Isolation of lightweight wood structures from ground-borne railway vibration

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Popularity of transit oriented residential development makes it highly desirable to place lightweight wood structures, such as townhomes, in close proximity to railways. These properties are susceptible to both air-borne noise and ground-borne vibration. There are not well developed methods of vibration control in such lightweight structures. Design efforts were carried out to develop an isolation scheme for one planned townhome project near Washington, DC, installing at the foundation closed-cell polyurethane pads (PUR elastomers) which offer sufficient low frequency vibration isolation, insignificant amplitude dependence, and long term dynamic performance over broad temperature and moisture ranges. To verify the effectiveness of the scheme, three mock-up structures were constructed on site in the proposed location of the future townhomes. Two units included the vibration isolation scheme while the third was used as a control. To determine the isolation performance, simultaneous triaxial vibration measurements were made in each unit as freight, commuter, and Amtrak trains passed. Results were analyzed according to the guidelines of the Federal Transit Administration - Transit Noise and Vibration Impact Assessment. Positive results at the first and second floor levels proved the scheme to be a viable method for ground-borne vibration isolation of lightweight structures.

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1 BACKGROUND

A residential developer in the Washington, DC area proposes a transit oriented, mixed use development within walking distance of the Washington Metropolitan Area Transit Authority's Shady Grove Metrorail Station. The proposed development includes 1,114 multifamily units, 407 townhomes, 40,000 square feet of retail and library space. While the Shady Grove Metro station is the last stop on the Red Line, the tracks run parallel to a Class 1 rail line used by CSX freight, MARC commuter rail, and Amtrak. This line runs along the entire western boundary of the development site. Plans include placement of 55 townhomes approximately 85 feet from the nearest tracks. The site plan and adjacent railway is shown in Figure 1.

Fig. 1 *- Site plan highlighting railway frogs in yellow.*

This rail line regularly hosts more than 30 events per day with a large number of freight operations occurring during the nighttime hours.

Initial ground borne vibration measurements made on the site revealed high levels in the area proposed for townhomes. Levels were especially high in the area of two "frogs" or switches, which generate abnormally high levels of both noise and vibration. In the area of the frogs the ground vibration levels regularly reach 78 to 84 VdB in the area proposed for the townhomes. On average the site is exposed to more than 30 railway events per day.

When considering the level of these measurements relative to the FTA Guidelines for residential occupancy and when considering the probable amplification of the ground borne vibration by lightweight wood structures (+6 VdB or more depending upon the structure) it was clear that some form of vibration isolation will be necessary in order to construct townhomes that will be acceptable to most occupants from a vibration standpoint.

It should be noted that with such proximity to the railway airborne noise is also an issue. Measures to mitigate the airborne noise include construction of a 24’ to 26’ tall concrete noise barrier as well as modifications to building shells in order to meet both locally and nationally recommended interior noise levels for residential occupancy. Details of this analysis are beyond the scope of this paper.

2 CURRENT INDUSTRY GUIDANCE

During the past 40 years, research has been conducted on human sensitivity to vibration. A variety of national and international standards and guidelines are available to educate the public, to create public or industry policies, and to educate owners and investors seeking consultation regarding investments exposed to vibration.

Currently, no applicable regulatory guidance document is available to describe human perception to freight train noise and vibrations. Additionally, there can be vast differences in legally enforceable local noise ordinances and environmental ordinances that could be applicable to vibrations and structure borne noise originating from vibration sources.

Since 1995, projects involving exposure to freight train vibrations are most often developed using interpretations of the Federal Transit Administration (FTA) *Transit Noise and Vibration Assessment (May 20006)*, which was primarily developed using experience from passenger trains and only limited experience with freight trains. Although the FTA guideline does provide some guidance on how a one might address freight train traffic, a lot is left to good judgment and conservative interpretation.

