Isolation of Buildings from Rail-Tunnel Vibration: A Review

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ABSTRACT

Many buildings close to railway tunnels are built on steel springs or rubber bearings to isolate them from the ground-borne vibration. This *base isolation* of buildings has been employed since the 1960s and is becoming increasingly common as pressure grows to construct high-quality buildings on existing urban sites.

This paper reviews the practice and theory behind base isolation, and discusses some recent developments in modelling base-isolated buildings with a view to predicting isolation performance.

1. INTRODUCTION

There are several sources of urban ground-borne vibration – busy roads [1, 2], trams [3], construction activity [4], for example – but the weight and speed of railway vehicles, and the proximity of tunnels to buildings and their foundations, ensures that rail tunnels are generally the most significant source. Typical vibration levels lie in the range from 0.1 to 1.0 mm/s and peak in the frequency range from 40 to 80 Hz [5]. Although the levels are unlikely to cause even light damage to buildings, they can cause unacceptable levels of internal noise and vibration [6].

Measures to control rail-tunnel vibration are normally taken either in the tunnel or at the building. Modifications to the tunnel take various forms, from rubber pads between the rails and sleepers [7] to floating-slab track, which involves mounting the entire track on a concrete slab that is isolated from the tunnel [8, 9]. At the building, damping treatments may be incorporated into the structure, floating floors installed or local stiffening undertaken to adjust resonance frequencies. With new buildings, the entire structure may be base isolated, that is, the building is designed with isolation bearings between the building and its foundation.

2. THE DESIGN OF BASE-ISOLATION SYSTEMS FOR BUILDINGS

Base-isolated buildings are not a new concept: the first UK example was Albany Court, a block of flats erected over St. James' Park Station, London in 1965 [10]. More recent examples may be found in all classes of building: residential buildings, office towers, concert halls, cinemas and hospitals [11].

Either laminated rubber bearings or helical steel springs are used as isolation bearings. As yet, there is no conclusive evidence indicating which provides the most effective isolation, although manufacturers cite various advantages and disadvantages of the two types [12, 13, 14].

2.1 Rubber Bearings for Base Isolation

The widespread introduction of rubber bridge bearings in the 1950s provided valuable experience that eventually led to their introduction in buildings with the construction of Albany Court. Since then, rubber bearings, rather than steel springs, have been popular in the UK. Recent examples include Eland House, London [11] and Glasgow Concert Hall.

Rubber bearings are available in two different types: either carbon-loaded natural rubber, reinforced and stiffened by laminating with steel plates, or synthetic rubber made more flexible by loading with cork particles and reinforced with layers of woven cloth [15].

2.2 Steel Springs for Base Isolation

Helical steel springs have been used extensively in continental Europe for the base isolation of buildings. Their use in the UK has not been as extensive as the rubber alternative; indeed, as recently as 1985, springs were considered too expensive, lacking in inherent damping and the number required too impractical [16]. These concerns are no longer valid, although steel springs are generally more expensive than rubber bearings. Recent UK examples of spring-mounted buildings are the IMAX cinema, London [17] and the Bridgewater Concert Hall, Birmingham [18].

2.3 Generic Design Principles

This paper is concerned with *base*-isolated buildings and usually designs do indeed locate the isolation bearings at the base of a building, such as on the pile caps or at basement level. In principle, it is possible to locate the bearings higher up the structure and isolate only the upper floors. However, theoretical evidence presented by Cryer [19] indicates that this is less effective due to amplification of the ground vibration by resonances of the unisolated structure below the bearings. *Side-restraint* bearings are used in addition to base bearings in exceptional cases, as discussed in Section 5.2.

No standards exist specifically governing the design of base-isolated buildings, although an outline International Standard has been proposed [20] and a British Standard, BS 6177 [21], provides general guidance on the use of rubber isolation bearings. In practice, designs are based on past experience and the requirements of the particular project. Usually only the vertical direction is explicitly considered: the horizontal component of ground motion is generally neglected on the assumption that the building's inherent flexibility in this direction provides sufficient isolation. Recent theoretical evidence suggests that this may not always be valid, as discussed in Section 5.1.

On the basis of vertical motion being dominant, base isolation systems are principally defined in terms of their *isolation frequency*. This is the frequency of vertical oscillation of the building assuming it behaves as a rigid mass on a spring. Typical isolation frequencies lie in the range from 5 to 10 Hz, and the lower the frequency the more effective the isolation is expected to be. The level of inherent damping offered by the bearings is also often quoted as an important design parameter. Base isolation relies on vibration isolation rather than energy dissipation, the basic requirement being a low dynamic stiffness. A low level of inherent damping might therefore be expected to maximise isolation performance, provided that sufficient is present to control the rigid-body resonances of the building on the bearings and any internal resonances of the bearings themselves.

Given the lack of conclusive experimental or theoretical evidence, the sensitivity of the overall isolation performance to changes in bearing damping and isolation frequency remains uncertain.

3. EXPERIMENTAL INVESTIGATIONS INTO BASE-ISOLATED BUILDINGS

There is little doubt that base isolation is effective but the precise nature of the isolation performance and the benefits of certain design features, such as a low isolation frequency or a particular level of damping, remain uncertain. The problem is that it is difficult to measure isolation performance directly. In principle, a building may be jacked up and the bearings removed or alternatives tried but this is difficult and expensive to achieve in practice and, to the authors' knowledge, has never been done. If it were attempted, an effective measurement programme would require careful thought concerning the measurement locations, the quantity to be measured and in what direction.

