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From Acoustic Specification to Handover: A Practical Approach to an Effective and Robust System For The Design and Construction of Base (Vibration) Isolated Buildings

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FROM ACOUSTIC SPECIFICATION TO HANDOVER. A PRACTICAL APPROACH TO AN EFFECTIVE AND RO-BUST SYSTEM FOR THE DESIGN AND CONSTRUCTION OF BASE (VIBRATION) ISOLATED BUILDINGS

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A typical building isolation system design specification will usually be based on a single degree of freedom model derived from vibration measurements taken from the site and typically ends up with one key performance criterion to be achieved, dynamic natural frequency. The flaws in this are widely discussed however notwithstanding the challenges in developing a robust performance specification, its ultimate success is reliant on a coordinated effort between all parties involved in the design and construction team including: the acoustic consultant, structural engineer, building isolation system supplier, architect, M&E designers, main, frame, fit-out and M&E contractors.

There are many factors which, individually or collectively and to a greater or lesser extent will influence on the ultimate acoustic performance of the building for its occupants. Examples include: the wide variety of building types (concrete, steel, lightweight steel frame..), foundation types (piled, raft, isolated or non-isolated basement, on top of an existing building or structure..), layout and shape (open plan, small discrete rooms, apartments..), specific details (offset and external columns, retained facades..). At the point the acoustic specification is created much of this detail will not be known or finalised and it could also be reasonably stated that there are significant gaps in our industries' knowledge about if and how each of these factors will influence the overall performance of the system. Finite Element modelling is often seen as the answer but in order to achieve credible results a model has to be very detailed including structure and fit out details. This in itself if expensive and time consuming and would have to be adapted to account for every change in feature from the design development process. This paper sets out the principles of a new matrix of responsibility for a robust design and construction process of base isolated buildings.

Keywords: ground-borne vibration, building vibration isolation

1. Introduction

Sitting on the 2nd floor of the British library, situated between Kings Cross and Euston stations in central London, one can hear, and through the floor, just about feel the London underground trains. The levels of noise are low and quite possibly below the official level that might lead to 'adverse comment' [1] but owing to the typically low levels of background noise, they are a regular disturbance. The same can be experienced in many other buildings in urban centres, for example on the 4th floor of a hotel in Manchester and the 7th floor of a hotel near Aldgate in London one can hear passing trams / underground trains via re-radiated noise through the structures. The author was not privy to the decision making or design process for these buildings but one would assume that it was considered a risk, but not sufficient to justify mitigation measures. It would then be for the end users to judge and decide if that decision was correct.

As our rail networks grow, property values increase and the population expects higher levels of comfort, the need for effective prediction, design and construction methods to mitigate the noise and vibration from rail and other sources becomes more and more important yet there are a number of significant challenges to providing a client (developer) with an assurance that a building will not be affected by structure borne noise and vibration. In an ideal world they would be provided with an accurate prediction of the resultant noise level within every room in the proposed building and those predictions could be achieved with minimal budget. Once constructed the end users of each room (each with their own opinions on the topic) were not adversely affected by noise intrusion. The reality is quite different as demonstrated by the volume of high quality but often inconclusive research [2, 3, 4, 5 and 6] looking initially at the complexities and uncertainties of predicting the anticipated energy input into a building (train wheel / rail interaction, effect of the tunnels, make-up of the intermediate ground strata and possible subterranean structures, distances, variation between existing and proposed new foundations etc) and then predicting the behaviour of the new building. The building's dynamic response behaviour will vary depending on whether the building is isolated or not and if so, what type of isolation system is adopted, the infinite variability of foundation and super-structure designs, the variability of human perception and acceptance of structure-borne noise and the client's (developer vs end user) expectations of what is acceptable etc. A fundamental barrier on the subject is the limited amount of post-construction testing information meaning that much of the published information on the subject is comparing theory with theory rather than theory with reality.

