Proceedings of 20th International Congress on Acoustics, ICA 2010

23-27 August 2010, Sydney, Australia

Dynamic properties of damping materials for reducing heavyweight floor impact sounds

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PACS: 43.55.Ti, 43.55.Wk

ABSTRACT

The effects of resilient isolators and viscoelastic damping materials on reducing heavyweight floor impact sounds in reinforced concrete structures were investigated using FEM simulations and field measurements. Dynamic properties of the materials were also measured with beam transfer function method to predict vibration characteristics and impedance of the floor structures; results showed that damping materials had larger loss factor and dynamic elastic modulus than resilient isolators. From the field measurement, it was found that the natural frequency of the floor structure increased and its vibration acceleration level decreased by the use of damping materials (heavyweight impact sound levels also decreased below 80 Hz), whereas the sound levels in the structure increased with the same range with the use of resilient isolators.

INTRODUCTION

Floor impact sounds can be categorized into heavyweight and lightweight; heavyweight impact sounds are usually caused at low frequencies by human walking, while lightweight impact sounds are often generated at high frequencies by dropping a lightweight object or dragging a chair. In multi-storey buildings, lightweight impact sounds can be easily relieved by a simple treatment in finishing layers such as carpeting, but heavyweight is harder to control than lightweight because it is mainly aggravated at low resonant frequencies. The ISO working groups are standardizing the current ISO 140 series by extending the impact source and using the complement index for evaluation of natural sources on the floors.

Several architectural treatments, such as floating floor, elastic coverings on floor, and resiliently supported ceiling have been used to prevent floor impact sounds. Floating floor has been used pivotally to reduce floor impact (structure-borne) and air-borne sound transmission by isolating upper parts of floors from structures. Lightweight impact sound (caused by “tapping machine”) insulation in European countries requires $L'_{n,w}$ 48 to 65dB in multi-storey housing depending on severity of impact noise exposures in each countries; accordingly, average floor impact sound level has been reported to be reduced since 1988 up to date with compliance of 90% households. The improved floating floors used polyethylene, expanded polystyrene and mineral wool or rock wool as elastic layers, which might reduce the floor impact noise level by 7 dB [1].

However, although the elastic layers easily reduce lightweight impact sounds at the IIC rating range from 100 to 4,000 Hz, the floor impact sound levels at the resonance frequency remain high [2]. The issue of floor impact sounds has risen particularly in societies where multi-storey residential buildings are the predominant form of dwelling, such as in Korea and Japan. In case of reinforced concrete structures, thickness of a slab ranges from 150 to 200 mm and from 250 to 300mm including a floor covering. In this type of slab structure, first natural frequency usually occurs at between 20 and 60 Hz, which generates low frequency impact noises through heavyweight impact.

Heavyweight impact sounds radiates impact noises at low frequencies, generated by bending modes of the floor of the low-order. Thus, in order to insulate the heavyweight impact sounds, damped structure may be required to control the peaks at mode frequencies of structures. Howerever, there have been not many researches on the effect of damping on a reduction of floor impact sounds at low frequencies in multi-storey residential buildings. Thus, in this study, effect of dynamic characteristics of reducing material such as elastic damping material on floor impact sound and vibration will be investigated throughout both experiments and computer simulations.

DYNAMIC PROPERTIES OF MATERIALS

Reducing material in multi-layerd floor system

Insulation performance of impact sound and vibration in the multi-layered floor structre is mainly dependent on the dynamic properties of reducing material. In general, reducing material with low elasticity such as polyethylene, expanded polystyrene, cellular rubber, polyurethane and rock wool has been used in the floor strucutres for isolating the transmission path of structure bone noise and vibration. Especially, lightweight floor impact sound can be much reduced by inserting those materials to the floor structures. DIN 18164 recommends the range of dynamic stiffness of resilient isolators to make the total floor structure have first natural frequency at frequencies lower than 100Hz. The smaller dynamic stiffness of inserted materials, the higher the capacity of preventing lightweight impact sounds at floor system.