The closest attempt at measuring isolation performance is the experiment undertaken by Sharif [22] using a test structure constructed on a concrete raft foundation above one of London's underground rail tunnels. The structure was a reinforced concrete box, approximately 7 x 7 x 2 m, with openings for doors and windows. Acceleration levels were measured on the floor of the structure in its unisolated condition, resting on concrete blocks, and when isolated on three types of bearing: steel springs, natural and synthetic rubber. In this way the isolation performance of the bearings could be determined.

Care must be taken when applying the results of this experiment to practical base-isolated buildings – given the small, relatively rigid test structure – but two important general conclusions may be drawn. Firstly, that the vibration modes of a building significantly reduce the efficiency of the isolation – something not predicted by simple theoretical models. Secondly, that inserting isolation bearings decouples a building from its foundation and results in greater foundation vibration than in the unisolated case. The latter highlights the inadequacy of basing isolation performance on vibration measurements made above and below isolation bearings [13, 18]. Lower vibration levels above a bearing should not be regarded as indicative of isolation performance because the measurements concentrate on the forced response of only a small part of a complex structure. In addition, as Sharif's measurements show, the performance may be exaggerated by greater vibration of the foundation than would otherwise exist beneath an unisolated building.

Cryer [19] describes a programme of measurements on a rubber-isolated apartment building at Gloucester Park, London. Of particular interest are Cryer's measurements of total and direct *transmissibility* between the basement (below the isolation bearings) and various floors within the building. The total transmissibility is the ratio of the vibration amplitudes at the two measurement points and does not distinguish between vibration arriving at the upper measurement point via different paths (it is of interest to the occupants who are not interested in where the vibration comes from). Direct transmissibility is the same ratio but considers only vibration at the two points that is correlated, thereby giving a measure of the importance of the particular input or transmission path. If the isolated building behaved as a single-degree-of-freedom system, both transmissibilities would be equal. The measurements clearly show that this is not the case: the building behaves as a multiple-input flexible structure with a series of resonance frequencies. The 9 Hz isolation frequency of the bearings is evident but the level of transmissibility is much less than that predicted by simple theoretical models.

The difficulties in making effective measurements ensure that reliable theoretical models are in demand. There is a clear need for a means of determining the effectiveness of base isolation and objectively evaluating the various types of bearing.

4. EXISTING MODELS OF BASE-ISOLATED BUILDINGS

Various models are reported in the literature that aim to predict the response of buildings to ground-borne vibration, although very few have been specifically designed to determine the effectiveness of base isolation. Models may be formulated in either the time or frequency domain. The former is often used for the seismic analysis of structures, where peak vibration levels due to a transient event are of interest. Non-linear behaviour can also be treated in the time domain. When dealing with rail-tunnel vibration the problem may be treated as linear, given the low strain amplitudes involved, and the response is of sufficient duration that the frequency domain is the most appropriate. This section therefore concentrates on frequency-domain models, which may be sub-divided into analytical and numerical models.

4.1 Analytical Models

The simplest model of a base-isolated building is the standard single-degree-of-freedom (SDOF) oscillator. This represents the isolated building as a rigid mass supported on a spring and some form of damping element to represent the isolation bearings. The model was originally used by Waller [10] when describing Albany Court, and this, together with its inherent simplicity, has probably resulted in the model's popularity. It is this model that forms the basis of defining base isolation systems in terms of their isolation frequency – the resonance frequency of the SDOF system.

Despite its popularity, the value of the SDOF model is extremely limited because it fails to describe some of the major features of a building's dynamic behaviour, in particular the flexibility and damping properties of the building and the effects of its foundation. Even the relatively rigid test structure investigated by Sharif (see Section 3) suffered from structural resonances and foundation behaviour that significantly reduced the performance of its isolation.

The SDOF model may be improved by replacing the rigid mass with a flexible column. Newland and Hunt [23] and Grootenhuis [15] use the analytical solutions for an elastic bar to demonstrate that a typical building column has several natural frequencies below 200 Hz at which the predicted level of isolation is significantly reduced. Swallow and Sharif consider two similar models based on a lumped parameter model [24] and an elastic bar [11].

Additional masses and springs are coupled to the bar to represent the connected floors and it is shown that this reproduces some of the low-frequency behaviour observed with real building columns. Column models may also be coupled to a simple foundation model to account for vibration radiation into the ground [23].

The column model is still limited by its one-dimensional nature. It does not account for flexural vibration and the fact that, in practice, buildings have multiple inputs at which the vibration may or may not be correlated. The work of Cryer [19, 25] takes the analytical models one stage further by using the dynamic-stiffness method to model a two-dimensional portal-framed building resting on a three-dimensional piled foundation. The computation time is minimised by treating the building as infinitely long and using periodic structure theory [26]. Cryer's model clearly demonstrates the importance of including a representation of the foundation: a significant amount of vibrational energy is radiated into the ground when the building is subject to a point excitation at one of the pile caps. While the model goes some way to accounting for the behaviour of a piled foundation, only the vertical pile behaviour is accounted for and no attempt is made to model interaction between neighbouring piles through wave propagation in the surrounding soil.

Balendra *et al*. [27] use a semi-analytical model to predict the response of buildings to rail-tunnel vibration. The two-dimensional plain-strain model comprises a rigid tunnel in an elastic half-space, with a rigid embedded footing coupled to a lumped mass to represent the building. The rigid-body representations of the tunnel and the building are considered major limitations of this model.

