Structural Dynamics, Noise and Vibration: Buildings Adjacent to Train Lines

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ABSTRACT

In architecture and civil engineering there is a growing interest in the study of the dynamics of structures. The dynamic effects are due to various actions, but their influence is widened or reduced according to the design of the structure. Structures can be highly susceptible to the action of dynamic loads produced by the action of wind, earthquake, industrial activities, blasting activities, construction sites, road vehicles, trains, building services and human activities. Noise and vibration can have significant environmental impact on buildings and structures and can damage track components, crack roadways, unsettle foundations, affect sensitive equipment, impact human comfort and damage structures. Structure-borne noise and vibration can be a major and often overlooked consideration in the planning, design and operation of existing or new developments. A reliable, considered approach to assessing noise and vibration is needed to achieve outcomes that meet client expectations while maintaining on-going compliance with relevant standards and regulatory and planning requirements.

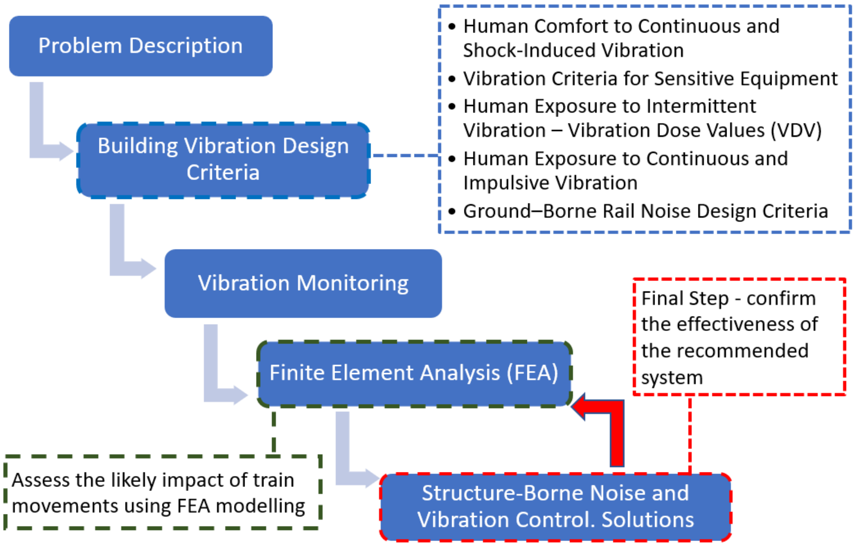
The proposed paper will focus on a general overview of the structure-borne noise and vibration risks, associated with new developments that are adjacent to existing rail lines during the early design stages, from commercial and residential buildings to sensitive research facilities. It will further explain the general description of the design process, including problem description, measurements of ground and structural vibration levels at the proposed site, vibration criteria, finite element analysis and provisions of the isolation system required to be considered at the building to achieve the relevant criteria. The procedures proposed are mainly aimed at structural and civil engineers who are working in construction and environmental engineers who are not specialists in vibro-acoustics.

1 INTRODUCTION

The major sources of noise and vibration in communities are road, railway and air traffic, industries, construction, public works and blasting activities. Vibrations can cause either serviceability problems reducing people's comfort to an unacceptable level or safety problems with danger of failure. In the early days of the railway, sites were reserved in the cities around industrial zones, however with the passing of time, these areas have subsequently been transformed into land dedicated to residential, mixed-use developments or commercial buildings. Therefore, the demands for comfort and wellbeing have been increased. Due to the lack of space in cities and in order to free up land that can be commercialized, the railway lines have been buried in tunnels, however, these infrastructures may generate vibrations and structure-borne noise affecting buildings and occupants. Waves propagating through a structure, radiating as sound into the air are called "structure-borne noise". If adequate insulation measures are not taken, these vibrations can reach unacceptable levels for the neighbourhood and human comfort, which causes continuous problems with the Council and Railway Administrations.