However, although the floating floor system can be effective to reduce the lightweight impact noises at mid-high frequencies, it may not efficient to reduce heavyweight impact sound generated at low frequencies, where resonance peak are generated by flexural vibration of the floor structure. In case of concrete structure, even if there are certain degrees of deviation, damping is extremely low and weak in resonant response because dynamic elastic modulus (30GPa) has generally high elasticity and loss factor of below 0.01. Therefore, in concrete structures (as a heavyweight structure), damping treatment such as rubber and viscoelastic damping materials can be effective to prevent floor impact noise and vibration.

Setup: Beam transfer function method

The dynamic properties of various reducing materials for floor impact insulation are measured. The measurement method is based on beam transfer function method proposed by Park (2005) because ISO 9052-1, which is based on 1-DOF system, is not suitable for measuring viscoelastic materials. Beam transfer function method is enough to obtain frequency-dependant dynamic properties at audio frequency. And effect of deformation of specimen by self-weight can be minimized [3].

In this study, Bakelite (thermosetting phenol formaldehyde resin) beam is used for measurement. Its length, mass per unit area and cross-section area are 0.9 m, 0.86 kg/m and 6 cm^2, respectively. Dynamic elastic modulus and loss factor of the beam are 13GPa and 0.02. The end of the beam is fixed by hydraulic bench vise. And another end of the beam was excited by controlled vibration generated by an electrodynamics shaker (B&K Type 4810). Structural vibration of the system was measured by using two miniature piezoelectric accelerometers (Endevco model 2250-A) and the transfer function was calculated between the two accelerometers.

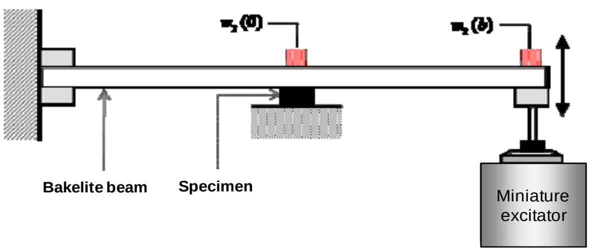

Figure 1. Setup for measuring the dynamic properties

Dynamic properties of specimen are determined as following procedure: (1) Transfer function of beam without specimen is measured, when the sinusoidal force is excited at the free end of beam. (2) Comparison between measured transfer function and predicted result from wave propagation model (based on Euler beam theory) is done. (3) Using the complex wave number obtained through the Newton-Rapson method, the dynamic elastic modulus and loss factor of the beam are calculated. (4) After installation of specimen, transfer function of the beam with specimen is measured. (5) Finally, complex stiffness of the specimen, which is modelled as a spring element, is obtained from the difference of repulsive forces with and without specimen.

Result

Typical reducing materials for floor impact sound insulation such as EPS (Expanded polystyrene), EVA (Ethylene-Vinyl Acetate), EPP (Expanded Polypropylene), Rubber, Cork and VEDS (viscoelastic damping material), were measured. The densities of measured polymer foams, rubbers and VEDS were 20-400 kg/m^3, 800-900 kg/m^3 and 1,024 kg/m^3, respectively. Each specimen is measured after maintaining the room temperature (20℃) over 24 hours. And the results were averaged in measurable frequency, i.e. 10-16,000 Hz.

Figure 2 shows the relationship between dynamic elastic modulus and loss factor of various reducing materials. Mostly, dynamic elastic modulus increases as loss factor increases by group. In terms of dynamic properties, the types of the reducing material can be categorized as following: (1) Polymer foam; loss factor of below 0.2 and dynamic elastic modulus of 0.4 to 22.3 MPa, (2) Rubbers; loss factor of 0.2 to 0.5, (3) VEDS; loss factor above 1.0 and dynamic elastic modulus over 200MPa. Especially, polymer foam has a role as a resilient isolator in floating floor. VEDS with high loss factor act as a damper for absorbing impact energy in floor structure. Therefore the reducing materials can be largely categorized as resilient isolator and damping material through the measurement of dynamic properties using beam transfer function method.