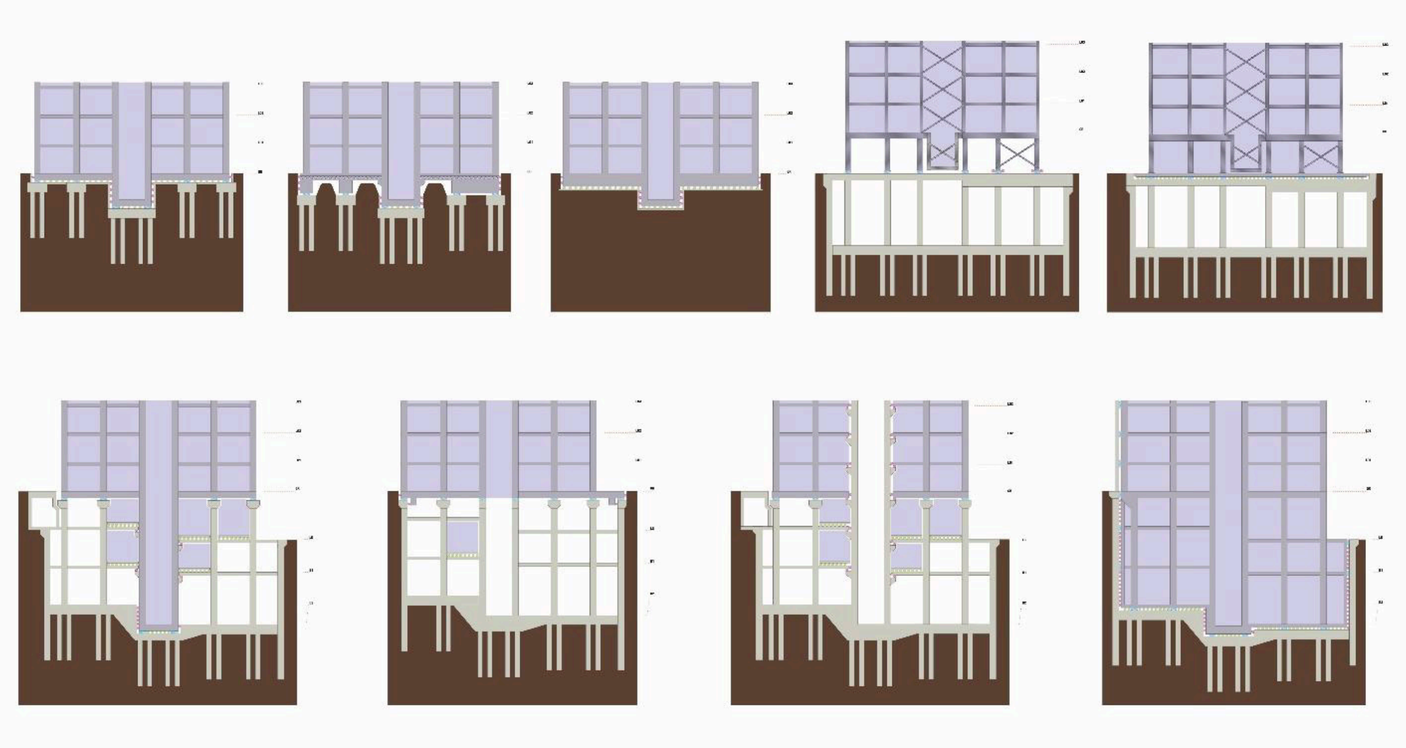

Figure 1: Examples of vibration isolated building design schemes showing the variety of founda-tion and super-structure designs

The intention of this paper is to take a step back from the complexities of absolute predictions and propose the stance that all predictions will involve a reasonably high degree of uncertainly. But where a risk of disturbance from structure-borne noise and vibration is anticipated it may well be that the precise natural frequency and dynamic structural interactions and behaviours play a smaller part in the ultimate acoustic performance than effective design and construction of mitigation measures such as building vibration isolation and acoustic box-in-box systems etc. and the quality and performance of the isolators within them. It is therefore proposed that the acoustic system supplier should be appointed to the project at the early stages of design because the successful acoustic isolation of a building is reliant on the comprehensive integration of the isolation system with almost every element of the building.