Transmission of structure-borne noise into and within buildings via foundations and other connections can also cause structural damage or disturb sensitive equipment, resonance in buildings especially due to low frequency excitations, feelable movement of building floors, rattling of windows, shaking items on shelves or hanging on walls and rumbling sound. The levels of noise and vibrations due to railway infrastructures must achieve the noise and vibration limits as specified in the relevant standards for each specific type of use such as residential, mixed-use development, commercial, theatres and auditoriums, hospitals, education or research facilities.

There are currently a wide variety of standards and guidelines to be considered during the design of a building near the railway lines. This paper provides the most common standards used in the Australian industry and a general description of the design process as presented in Figure 1.



Source (Pablo Reboredo Gasalla, 2021)
Figure 1: Description of the design process

2 PROBLEM DESCRIPTION

Dynamic forces generate noise and vibration, caused by rail traffic and subway tunnels and can be transmitted through the air (railway lines at ground level) and through the soil (railway lines at ground level and underground). Vibration is generated by rail traffic over a wide range of frequencies and amplitudes; the critical frequency band extends up to about 150 to 200 Hz. Human sensitivity to vibration also depends on the frequency at which it occurs. It is important to understand that sound with frequencies of more than 16 Hz can be heard by the human ear. For structural vibration in the vertical direction (z-axis), vibration is most detectable between the frequencies of 4 and 8 Hz, with velocities below the curve: f = 4 Hz – $V_{RMS}2x10^{-4}$m/s; f > 8 Hz – $V_{RMS}1x10^{-4}$m/s, are generally not perceptible to humans.

Excitation frequencies of railway induced vibrations between 40 and 80 Hz may cause significant structure-borne noise. Vibration at higher frequencies is generally attenuated rapidly with distance along the transmission path through the ground. The influencing factors in the propagation of vibration are mainly associated with the type of infrastructure such as a specific train (e.g., passenger, freight train, tram), speed, rail and wheel unevenness or roughness, track irregularities, rail support stiffness and sleepers, ballast composition, distance of the railway from affected structures and the dynamic characteristics of the soil.

Buried sub-structures or adjacent structures may be affected by these dynamic excitations. Considerable resonance effects may take place in the higher storeys of such structures. Slabs and walls are frequently excited to near-resonance amplitudes. The fundamental frequency of these elements lies between 10 and 30 Hz, whereas the horizontal fundamental frequencies of entire structures often are between 5 and 10 Hz. Structure-borne noise from the subway tunnels can be noticed in the adjacent building as vibrations in the frequency range between 1 to 80 Hz. Floors with a natural frequency in the range from 6 to 25 Hz are particularly sensitive to this excitation. Natural frequencies and damping properties of structures affected by structure-borne noise can vary in a wide range. Whether a structure shows structure-borne noise or not, depends on its properties (frequency response function, stiffness and damping) as well as on the parameters of the dynamic action (frequencies, amplitudes and time). Therefore, understanding the type of building, e.g., reinforced concrete, steel, cross laminated timber (CLT), type and depth of foundations, building height, number of floors and their associated frequency responses must also be considered in the design of new developments adjacent to rail lines. The goal is to achieve client expectations while maintaining ongoing compliance with relevant standards and regulatory requirements.

If the vibrations in a building from ground-induced excitations are larger than the relevant criteria, then remedial measures need to be adopted. These can be applied at the source, in the surrounding medium, or at the affected building itself. It is important to note, the most effective method is to always reduce the vibration at the source and a detailed analysis is beyond the scope of this presentation, today. This paper provides general recommendations to be considered for new developments, close to existing rail infrastructures, at the building itself.

3 BUILDING VIBRATION DESIGN CRITERIA

The transmission of vibration through a building has the potential to adversely affect occupants within the building or sensitive equipment. The building structure must be designed to achieve appropriate levels of vibration to minimise such adverse effects. The following section outlines commonly used vibration criteria for assessing human comfort and responses to building vibrations in Australia.

3.1 Human Comfort to Continuous and Shock-Induced Vibration

Human response to floor motion is a complex phenomenon. There are wide variations in vibration tolerance of humans and accordingly the acceptance criteria for human comfort are difficult to define and quantify. Acceptable values of human exposure to vibration are primarily dependent on the activity taking place in the occupied space (e.g., residential, offices, meeting rooms, laboratory, teaching spaces, for example) and the character of vibration (e.g., continuous or intermittent). In addition, specific values are dependent upon social and cultural factors, psychological attitudes, expected interference with privacy and ultimately the individual's perceptibility.