Talbot and Hunt [28] use a two-dimensional portal-frame model coupled to an approximate piled-foundation model to further investigate the behaviour of base-isolated buildings. This work illustrates fundamental problems with measures of isolation performance based on vibration amplitudes and introduces an alternative based on vibrational power flow, as discussed in Section 5.

4.2 Numerical Models

The finite-element method (FEM) [29] is now the most widely used numerical technique for engineering analysis and it has naturally been used to model vibration of buildings. Manning [30] describes how, for design purposes, building vibration levels are estimated using simple FEM models excited by a digitised copy of measured railway vibration applied to the base of the model. A similar approach is used by Hao *et al*. [2] to predict vibration due to road traffic. Such approaches are limited as they ignore the presence of the ground, which, as Cryer's work demonstrates, can significantly alter the response of a building [19]. Chua *et al.* [31] use a two-dimensional FEM model to predict vibration levels in a four-storey office block directly above four underground railway tunnels. This includes a representation of the foundation, using wave-absorbing boundaries to reduce unwanted reflections.

It is fair to conclude that the FEM requires considerable computing power to achieve reasonable results, even with relatively simple two-dimensional models. Results are usually obtained using modal analysis and are therefore inaccurate at higher frequencies unless large numbers of elements are used.

Thornely-Taylor [32] uses the finite-difference method (FDM) [33] to model the tunnel-soil-building system in the time-domain based on the equations governing Euler beams, thin plates and elastic solids. Again the model is computationally expensive despite being two-dimensional.

Statistical energy analysis (SEA) is another major numerical technique for analysing structural vibration. Craik [34] describes in detail how it may be applied, within the audio frequency range, to modelling noise and vibration transmission through buildings. However, the success of SEA relies on a structure having sufficient modal density such that individual modes are unimportant and vibration levels may be described in terms of the average vibrational energy. The problem with applying SEA to rail-tunnel vibration is that the frequency range of interest extends down to only a few Hertz, where modal behaviour is important. Despite its computational efficiency, SEA is therefore considered inappropriate for studying base-isolated buildings.

5. RECENT DEVELOPMENTS

Recent work in Cambridge has concentrated on producing theoretical models specifically designed to predict the performance of base-isolated buildings. The general approach has been to develop models that represent the essential dynamic behaviour of a base-isolated building while remaining computationally efficient, such that the various isolation designs may be readily evaluated.

Results from two models are presented here, using the parameter values listed in the appendix. Full theoretical details may be found elsewhere [35, 36].

5.1 A Generic Model

Figure 1 shows a generic model based on a modern concrete-framed building on a piled foundation. The primary structure of the building is represented as a two-dimensional portal frame, and uses the same dynamic-stiffness method used by Cryer for studying vibration transmission in buildings [19, 25]. The method describes the dynamic behaviour of the portal frame in terms of the analytical solutions for an elastic bar and Euler beam, thereby accounting for the longitudinal and transverse behaviour of the individual floors and columns, and the dynamic coupling between them.

