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Structure borne noise and vibration control in performing arts facilities.

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Control of structure borne noise and vibration from sources external to a performance hall is one of the most important design features of modern performance facilities. Location of new performance halls near or over rail facilities; in downtown or central areas; within or as part of multipurpose buildings; and near to parking and central plant facilities can all lead to structure borne noise impact on the performance space. There is a wide range of noise and vibration sources which should be considered significant and included in the structural design review and isolation design provisions. This paper presents discussion of the basic principles of large performance hall structural isolation including review of effective modeling and noise control prediction. Also included are the identification of practical materials and design configurations which can achieve the noise control needed. The design can consist of base isolation of the entire building, however; isolation of the performance space within the building, a box-in-box configuration, is usually more practical and two examples are presented and discussed. There are also frequently other structures or features which must be supported on the isolated hall without compromising the noise isolation and two examples of this type of structural isolation are reviewed.

1 INTRODUCTION

Providing structural vibration and noise isolation in the design of a performance hall has become an important design feature for a number of reasons. Two of the most important reasons are: 1) the current and expanding desire to have very low background noise to improve the audience experience, and 2) the increasing need and desire to locate performance halls in central or multi-use areas, sometimes as in-fill developments. Other reasons include more conventional considerations such as: 1) providing sound insulation between the performance space and outer lobbies or other adjacent spaces: 2) providing control of structural vibration and noise from

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HVAC equipment, elevator equipment and toilets, and: 3) assuring that other sources of vibration and noise such as people walking, doors closing and vehicles moving in parking areas within the building do not affect the performance space.

The location of new performance halls near or over rail facilities; in central downtown areas with heavy traffic; within or as part of multipurpose buildings with occupancies that cause structure borne noise and vibration; and with parking and central plant equipment within the building envelope are all factors that lead to the need for complete structural isolation of the performance hall from the remainder of the building or from the building foundations. This paper presents the basic isolation designs and procedures that have been developed and refined to achieve low background noise and eliminate intrusion from sources exterior to the main building and exterior to the performance hall but within the main building.

2 ISOLATION PRINCIPLES

The basic procedure for providing vibration isolation, and thereby to provide structure borne noise isolation, is to support the vibration and noise making device or machine on a spring system that separates the device from the supporting structure in a manner to prevent transfer of the vibration and noise energy to the supporting structure. The simplest representation of this concept is the single-degree-of-freedom spring-mass system as represented in Figure 1 with the vibration and noise generating device, the mass of that device and the resilient support element which is mounted or supported on a foundation. There is usually some type of damping in parallel with the spring, either naturally occurring or added as a support component.

The theoretical analysis of such an isolation concept is generally based on the assumption the foundation is immoveable, i.e. of infinite mass and stiffness and the spring is an ideal resilient component without internal resonances. For such an idealized system the vibration and noise transmitted to the foundation follows an ideal characteristic as shown by Figure 2.[1] The amplification at the resonance frequency is dependent on the damping factor and the reduction at higher frequencies continuously increases with increasing frequency. Therefore, if the natural frequency of the system is selected or designed to be below the frequencies generated by the device or machine, the isolation system will reduce the noise and vibration transmitted to the support structure or foundation over the entire frequency range from the machine.

2.1 Real Isolation System Characteristics

In actual installations of isolation systems the springs are not ideal, the foundations are not rigid or infinitely stiff, and the machine or device is not a rigidly stiff mass. Steel spring coils have a natural frequency or surge frequency which causes direct transmission of the vibration through the spring to the foundation or support structure. This generally occurs at about 100 to 130 Hz and results in substantial reduction of the isolation effect at that frequency. Further, because the spring coils are a solid transmission path for vibration and solid borne noise, above the surge frequency the isolation effect is greatly reduced. To correct this effect and make steel spring isolators effective over a wide frequency range, Neoprene or rubber pads are inserted between the spring base and the support structure or foundation.