The concept of using base curves to assess human comfort has been adopted from Australian Standard AS 2670.2:1990 Evaluation of human exposure to whole-body vibration, Part 2: Continuous and shock-induced vibration in buildings (1 to 80 Hz). N.B. – Please note that this standard was superseded by Australian Standard ISO 2631.2:2014 Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration, Part 2: Vibration in buildings (1 to 80 Hz); however, it is accepted practice within the Australian market to adopt the multiplying factors (R) as presented in Table 2 Appendix A (AS 2670.2:1990) for building vibration from human comfort.

A base curve marks the threshold of human perception and is defined in one-third octave bands from 1 to 80 Hz. Vibration levels below the base curves typically do not result in adverse comments or complaints from occupants. The vibration criteria for different occupancy types are obtained by multiplying the base curve by a factor (R). Multiplying factors for different occupation types are listed in Table 1.

Table 1: Multiplying factors for building vibration with respect to human response

Place	Multiplying Factor (R)	
	Continuous or Intermittent	Transient Vibration excitation with several occurrences per day
Critical working areas (e.g., hospital operating theatre, precision laboratories or similar)	1.0	1.0
Residential	2.0 to 4.0 (Day) 1.4 (Night)	30 to 90 (Day) 1.4 to 20 (Night)
Office	4.0	60 to 128
Workshop	8.0	90 to 128

3.2 Human Exposure to Intermittent Vibration – Vibration Dose Values (VDV)

When assessing intermittent vibration, use the Vibration Dose Values (VDV). The vibration dose is fully described in British Standard BS 6472: 2008 Guide to Evaluation of human exposure to vibration in buildings – Part 1: Vibration sources other than blasting. Table 2 below presents the vibration criteria for human comfort, in terms of preferred and maximum vibration dose values as described in BS 6472 and also provided by NSW Environmental Noise Management – Assessing Vibration: a technical guide (February, 2006). The VDV level can be directly related to vibration discomfort experienced by a person. VDV accumulates the vibration energy received over day and night time periods.

Table 2: Maximum vibration dose values for intermittent vibration

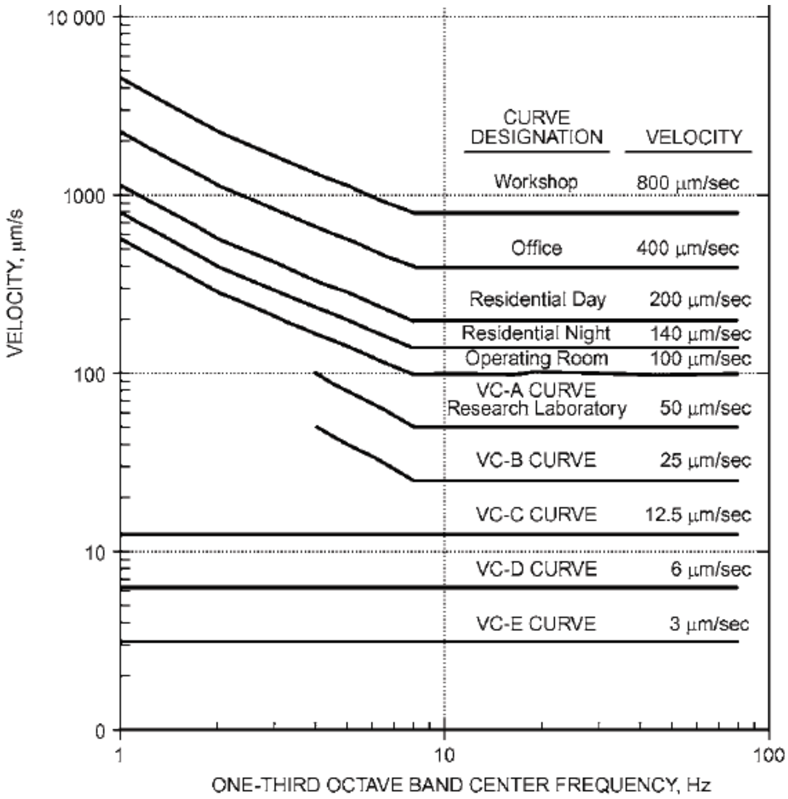
Place	Vibration Dose Values ($m/s^{1.75}$)			
	Day time (7am – 10pm)		Night time (10pm – 7am)	
	Preferred	Maximum	Preferred	Maximum
Critical areas: hospital operating theatres and precision laboratories where sensitive operations are occurring	0.10	0.20	0.10	0.20
Residential	0.20	0.40	0.13	0.26
Office, schools, educational institutions and places of worship	0.40	0.80	0.40	0.80
Workshops	0.80	1.60	0.80	1.60