Freight train traffic differs from commuter traffic in a number of ways which contributes to challenges during assessment methodology that was created primarily to address commuter trains. Major differences between commuter and freight train traffic can be summarized by the following:

- Freight Train Length exceeds commuter train length – *The length of freight trains results in increased exposure times to freight train vibrations. Typical commuter train durations are approximated at 10 seconds; freight trains are approximated at 2 minutes on average.*
- Freight locomotive horsepower exceeds that of commuter locomotives.
- Freight trains are typically more frequent during nighttime hours compared to commuter trains.
- Freight train axle loads exceed commuter train axle loads -
- Freight train speed is typically lower than commuter trains– *The different train speeds shifts the periodic excitation based on the relationship between vehicle axle spacing and tie spacing.*

The FTS Assessment provides “Ground Borne Vibration Impact Criteria for General Assessment” to determine impact from railway upon various land uses including residential use. These criteria are base not only on the vibration level but also the number of events during a 24 hour period. Shown in Table 8-1 of the Assessment. For “Occasional Events” which are defined as 30 to 70 events per day, the Impact Criteria is 75 VdB re 1 micro inch/sec.

3 VIBRATION ABATEMENT METHODS

Materials designed to reduce the amplitude of vibrations can be deployed at the railroad tracks or at the structure to prevent amplification of vibrations at the structure’s dominant frequencies.

Vibration abatement deployed at the tracks is the most efficient way to shield a large residential area from railroad vibrations, and should also be considered during conversations between the developers and railroad operations.

3.1 Vibration Abatement Methods for Ballasted Railroad Tracks

Insertion loss as high as 24 VdB (relative to 1x10-8 m/sec) at 63 Hz can be achieved using ballast mats produced out of closed-cell engineered polyurethanes with low mechanical loss factors. Ballast mats are best suited for new tracks located to sensitive structures, or residential areas. Installing ballast mats on an existing track would require an interruption in service since ballast mats are installed between the compacted subgrade and the ballast (rocks) that support the railroad ties.

Under tie pads are the next most effective abatement treatment for reducing rail vibrations on ballasted track. Insertion loss for under tie pads produced out closed-cell engineered polyurethanes with low mechanical loss factors is typically in the range of 3 VdB to 15 VdB at 63 Hz. Under tie pads might are a preferred retrofit compared to ballast mats. Existing ties with no under tie pads can be replaced with new ties equipped with under tie pads using normal automated track renewal trains. This leaves the existing ballast in-tact, making a retrofit with under tie pads a more affordable option for the railway.

Fig. 2 *- (Left) Ballast Mat shown in (optional) concrete trench as is typical for ballasted bridge deck. (Right) Under tie pad on a concrete tie, shown without ballast.*

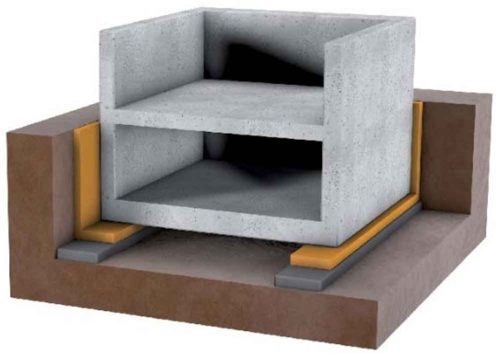
3.2 Vibration Abatement in Structures

When vibration abatement at the railroad tracks is not possible due to financial, technical, or political reasons, vibration mitigation can be specified by prescribing the construction of an isolated structure. The real estate development firm at this project determined early in the life of the project that structural isolation was the only approach feasible at the project site. Several methods of vibration control were investigated for the site including trenching and track bed isolation. However it was decided that isolation of the new structure from the ground borne vibration would be pursued by employing elastomeric material:

Variables Critical to Vibration Isolation Specification:

- Intended use of the structure (performance requirements)
- The fundamental characteristics of the vibrational excitation

- The size of the structure (mass and area)
- The required foundation design
- Required depth below grade (consider frost line, and location of the water table)
- Requirements for piles
- The geological soil conditions
- Cost of materials, design, and installation


a)

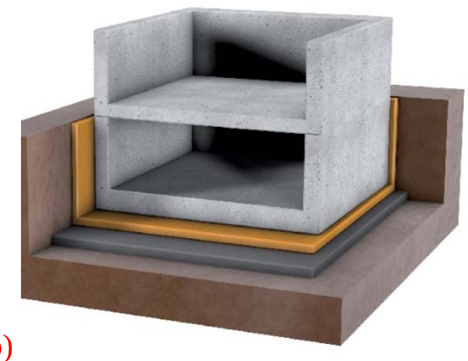

b)