The other actual characteristics that can strongly affect the results of the isolation are the mass and stiffness or mechanical impedance of the supporting structure below the springs. For example, a light weight wood frame structure and floor will not provide sufficient mass and stiffness for a steel spring isolator to be effective; a soft, low impedance resilient isolator of sufficient thickness to have a significantly lower impedance than the supporting structure is necessary. In many instances, replacing steel springs with thick fiberglass or rubber isolators has corrected an ineffective steel coil spring isolation system and achieved satisfactory results. In other instances it has been necessary to insert a concrete or other heavy layer of material on top of the light weight structure to provide a sufficient mass to support the springs. Another alternative is to place the springs on top of extended columns to provide a high stiffness support. The point is that the total mechanical impedance of the supporting structure must be adequate for a spring isolation system to perform as expected.

In providing structure borne isolation, the basic procedure is the same except the direction of the vibration and noise energy flow is reversed. The vibration and noise enter the building structure at the foundation or at some interior location and the spring isolation system must decrease the energy flow into the performance hall structure supported on the isolation springs or resilient support elements. The same modeling principles apply and the single-degree-of-freedom spring mass system type of analysis can be used to determine the appropriate isolation spring characteristics and the expected performance. The differences are that it is necessary to recognize that the structure must be designed to approximate the theoretical assumptions of nearly infinite mass and stiffness for the foundation and matching high mass and stiffness for the supported structure. In real buildings this design goal is limited by the fact that natural or modal frequency response of the building structure, floors and walls decrease the effective mass with increasing frequency. Therefore, it is required that alternative or additional decoupling or lowering of the isolation system transmission impedance is necessary to obtain successful structural isolation over a broad frequency range.

The provision of additional decoupling or lowering transmission from one structure to another adjacent structure or part of a structure is to insert a low mechanical impedance layer of material between the two structural entities. This is best accomplished by using a low mass, low stiffness resilient material between the two structures or elements. With steel springs supporting a machine this can generally be accomplished by inserting a layer of resilient material such as Neoprene or rubber between the spring base and the supporting floor or structure. Because the dimensions and relative masses are small, for most structures a thin layer generally is sufficient; a 12 mm (1/2”) layer for a high mass and stiffness support or a 25 mm (1.0”) layer for a lighter weight and lower stiffness support. However, for a light weight wood frame type of support the resilient layer must generally be 50 t0 100 mm (2” to 4”) thick and is usually substituted for the steel springs to achieve satisfactory isolation.

The use of steel coil spring isolation systems has been successful in some applications of building isolation, however the structures involved are of relatively small size and total weight. The most common applications are the isolation of performance studios, usually a single room configuration and with limited frequency range required for the isolation. Other types of vibration and noise sensitive space sometimes isolated on steel springs are laboratory spaces, including acoustical testing laboratories. Again these are generally single, relatively small rooms and the frequency range required for the isolation is generally limited.

To provide successful vibration isolation of large building structures such as a performance hall or a residential building, in addition to acting as a spring, the isolator design must include a layer of resilient material of sufficient thickness to create a significant impedance mismatch or discontinuity between the supporting foundation structure and the building structure. Because the vibration and noise wavelengths are long and the structures are large and massive the resilient layer must be at least 100 mm (4”) to 200 mm (8”) thick. A thin 12 to 25 mm (1/ 2” to 1.0”) layer will create some loss but only at higher frequencies and of limited value. [2]

2.2 Materials for Structure Borne Vibration and Noise Isolation

Over the past 60 years there have been several materials or configurations used to attempt to structurally isolate performance halls and other noise sensitive types of buildings from external vibration and noise sources. These have been primarily steel coil springs, lead-asbestos pads, loadbearing fiberglass pads and various types of elastomers including natural rubber, Neoprene, synthetic rubbers, polyurethane and other expanded plastic foam materials. The most common of these for many years has been Neoprene because of the extensive marketing and claims of superiority to natural rubber. In recent years the advantages and value of natural rubber as a durable structural material with long service life has become more well known and it has become the preferable choice for resilient bearing pads.

