A CONSTRAINED LAYER DAMPING SYSTEM FOR COMPOSITE FLOORS

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SYNOPSIS

The continuing trend towards lighter and longer span floor construction and large partition-free office layouts has brought the issue of floor vibration to the attention of designers and owners. In composite construction, footfall induced floor vibration is now an essential consideration in the design of floors, and has become the governing factor in some circumstances.

Increasing the damping can be an effective means of reducing floor vibration. This paper describes how a constrained layer damping system may be incorporated into a composite floor, potentially improving the floor's dynamic performance by a factor of 2 or more. The increase in damping is achievable without additional structural mass or depth and so offers considerable cost savings over alternative methods for reducing footfall vibration (such as increasing the mass and/or stiffness). The system is now available as the commercial product Resotec

This paper provides some background to the floor vibration problem and discusses various vibration reduction techniques. The principles and performance of the Resotec product are then discussed in detail and three example applications are used to illustrate its potential.

INTRODUCTION

As architectural and cost constraints drive composite floor design towards lighter, shallower and longer spans, it is increasingly the dynamic performance of floors that governs design. At the same time, tenants and developers in the commercial sector are becoming more concerned about the perceived quality of their buildings, particularly at the higher quality end of the market, leading to more onerous specifications relating to floor vibration. Whilst increasing the stiffness and mass of floors can improve their dynamic performance, these measures have significant drawbacks including increased overall weight and construction depth. Increasing the damping would often be effective if it could be achieved in an unobtrusive and cost effective manner.

The Resotec product has been developed by Arup in collaboration with Richard Lees Steel Decking to provide additional damping to modern composite floor construction. The product comprises a thin layer of high-damping visco-elastic material sandwiched between two thin steel plates; the overall thickness of the product is about 3mm. Resotec is placed on top of the top flange of a steel beam for a proportion of the beam near each end. The steel decking is placed normally over the beam (on top of the Resotec product in the end zones) and shear studs are fixed in the central zone of the beam only. The concrete slab is cast normally. In the completed floor the visco-elastic layer is effectively sandwiched between the steel beam and the concrete slab to create a constrained layer damping mechanism. The steel beam is therefore fully composite with the floor slab only over a portion of its length centred at midspan.

Prototypes of the system were constructed and tested at Richard Lees Steel Decking’s premises in Ashbourne. The system was then successfully implemented on Plot 1 of the More London Development, where, by increasing the damping of the floor by up to 2% of critical, the response factor of the floor was reduced by a factor of two in many areas. A second installation of the product at Derby Hospital has been independently tested and the additional damping has been found to be up to 4.5% of critical.

FOOTFALL INDUCED VIBRATION OF FLOORS: BACKGROUND

It is well known that pedestrians exert significant dynamic forces as they walk [1], and thereby induce dynamic responses (i.e. vibration) in floor and bridges. Whilst the vibration is generally not sensed by the pedestrian it may be perceptible, and sometimes considered unacceptable, by stationary building occupants. At the design stage it is desirable to know how strongly a floor will vibrate, whether occupants will consider this acceptable, and what might be done to reduce the vibration.

Vibration criteria for floors

Guidelines on acceptable levels of floor vibration are published in a number of documents [1][2][3][4] as a function of the intended use of the floor. Criteria are defined in terms of a "response factor", the ratio of the actual level of vibration to the level at the threshold of human perception. The base line curves for this threshold are defined in BS6472 [2]. A response factor of 1 (R=1) is the level of vibration that can just be perceived by humans. R=2 is twice as much as can just be felt, etc. Typical criteria for footfall-induced vibration are illustrated below.

"Normal Office":	R = 8 [1]
"Busy Office":	R = 12 [1]
"Special Office":	R = 4 [1]
Operating Theatre	R = 1 [3]
Hospital Residential Wards[1]	R = 1.4 (Night time), R = 2-4 (Day time) [3]
Residential	R = 1.4 (Night time), R = 2-4 (Day time) [1]

Although not stated explicitly, these criteria are applied to typical 'worst case' predictions or measurements of vibration caused by a single walking person.

Note that it is the authors' experience that office floors in which response factors of between 4 and 8 occur regularly can attract adverse comment from some users, whilst levels below 4 are generally acceptable.

Vibration dose value criteria

Footfall induced vibrations are usually intermittent rather than continuous, and in recent years it has been proposed that the effect of intermittent vibration on humans should be assessed on the basis of a Vibration Dose Value (VDV). The VDV is a measure of the combined intensity and duration of vibration during a period of time, usually a 16-hour day period or an 8-hour night period. The approach is described in Appendix A to BS6472[2] and in the HTM 2045 note[3]. The advantage of the VDV is that it makes a formal link between vibration intensity, duration and acceptability. The disadvantage is that a small number of short bursts of strong vibration would be deemed acceptable, which may not be the case in all circumstances. Whilst VDV can be measured with appropriate instrumentation, at a design stage it requires the designer to decide on the proportion of the time that should be assigned to different levels of vibration generated by possible sources.

Figure 1 illustrates the relationship between vibration level and proportion of time it is experienced for a constant VDV. If vibration is continuous then the proportion of time is 1.0, and the acceptable vibration level is 1.0 times the BS6472 permissible. If the vibration is intermittent with equal bursts covering 10% of the total time, then the level of that vibration may be 1.8 times the basic permissible level for continuous vibration.

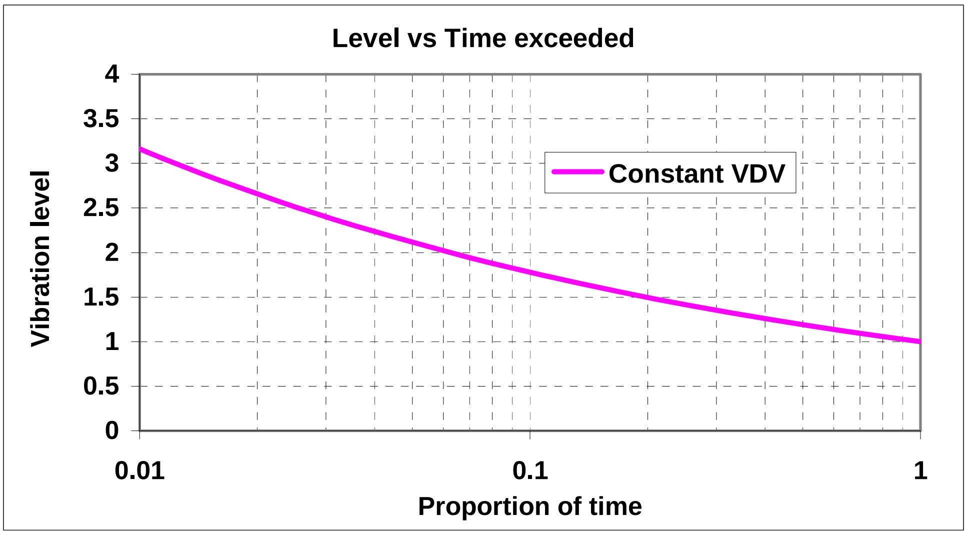

Figure 1 Vibration level vs. time for constant VDV

Floor vibration: Prediction methodologies

A number of methods are currently available for the prediction of footfall-induced vibration of structures [1][5][6][4][7][8][9]. For floors, the methods most commonly used in the UK are described in [1]. Arup has developed improved techniques [5] based on further extensive research, which permit more detailed assessments to be made.