Fig. 3 – Isolation Strategies Considered *(a) Strip Foundation or Grade Beam Isolation – requires pre cast concrete elements or engineered filling materials, (b) Full Surface Foundation Isolation – simplest of all isolated foundation strategies.*

Wood framed townhomes constructed in states having a 12-inch (12”) minimum frost-line requirement are typically constructed on slab-on-grade foundations, without basements. Therefore both isolation strategies (Fig. 3) were presented to the real estate developer: Strip Foundation or Grade Beam Isolation and Full Surface Foundation Isolation. Examples of each as applied to the foundations below the wood structure are shown in Figure 4.

a)

b)


Fig.4 - *(a) Example: Installation of Isolated Strip Foundation (b) Example: Installation of Full Surface Mat Slab Foundation*

A cost benefit analysis of various solutions was conducted with the developer, builder, the acoustic consultant, and the vibration control manufacturer to understand the project costs of each proposed solution. Together, a design was selected that would consist of a grade beam foundation - supported by engineered isolation materials located above standard island foundations (footings). Above the grade beams, two different ground floor design schemes were investigated. The first used precast concrete hollow core planking for the first floor and the second used traditional wood floor trusses for the first floor. In both cases the only connection to the ground was through the grade beams which were isolated from the ground using the isolation material.

4 ISOLATED STRUCTURE INVESTIGATION

For this project, the process for designing an isolated structure consists of xxx key steps:

1. Site measurement
2. Vibration analysis of similar structure
3. Specification of vibration abatement materials
4. Construction and measurement of mockup units
5. Data analysis

4.1 Site Measurements

As mentioned earlier, preliminary site measurements indicated ground level impacts greater than 80 VdB. Per the FTA Assessment the structure is likely to amplify this level by another 6 VdB clearly indicating the need for mitigation.

4.2 Vibration Analysis of Similar Structure

To determine the resonant frequency of the finished structure, a series of heel drop tests were made at another site with townhome models very similar to those proposed for the subject site. The results indicated the fundamental resonant frequency to be in the 15 to 18 Hertz range. The tested units were complete with typical furnishings.

4.3 Specification of vibration abatement materials

Proper specification of vibration abatement materials requires coordination between the structural designer, the acoustic/vibration consultant, and the manufacturer of the vibration abatement materials. It is important to recall that the vibration abatement materials perform <u>two-functions</u>. First, the products specified will be used to support the building structure. Secondly, the products will reduce vibrations as they propagate from the building's foundation to the upper structure – through the abatement material – as function of the product's design.

<u>Long Term Functionality:</u> To ensure long term functionality as a building support material, the specified product should have chemical stability. When subject to fluctuations in environmental conditions such as moisture, temperature, and humidity over long periods of time the material should not be compromised. Short term and long term deflection (creep) estimates must be communicated to the engineers and architects on the project to ensure that sound bridges do not develop over time as the building and the material begin to settle under long term static loading.

<u>Reserve Structural Capacity:</u> Materials should have reserve capacity. Vibration abatement materials should not be destroyed or experience plastic deformation during short term loadings exceeding the expected static loading on the material.

<u>Material Selection Based on Occupancy Load:</u> It is critical that the structural engineers and vibration consultants understand the loading environments critical to each other's work. Structural

engineers are required, by law, to design structures according to load combinations incorporated into state and local building codes. These load combinations have been developed to ensure the safety of the occupants of the building, and may not reflect the actual masses/loads which will be present during normal occupancy of the building. An estimate of the building's actual mass (actual dead load plus live load) under normal occupancy conditions is critical to meaningful vibration performance calculations.

Dependence on amplitude: The amplitudes of rail vibrations are typically 75 VdB. Consideration of a material's dynamic stiffness at low amplitudes should be made. Polyurethanes exhibit less dependence on vibration amplitude in comparison with synthetic rubbers.

Understanding Soil Contribution: The specification of vibration abatement products below the foundation must consider the stiffness of the structures/soil supporting the elastic vibration-reducing layers. The elastic properties of the soil should be understood, or conservatively estimated to understand if the resulting mass-spring system should consider the soil's own spring properties.