A major problem with synthetic elastomers is the limited typical service life. For materials such as Neoprene or butyl rubbers the service life with compressive load is typically 15 to 20 years maximum with the requirement that the pads be replaced to retain the resilience. Polyurethane materials tend to be hygroscopic and in some cases have had to be replaced after only a very short service life. For natural rubber there are numerous records of long durable service life even when imbedded in water. With high quality formulation during manufacture of the rubber and with appropriate loading design, natural rubber bearing pads can be expected to provide 50 to 100 year or longer service life.

One of the reasons that natural rubber is preferable as a structural element supporting a compression load is dynamic-to-static stiffness ratio. For high quality natural rubber the dynamic-to-static stiffness ratio is typically 1.2 to 1.4. For Neoprene and other synthetic materials the ratio is 2.0 to 2.5 or even higher. This means that for a given isolation design natural frequency, the static or dead weight load deflection for a Neoprene pad is 1.7 to 2.1 times the deflection or strain on a natural rubber pad designed for the same application. This reduced strain on the natural rubber pads allows for very low stress and strain on the pads in service, contributing to the excellent dynamic performance and long service life.

2.3 Example Results

To demonstrate the basic difference in performance of a steel spring isolation system and a thick natural rubber type installation, the results from two designs of resiliently supported floating track slab are presented. At the Toronto, Ontario steel wheel and rail subway transit facilities, the tracks are mounted on floating track slabs supported on 75 mm (3”) thick natural rubber bearing pads in a manner to completely vibration isolate the track slabs from the supporting structure. At the Basel, Switzerland light rail steel wheel system the tracks are imbedded in floating track slabs supported on steel coil springs. The Toronto floating slabs have a 16 Hz natural frequency design and the Basel system design is for a 5.2 Hz natural frequency.[3]

Thus it should be expected that the Basel system would be more effective in reducing structure borne vibration and noise transmitted from the trains to the supporting structure.

Figure 3 presents the results of similar measurements completed in Toronto and in Basel to determine the actual insertion loss or transmissibility of the two isolation systems. The insertion loss of the spring/mass floating slab systems were determined by measuring the vibration from trains at nearby locations with the floating slab track and for similar nearby locations with standard track support. The difference for the two otherwise similar locations represents the effectiveness of the isolation systems. As is evident on Figure 3, the higher natural frequency isolation of the Toronto design is less effective at the low frequencies but the isolation does continuously increase with frequency and is fully effective over the entire frequency range that could transmit into adjacent buildings. In contrast, the result for the Basel system shows excellent low frequency isolation but at 100 Hz the isolation effect decreases due to the steel spring surge frequency, and at higher frequencies the isolation system provides little benefit.

Some of the reduced isolation effect at frequencies above 160 Hz may be due to background noise affecting the measurements. However, the sudden large reduction at 100 Hz can be due only to the coil spring internal resonance causing transmission directly through the springs to the support structure. In the Basel installation the necessary secondary or supplementary pads under the spring bases were evidently not provided.

The other important factor demonstrated by the data graphs in Figure 3 is the large change in low frequency insertion loss with different design natural frequencies. This emphasizes the need for on-site measurements at each project site to determine the frequency content of the ground borne and/or structure borne vibration and noise. The frequency range of the intruding vibration is a major factor in selecting the design natural frequency of the isolation system. With such information and designing using the principles outlined in this paper allows for achieving effective, economical designs without need for expensive finite element or other dynamic analyses.