One of the key parameters determining the susceptibility of a floor to excessive vibration is its natural frequency, which is a function of the ratio of stiffness to mass; a floor with a higher stiffness and lower mass will have a higher natural frequency. In terms of footfall induced vibration it is convenient to make a distinction between “low frequency” and “high frequency” floors. Low frequency floors (natural frequencies below about 7 to 10Hz depending on walking rate) are susceptible to resonant built-up of response under repeated footfalls at certain walking rates. Typical idealised vibration responses are shown in Figure 2; the solid line shows resonant response a floor of frequency 2 times that of the excitation while the dashed line shows non-

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[1] Note that these R values are based on continuous vibrations; for footfall induced vibrations slightly increased values could be considered acceptable.

resonant response of a floor of frequency 2.5 times that of the excitation. The response of "high frequency" floors (natural frequency above 10Hz) is dominated by the transient, decaying response resulting from the impulse of each footfall. A typical idealised response is shown in Figure 3.

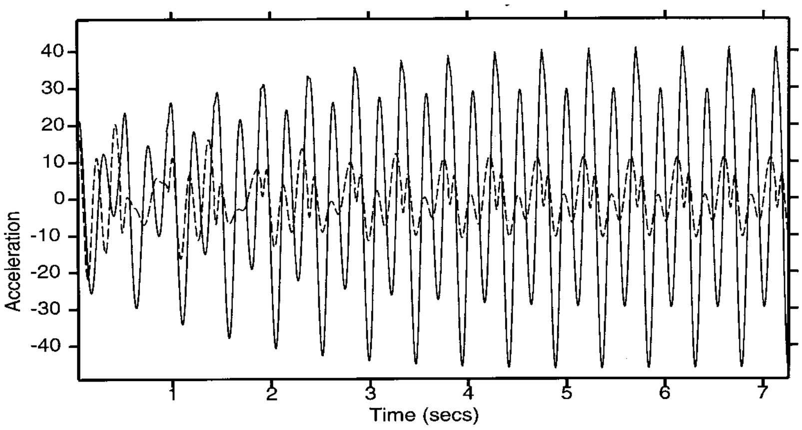

Figure 2 Response of low frequency floors to footfall

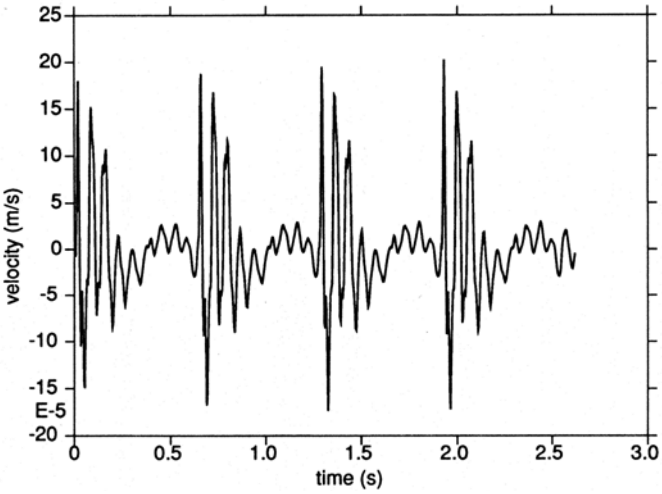

Figure 3 Response of high frequency floor to footfall

The distinction between high frequency and low frequency floors is important when considering methods to reduce footfall induced vibrations. Most modern floors for commercial or residential developments are in the low frequency category. High performance floors (for laboratories, operating theatres etc) generally have to be designed with a high frequency, since their stringent vibration criteria cannot usually be met if resonant response is possible. The response of high frequency floors is governed principally by modal mass and natural frequency, and whilst damping is beneficial, additional damping will not usually have a dramatic effect on performance [1][5]. The dynamic design of high frequency floors is not considered further here.

For low frequency floors equation (1) characterises the acceleration amplitude a that might be induced by a repeating harmonic force F applied at the natural frequency of a floor mode, where ξ is the structural damping (fraction of critical) and M is the modal mass. This is a conservative formula because it assumes that all footfalls are applied at the worst point on the floor and that there are sufficient footfalls to induce a steady state resonant response. Reduction factors to account for these effects can be incorporated for a given walking path across the floor.

$$a = \frac{F}{M}\frac{1}{2\xi} \qquad (1)$$

The magnitude of the harmonic force is the product of the weight of the person and the dynamic load factor (DLF). The DLF depends on the footfall rate and can be obtained from Figure 4 for each frequency. The basis of the Arup curve is in reference [5].

Improving the dynamic performance of low frequency floors

Equation 1 shows that resonant vibrations are reduced if the mass and/or damping of the floor are increased. In order to halve the dynamic response by increasing the mass alone, it is clear that the mass must be doubled. Beam, column and foundation sizes will usually need to be increased to support the extra mass. Care must also be taken that increasing the mass does not reduce the natural frequency to a point where the force F is higher. If the mass is doubled (with no increase in stiffness) the natural frequency will reduce to $1/\sqrt{2}$ of its previous value.

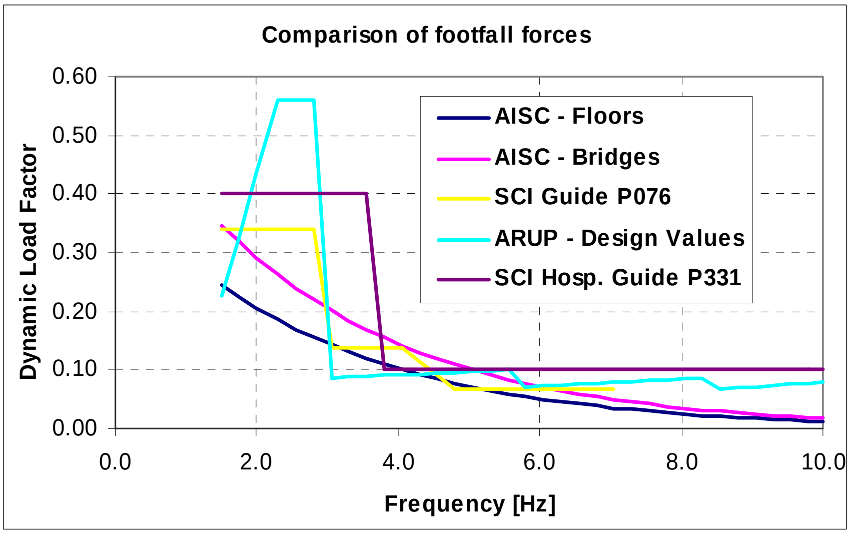

Figure 4 Dynamic load factor for footfalls

The reduction of resonant footfall induced response by added damping is considerable, but not as great as implied by increasing the value of ξ (damping) in Equation 1. When walking across a floor only a limited number of cycles are available. Although the steady state response would be halved by doubling ξ, when the damping is higher the lower steady state is approached in fewer vibration cycles. Additionally, a component of the total response of the floor will be the non-resonant response in other modes. This portion of the response will not be reduced equally by the damping.