Performance: The SDOF vertical natural frequency of vibration isolation scheme selected for the development's townhomes was selected at approximately 8.5 Hz, which was calculated considering estimates for some elasticity in the soil. This isolation frequency was selected after performing heel drop tests at finished townhomes built locally by the developer. Heel drop tests indicated that typical floor frequencies were 15 to 18 Hz.

4.4 Construction and Measurements of Mockup Units

To fully investigate the viability of the concept, three mock town home units were constructed on site in close proximity to one another. The mock up unit were constructed at full scale with a 22' x 40' foot print, 9' 1" ceilings, a 2^{nd} floor, full roof trusses, and roof finished with standard shingles. The mock up units were incomplete in that there were no interior walls, plumbing, electric, exterior finishes, windows, interior drywall, etc. The idea of the mockups was to provide insight as to how much vibration isolation could be achieved and how much amplification the building, specifically upper levels, could be present. To better simulate the true finished structure the building was loaded using sand bags to the extent that the foundation and the isolation material were exposed to the expected occupancy conditions and loading. Certainly the vibration characteristics would differ from a fully built out unit but by constructing the control unit comparisons to the "typical" condition could be made and provide an accurate way of accounting for the differences.

The intention of the testing was to determine the effectiveness of foundation isolation schemes on wooden structured townhomes. Three mock townhome structures were constructed on site in the location of the proposed townhomes, using three different configurations. The first was conventional slab on grade construction and used as a control, the second with hollow core concrete plank construction on the first floor and the third with a wooden truss on the first floor. The wooden truss and hollow core plank conditions differed from the conventionally constructed condition in that the buildings' foundations were built upon grade beams isolated from the footings by 3 inch thick closed cell polyurethane (PUR elastomers) mats. The remainder of the construction for the three buildings was identical. Figures 5, 6 and 7 show plans and photographs of the isolation scheme, partial construction and finished mockups.

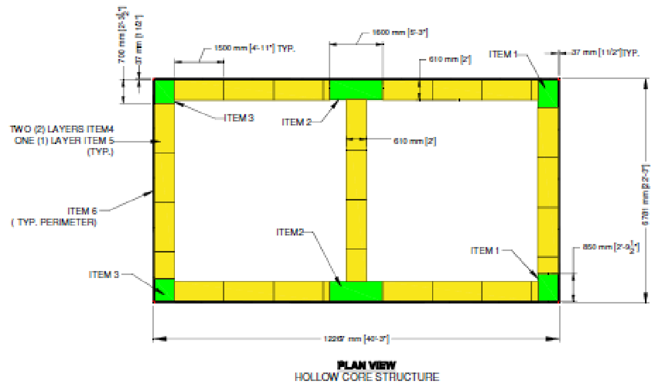
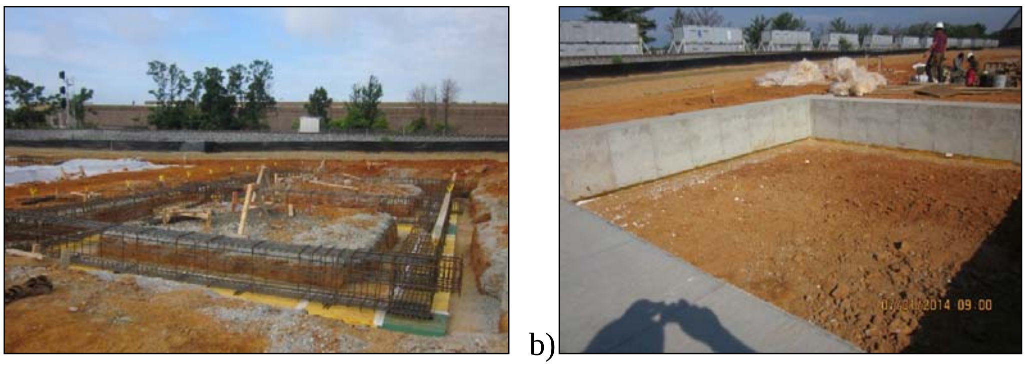


Fig. 5 *– Isolation Installation Plan for Hollow Core Structure*



a) b)

Fig. 6 *– Plan and Installation (a) Rebar Installation for Grade Beams (b) Finished Concrete Grade Beam Foundation (Note: Freight train passing in background of photo)*