3 EXAMPLE PERFORMANCE HALL ISOLATION DESIGNS

3.1 Benaroya Hall in Seattle

One of the first examples in North America of a full vibration and noise isolation design using the box-in-box configuration is the Seattle, Washington Concert Hall, Benaroya Hall. This Hall is located directly over a railroad tunnel and directly adjacent to a light rail system tunnel. Also the streets on all four sides of the main building have heavy vehicles and large traffic volumes. It is a site the Hall acoustical consultant, Cyril Harris, was opposed to and which, based on prior experience, he did not believe could be adequately isolated from the ground borne noise present at the site. The criterion he requested was that the train noise not exceed the threshold of hearing and not be audible with the air conditioning system turned off. To achieve this design goal it was determined that a two stage isolation system should be incorporated in the building design.

The isolation configuration developed for the Benaroya Concert Hall space consists of two main elements: 1) a large mass matt slab foundation directly below the concert hall and above the railroad tunnel, and 2) a completely isolated box structure within the main building and supported on natural rubber pads of 175 mm (7”) rubber thickness. The inner box structure is poured concrete floors and beams with precast concrete panel walls separated from the concrete block outer building walls by not less than 175 mm (7”) air space. The separated double wall configuration provided for air borne sound insulation and structural isolation to achieve the full potential of the rubber pad isolation system. Because of the high degree of isolation needed, the rubber pad isolation design was based on a 4.5 Hz natural frequency for the support pads. The matt slab high mass foundation was designed to achieve an additional 10 dB of coupling loss at the soil/foundation interface in comparison to a more standard foundation.

One factor that was not adequately recognized at the time of the Benaroya Hall design was the necessity for adequate separation of the isolation system natural frequency from the fundamental natural frequencies of the floor and beam structures directly above the isolation bearings. At Benaroya Hall the structural engineer made the structure directly above very massive and stiff. However, no additional design limitations were requested. The performance Hall structural design developed is a wide span main floor in the audience area. The result is that the main floor fundamental frequency is about 5.0 Hz. This is close enough to the isolation system vertical natural frequency that there is considerable interaction and the result is about 22 dB amplification of the main auditorium floor response at 5 to 6 Hz. The interaction also results in reduced effective mass loading of the rubber springs causing the natural frequency of the isolation system to rise to about 6 Hz. The result is about 5 dB less insertion loss than expected for the isolation system.

Figure 6 presents response curves developed from measurements with trains passing by in the tunnel below. As is apparent a large amplification of motion occurs at about 5 to 6 Hz in the main auditorium floor. Fortunately there is little excitation from the trains at that low frequency range so there is no noticeable vibration or intrusion due to the amplification. Figure 7 presents the insertion loss of the rubber pad isolation system determined from structural vibration measurements just below and just above the isolation bearings. The data in Figure 7 also present the insertion loss that was expected not considering the effects of the coincident resonances. As is apparent the effective upward shift of the isolation system natural frequency did reduce the insertion loss from the expected by about 5 dB over the entire frequency range. Fortunately, the factor of safety created by the two stage isolation system did give enough overall reduction of the structure borne noise so that the trains are not audible and the overall design goal of threshold level noise intrusion was achieved.

3.2 Four Seasons Centre for the Performing Arts Opera House in Toronto

A recent project and an example of the improved performance achieved by including limitations on structural fundamental modes is the Four Seasons Centre for the Performing Arts in Toronto, Ontario, Canada. This facility, which includes an isolated Opera House and an isolated Rehearsal Hall, was designed and constructed in 1999-2006 and opened in June 2006. The site for this is in a location with very high ground borne vibration levels. There is a surface light rail line on one side of the building and a heavy rail subway line under the street in front of the facility. Further there is heavy truck and bus traffic on all four sides. The isolation design principles and materials were essentially the same as for Benaroya Hall except that there was a strict requirement that the structural fundamental modal frequencies be above 15 Hz for the floors directly above the isolation plane for the first two levels where applicable or where there could be interaction or coupling.