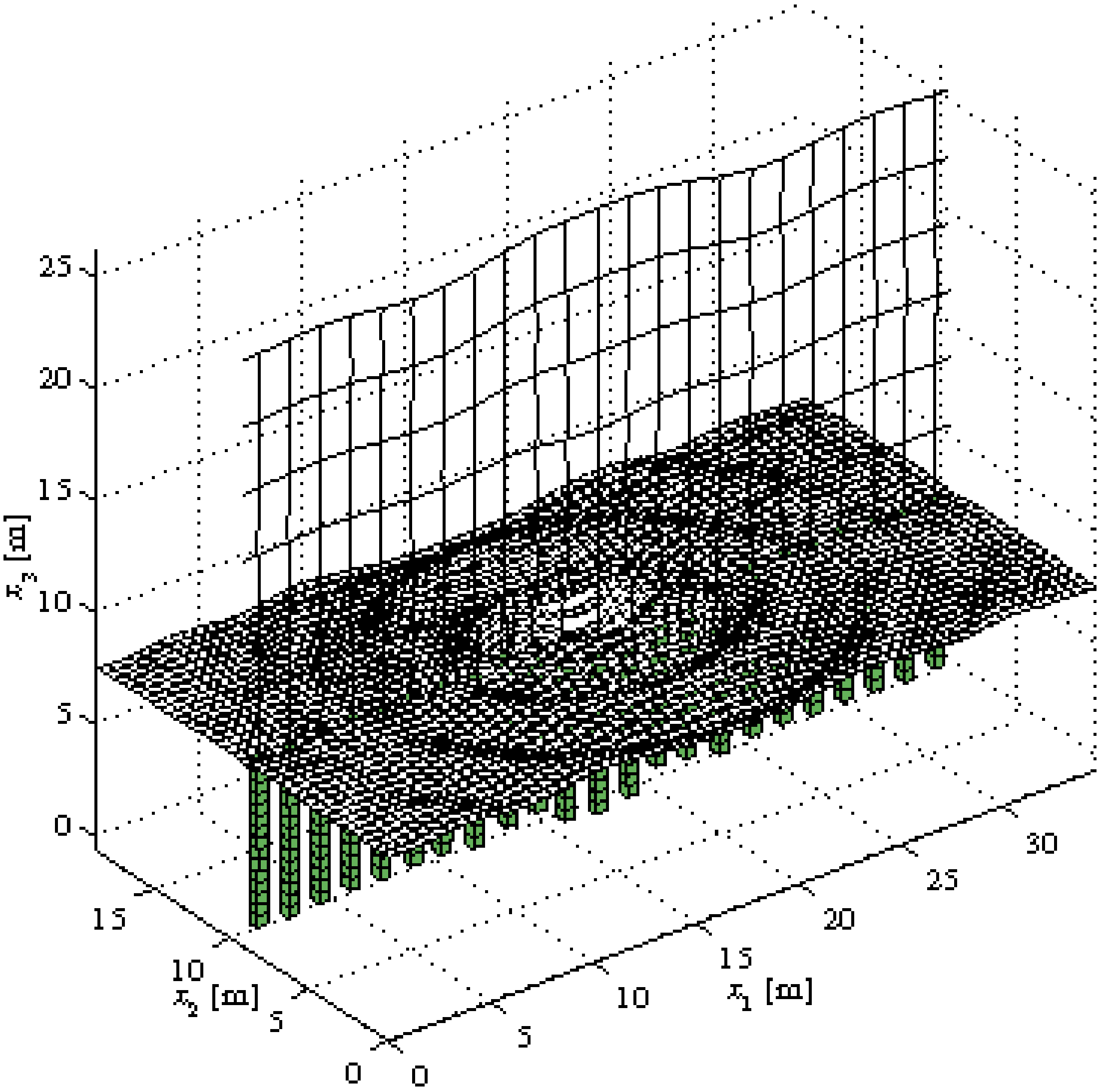

Figure 1: The generic base-isolated building model is based on a two-dimensional portal frame coupled to a three-dimensional model of a piled foundation. The excitation corresponds to a buried unit-amplitude force applied in the vertical direction 1 m below the central pile tip.

The foundation is represented by a three-dimensional piled-foundation model based on the boundary-element method (BEM). The BEM [37, 38] is ideally suited to modelling wave propagation in the ground, primarily because it avoids the need to discretize the bulk of the soil – as with the FEM and FDM – and automatically accounts for the radiation of waves to infinity. The pile model used here is comprehensive in that it accounts for the vertical, horizontal and rotational motion of the piles due to both pile-head loading and interaction between neighbouring piles through wave propagation in the surrounding soil.

Both the building and foundation models make use of periodic structure theory [26]. The models are assumed to be infinitely long and based on a repeating unit comprising a column, supporting several floors, coupled to a pile in a 'slice' of ground. The advantage of this approach is that a full solution may be derived from just one repeating unit, with a significant saving in computation time.

Figure 1 illustrates the response of an unisolated building to a buried unit-amplitude force applied in the vertical direction 1 m below the central pile tip. This generates pressure and shear waves that radiate outward, interacting with the piles and the building in a similar way to the excitation from a rail tunnel. Figure 2 compares this response to that of the same building but with '6 Hz' isolation bearings located on each pile cap, each bearing being modelled with three linear springs to represent the vertical, shear and rotational stiffness. Qualitatively it is clear that the isolation significantly reduces the vibration levels in the building, at least at 50 Hz.

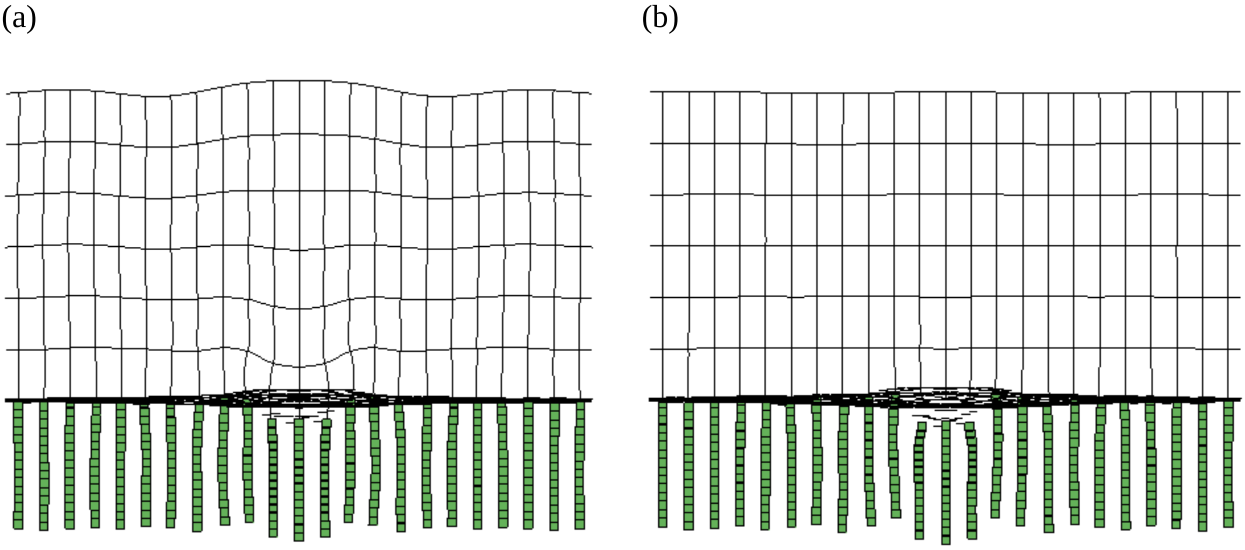

Figure 2: Side elevation of the generic model showing the response at 50 Hz of (a) an unisolated building and (b) the same building with 6 Hz base isolation. The excitation corresponds to a buried unit-amplitude force applied in the vertical direction 1 m below the central pile tip. All displacements are magnified by 2×10^{10}.