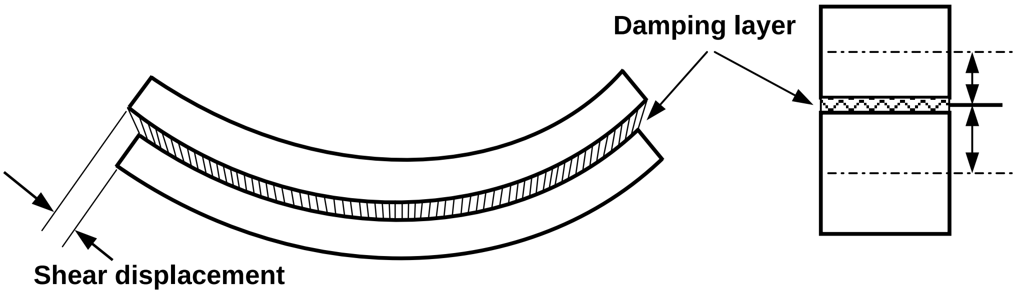

Figure 5 Constrained Layer Damped Beam

Adding extra damping to floors

In view of the consequences of increasing the mass, the motivation to seek ways to increase the damping are clear. Structural damping can be increased by three generic techniques:

- Inertial devices at discrete points, e.g. tuned mass dampers (TMDs)
- Discrete damping elements connecting between two points (e.g. viscous and visco-elastic dampers)
- Incorporation of high-damping materials within the form of construction (e.g. constrained layer damping with high-loss materials)

Individual TMDs have a narrow frequency range of effectiveness and a substantial number of devices would be required to damp an entire floor structure with multiple modes of vibration [10]. Being mechanical devices they are relatively expensive and tend to be used only as retrofit measures in areas where floor vibration has been found to be unacceptable.

Discrete dampers are difficult to incorporate into floors since they need to connect two points that are moving relative to each other (along the axis of the damper) in the vibration mode [6].

Constrained layer damping solutions [11][13][14][15] can in principle be concealed within the structure of the floor and can simultaneously damp several modes, reducing vibration throughout.

Constrained layer damping

The introduction of a layer of a high damping material into a beam as shown in Figure 5 can significantly increase the damping (e.g. [11]). Vibration of the beam causes the high damping visco-elastic material to be subjected to cyclical shear deformation, and the energy dissipated in this material increases the overall damping of the structure. This concept works best when the constrained layer is located so as to maximise the shear strain it is subjected to; it is therefore most effective if the layer is close to the neutral axis of the beam and towards the ends rather than midspan. Whilst the level of damping generated is proportional to the loss factor of the visco-elastic material, there is an optimum shear stiffness of the layer that will deliver the maximum amount of damping at any frequency.

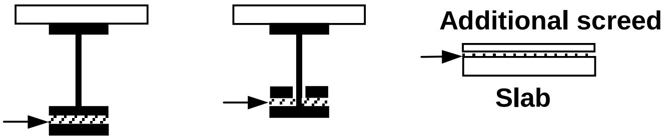

Figure 6 Possible constrained layer applications (arrows point to damping layer)

Constrained layer damping of this type has previously been used as a retrofit [14] to an excessively lively existing floor using an extra cover plate to constrain a layer of visco-elastic material (Figure 6) attached to the lower flanges of the beams. The effectiveness is limited by the axial stiffness of the cover plate, as the shear strain across the damping layer increases as the area of the section added to the original beam is increased . Another implementation [13] uses a non-structural screed as a constraining layer (Figure 6). Here the effectiveness improves as the screed stiffness (thickness) increases and clearly this concept has significant implications on structural depth and overall floor weight.

DAMPED COMPOSITE CONSTRUCTION

The concept behind the Resotec product is to add constrained layer damping into composite steel-concrete construction in a practical and cost effective manner. The damping material is introduced between the top of the steel beam and the bottom of the concrete slab, which is usually near the neutral axis. The product itself comprises the visco-elastic material sandwiched between two thin steel plates forming a three layer sheet which is easily handled and installed on site. Resotec is simply laid on the top flange of the steel beams before the decking is laid out as normal. It does not need to be fixed to the beam or slab, as frictional resistance is sufficient to provide the necessary load transfer for the very small dynamic strains resulting from footfall excitation. (Note: Health & Safety requirements during installation are discussed later.)

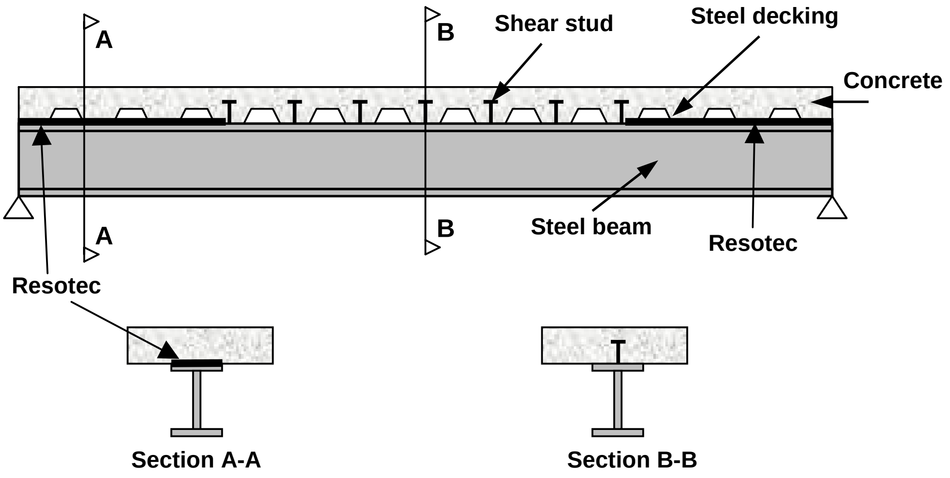

Figure 7 Partially composite beam with Resotec visco-elastic layer

A typical arrangement is shown in Figure 7. The product could be provided over the entire length of the beam (which would develop a large amount of damping), but this would make the entire beam non-composite, which would adversely affect its strength and stiffness. The intended use is to apply the damping material at the end sections of the beams only (where the beam does not need to be composite and where the potential shear strain in the damping material is greatest), and maintain composite action over the middle part of the beam where it is most needed for stiffness and strength. This does lead to a reduction of the stiffness of the span, and requires the non-composite part of the beam to resist the bending moment along the damped length of the beam.