2. Developing a Performance Specification

Taking an example of a proposed new building development where a risk has been identified that structure-borne noise could cause disturbance within the building. At some point, typically in RIBA Stage 2 (Concept Design = Outline proposals for structural and building service designs and preliminary costs) and Stage 3 (Developed Design = Coordinated and updated structural and building service designs) [7] an acoustic consultant would be appointed to assess whether mitigation measures were required. Assuming the source existed at the time, a vibration survey would be undertaken and it is from here that the uncertainties and assumptions start;

1. Does the acoustic consultant have knowledge and experience of vibration (since acoustics is a very broad subject, many do not)?
2. Have the measurements been taken correctly, in appropriate locations and at appropriate times for the key noise sources? [2, 8 and 9]
3. Have the measurements been processed and interpreted correctly?

Assuming all of the above have been done according to best practice then the results need to be analysed and processed in order to predict the likely levels of tactile vibration or re-radiated noise within the specific design of the proposed building. Herein lie more uncertainties and assumptions;

4. Have appropriate target noise levels have been adopted?
    a. Crossrail guidance
    b. BSA233
    c. Client’s expectations
5. Are the foundation, building design and proposed construction type sufficiently developed in order to factor in their individual and combined behaviours?
6. How has the performance specification for the building vibration isolation system been deduced?
    a. Basic single degree of freedom model
    b. Experience
    c. Numerical modelling
    d. Finite Element (F.E.) modelling
7. Is there any evidence of verification and / or validation of any of the above?

Based on the number of assumptions and uncertainties at each stage of the process it is inevitable and understandable that a definite answer cannot be provided or should not be entirely trusted. Nevertheless the culmination of this process is that the acoustic consultant must conclude whether or not the building, or parts of the building, should be isolated and if it does what ‘High Level’ Vibration Isolation System (HLVIS) specification would achieve the ‘desired’ performance. The key performance metric of a typical HLVIS is the generally limited to the dynamic natural frequency. In theory any frequency could be specified but specifications for such systems are typically grouped as: Me-dium: 16-20Hz elastomeric system, High: 8-12Hz elastomeric system or Very High: 3-4Hz coil spring system where the specified natural frequency should occur at a particular load condition such as Dead Load (for theatres and concert halls) or Dead Load + 20-40% Live Load for residential / office buildings.

3. Detailed Design Process vs Performance Specification

A building vibration isolation system is typically characterised by the main structural column and core bearings which as we have seen in Figure 1 can be arranged in a variety of permutations. How-ever the overall success of the system requires effective design, detailing and construction of a vast array of additional elements across structural, architectural, façade, fit out and mechanical & electrical (M&E) disciplines. Each discipline has its own preferences, each of which can contradict another's and each preference could lead to a reduction or compromise of the ultimate acoustic performance of the building. The following is a non-exhaustive list of examples of details and features which could affect or risk affecting the performance of a building vibration isolation system:

- Structural foundation and super-structure design, e.g. dynamic behaviour of the building including potential resonance of lightweight building structures coinciding with isolation system natural frequency
- Excessive lateral restraint
- Lateral restraint that restricts the vertical isolation system's performance
- Perimeter soil pressure resistance [6]
- An isolation system that requires tension anchors in cores and shear walls
- In-effective detailing and construction of elements that cross or contact the external isolation line including: construction up to adjoining buildings and structures, retained and new façades/cladding, waterproofing, insulation & gas membranes, perimeter backfill, landscaping/paving, incoming services etc.
- In-effective detailing and construction of internal elements that cross the isolation line including: stair cases, lift shafts & cores, floor / ceiling finishes designed to hide isolation bearings, plant and services duct/pipework, fire protection systems, acoustic movement joints along the isolation line within the finishes and building thresholds etc.
- Over-complex isolation details or ones that are over-reliant on contractor workmanship
- Tolerances on structural loadings leading to incorrect loading of the acoustic isolators
- Construction sequencing leading to variation in loadings from the structural predictions
- Poor workmanship and quality control of the entire construction and fit out process