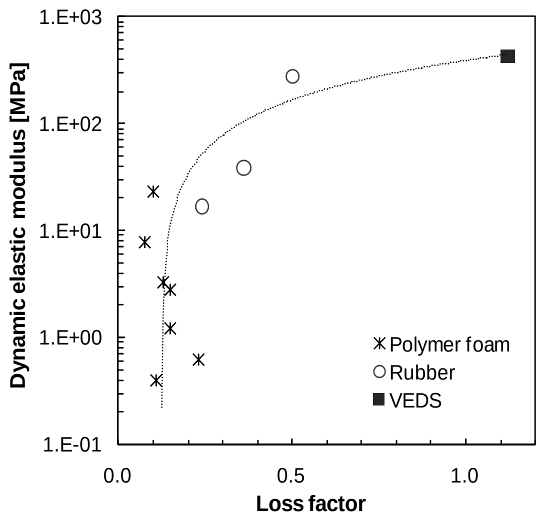

Figure 2. Relation between dynamic elastic modulus and loss factor of various reducing materials

FEM SIMULATION

Dynamic behavior of the model significantly depends on the physical properties, especially dynamic characteristics of each layer. And the variation of dynamic characteristics of reducing material is comparatively lager than those of other layers. Thus the effects of reducing materials on insulation of floor impact sound in multi-layered floor structure were investigated by FEM (finite element method) simulation. And the shape and dimension of the simulated room was modeled after test room for floor impact noise.

Setup

Floor plan of simulated model was rectangular shape with an area of 4.6×5.1 m^2. And multi-layered floor structure is composed of reinforced concrete slab (RC slab), reducing material (resilient isolator and damping material), and lightweight concrete and finishing mortar in order. Physical properties of each layer such as dynamic elastic modulus, loss factor, density, poisson ratio and thickness are determined by actual condition. And as shown in table 1, dynamic properties of reducing layer were varied according to the measured result from previous chapter.

Table 1. Material properties of each layer

	Dynamic elastic modulus [Pa]	Density [kg/m^3]	Poisson ratio, ν	Thickness [mm]	Loss factor, μ
Mortar	1.5×10^{10}	1800	0.15	40	0.01
Light concrete	0.5×10^{9}	400	0.15	40	0.02

RC slab	3.0×10^{10}	2400	0.15	180	0.01
Resilient isolator	0.5 / 1 / 3 ×10^{6}	100	0.35	20	0.1 / 0.2 / 0.4
Damping material	5 / 10 / 50 ×10^{6}	1100	0.45	20	0.5 / 1.0 / 1.5

Three dimensional solid elements were used. Nodes between each layer were linked and the boundary conditions of simple support on vertical direction. And surface velocities at the ceiling of the receiving room were calculated when the sinusoidal excitation force was applied at the center of the floor. And transfer impedance of floor was calculated.

Result

As a validation of the FEM model, impedance levels from the actual measurement and computer simulation were compared. The result shows that the frequency response of the structure is similar in terms of modal frequency characteristics and impedance level. Thus the simulation model considered in this study would be efficient to predict actual condition.

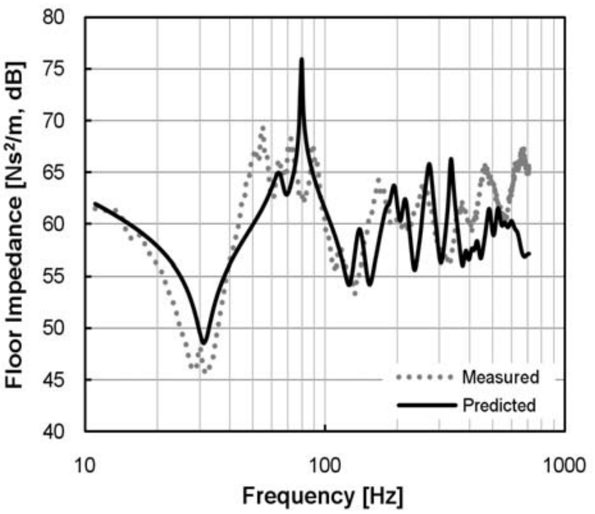

Figure 3. Comparison between measured and predicted impedance level of floor structure

Characteristics of floor impedance were predicted according to variation of dynamic elastic modulus of inserted reducing materials. As shown in the figure 4, dynamic elastic modulus of reducing materials increased as natural frequency of floor structure increased. 1st resonant frequencies of floor structure using damping material varied 23 to 27Hz, whereas those of floor structure with resilient isolator varied 22 to 24 Hz. The structure with damping material showed high impedance level at low frequency near the 1st resonant frequency. Thus damping material would be more effective to control the impact vibration at low frequencies than resilient isolator. On the other hand, the structures with resilient isolator showed high impedance level at mid-high frequencies. Therefore, the material with lower dynamic elastic modulus woud be better for insulation of floor impact above 250 Hz.