3.3 Human Exposure to Continuous and Impulsive Vibration

Guidelines for human comfort with respect to vibration within a building are also provided by NSW Environmental Noise Management – Assessing Vibration: a technical guide (February, 2006). This guideline is a useful reference during the land-use planning stage, to reduce conflicts that vibration may cause, such as the determination of railway corridors and the design of building footings. This technical guideline provides acceptable RMS acceleration and velocity levels for continuous, impulsive and intermittent vibration in each orthogonal axes for use in assessing human responses to vibration and provides recommendations for measurement and evaluation techniques.

3.4 Vibration Criteria for Sensitive Equipment

Vibration Criteria (VC) curves are used extensively in scientific and research environments. The VC curves were introduced by Colin Gordon in 1991 in his publication by SPIE in 1991 and by IEST in 1993 and adopted in the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE Applications Handbook – Chapter 49 Noise & Vibration control) as widely accepted criteria for the design of facilities accommodating vibration sensitive equipment. Figure 2 presents recommended acceptable criteria for vibration in a building structure to assess vibration impacts on sensitive scientific laboratory equipment. Velocity vibration criteria curves (RMS) defined in one-third octave frequency bands in a range from 1 to 80 Hz are shown in Figure 2.



Source (ASHRAE, 2019)

Figure 2: Building vibration criteria for vibration measured on building structure

3.5 Ground–Borne Rail Noise Design Criteria

There is no Victorian or Australian national document that provides specific requirements regarding ground-borne noise limits due to train lines. However, the New South Wales (NSW) Environment Protection Authority (EPA) does, provide guidelines in the Rail Infrastructure Noise Guideline (RING), (May, 2013). The key objectives of these guidelines are to ensure that the adjacent development achieves an appropriate acoustic amenity by meeting internal noise and vibration criteria specified in the State Environmental Planning Policy (Infrastructure) 2007 (SEPP).

The noise and vibration trigger levels presented in RING indicate when noise and vibration mitigation measures should be considered. If the environmental impact assessment of a proposed rail project shows that the trigger levels are likely to be exceeded, the assessment is required to outline feasible and reasonable noise mitigation measures that could be implemented to ameliorate the predicted impacts. Ground-borne noise excludes direct airborne noise. The trigger levels are presented in Table 3. L_{ASmax} refers to the maximum noise level not exceeded for 95 per cent of rail pass-by events and is measured using the ‘slow’ (S) response setting on a sound-level meter.