Resotec differs from previous constrained layer damping applications because:

- Existing structural elements are used as the constraining layers. No additional structure is required.
- The constrained layer is located where it is most effective, close to the neutral axis of the composite section and at the ends of the beams. (Locations of high shear)
- It preserves strength at mid-span.
- There is no increase in the overall floor depth.
- The product is easily installed with the steel decking and no additional site operations are required.

Clearly, installing Resotec has consequences for both the static and dynamic design of the floor, which are described below. Currently, Resotec can be supplied with two types of visco-elastic material (standard and high-performance with loss factors of around 0.65 and 1.1, respectively). The shear modulus of both materials is temperature dependent, but is typically around 1MPa at room temperature. The higher damping material is more costly.

DYNAMIC DESIGN AND PERFORMANCE

Dynamic design

Accurate prediction of the dynamic performance of composite floors (with or without Resotec) requires reliable estimates of their modal properties (natural frequency, damping, mode shape and modal mass). Analytical solutions exist for beams and regular plates (e.g. [12][18]) and most finite element packages now include a “natural modes” solver for analysing more complex structures.

High quality testing by the authors and others shows that a bare composite floor with no fit out, services or surface finish might have between 0.7% and 1.5% of critical damping. Finished, fitted out and occupied composite floors have between 1.5% and 4.5% of critical damping. It is not currently possible to predict this figure with precision in design, and a value of 3% of critical is often used for a furnished composite floor in use.

The additional damping in regular “sandwich” structures such as beams having a constrained layer along the entire length can be calculated by the theory described in Ross *et al* [15]. The authors of this paper have extended the theory to deal with partial length constrained layers. Finite element modelling has also been used to predict ‘complex modal’ properties including effective damping.

Simply supported beams

The dynamic characteristics of partially composite beams (ranging between 10% composite and 100% composite) with a constrained damping layer are illustrated with an example beam having properties listed in Table 1.

Beam span	12m simply supported, unpropped construction
Overall slab width	2.3m
Beam	UB 457x191x67
Decking	RLSD Ribdeck AL 1.2mm gauge
Overall concrete depth	130mm, NWC
Percentage of length composite	10% to 100%

Table 1 Example composite beam properties

In the dynamic calculations the flexural stiffness has been idealised as fully composite (with the full flange width participating) in the section where shear studs are provided and partially composite (stiffness computed for the beam and slab connected through a flexible visco-elastic layer of given stiffness) in the non-composite regions. The stiffness of the visco-elastic layer depends on its width, thickness and dynamic shear modulus.

The mode shape and curvature of the first flexural mode of the beam are plotted in Figures 8 and 9 for different percentages composite. There is a step in curvature at the point at which the composite section begins. For each case the width of the visco-elastic layer was optimised to provide as much damping as possible.

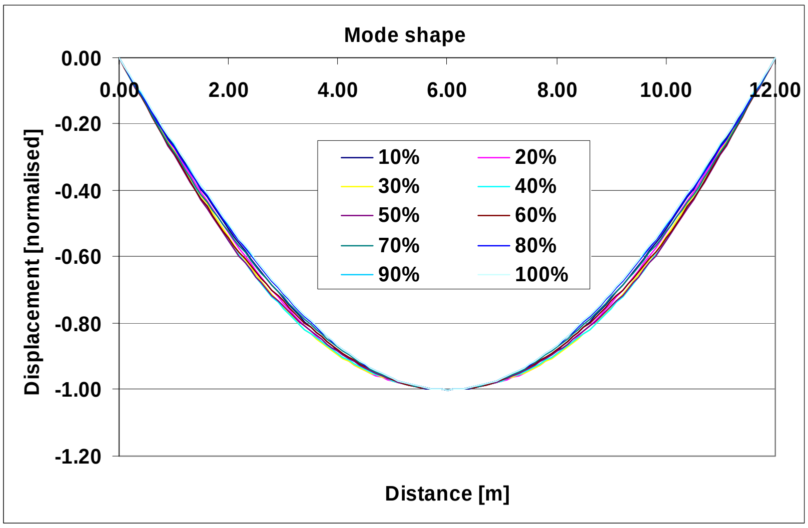

Figure 8 Mode shapes of first flexural mode of partially composite beams, 10%-100% composite lengths, normalised to unit displacement

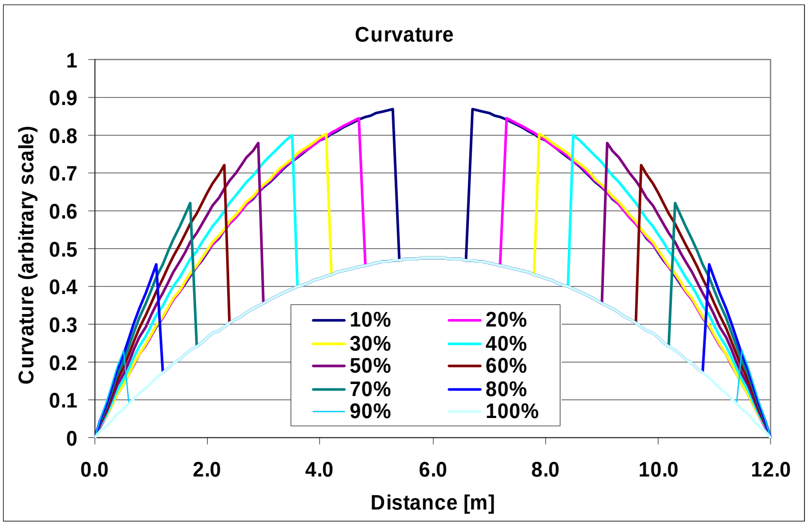

Figure 9 Curvatures of mode shapes of Figure 8, 10%-100% composite lengths

The variation in natural frequency with percentage composite of this particular system is shown in Figure 10. The maximum longitudinal displacement in the visco-elastic layer, shown in Figure 11 (based on modal midspan displacements scaled to 1), may be integrated over the length of the beam to calculate the energy dissipated per vibration cycle from which the additional damping of the beam is calculated. Figure 12 plots both the additional damping as a function of percentage composite for standard and high performance Resotec.