Figure 8 shows the Four Seasons Centre with a view of typical directly adjacent traffic which creates ground borne vibration and noise at the building foundations. Figure 9 presents the average insertion loss measured at the Opera House isolated performance hall. The measurements included light rail trains, subway trains and truck/bus traffic. The data in Figure 8 also include the expected insertion loss based on the 6 Hz design natural frequency for the natural rubber pad isolation. As is evident, in this case the measured insertion loss is essentially the same as projected, with no loss of effectiveness due to coincidence with structural natural modes. Because of the offset to the side of the vibration and noise sources, and because of the expected greater effectiveness of the isolation bearings than at Benaroya Hall, no special high mass matt foundation was included in the Four Seasons building design. Of course, the foundation is of heavy concrete elements as normally used for a performance center. The result is that the isolation achieved the N-1 design goal (threshold of hearing) for noise from exterior sources and the Opera House has been characterized as "the quietest opera house in the world".

4 EXAMPLE SUPPLEMENTARY ISOLATION DESIGN FEATURES

There are many situations or building designs where the structural design requires that other noise exposed structures or features be supported on the isolated performance hall. To avoid potential noise intrusion these structures must be isolated from the performance hall at each support point. In some cases this involves simply providing a steel bracket bolted to the wall of the isolated hall with the exposed structure beam or girder static load supported only on a rubber pad on the bracket with no direct connection to the isolated hall. This works well if the load is small and does not significantly affect the isolated hall rubber support bearing deflection. In other cases the connecting structure may have multidirectional loads or may be a significant load. This latter case may result in a statically indeterminate loading situation requiring special adjustable rubber pad assemblies to allow setting the isolator load to the specific support force required for the structure.

4.1 Multidirectional Force Isolation Example

At the Esplanade Theatres on the Bay facility in Singapore, designed and constructed in 1993 to 2002 and opened in October 2002, the performance spaces were isolated to control ground borne noise from multiple sources including: four nearby rail system subway lines, noise from diesel engines in ships on the adjacent shipping channel, and noise from large salt water pumps providing cooling water for a nearby shopping center and hotel. The two performance halls, a concert hall and a ballet theater, are in separate buildings with glass roofs suspended over the entire performance hall structure. Figure 10 is an overview of the buildings showing the continuous curved glass roofs over the halls, an arrangement that necessarily required the center portions of the roofs to be supported on the isolated hall structures.

There was concern that high wind velocities frequently occurring in Singapore would cause structure borne noise transmission to the performance spaces so that it was necessary to provide vibration and noise isolation at each location where the roof structure is supported on the isolated hall structure. Because the wind could cause uplift and lateral forces on the roof, it was necessary that the isolators be double acting and remain effective regardless of load direction. Double acting or symmetrical spring assemblies were designed and located to provide both vertical and lateral support for the glass roof metal framing with no direct connections to the isolated performance hall structures. Figure 11 presents a photograph showing the configuration for two of the roof isolator assemblies.

4.2 Statically Indeterminate Load Isolation Example

Another unusual isolation requirement occurred at the Esplanade Theaters on the Bay facility because of the need for a central support for a long span roof beam extending across the side stage at the Ballet Theater facility. This beam is supported on non-isolated columns at each side of the side stage structure but because of the long span required a central support located directly on the side stage structure. Because the side stage structure is isolated along with main stage the exact vertical location of the support point was variable and depended on the stage of construction and the total weight deflecting the support bearing pads. The beam support could not be set until theater construction was complete. Because the support height could vary relative to the end column heights, it was necessary for the structural engineer to determine the exact support force needed at the center support location. The rubber isolation pad assembly was then designed to allow adjustment of the pad compression during final setting to achieve the support force needed for the roof beam without compromising the theater isolation.

Figure 12 presents a photograph of the long beam isolation support located on the side theater structure. The photo is of the completed final installation with the rubber pad shims in place and set at the proper expected deflection across the long span. This design provided for supplementary support at the center of the long span beam reducing the required depth and the cost of the beam.