Table 3: Ground – borne noise trigger levels for heavy or light rail projects

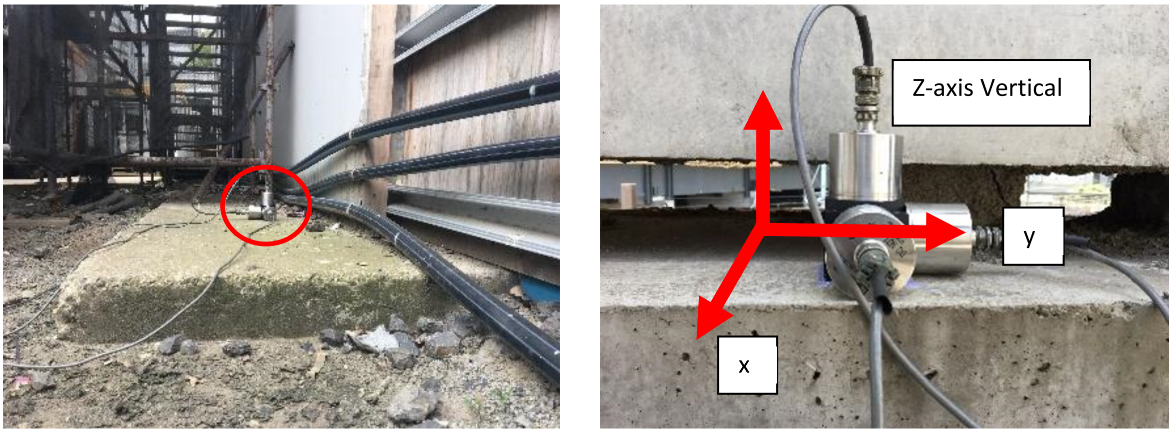
Place	Time of Day	Internal Noise Trigger Levels, L_{ASmax} dB(A)
Residential, aged-care facilities and caravan parks incorporating long-term residential use	7.00am to 10.00pm	40 L_{ASmax} and an increase in existing rail noise level by 3 dB(A) or more
	10.00pm to 7.00am	35 L_{ASmax} and an increase in existing rail noise level by 3 dB(A) or more
Schools, educational institutions, childcare center, places of worship	When in use	40 – 45 L_{ASmax} and an increase in existing rail noise level by 3 dB(A) or more

4 VIBRATION MONITORING

When planning new buildings in cities and urban areas which are close to an existing railway infrastructure, the impacts of noise and vibrations on the building to be constructed, frequently have to be investigated and structural adaptation measures may be required to achieve the relevant criteria as specified in the previous section. As part of these investigations, vibration monitoring should be considered at the proposed site during the planning and design of new developments.

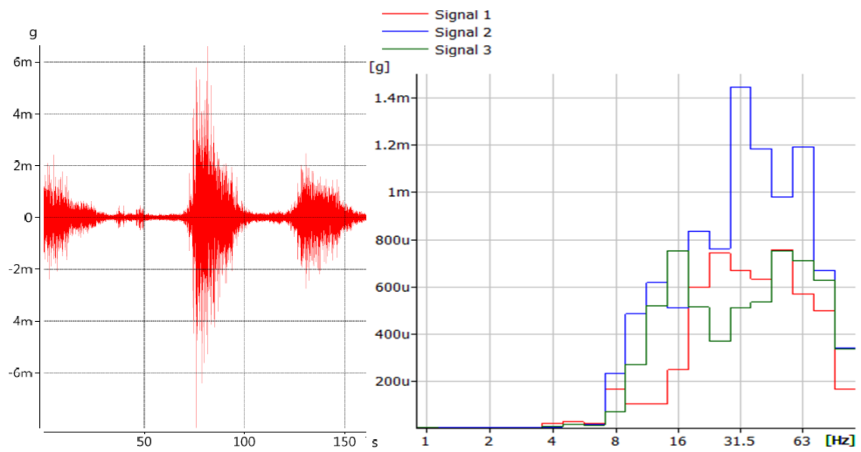
The purpose of the vibration monitoring is to locate and quantify the vibration levels at ground level surrounding the proposed building to understand the potential impacts that external vibration sources, such as trains, trams or road traffic, will have on the design and operation of the proposed development, adjacent to the rail lines. There is a wide range of instruments that are suitable for the measurements of ground and structural vibration. They all consist of at least: a transducer (e.g., accelerometer or geophone), a signal processor and a display or indicator. A vibration sensor or transducer is a device that converts some property of the vibration associated with the ground or structure into an electrical signal. This signal is then amplified, attenuated, or transformed in some way so that it can be analyzed and/or processed to provide the data of particular interest. The instruments that utilise geophones are known as seismographs, while the instruments that utilise accelerometers are called vibration meters.