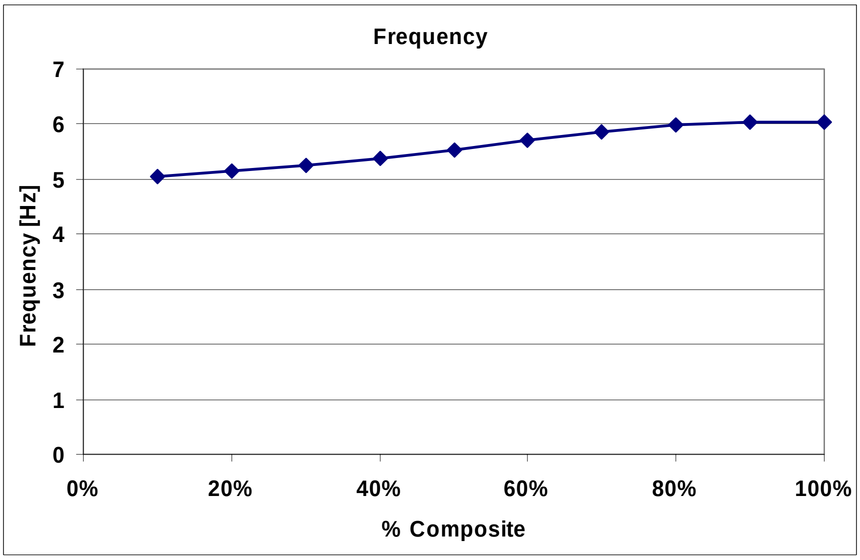

Figure 10 Frequency vs. percent composite

Whilst only modest amounts of additional damping are achieved if more than 70% of the beam is composite, beams incorporating Resotec over 50% of their length achieve additional damping of 3% of critical or more. Much more damping can be achieved with composite lengths shorter than 50%, although the consequences for static design and erection then become more significant.

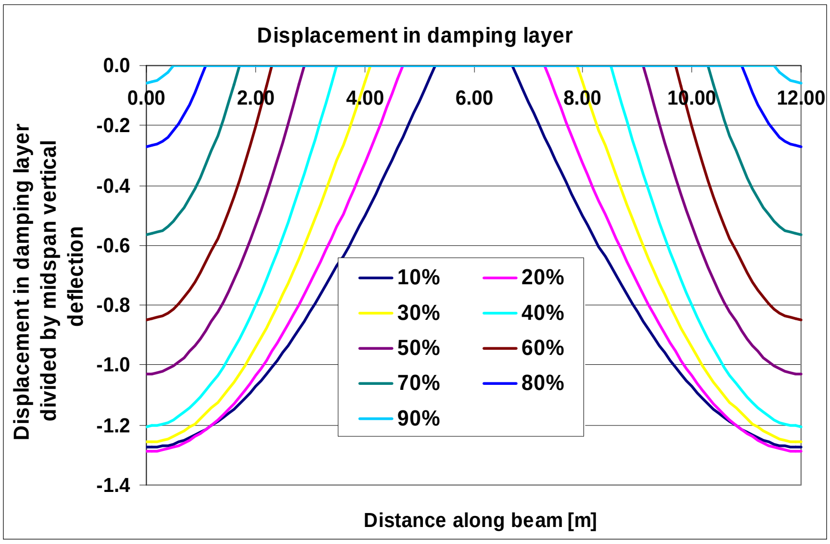

Figure 11 Longitudinal displacements in damping layer over midspan vertical deflection for various percentages of composite length

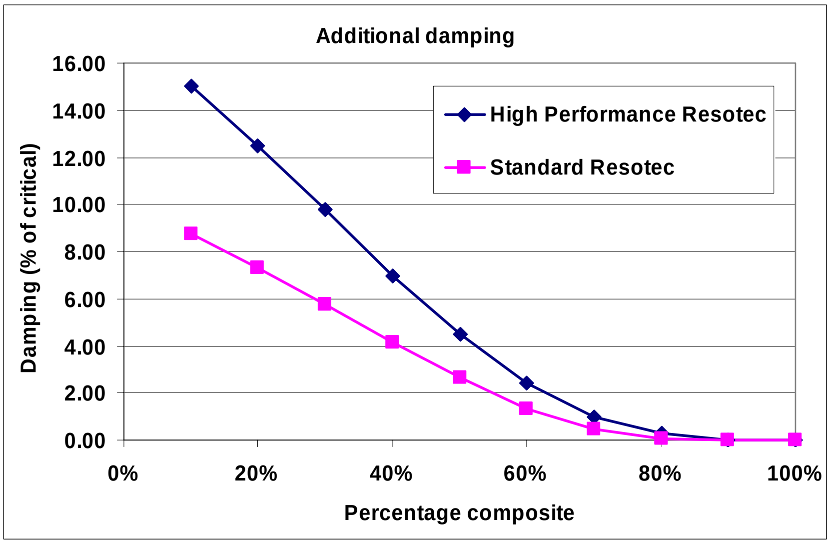

Figure 12 Additional damping with Resotec in partially composite beams

Influence of floor layout

The effectiveness of Resotec is sometimes limited by the floor layout. The system works best for regular layouts where identical secondary beams have the same parallel lines of support. Where the ends of the beams are staggered due to curved or angular edges to the floor, composite and non-composite sections of adjacent beams are positioned next to each other. Consequently constrained layer damping will be less effective. Similarly, if internal supports (e.g. a stair well) reduce the span of some beams such that adjacent beams are not similar, Resotec will be less effective.

Validation of dynamic performance

To demonstrate the effectiveness of Resotec, and to validate the design methods outlined, full scale prototype tests were performed using sections of composite floor built at Richard Lees Steel Decking's facility in Ashbourne; these tests are described below.

Resotec has since been installed in a commercial London development and a new hospital building at Derby. The authors have verified the performance of the London installation using modal testing techniques and an instrumented hammer. The University of Sheffield conducted extensive, sophisticated modal testing at Derby Hospital using multiple shakers. One floor with and one without Resotec were tested and the Resotec was found to have added damping of up to 4.5% of critical.

Prototype Tests

Two test prototypes were built, each consisting of two identical simply supported 12m long beams 3m apart supporting 130mm normal weight concrete on trapezoidal decking. One prototype was made fully composite by providing shear studs over the full length, while only the centre 50% of the span was composite in the other, the remainder being treated with standard Resotec.

Test procedure

The natural frequency and damping of the prototypes was evaluated by measuring and analysing the acceleration time history resulting from a "heel drop" at mid span. (A heel drop is produced by a person standing on tiptoe and dropping onto their heels with their legs straight.) The damping was calculated using the logarithmic decrement technique.

Test results

Example acceleration traces (recorded at mid-span) for the tests are shown in Figure 13 and Fast Fourier Transforms (FFTs) of these in Figure 14. Frequency and damping values are summarised in Table 2.