5 DISCUSSION AND CONCLUSIONS

This paper presents an outline of the basic principles and materials for successfully controlling structure borne noise in performing arts facilities. By applying relatively uncomplicated structural design requirements and using large thickness natural rubber support bearing pads it is possible to have quiet interiors at sites with even the most severe ground borne noise encountered at proposed sites. The conclusion is that the knowledge and technology now exists to confidently make any site acceptable for constructing a performing arts facility without fear that the noise will be intrusive or even audible within the performance hall.

6 REFERENCES

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2. L. E. Kinsler, A. R. Frey, A. B. Coppens, and J. V. Sanders, *Fundamentals of Acoustics*, Chapter 6, Transmission Phenomena, Third Edition, (1982)

3. M. Loewestein, “GERB Vibration Control Systems”, http://www.gerb.com

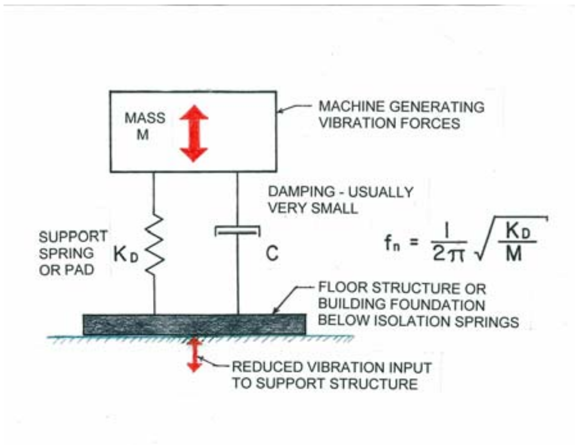

Figure 1 -- Single degree-~~of~~-freedom model

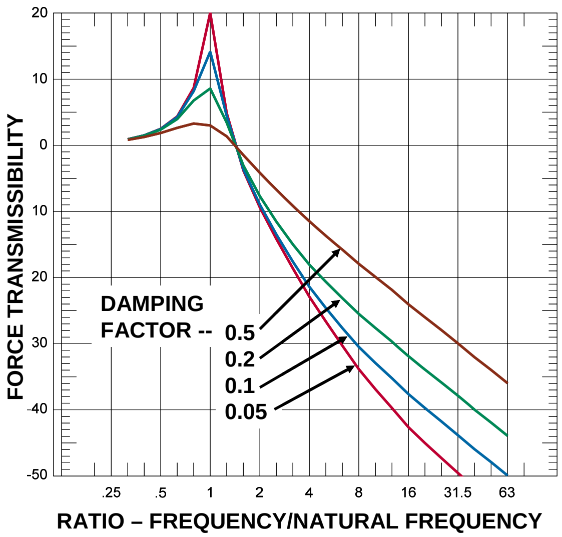

Figure 2 -- Transmissibility of idealized model

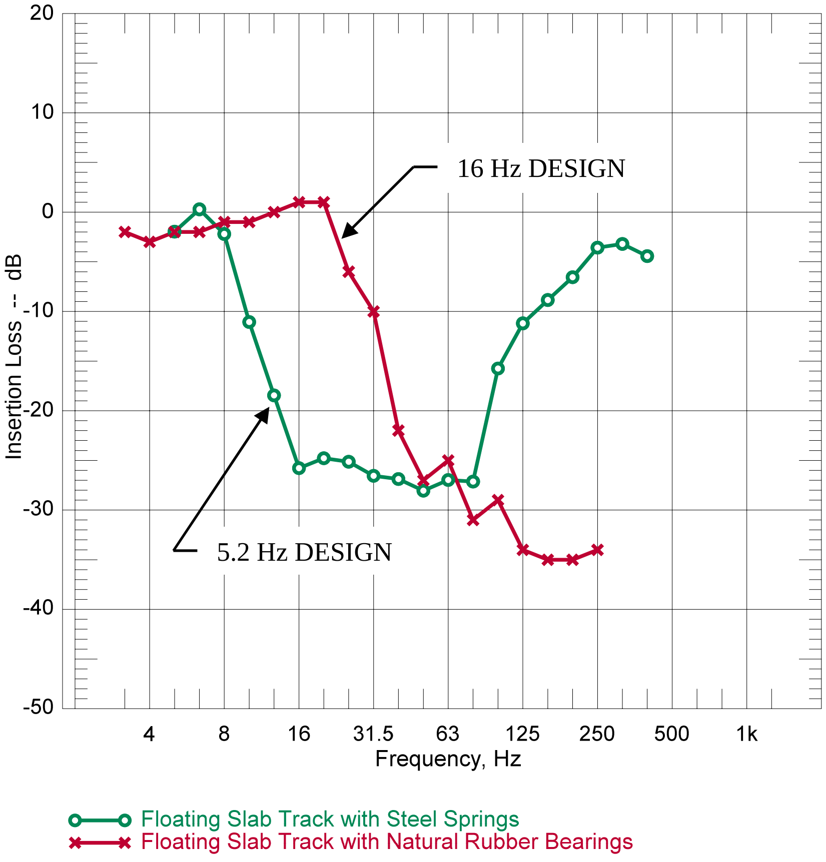

Figure 3 -- Comparison of steel coil spring and natural rubber isolation systems

Figure 4 – Benaroya Concert Hall in Seattle – designed and built 1993/97 – opened 1998

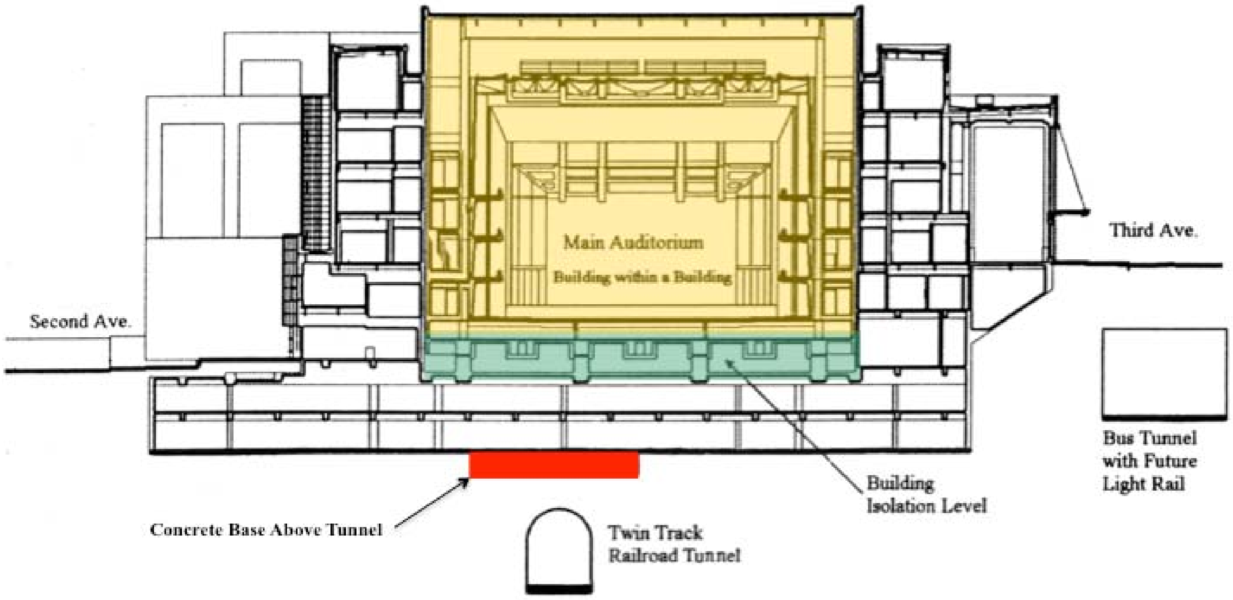

Figure 5 – Cross-section of Benaroya Hall showing the isolation system elements and the Isolated box-in-box concert hall within the city block size building

