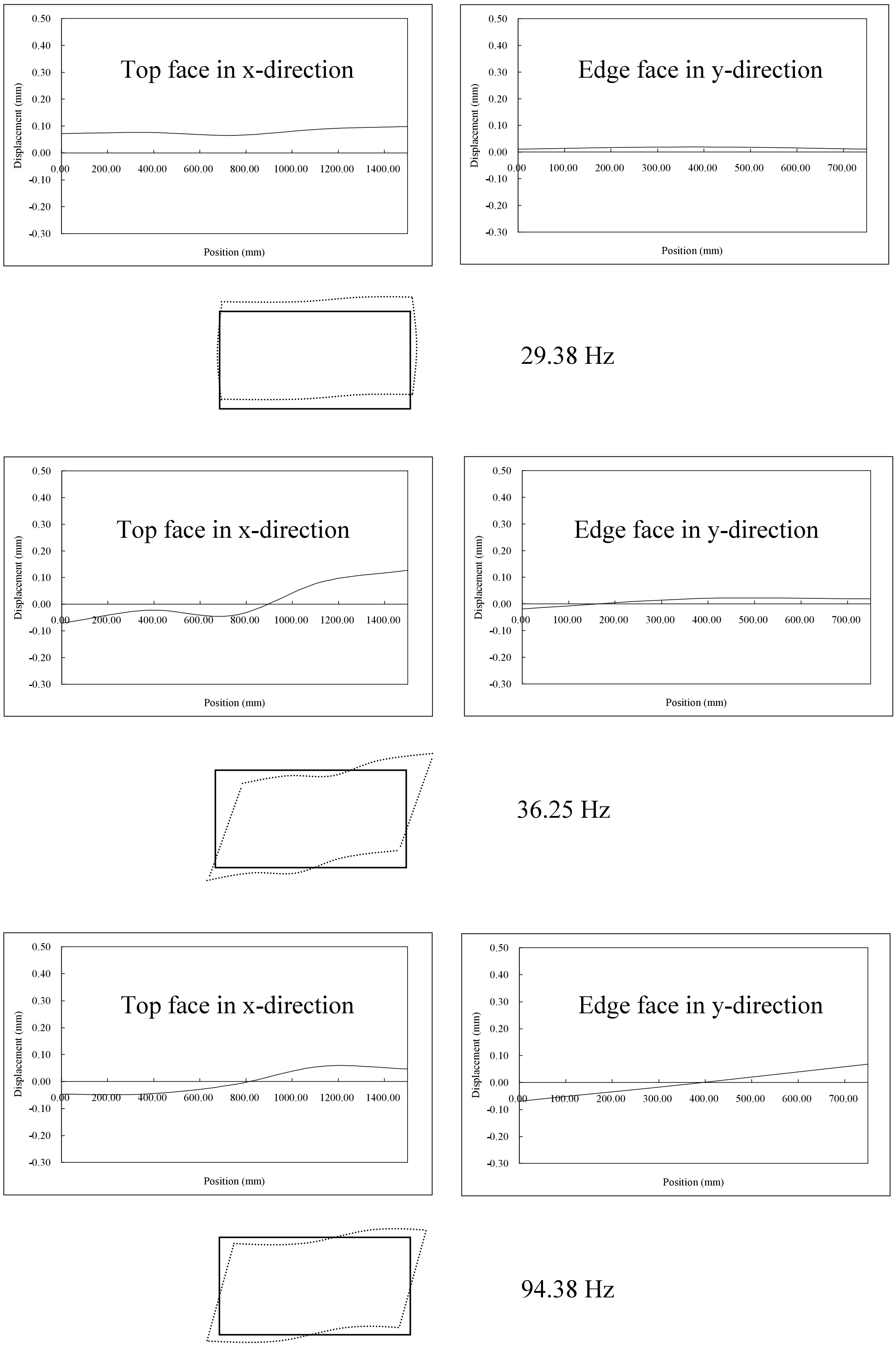


(a) Mode shapes at 29.38 Hz, 36.25 Hz and 94.38 Hz of concrete box model for quarter excitation
—— Original shape ······ Resonant mode shape