Fig. 7 *– Three Completed Mockup Units –* ***Left Building:*** *Isolated Grade Beams & Timber Truss 1st Floor.* ***Center Building:*** *Isolated Grade Beams & Hollow Core 1st Floor,* ***Right Building:*** *Control Building with slab on grade foundation.*

The mockup units were then instrumented with vibration transducers to simultaneously measure the vibration within each structure during railway events. The measurement set up included 9 triaxial measurement locations, 3 of which were ground based measurements at the base of each house foundation, 1 first floor measurement in each house, and 1 second floor measurement in each house. First and second floor measurements were in the center of the floor about 12 feet back from the house face closest to the tracks. One of the ground measurements triggered the entire chain based upon an established ground vibration threshold. All channels were measured simultaneously for approximately 45 seconds for every trigger using a 32 channel data acquisition system, Each measurement captured the raw time signal which was subsequently analyzed in 1/3 octaves and included Max and Leq values. A schematic of the measurement set up is shown in Figure xx.

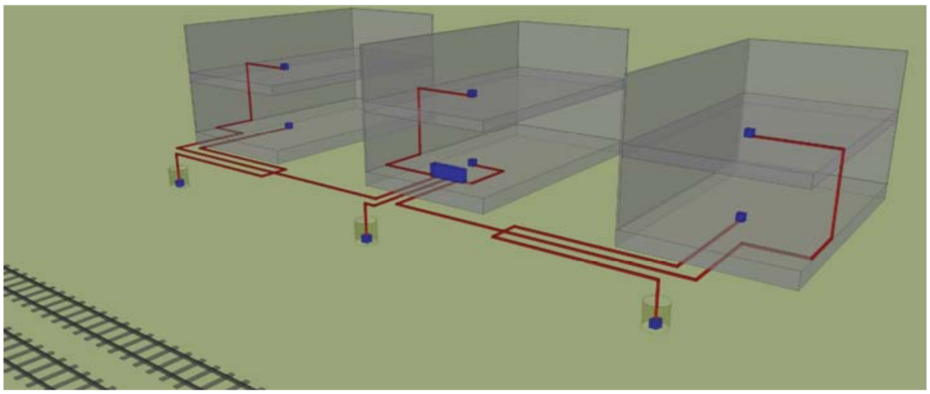


Fig. 8 - *Vibration measurement setup schematic*

Ground measurements were made approximately 6 feet from the base of each building in pits dug to the depth of the foundation to verify the exact ground level vibration input into each structure allowing for accurate determination of the relative vibration reduction provided by each house type.

Measurements were made continuously for 7 days to capture a sizeable sample of the railway activity upon the site. Results presented included the maximum vibration level measured during each train pass by presented in terms of velocity dB re 1 micro inches/sec (VdB).

4.5 Data Analysis

During the 7 day measurement 86 freight trains and 62 passenger trains were captured and analyzed. The mockups are referred to by number with the following designation:

Unit 1 – Untreated
Unit 2 – Precast Concrete Planks on 1st Floor 1, Wood Trusses on 2nd Floor
Unit 3 –Wood Trusses on 1st and 2nd Floors

The data was averaged and compiled into a series of frequency spectrum charts separated according to freights and passengers. Examples of two Z direction frequency charts are shown in Figures 9 and 10.