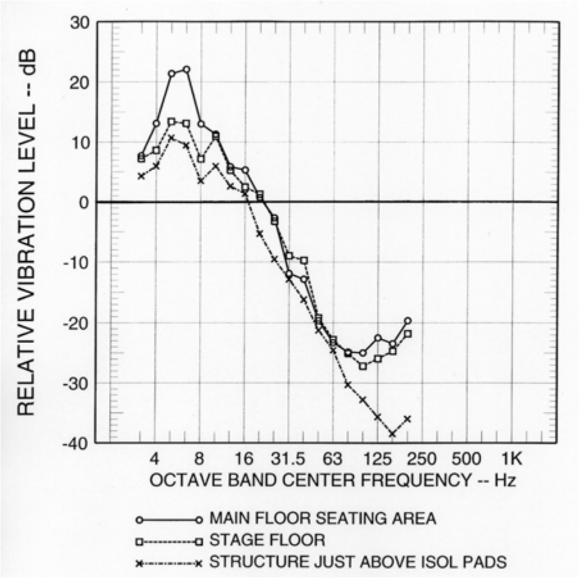

Figure 6 – Relative vibration levels at main floor and other areas at Benaroya Hall

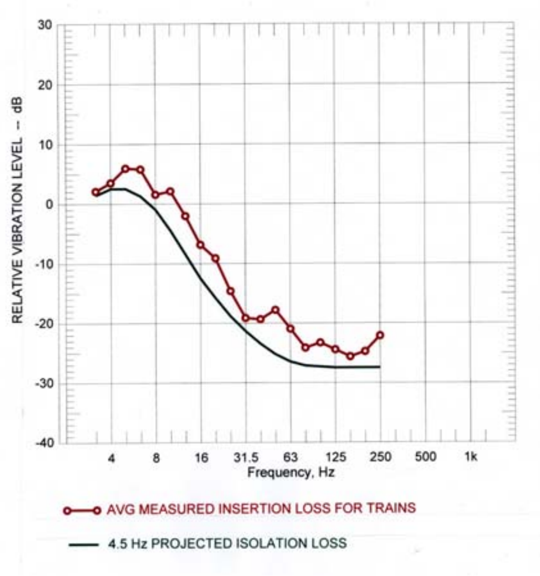

Figure 7 -- Insertion Loss of Rubber Pad Isolation System at Benaroya Hall

Figure 8 -- Four Seasons Centre for the Performing Arts near the end of construction showing the proximity of rail and heavy vehicle traffic

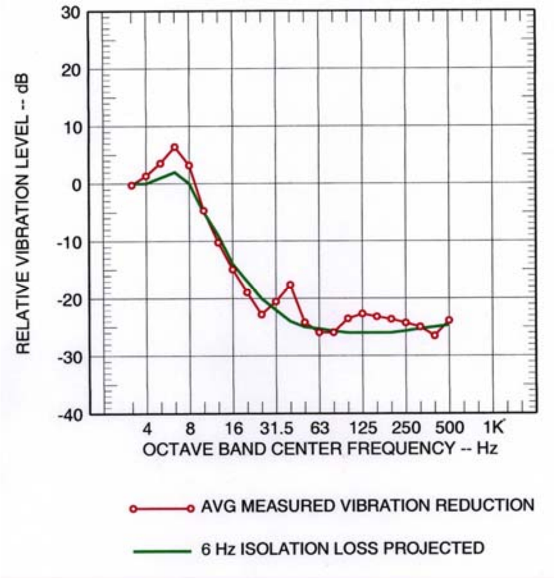

Figure 9 -- Average insertion loss of the Four Seasons isolation system

Figure 10 -- The Esplanade Theatres on the Bay in Singapore – two isolated halls

Figure 11 -- Roof structure double acting rubber isolator assemblies at the Esplanade performance halls

Figure 12 – Photo of the beam center pad at the long span beam above the isolated side stage