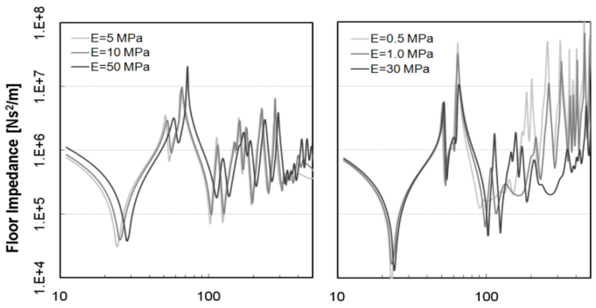

Figure 4. Point impedance of multi-layered floor structure (left: damping material; μ 0.5, right: resilient isolator; μ 0.2)

Floor impact sound level at octave band center frequencies was predicted by using impedance method [4]. Bang machine, tyre was used as an impact source and impact forces of bang machine applied in the calculation are shown in Table 2. Averaged absorption coefficient of the receiving room is assumed as 0.2.

Table 2. Impact force characteristics of heavyweight impact source (Tyre of Bang machine, KS 2810-2)

	Octave-band center frequency [Hz]				
	32	63	125	250	500
Impact force, F_{rms}[N]	220.6	98.6	13.0	5.6	1.3

Figure 5 shows the results of the calculated impact sound pressure level (ISPL) at each octave band according to the dynamic elastic modulus of the inserted reducing material. In case of resilient isolator, the ISPL is increased by increasing dynamic elastic modulus of resilient isolator above 125 Hz and it is effective to reduce mid-high frequency sound. On the other hand the ISPL is inversely proportional to the dynamic elastic modulus of damping material. Thus ISPL is increased by decreasing dynamic elastic modulus. And it is also found that ISPL in the structures with damping material indicates lower level at 63 Hz near the resonance peak than in case of resilient isolator. The deviation between maximum and minimum level is nearly 16 dB at 63 Hz according to the dynamic elastic modulus of reducing material. Therefore, the floor structures with viscoelastic damping material are effective to reduce low frequency sound such as heavyweight impact sound.

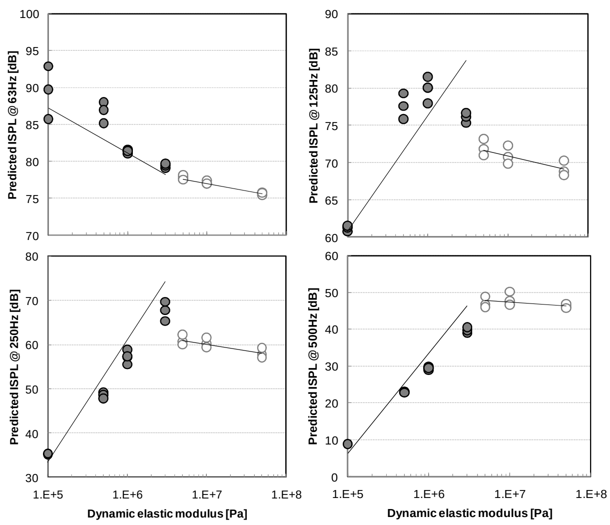

Figure 5. Predicted impact sound pressure level with different dynamic elastic modulus of inter layer (solid dots: resilient isolator, hollow dots: damping material)

FIELD MEASUREMENT

Setup

In situ measurements were conducted to validate the result from computer simulation. The measurements were performed three times: with damping material, with resilient isolator and without any finishing. The real-scale test building has rigid boundary condition through box-frame type RC structure and rectangular shape floor area of 23 m^2. Table 3 shows the thickness of each layer in floor structure. The construction order is same as previous FEM model. Dynamic elastic modulus of resilient isolator and damping material are 3 MPa and 400 MPa, respectively. Loss factors of resilient isolator and damping material are 0.15 and 1.07, respectively. Densities of resilient are isolator and damping material is 20 kg/m^3 and 1024 kg/m^3. Each reducing material is installed as a plate-like on the entire reinforced concrete slab.