For a quantitative measure of this vibration reduction, we must consider the *insertion performance* of the bearings. Insertion performance quantifies the benefit of inserting isolation bearings beneath a building: it is of interest to the client who pays for the additional cost of base isolation and the Engineer who wishes to evaluate alternative types of bearing. A common measure of insertion performance is *insertion gain* (IG), as investigated experimentally by Sharif [22] (see Section 3). This is the ratio of the vibration response of the building with the isolation bearings in position to that with no bearings at all. IG is based on vibration amplitudes and is unable to provide a single measure of isolation performance due to the fact that it only accounts for vibration occurring in one direction and varies with position in a building. A more effective measure is *power-flow insertion gain* (PFIG) [28]. The principal behind PFIG is that the mean vibrational energy entering a building drives all internal noise and vibration, assuming there are no internal sources of either. A reduction in PFIG is therefore guaranteed to reduce the average noise and vibration levels in a building:

$$\mathrm{PFIG} = 10\log_{10}\left(\frac{\overline{P}_{isol}}{\overline{P}_{unisol}}\right) \tag{1}$$

where $\overline{P}_{isol}$ and $\overline{P}_{unisol}$ are the total mean power flows entering a building in the isolated and unisolated cases respectively.

PFIG has clear advantages over performance measures based on vibration amplitudes because it accounts for multidirectional vibration at multiple inputs and is insensitive to the spatial distribution of vibration levels within a building. It is also useful in design because the variation in isolation performance with frequency, for a particular set of design parameters, may be represented by a single curve. Note that, for the case of a single-input single-output system, PFIG may be shown to be directly equivalent to IG [35].

Figure 3 shows the variation with frequency in the PFIG when the model depicted in Figure 1 includes base isolation bearings giving isolation frequencies of 3, 6 and 9 Hz, with internal damping loss factors of 0.1 and 0.01. This range of parameters covers those typically found in practice: a 9 Hz isolation with a loss factor of 0.1 is representative of high-hysteresis rubber bearings while a 3 Hz isolation with a loss factor of 0.01 is representative of undamped steel springs.

The first thing to note about Figure 3 is the smoothness of the curves: there are no strongly defined resonance peaks. This is due to the infinite nature of the model, which radiates energy away from the excitation and prevents resonances from being established. This behaviour was originally noted by Cryer [19] when developing the infinite building model and was found to be more representative of real buildings, which do not exhibit the strong resonant behaviour of finite models. The peaks that are evident in Figure 3 are due to peaks in the total mean vibrational power flow into the *isolated* building. The first of these occurs near the isolation frequency and corresponds, in essence, to the global ‘bounce’ mode of the building on the isolation bearings. The smaller peaks – in the region of 30 and 50 Hz occur at frequencies when vibration can propagate freely along the structure in the region of the building-foundation interface.