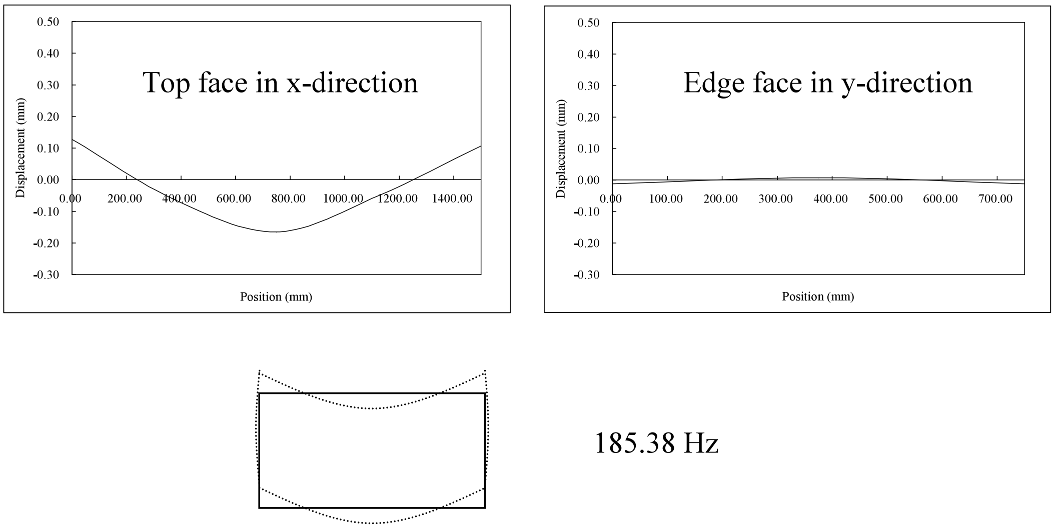


(b) Mode shapes at 105 Hz, 185.63 Hz and 296.88 Hz of concrete box model for quarter excitation
—— Original shape ······ Resonant mode shape

Fig. 5 Results for quarter excitation



(a) Mode shapes at 29.38 Hz, 36.25 Hz and 94.38 Hz of Concrete box model for edge excitation
—— Original shape ⋯⋯ Resonant mode shape



(b) Mode shapes at 185.38 Hz of Concrete box model for edge excitation
—— Original shape ······ Resonant mode shape

Fig. 6 Results for edge excitation

185.8 Hz which can generate the highest noise peak if it is near the coincidence frequency of the concrete box.

6. Control of Local Modes and Structure-Borne Noise

The acoustic radiation efficiency is usually high at and above the coincidence frequency. The coincidence frequency of the top face of concrete box model is estimated to be 221 Hz using the equation:

$$f_c = 0.55c^2/(c_L h)$$

where c := speed of sound in air
c_L := compressive wave speed
h := panel thickness

For this concrete box structure, the coincidence frequency estimated as 221 Hz, the radiation efficiency close to and above 221 Hz is high. Thus the experimental data show that the centre and quarter excitation are more likely to radiate low-frequency structure-borne noise. The structural resonance at 185.8 Hz can give high acoustic radiation efficiency and produces high level of low frequency noise tonal peaks.

The combined centre and web mode at 185.8 Hz is comparatively good acoustic radiators. A close-fitting enclosure(13) with honeycomb panel with high resonance frequency is used to reduce the vibration transmission from this combined mode. The design can be used as an alternative to floating slab for reducing noise.

7. Honeycomb Panel to Reduce Structure-Borne Noise

A plastic honeycomb panel of size 15 mm thick, 0.5 m wide, 0.5 m long was used to cover the top the concrete box and connected by an isolator (Fig. 8). Test is performed by impact on the edge of the box (Fig. 8) and the test repeated for a cement panel of same size. The panel is designed to have first bending resonance of 460 Hz and is verified by test(14). The cement panel is found to have first bending resonance of 140 Hz and 200 Hz. The noise level from honeycomb panel is compared with that of the box in Fig. 9.

It can be seen that the honeycomb panel can reduce the structure bone noise at the dominant peak at 186 Hz by 10 dB. It is because there is no bending resonance in the frequency range up to 400 Hz below the resonance frequency of 460 Hz. For the cement panel there is no noise reduction as there is resonance of 200 Hz near 186 Hz. Therefore, the honeycomb panel is recommended for reducing the noise from the concrete box.

8. Conclusions

The findings suggested that the vibrations of local modes are of two types: (1) Centre mode — the centre of top panel can move but the edge is fixed. (2) Edge (web) mode — the centre of top panel is fixed but the edge (supported by web) can move. The model of local vibration with center and edge modes can be used for the design of viaduct with lower vibration responses and noise.

It is found that by supporting the machines on the edge, the center mode will not be excited but the combined mode of edge and center mode can give rise to significant noise radiation. A honeycomb panel with high resonance frequency is used to reduce the vibration transmission from this combined mode. The design can be used as an alternative to floating slab for reducing noise.