The accelerometers must be mounted at the proposed building foundations or at other relevant structural connections, in three orthogonal directions. It should be noted that poor mounting techniques can have a marked effect on the frequency response, therefore, sensors must be fixed directly onto the ground or structure with a threaded steel stud. When this mounting method cannot be used, cement or a glue gun is also acceptable. Refer to Figure 3 for samples of standard installations using three seismic accelerometers mounted to a steel cube via studs and then fixed to the floor or relevant structure.



Source (Pablo Reboredo Gasalla, 2021)
Figure 3: Example of sensors locations

In order to determine the characteristics and levels of vibration at the proposed site, a signal can be analysed as the recorded waveform, e.g., the amplitude as a function of time. To analyse the frequency content of the signal, a conversion to the frequency domain is necessary, which can be done using a Fast Fourier Transform (FFT) algorithm. The FFT is used to study the response of vibration systems to periodic and impulse forces transforming the signal from time domain to frequency domain. Refer to Figure 4 for a typical recorded data of a freight train at frequencies of interest.



Source (Pablo Reboredo Gasalla, 2021)

Figure 4: Data recorded – train signal measured at building foundations at approximately 15m distance from the rail trucks

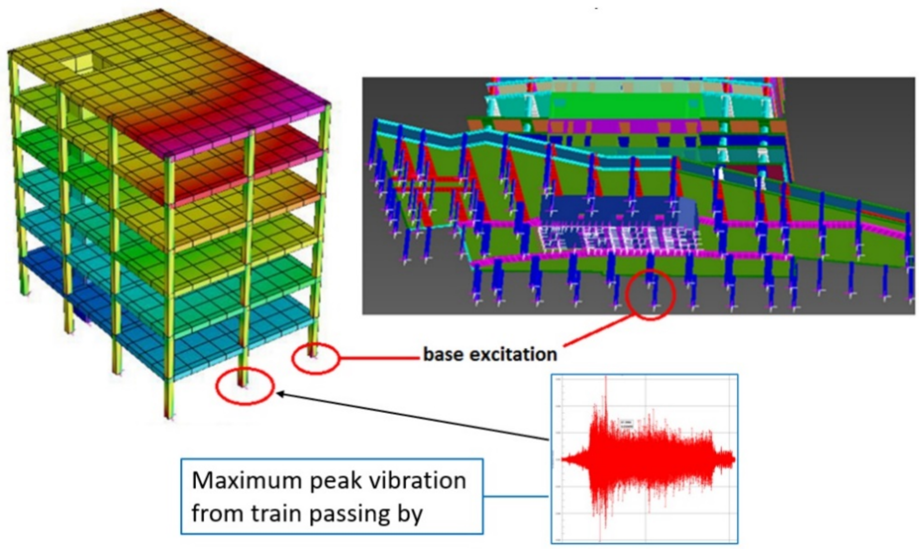
5 FINITE ELEMENT ANALYSIS

The dynamic behavior of a structure is closely related to its natural frequencies and corresponding mode shapes. A well-known phenomenon is that when a structure is subjected to a sinusoidal force and the forcing frequency approaches one of the natural frequencies of the structure, the response of the structure will become dynamically amplified, e.g., resonance occurs. Resonance can cause discomfort or significant impact on buildings and structures, affect sensitive equipment, impact human comfort and damage structures. Resonance must be avoided. Therefore, investigating and analysing potential resonances and structure-borne noise problems in the structure must be considered as part of the building design adjacent to train lines.

Today a number of sophisticated mathematical methods are available to calculate the dynamic behavior of structures resulting from vibrations transmitted through the ground and the foundation into a structure. It is even possible to take the soil-structure interaction into account. Finite Element Analysis (FEA) can be used for static and dynamic analysis of beams, plates, shells, trusses, and other solid bodies. The FEA involves generation of a finite-element mesh to represent the building structure and soil to be analyzed. The finite element method is the most widely used method and accurately for solves problems of structural vibration engineering, to predict the frequency response of a building subject to an external dynamic load.

To obtain reasonable estimations of the vibration response of the structure, a transient dynamic analysis is normally used to calculate the entire time history of the dynamic response of a structure subjected to external dynamics loading. The external dynamic loading can be an arbitrary time function with or without initial conditions. Figure 4 presents an example of the acceleration time data and Constant Percentage Bandwidth (CPB) spectrum analysis from a freight train recorded at the building foundations of a new development adjacent to rail lines.