	Frequency [Hz]	Damping [% crit.]	Additional damping [% crit.]
Fully composite	6.1	0.9	N/A
50% composite	5.5	3.1	2.2

Table 2 Measure frequencies and damping

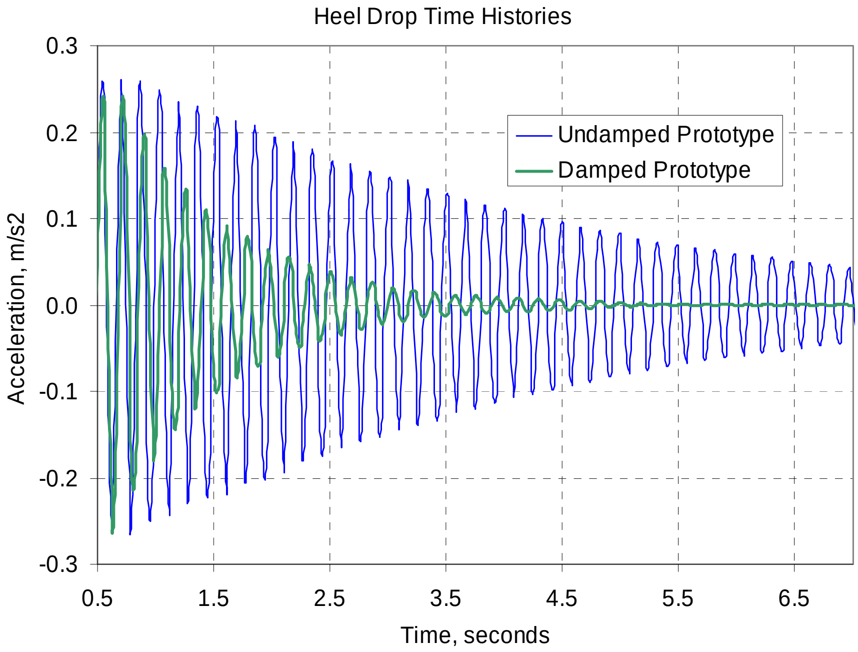

Figure 13 Time history responses for the damped and undamped test floor prototypes

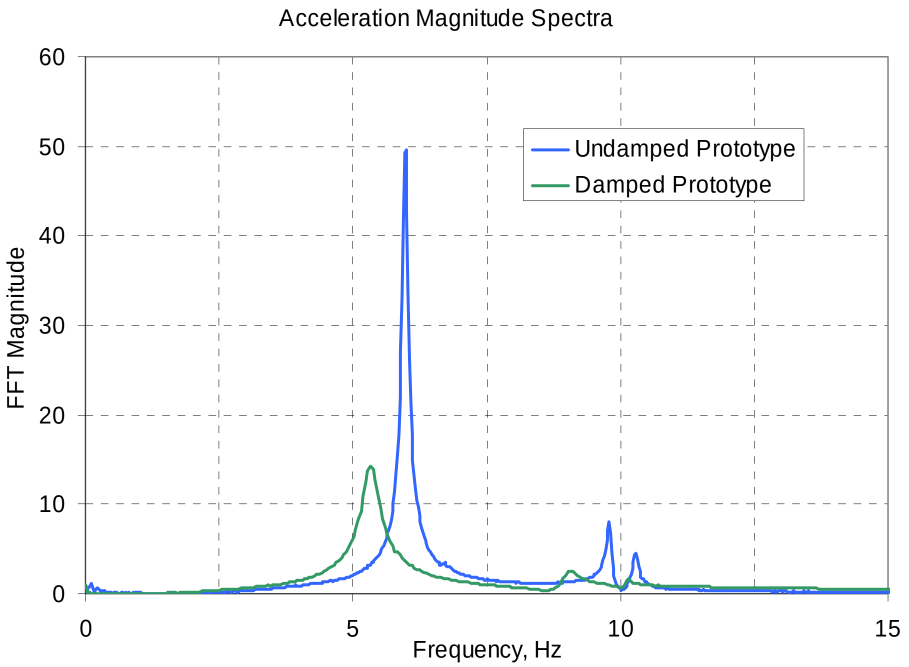

Figure 14 FFT magnitude spectra of the damped and undamped test floor prototypes

The damping measured for the fully composite prototype was 0.9% of critical and that of the partially composite prototype 3.1%. The damping due to the damping layer alone is therefore 2.2%. The difference in frequency between the two is consistent with the predictions shown in Figure 10.

The measured damping is slightly less than that predicted for the 50% composite beam (2.2% c.f. 2.6%). However, this is simply a function of the temperature on the day that the measurements were made (15°C). The predictions were for a normal operating temperature of 22°C; if properties for the visco-elastic material at 15°C are substituted into the analysis then additional damping of around 2.2% is predicted. This illustrates that the properties (particularly shear modulus) of visco-elastic materials are sensitive to temperature, and that calculations should be performed for the range of temperatures expected in operation.

STATIC DESIGN

Omitting the shear studs from sections of a composite beam clearly affects strength and stiffness and so the following factors must be taken into consideration:

- Slightly reduced mid span capacity of the beam.

- The beam alone must resist the maximum moment in the non-composite zone
- Increased mid-span deflection
- Lateral torsional buckling of the compression flange of the steel beam in the non-composite section
- Partial interaction of the beam

Full consideration of the implications for static design is beyond the scope of this paper, but these are dealt with in detail in [16]. To help illustrate some of the issues a design example is considered briefly below.

Bending moments at ULS

A typical bending moment demand at the ULS and the capacity graph for the partially composite beam considered in the prototype tests is shown in Figure 15. In composite beam design to BS 5950 Part 3 [17], the simply supported bending moment capacity is based on the steel beam acting compositely with the concrete flange of width taken as the span divided by 4. For partially composite beams however, the capacity in the two end regions is based solely on the capacity of the steel beam. The effective concrete flange width of the composite section is increased assuming a 45° spread from the point of provision of shear studs until it equals the composite length divided by 4. The difference in the ultimate moment capacity between fully and partially composite beams is evident in Figure 15.