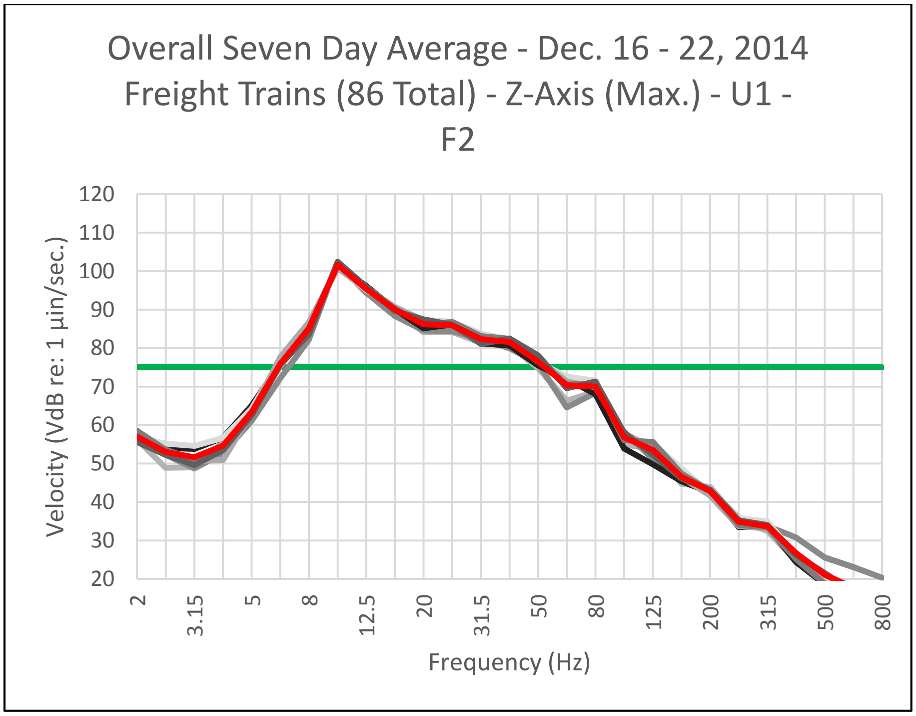


Fig. 9 *- Unit 1, floor 2 results, red showing overal average, grey daily average*

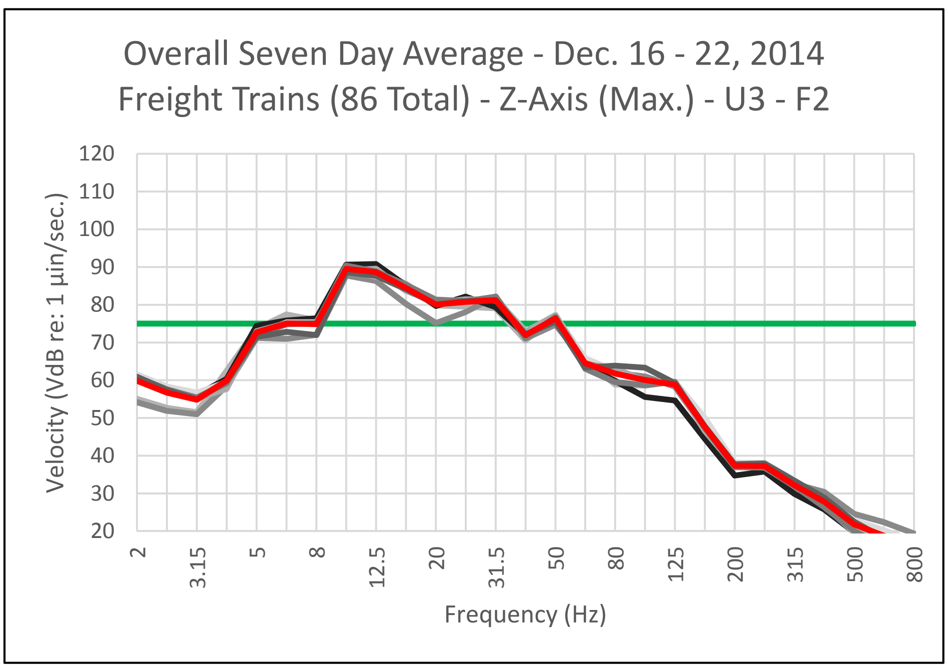


Fig. 10 *- Unit 3, floor 2 results, red showing overal average, grey daily average*

The data was further reduced by listing the highest measured value in each location in Tables 1 and 2. From these values it was determined how much amplification each floor added to the ground borne vibration simply by subtracting the level measured in the ground outside each unit from the measured level on the floor. Negative numbers indicate that the structure is reducing the ground vibration and positive numbers indicates amplification.