It is vital that a co-ordinated approach throughout the design and construction phases is adopted and in the author's opinion the HLVIS should be available during RIBA Stage 2 and definitely by Stage 3. At that at that stage it is highly unlikely that the acoustic consultant could be aware of all of the technical details and features of the building and they are likely to evolve and change throughout the design development period and each decision along the way could detrimentally affect the overall performance of the system. It is therefore the challenge of the design team to work together to develop the design of the building to stay as close as possible to the acoustic consultant's performance specification whilst at the same time establishing / agreeing which are the critical drivers to give the client what they ultimately want and what trade-offs can or must be accepted by which parties.

In order to mitigate such risks, it is proposed that once the HLVIS specification is available, a building vibration isolation system supplier should be brought into the design team to work alongside the architect, structural engineer, acoustic consultant, M&E and potentially façade consultants under a clear matrix of responsibility. The building vibration isolation system supplier should be sufficiently experienced and capable so as to understand the drivers behind the various design team members, many or all of whom may never have worked on a building isolation project before, and therefore help in reaching best case compromises and ultimately functional and buildable details throughout the building. This can and usually includes the elements listed above as well as specific structural and isolation system principles such as:

- Detailed structural modelling to harmonise the various combinations of vertical and lateral structural loadings with isolator spring constants
- Incorporation of sufficient and efficient structural and robustness details such as: effective length of columns, vertical ties, lateral restraints etc
- Packaging the isolation system within the structural and architectural constraints and ensuring that fit out details do not restrict the performance

In order to provide the client with a degree of control of costs, a high level budget for the anticipated supply of the isolation system should be given which can then be updated as the design is developed and refined with different options holistically costed along the way to enable effective decisions to be made.

An important contribution that the vibration isolation system supplier should bring to the process is ensuring that isolation details can be constructed with minimal risk of bridging. As we can see from Figure 2 the realities of construction processes will always challenge the neat, clean details that a design team will create but often, to be effective, isolation details have to be constructed where sub-sequent access, to make good, is not possible making the detailing, construction methodology and execution critical to the success of the system.

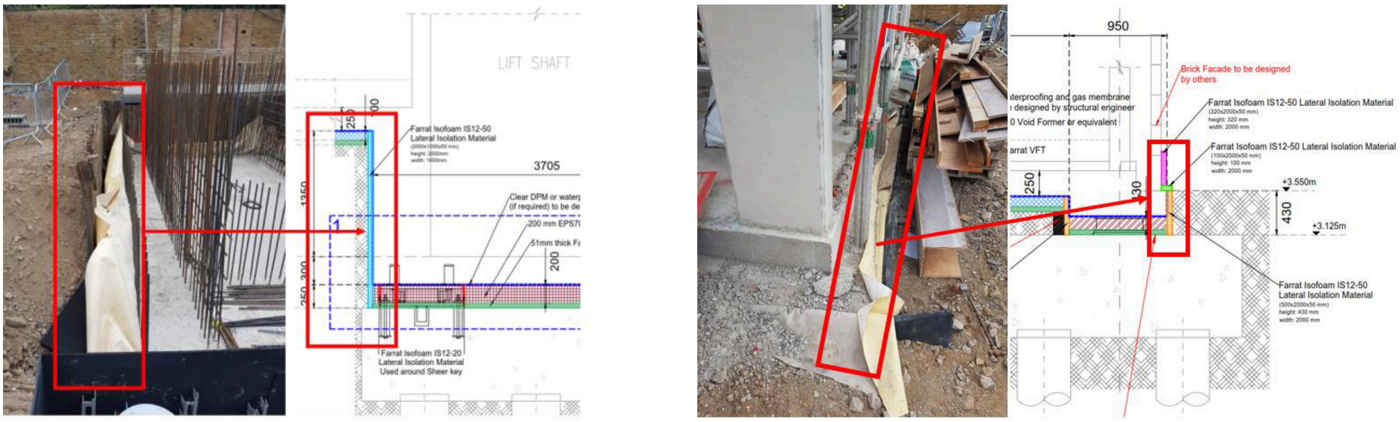

Figure 2: Typical examples of the challenges of constructing robustly isolated details