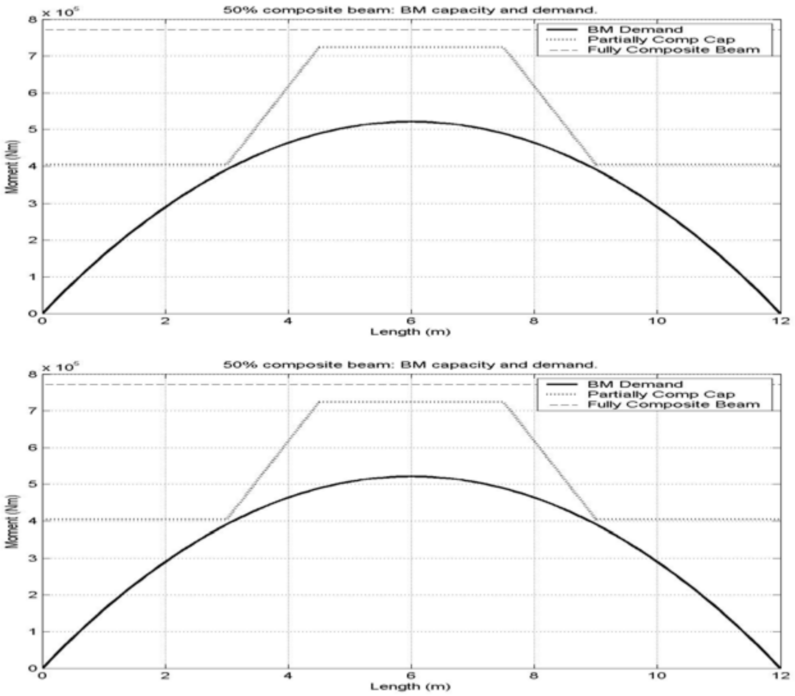

Figure 15 Bending moment demand and capacity of 50% composite beam

Lateral torsional buckling

In fully composite floors, the top flange of the steel beam is always well restrained against lateral torsional buckling through the shear studs. In partially composite beams, the top flange of the steel beam is less well restrained in the non-composite zones. The non-composite length might therefore be susceptible to lateral torsional buckling and this must be considered as set out in BS 5950 Part 1 [18]. For this example the unrestrained lengths are 3.0m and lateral torsional buckling is found not to be a limiting factor.

Partial interaction

The interaction level is related to the shear capacity of the studs and the axial strengths of the steel beam and concrete slab. BS 5950 Part 3 specifies conditions in which partial interaction is permitted and the same requirements are proposed for partially composite beams as detailed in reference [16][4].

Deflection Considerations

Deflections due to dead and imposed load are calculated in accordance with BS 5950 Part 3 [17]. In the non-composite regions, the flexural stiffness is calculated as the sum of the individual bending stiffnesses of the steel beam and the concrete slab, the long term shear stiffness of the visco-elastic layer being neglected as being small. An irreversible deformation check is also carried out by ensuring that the stress at SLS does not reach yield, again according to [17]. For the design example discussed previously, the variation in total displacement (under self weight and imposed load) with percentage composite is shown in Figure 16.

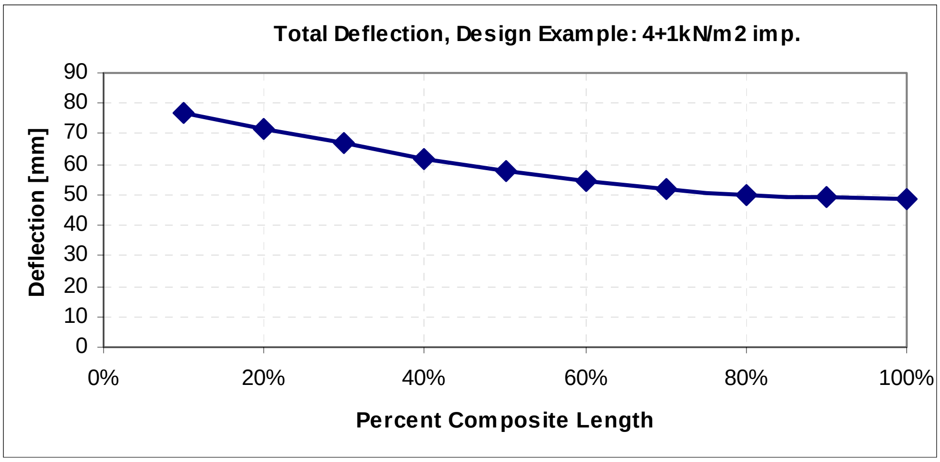

Figure 16 Total deflection under self-weight and imposed load for differing percent composite

HEALTH AND SAFETY CONSIDERATIONS

During installation, the damping layer sandwiched between two thin steel plates is laid down on the top flange of the steel beam prior to installation of the decking. For safety considerations at this stage, the maximum width of the damping layer should not exceed the flange width. Once the decking is installed, the presence of the damping layer does not affect the construction process. Currently, a minimum composite length of 50% is recommended to tie down the decking during construction using traditional profiled steel decking composite construction. In applications where the benefit of increased damping is high, and the need for composite behaviour for strength design is not critical, it is worth considering shorter composite lengths and employing temporary deck restraints or an alternative deck installation procedure. In a fire, the damping material would be sacrificed, but this would not affect the strength of floor.

EXAMPLES OF APPLICATION

The following cases illustrate the benefits of incorporating Resotec into floors for various projects. A number of ‘pitfalls’ in the assessment of dynamic response are also highlighted.

Example 1: Light-weight, short span office floor

The typical bay of an office block is shown in Figure 17, where seven UB304x165x46 secondary beams of 9m span are spaced at 3m to form a bay 18m wide. The lightweight concrete slab is 130mm deep on trapezoidal decking. The total mass of the floor including self-weight, permanent dead load and 10% imposed load is 340kg/m². Damping of 3% of critical is assumed.

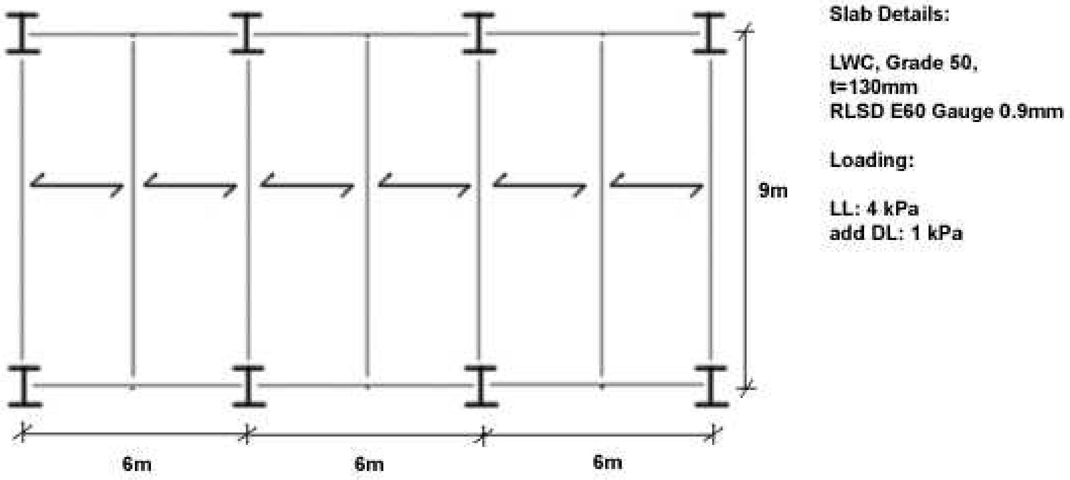

Figure 17 Example 1: Dimensions of a typical bay, details of and loading of slab

Dynamic performance of normal construction

The primary beams are relatively stiff, and so the secondary beam modes are critical. The first natural frequency is 5.8Hz, calculated using the simply supported anisotropic plate method (for the 9m by 18m bay) given in [5]. Walking footfall rates up to 2.4Hz are considered, and the maximum calculated response factor is approximately 9.0, under 3rd harmonic excitation from a 1.93Hz footfall rate, using the Arup dynamic load factors in Figure 4. This is marginally above a standard target for office floors of 8.