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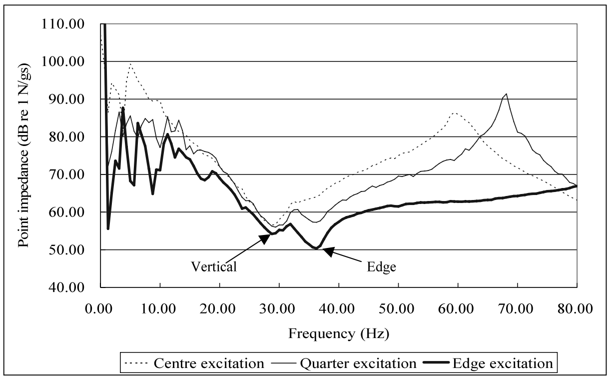
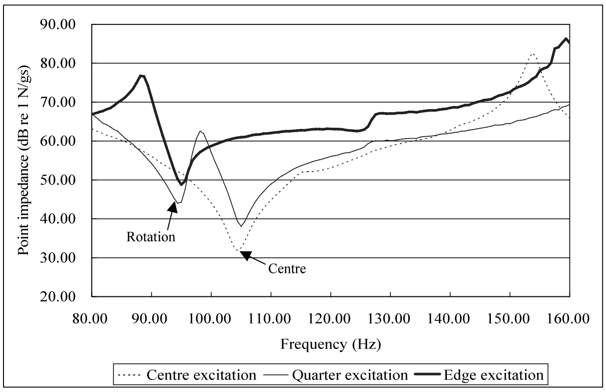
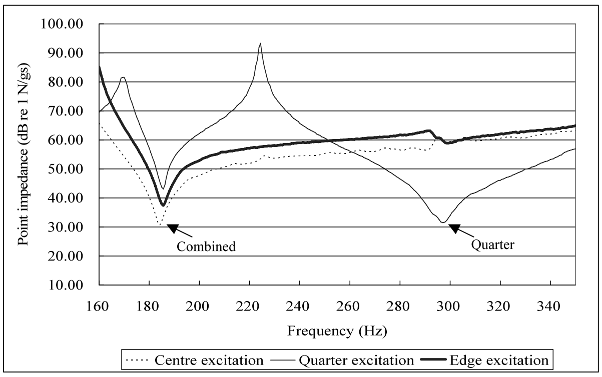


(a) Magnitudes of point impedance (force/ velocity) for the centre, quarter and edge excitations of the concrete box model



(b) Magnitudes of point impedance (force/ velocity) for the centre, quarter and edge excitations of the concrete box model



(c) Magnitudes of point impedance (force/ velocity) for the centre, quarter and edge excitations of the concrete box model

Fig. 7 Results of impedance of concrete box

Table 1 Impedance at various excitation point

Frequency	Type of Mode	Impedance Center excitation	Impedance Quarter excitation	Impedance edge excitation
29.38 Hz	Vertical rigid body	55 dB lowest	58 dB	58 dB
36.25 Hz	Edge local	65 dB	59dB	56dB lowest
94.38 Hz	Rotation rigid body	52dB	45dB lowest	50dB
105 Hz	Center local	32 dB lowest	38 dB	62 dB
185.6 Hz	Edge & Center	30 dB lowest	45 dB	38 dB
296.9 Hz	Center	60 dB	32 dB lowest	60 dB

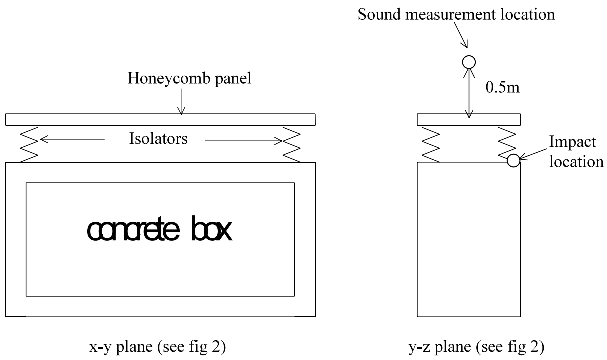


Fig. 8 Test of vibration transmission to honeycomb panel

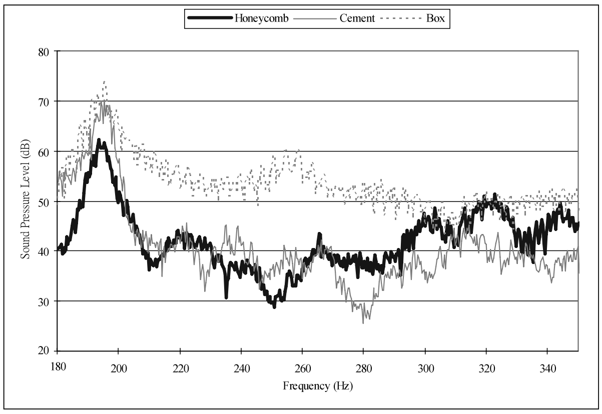


Fig. 9 Sound pressure level from concrete box, honeycomb panel and cement panel due to impact on the edge of box

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