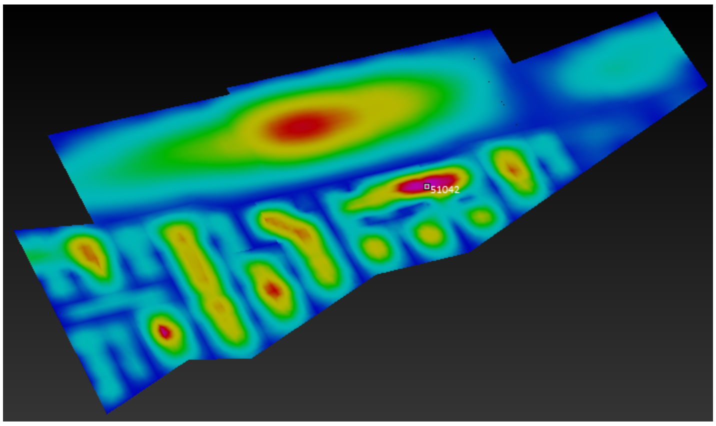
After analysis of the recorded data on vertical and horizontal directions, load was applied and imported into the FEA model as a base excitation as presented in Figure 5.



Source (Pablo Reboredo Gasalla, 2021)

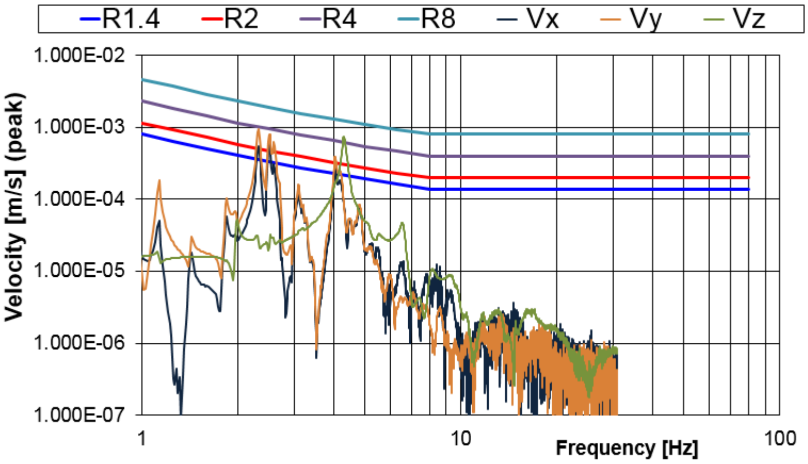
Figure 5: Finite element analysis – building foundations and core lift

Note that this type of calculation is often used to analyse a structure under a loading that has a short duration but perhaps a wide frequency range. It is also used to calculate time history response of buildings, subjected to train excitation by way of an acceleration time history applied to the ground or other relevant structural connections. The predicted RMS velocity levels are compared with the vibration criteria for the building structure and correlate this with the critical frequency input from the vibration monitoring as presented in Figure 6 and Figure 7.



Source (Pablo Reboredo Gasalla, 2021)

Figure 6: Finite element analysis – maximum RMS velocity levels on suspended slab



Source (Pablo Reboredo Gasalla, 2021)

Figure 7: Predicted velocity levels vs frequency for a freight train signal on suspended slab including vibration criteria (Multiplying Factor, R)

If the predicted RMS velocity levels in a building from ground-induced excitations are larger than the relevant criteria, then remedial measures must be adopted.

6 NOISE AND VIBRATION CONTROL

The concept of protecting a building structure from railway infrastructure effects, is already being implemented all around the world. To minimise these forces to the structure, a base isolation system has become a practical strategy for structure-borne noise and vibration isolation. Basically, the isolation system introduces a layer of low lateral stiffness between the building structure and the foundation or alternatively, between the structure and the ground. An alternative system is the use of steel spring isolators with low natural frequency, however in this paper, I will only present isolation systems incorporating elastomeric materials such as natural rubber or polyurethane. These types of systems are also very effective solutions in reducing the particular perturbancy frequencies generated by trains. The elastic properties of the vibration isolation element are therefore of crucial significance to determine the effectiveness of vibration isolation.