Table 1 *Freight train vibration levels and floor amplification*

Freight Trains	7 Day Average Level, VdB			Amplification Above Ground Vibration, VdB	
Unit	**Ground**	**1st Floor**	**2nd Floor**	**1st Floor**	**2nd Floor**
1	81	78	102	-3	21
2	81	74	91	-7	11
3	78	89	90	11	12

Table 2 *Passenger train vibration levels and floor amplification*

Passenger Trains	7 Day Average Level, VdB			Amplification Above Ground Vibration, VdB	
Unit	**Ground**	**1st Floor**	**2nd Floor**	**1st Floor**	**2nd Floor**
1	81	79	100	-2	19
2	79	71	88	-8	9
3	77	86	86	9	9

5 DISCUSSION AND CONCLUSIONS

As expected due to direct coupling with the grade, the first floor vibration of Unit 1 (Slab on grade) is very similar to the ground borne vibration. Unit 2 first floor (hollow core pre-cast slab) provides a significant reduction to the ground borne vibration, (-7 to -8 VdB) and successfully reduces ground borne vibration to levels below the recommended limit of 75 VdB. Unit 3 first floor (timber truss) increases the ground borne vibration by 9 to 11 VdB which this is a very significant increase, however it is still significantly lower than the 2nd floor vibration level of the untreated Unit 1. Unit 1 second floor exhibits the highest vibration levels of all three units by a 10 VdB margin over all the other second floors. This level is 25 VdB higher than the recommended residential level. Unit 1 second floor is 28 to 29 VdB higher than the first floor of unit 2.

Ground borne vibration from passenger trains were not significantly lower than the freight trains however passenger trains are very short term events generally lasting less than 2 seconds while freights might last 3 minutes giving the impression that they have higher vibration levels.

Based upon the both qualitative and quantitative observations by the developer's staff, it is known that the vibration levels measured are higher than what would be expected by a fully built out unit. Simply walking around in the upper floors results in vibration levels higher than normally perceived. Following the first phase of testing, it was determined that the lack of partition walls in the test units had a significant effect on the floor frequency. Heel drop tests in the test units indicate that the natural frequency of the floor system is approximately 10Hz, which is far from the 15Hz floors that the isolation scheme was selected for. Due to the relationship between the floor frequencies and the isolation frequency – the wood floor systems in the test units are being amplified. Therefore, based on quantitative analysis of the effects of partition walls on the effective length of the floor trusses, it is expected that vibration levels in the finished units will fall far from what is presented here. It is expected that vibration levels could improve more than 10 VdB, as the isolation frequency shifts from amplification region to reduction.

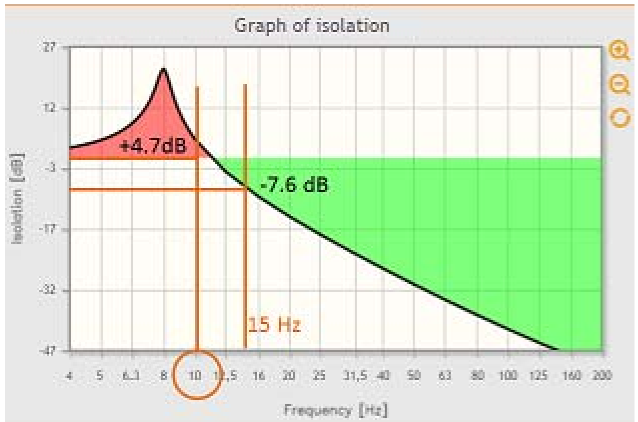


Fig. 11 *– Relationship between vibration isolation & floor truss natural frequencies.*

Overall, Unit 2 provides the highest level of reduction to both floors with levels on the first floor below the recommended 75 VdB limit. While unit 3 does have higher first floor vibration than the untreated condition, the second floor of Unit 3 is well below the 2nd floor of the untreated condition. Unit 2 and Unit 3 second floor vibrations are equal, which is expected based on the relationship between the isolation frequency and the floor natural frequency. In conclusion, Unit 2 provides the best level of reduction. Considering the measured in-field performance in combination with the quantitative predictions based on a 15 Hz floor frequency, it is probable that vibrations in these isolated townhomes could be at or within 3VdB of the FTA recommendations, compared to the 100VdB measured at the second level in the untreated structure.

6 ACKNOWLEDGEMENTS

This work was sponsored by EYA, Bethesda, Maryland, developer and builder of the project.

7 REFERENCES

1. Federal Transit Administration, "Transit Noise and Vibration Impact Assessment," Report FTA-VA-90-1003-06 (May 2006).