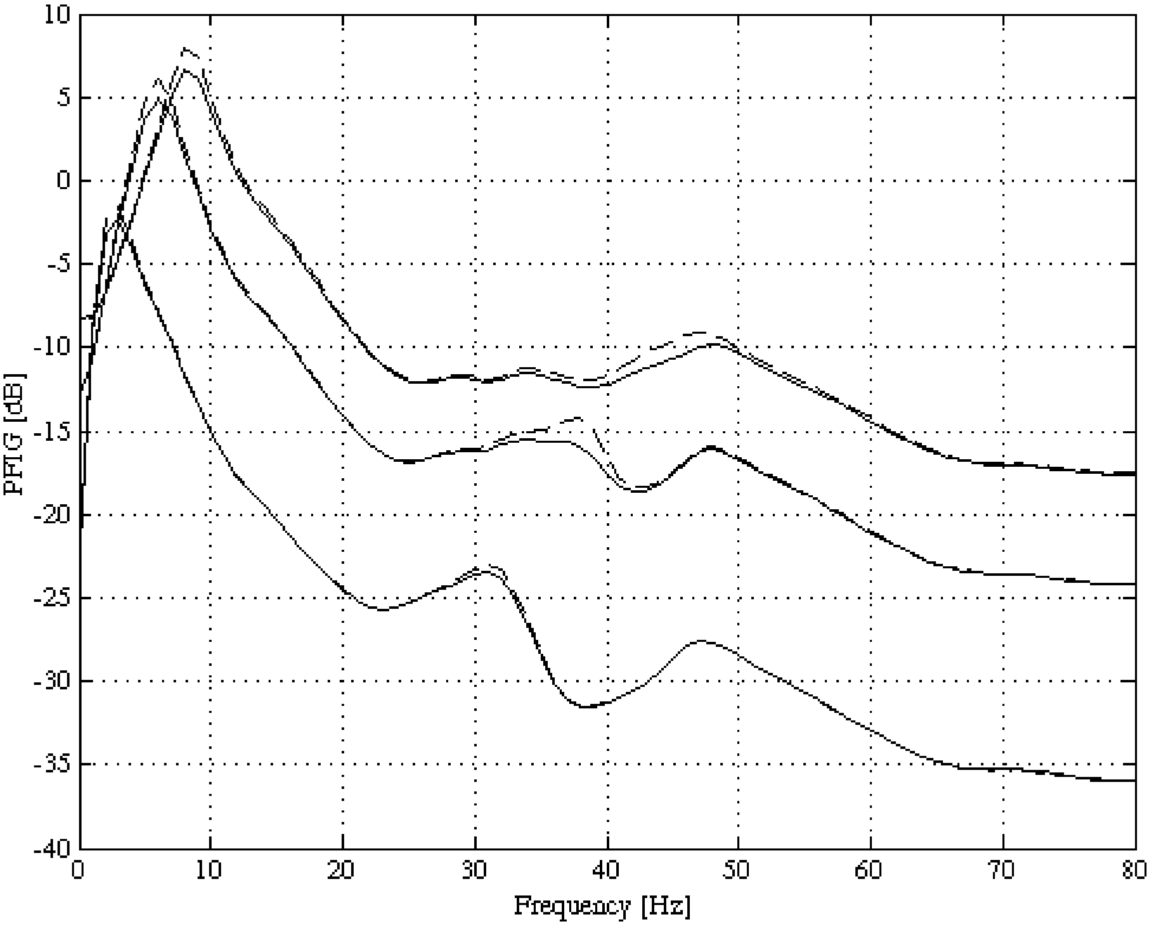

Figure 3: Variation with frequency in the power-flow insertion gain of a base-isolated building. Isolation frequencies of (from top to bottom) 9, 6 and 3 Hz are considered, provided by bearings with internal damping loss factors of 0.1 (solid) and 0.01 (dashed). The excitation corresponds to a buried unit-amplitude force applied in the vertical direction 1 m below the central pile tip.

It is interesting to note that the choice of isolation frequency makes a large difference to the efficiency of the isolation. The differences are not as great as predicted by simpler models but they are nevertheless significant and would certainly influence a design decision. In general, the level of internal damping in the bearings has a negligible effect on performance. However, it does have an effect at frequencies when relative motion between the pile heads and the bases of the building columns is significant, that is, when the isolation bearings undergo significant deformation. It must be stressed that the predictions presented here are for a single point-force excitation and that a different conclusion may be drawn for less localised excitation.

Before leaving the generic model, it is worth considering the significance of horizontal motion. It was noted in Section 2.3 that usually only vertical motion is explicitly considered in design. Figure 4 shows the variation with frequency in the three components of the mean power flow entering the building, as percentages of the total flow. These are calculated by considering the vertical, horizontal and rotational motions of the bases of the building columns. It is clear that horizontal motion can contribute a significant proportion of the total power flow at certain frequencies – the proportion being greater the lower the isolation frequency, and therefore the greater the decoupling between the building and its foundation. The significance of this in terms of the flexural response of individual floors and walls – which ultimately leads to the complaints from building occupants – has yet to be established, although it is likely that vibration entering in any form will eventually contribute to flexural vibration due to coupling at structural joints.