The choice of the type of system will require a careful study during the design stages, since the important frequency bands such as wind, earthquake or railway do not overlap and an improvement in a certain band can imply a worse behaviour in other bands. At the same time, the excitation frequency must be well separated from the natural frequencies of the structure to avoid unwanted resonances and vibration amplifications.

The basic concept is to prevent vibrations from penetrating the structure by inserting an isolation system with low natural frequency in order to let the attenuation of vibrations start at the lower end of the excitation frequency spectrum. Normally, the calculated natural frequency of a mass-spring-system with steel springs for building isolation are in the range of 2 Hz to 7 Hz natural frequency, meanwhile with elastomers, the natural frequencies are approximately from 7 Hz upwards.

The static stiffness of the component is significant to ascertain the deformation under static load AND the dynamic stiffness is a crucial parameter to determine the natural frequency of an oscillatory system. The natural frequency of an elastomer compressed is dependent upon Young's Modulus (E), its shape and size such as thickness, area and dynamic stiffness (K_{dyn}). Consequently, increasing the thickness and reducing the size of the proposed pad, the natural frequency decreases, until the desired degree of isolation is achieved. Based on the simple degree of freedom system (expressed in terms of transmissibility), effective isolation; as a general principle, the ratio (r) of the excitation frequency (f) to the natural frequency of the mass-spring system (f_0) should be at least $>\sqrt{2}$ (e.g., $r = f/f_0 > \sqrt{2}$). The isolation system must provide a sufficient gap with respect to the excitation frequencies of the train and the natural frequencies of the structure.

The most common type of isolation system uses point bearings and alternating layers of steel plates under lateral forces and hard rubber or polyurethane. The elastic point bearings can achieve 5.5 Hz natural frequency by suitable choice of material and dimensions. These point bearings must be strong and stiff under vertical loads and flexible under lateral forces. The stainless steel plates are used to better distribute the forces within the point bearings. Additionally, this also increases the performance of the point bearings since the full extent of the shape-factor of the material can be utilized. Figure 8 presents two samples of point bearings using polyurethane (Sylodyn, Getzner) and stainless steel reinforced point bearings to be installed at the building foundations or at other strategic structural locations. Figure 9 presents two natural rubber point bearings (Mason, 2020) to protect the future building from train induced-vibration at Federation Square in Melbourne CBD, Australia.

Source (Getzner, 2020)

Figure 8: Polyurethane and stainless steel reinforced point bearings (HRB-HS 6000 Sylodyn)

Source (Mason, 2020)

Figure 9: Natural rubber point bearings

An alternative method to the point bearings is the use of a full surface vibration isolation with elastomeric material between the building structure and ground. Implementing this full surface vibration isolation will require more material (compared to point bearing), but the required installation time can be reduced since the implementation process is simple and fast. Straight on top of the isolation layer, the construction workers can install the steel reinforcement (adding spacers so the vibration isolation layer will not be punctuated) and pouring the concrete. These types of systems are becoming more popular due to the lower costs of construction while presenting a very effective solution to reduce train induced forces in buildings. Refer to Figure 10 for a full surface vibration isolation system with elastomeric material (Sylomer, Getzner) between the structure and ground.

Source (Getzner, 2020)

Figure 10: Full surface vibration isolation (Germany). Installation prior to foundation slab

7 CONCLUSIONS

As a final step, it is recommended to conduct a finite element analysis, implementing the required isolation system. This will confirm the effectiveness of the recommended system. Thus, we are able to compare the predicted vibration levels with the vibration criteria and correlate this with the critical frequency input from the vibration monitoring conducted. The isolation system must achieve the required transmissibility to reduce the main perturbancy frequencies due to the train lines. It must also guarantee the structural stability and security of the fully supported structure, as well as provide long-term effectiveness of the dynamic properties, no increase of natural frequency due to static load and consistency of physical properties during the lifetime of the building.

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