As is so often the case, if the design is developed without the committed contribution of a system supplier it is likely that details could be missed or poorly designed and since most vibration isolation system suppliers offer different solutions the likelihood is that if a project went down the normal tendering route and appointed the supplier through an open tendering process just before or once construction has started then this would inevitably require an intensive, accelerated design-development exercise to integrate the chosen system into the design. This would likely lead to structural, architectural or fit out changes to be made late on in the process which can delay the construction programme and could lead to more significant cost increases than the value of the isolation system package. In addition, building isolation systems are typically long lead time items with some or all of them being bespoke and manufactured to order meaning that often production cannot start until the design has been concluded. The appointment of the system supplier to the project team could mitigate this by providing the facility to reserve production space.

There is a philosophical dimension to this topic whereby budget may play a part in the ultimate performance of a building vibration isolation system. An example here is comparing an, inherently high value, coil spring system with an elastomeric option which has been chosen on a cheapest tendered price basis. It is likely that there may be more whole project focus on the more expensive coil spring system to ensure that money is not wasted than a low budget alternative as the latter would not command the same level of attention to detail / importance in design and construction.

During the detailed design stages, where more accurate details have been developed and agreed, a more advanced vibration analysis could be undertaken to re-assess the overall performance specification. In an ideal world this could be tied in with Building Information Modelling (BIM) but would ultimately lead to a ‘Detailed’ Vibration Isolation System (DVIS) specification which would ideally provide a higher degree of certainty in performance than the HLVIS specification.

4. Building Vibration Isolation System Specification

We have so far discussed an overall performance specification but not a detailed system specification. Traditionally, when considering elastomeric systems, there would be a detailed specification for the acoustic bearings that includes compound preferences and testing regimes etc. Often the acoustic consultant would be required to provide such a specification but in reality its content sits between the acoustic consultant and the structural engineer.

Increasingly there are occurrences where there may be a ‘High Level’ Vibration Isolation System (HLVIS) specification but no System Specification. This could lead to problems in design and construction where important engineering principles are missed and products may not actually be best suited to a particular application. It also leaves the end user / asset manager / building owner at risk in the future as once constructed and handed over, the matter of longevity and creep/degradation of the vibration isolation system, which have limited relevance/priority for the Design and Build con-tractor, are of critical importance. For example high strains and/or excessive loading on a highly filled rubber or polyurethane will lead to higher levels of creep from which we would expect to see a degradation in acoustic performance the effects of which would only be seen once the warranty period has expired. Also if for example the building were to be expanded at some point in the future or if it were damaged by fire, then the only operation and maintenance record would be the system supplier’s information which may not be relevant or available in the future whereas a detailed System Specification would allow additional or replacement components to be sourced.

Currently, in many ways the elastomeric, acoustic bearing supplier market is unregulated since the only applicable standard is EN 1337-3 [10] is a bridge bearing standard (demonstrated in section 4.2 where it states that ‘Elastomeric Bearings shall be designed and manufactured to accommodate translational movements in any direction and rotational movements about any axis by elastic deformation..’). One could argue that this could be seen as a benefit as, unlike bridge or seismic bearings, it allows creativity in design but on the other it is strange to think that there is no official, targeted guidance or standard for such critical products, especially when there is a distinct lack of knowledge of rubber and elastomers in general in our industry today. With this in mind, a closer look at EN 1337-3 indicates that apart from its main flaws (the lack of specific vibration isolation and dynamic testing guidance as was provided in the now withdrawn BS 6177 [11] and the restriction on the thickness of the elastomer layers to 25mm), it does provide a significant amount of constructive guidance and governance for a designer and client including:

- Compound design, including limits in:
  - Shear modulus limits at normal, low and very low temperatures and after ageing, tensile strength, minimum elongation at break, tear resistance, compression set, ozone resistance and accelerated ageing
- Bearing design and manufacture, including guidance on:
  - Internal steel reinforcement plate design and vulcanised bond (between the internal steel reinforcing plate and the rubber) shear strength at ambient temperature and after ageing, buckling, rotation and translation stability limits, maximum design strain, manufacturing tolerances, type and routine testing of raw materials and finished product and marking and labelling.
- Structural design and installation requirements for the installation of the bearings including:
  - Surface conditions, flatness and level as well as grouting.