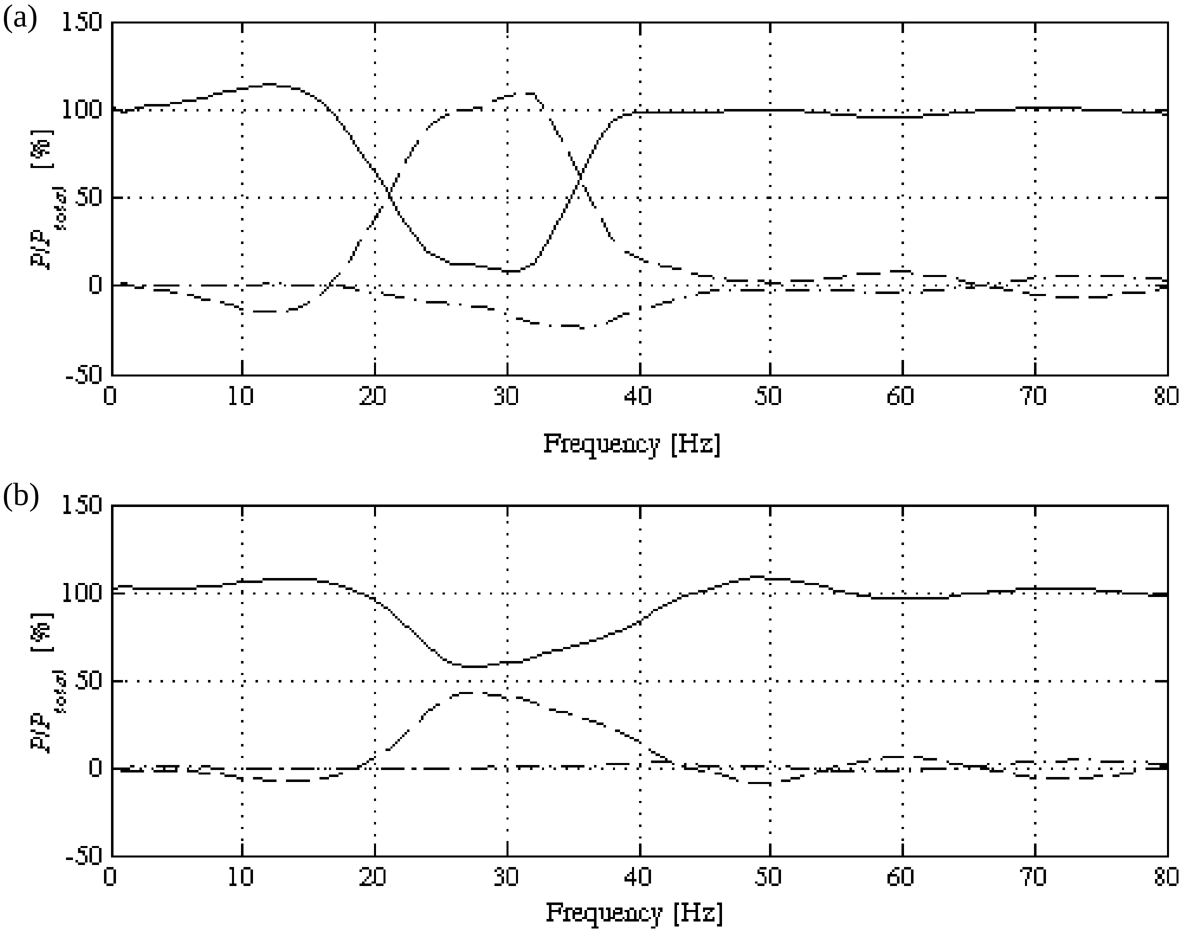

Figure 4: Variation with frequency in the vertical (solid), horizontal (dashed) and rotational (chained) components of the mean power flow entering a base-isolated building, presented as percentages of the total mean power flow. Bearings with isolation frequencies of (a) 3 Hz and (b) 9 Hz, and internal damping loss factors of 0.1, are considered. The excitation corresponds to a buried unit-amplitude force applied in the vertical direction 1 m below the central pile tip. Note that a negative value corresponds to vibrational power *leaving* the building.

Note that Figure 4 shows *negative* components of power flow at certain frequencies, corresponding to vibrational energy re-radiating into the foundation. This raises the interesting point that not all vibration transmission paths between a building and its foundation are detrimental. Paths that, on average across the frequency range of concern, allow energy to leave the building ensure that less is dissipated within, thereby reducing internal levels of noise and vibration. Whether or not a transmission path is beneficial is not obvious and may only be determined by careful modelling.

5.2 The Effect of Side-Restraint Bearings

Conventional base-isolation designs locate the bearings at the base of a building, aligned in the vertical direction so as to isolate the building from vertical motion of its foundation. In some cases, in order to accommodate horizontal loads, additional bearings are required aligned in the horizontal direction. The requirement for these *side-restraint* bearings varies and may involve the restraint of small building elements, such as lift shafts, or, in some cases, the retention of neighbouring structures.

This section considers the effect on the overall isolation performance of a building with side-restraint bearings supporting the retaining walls of its basement cavity. In this case the building structure is used to prop the basement walls, and the aim of the side-restraint bearings is to minimise any ‘short-circuiting’ of the base bearings. In the light of the discussion in Section 5.1, this short-circuit may in fact be minimal or even beneficial, allowing a proportion of the vibrational power delivered via the base bearings to re-radiate into the soil. Clearly some form of model is required to assess this.

Figure 5 shows one such model. The building is represented in a similar way to the generic model described in Section 5.1 but this time the model is finite. The isolation consists of six base bearings and two side-restraint bearings, each one modelled by three linear springs. The slab foundation is coupled to a boundary-element representation of the ground, and the excitation is provided by a buried unit-amplitude force applied in the vertical direction 7 m below the foundation slab on the centre-line of the building.

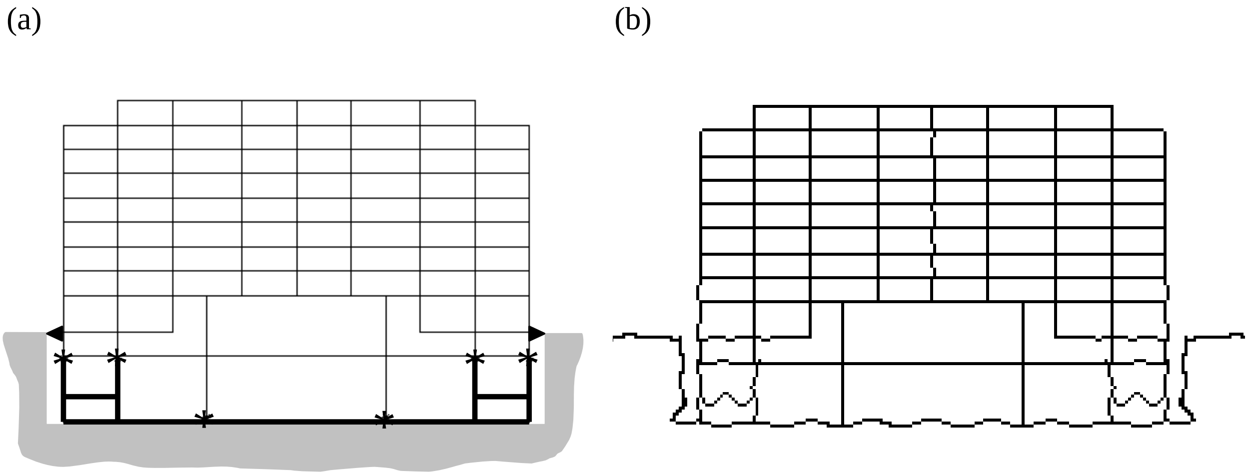

Figure 5: A two-dimensional model of a base-isolated building used to investigate the effect of side-restraint bearings: (a) the building is represented by a portal frame, isolated from a boundary-element representation of the ground by six base bearings (∗) and two side-restraint bearings (▶); (b) the response of the building at 50 Hz to a buried unit-amplitude force applied in the vertical direction 7 m below the foundation slab on the centre-line of the building.

Figure 6 shows the variation with frequency in the PFIG when the stiffness of the side-restraint bearings is varied from 1.00 to 0.30 and 0.10 times the stiffness of the base bearings. These cases correspond to 'horizontal isolation frequencies', as would be observed with a single-degree-of-freedom model, of 0.58, 0.32 and 0.18 times the vertical isolation frequency of 3.5 Hz.