Table 3. Thickness of each layer in floor structure [unit: mm]

	Reinforced concrete	Reducing material	Lightweight Concrete	Finishing mortar
Resilient isolator	180	20	45	45
Damping material		15		

The vibration responses are evaluated in terms of vibration acceleration level of the center point of the ceiling when the upper surface of the floor excited by bang machine.

In case of the floor impact sound, measurement was performed based on KS F2810. The receiving and impact points were five points respectively, uniformly distributed. The averaged sound pressure level was evaluated in accordance with a single-number rating method using the inverse A-weighted impact sound pressure level ($L_{i,Fmax,AW}$). Bang machine was used as a heavyweight impact source while ISO Tapping machine was used as a lightweight impact source.

Result

The frequency and vibration level of 1st resonant peak are dominant factor in sound radiation on the plate-like structure. As shown in Figure 6, In case of 1st resonant peak, resonance frequencies of each floor structure show similar results to each other around 32 Hz. And vibration acceleration level of floor structure with resilient isolator is 6 dB lower than bare slab at the first peak. In case of using damping material, vibration acceleration level is 4 dB lower than that of resilient isolator. Therefore, damping material is effective to reduce the floor vibration at flexural mode (1st peak) of floor structure.

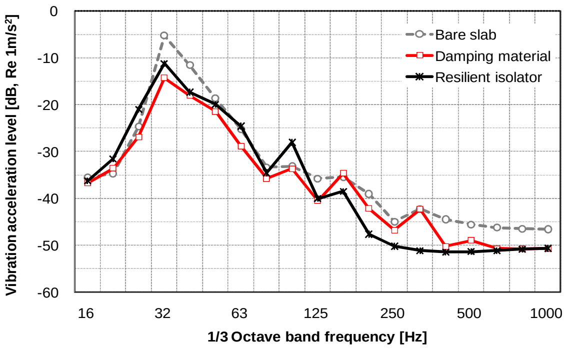

Figure 6. Vibration acceleration level of the floor structures, excited by Bang machine

Figure 7 shows the difference of ISPL between bare slab and each multi-layered floor structure at the octave band frequencies. It is found that resilient isolator is not effective to reduce heavy weight sound at low frequency near 63 Hz. However, resilient isolator was effective to reduce mid-high frequency sound such as lightweight impact sound. On the other hand, floor structure using damping material was shown the higher isolation performance at low frequencies, such as at 32 and 63 Hz octave band frequencies. The insertion loss of damping material was 10 dB higher than resilient isolator at 32 and 63 Hz. However, in case of lightweight impact sound, damping material is much lower than resilient isolator because insertion loss at each frequency band is nearly flat. And in terms of single number rating, insertion loss of damping material was 5 dB higher than resilient isolator.

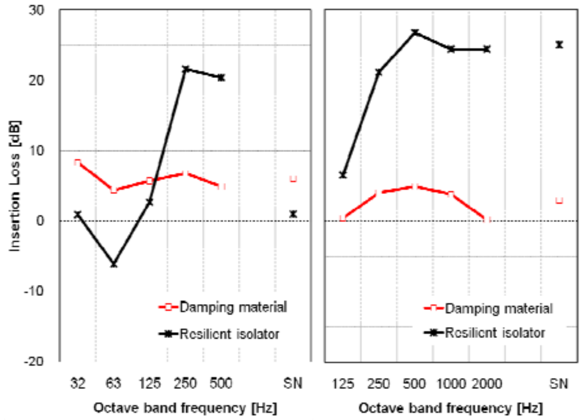

Figure 7. Insertion loss with different reducing layer in field measurement (left: bang machine, right: tapping machine)

CONCLUSION

The isolation methods on heavyweight floor impact sound, which are related to dynamic characteristics of the multi-layered floor structures, have been investigated. The dynamic characteristics of various materials for reducing floor impact sound were measured using beam transfer function method. The materials were categorized into resilient isolator and damping material in terms of dynamic elastic modulus and loss factor. Then, the effects of reducing materials on floor vibration and radiated sound in the multi-layered floor structures are investigated using FEM simulation and field measurements. Results showed that the floor structure with resilient isolator with low dynamic elastic modulus and loss factor was effective to reduce floor impact sound at high frequencies. However, the floor impact vibration and sound pressure level increased at low frequencies near the first resonance frequency. On the other hand, floor structure with damping material was effective to reduce heavyweight floor impact sound at low frequencies.

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