It is possible to manufacture high performance acoustic bearings whilst following EN 1337-3 precisely, thus enabling the product to be CE marked but based on the variety of variants required to meet project specific performance requirements it is not feasible to restrict all acoustic bearings to EN 1337-3 but the designer should be able to draw upon key elements of the Standard and its associated guidance document PD 6703 [12], into a project specific product specification. Finally, there is no harmonised standard for full-area isolation mat systems wherein there can be significant variations in product quality and performance from the variety of new and recycled products available in the market today.

What seems to be happening at present is because of the lack of knowledge, time and the desire to shed risk, design teams are deliberately allowing the bearing manufacturer to take responsibility for their product allowing them to decide which standards and tests etc, or not, are appropriate. This does not seem appropriate, especially since these are critical components of the primary structure intended to last the life of the building.

It is therefore suggested that the Acoustic System Specification is compiled as a joint exercise between the Acoustic Consultant and Structural Engineer with input from the Isolation System Supplier so that it can accurately be based on the products that are to be used on the project as well as viable and meaningful testing techniques and regimes to provide appropriate and sufficient reassurances of performance and quality. And in order to empower the Acoustic Consultant and Structural Engineer to regain the initiative and lead in the process it is suggested that better, impartial industry guidance is available on the best practice use of elastomers and springs when used in vibration isolation scenarios in buildings.

5. Detailed Design Process vs Performance Specification

For all the effort, time and expense required to create a viable and functional building isolation system design that takes all the above-mentioned points about vibration isolation system, structural, architectural and M&E design into account then the barometer of its success or failure is whether it is constructed properly. There are accounts of building vibration isolation systems not performing as predicted but investigations have typically concluded that causes were generally down to poor workmanship, for example concrete overspill bridging, and/or dirt and construction debris bridging the isolation line [4]. Other investigations have concluded that services crossing the isolation line were not resiliently decoupled resulting in train noise propagating through the isolated building. It is there-fore critical that all contractors are made aware of the principles of the vibration isolation system and the progress needs to be constantly monitored to ensure that the isolation line, wherever it travels within the building, is maintained. Often by this stage the acoustic consultant has little if any role in the project.

In the author’s opinion this monitoring should be a combined undertaking between the acoustic consultant, vibration isolation system supplier and structural engineer. These parties can support the contractors to overcome problems encountered on site and have the collective power to decide whether as-built details are acceptable or not.

6. Conclusions

We know that structure-borne noise and vibration from underground and over ground rail can and does lead to disturbance within buildings but because of the number of assumptions and uncertainties at each stage of the process and the lack of post-construction test data it is inevitable and understand-able that a definite answer on what to do cannot be provided or should not be entirely trusted. If mitigation measures are required they can be complex and costly but the manner in which they are specified, tendered, incorporated into the design and constructed can post significant risks to whether such an investment has provided the intended benefits.

In order to reduce such risks it is proposed that a vibration isolation system supplier is brought into the project at an early stage to provide specialist input to the design process with the aim of creating a functional and buildable design within the normal design process stages rather than having to re-work the design once construction has already started. This is important, and differs from many other components in the supply chain of a building that can be tendered later on, because the successful acoustic isolation of a building can be and often is reliant on the comprehensive integration of the isolation system with almost every element of the building.

Finally is proposed that more industry best practice guidance should be available to empower the acoustic consultant and structural engineer to compile an appropriate and suitably detailed system specification and once in construction a more coordinated approach should be adopted to support and supervise the contractors to ensure that the vibration isolation system performance is actually achieved.

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