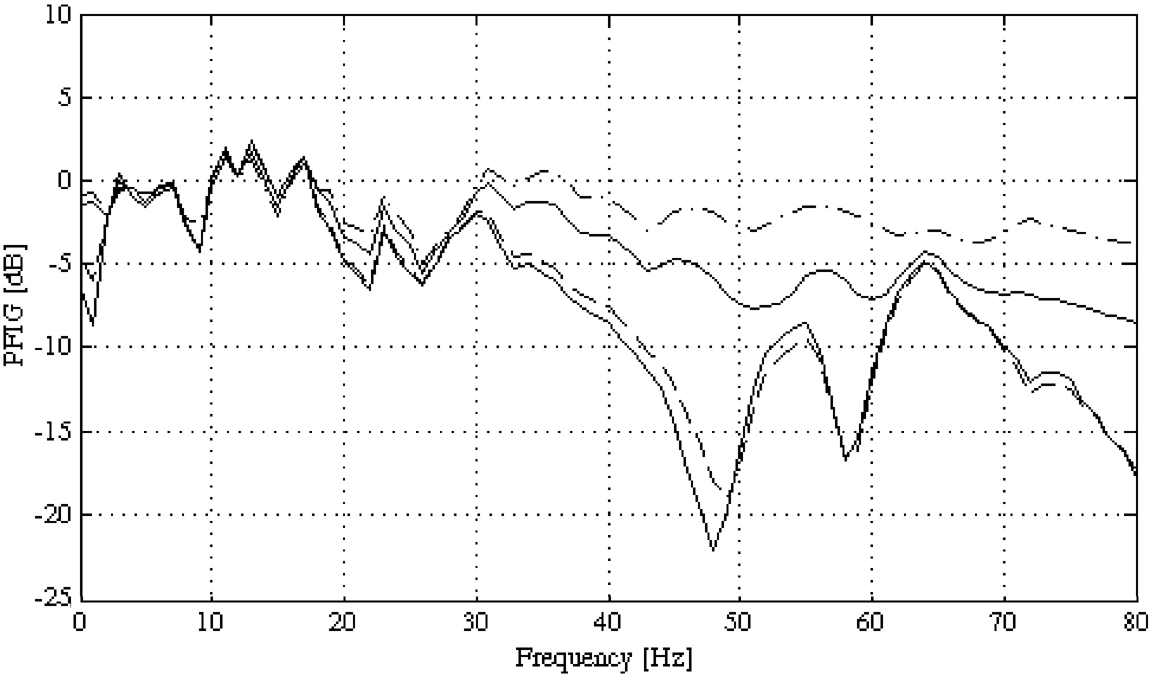

Figure 6: The effect of side-restraint bearings on the power-flow insertion gain of a base-isolated building. The results correspond to side-bearing stiffnesses of 1.00 (chained), 0.30 (solid) and 0.10 (dashed) times the stiffness of the base-bearings. The case corresponding to no side-restraint bearings is shown bold.

These results again highlight the value of considering PFIG: from one figure it is clear that minimising the stiffness of the side-restraint bearings maximises the overall isolation performance. It seems that the side-restraint bearings are ideally located to deliver additional vibrational power to the building through flexure of the structure against which they bear, and this outweighs any benefit from power leaving the building to be dissipated in the soil.

6. CONCLUSIONS

Base isolation is now well established as a means of isolating buildings from rail-tunnel vibration. Despite this, there is no conclusive evidence, practical or theoretical, indicating the sensitivity of the isolation performance to various design parameters.

The difficulties in making effective measurements ensure that reliable theoretical models are in demand. New models are being developed specifically designed to predict the performance of base-isolated buildings. These are now highlighting the inadequacies of simpler models and raising new questions, such as those concerning the best measure of isolation performance and the relative significance of different vibration transmission paths. It is clear that such questions cannot be answered without careful modelling.

Future work must concentrate on developing the modelling approaches outlined here and, ultimately, validating them through careful measurements.

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APPENDIX

Tables A1 and A2 give the essential physical properties used in the models of Section 5. The generic model of Section 5.1 is based on a periodic concrete-framed building founded on concrete piles, while the model of Section 5.2 is based on a finite concrete-framed building founded on a concrete slab foundation.

Building property	**Value**	**Foundation property**	**Value**
Number of storeys	6	Length of piles [m]	7.5
Height of columns [m]	3	Radius of piles [m]	0.354
Length of floors [m]	1.5	Spacing of piles [m]	1.5
Bending stiffness of elements [GPam^4]	0.4	Bending stiffness of piles [GPam^4]	0.34
Axial stiffness of elements [GPam^2]	5.0	Axial stiffness of piles [GPam^2]	11.0
Young's modulus of elements [GPa]	10	Young's modulus of piles [GPa]	28
Density of elements [kg/m^3]	2400	Density of piles [kg/m^3]	2667
Damping loss factor of elements	0.1	Young's modulus of soil [GPa]	0.28
		Density of soil [kg/m^3]	2000
		Poisson's ratio of soil	0.4
		Damping loss factor of soil	0.02

Table A1: The parameter values used in the generic model.

Building property	**Value**	**Foundation property**	**Value**
Height above ground-floor level [m]	38	Young's modulus of soil [GPa]	0.56
Total width [m]	77	Density of soil [kg/m^3]	2000
Young's modulus of elements [GPa]	10	Poisson's ratio of soil	0.4
Density of elements [kg/m^3]	2400	Damping loss factor of soil	0.02
Damping loss factor of elements	0.1		

Table A2: The parameter values used in the side-restraint model (building section properties vary).