Effect of Resotec

Figure 18 shows the moment demand on a secondary beam, along with the capacity of two partially composite beam designs. If the original beam (UB305x165x46) is retained its strength is sufficient if at least 60% of its length is composite. If the beam is increased by one size (to UB305x165x54) then it is possible to reduce the composite section to 50% of the total length without compromising strength.

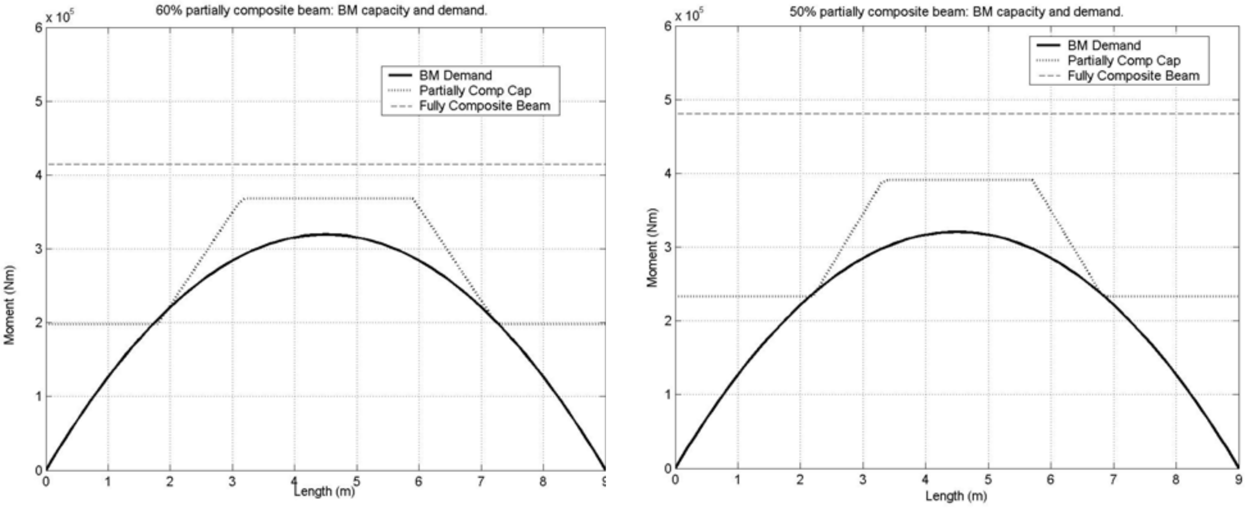

Figure 18 Bending moment demands and capacities for two designs

The additional damping of the two partially composite designs and corresponding response factors are for the standard and high-performance Resotec products are given in Table 3. The figures applicable to the high-performance Resotec are given in brackets.

Example 1	Beam	Frequency [Hz]	Total Damping [%]	Response Factor
100% composite	UB305x165x46	5.8	3.0	9.1
60% Composite	UB305x165x46	5.4	4.2 (5.4)	6.6 (6.0)
50% Composite	UB305x165x54	5.5	5.2 (7.0)	5.9 (5.3)

Table 3 Example 1: Light office floor, fully and partially composite beams

Without any increase in steel weight, the dynamic performance of the floor is improved by 27 - 34% depending on the type of Resotec. Reductions to 34-42% are possible if the beam is increased one size to UB305x165x54. To put this performance improvement into context, a 30% benefit could otherwise be achieved by:

- Adding mass: An increase of self-weight of 50% is required which can be achieved using 130mm of normal weight concrete on a Holorib profile (as opposed to trapezoidal) together with a UB305x165x54 beam size. These increases in mass and stiffness lead to an unchanged natural frequency of 5.8Hz.
- Increasing the frequency so that the floor becomes a high frequency floor. A first mode frequency above 10Hz is achieved using 457x191x98 beams and the same lightweight concrete slab.

Both of these options add significantly to the cost of the structure, as well as increasing the structural depth for the higher frequency solution. Even greater structural changes would be needed to meet the performance achieved using high performance Resotec and 50% composite length.

Day Wards	R = 2 to 4
Night Wards	R = 1.4
Operating Theatre	R = 1.0

Table 4 Response factor requirements for hospital areas

Example 2: Hospital ward area

Traditionally it has not been considered cost effective to use composite construction for hospitals because of concerns over vibration. This example, a scheme for a planned extension, shows that the vibration criteria of Table 4 [3] may be met if Resotec is used to provide additional damping.

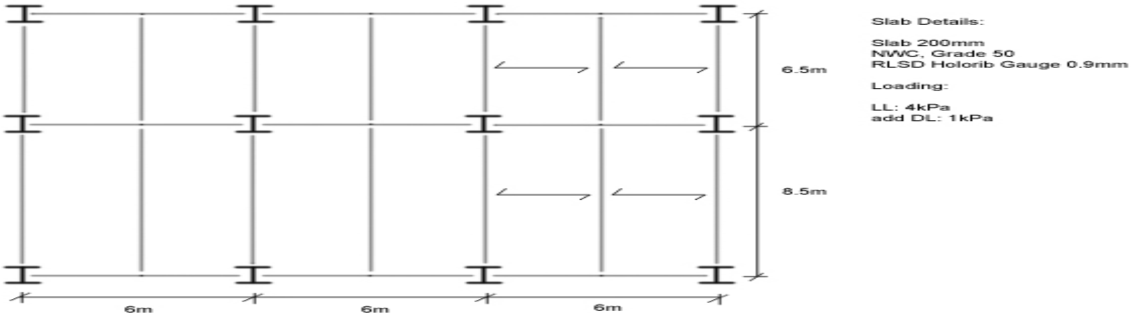

Figure 19 Example 2: Dimensions of a typical bay, details and loading of slab

A typical bay is shown in Figure 19. The secondary beams (UB457x191x74) have a maximum span of 8.5m and are spaced at 3m. The width of the floor is 18m and 200mm of normal weight concrete is used on dovetail steel decking profile to maximise mass. The secondary beams have sufficient strength to support the floor non-compositely, and therefore there is no concern over minimum composite requirement. In this simplified calculation the primary beams are considered stiff, the secondary beams assumed pinned at their ends, and the shorter span bay is not considered. A more accurate assessment could be made using FE analysis.

Although the design of low frequency floors is usually governed by resonant response, a transient response remains and may become critical if the resonant response has been significantly reduced by additional damping. For structures such as hospital floors it is important to ensure that the transient response does not exceed the performance criterion. Therefore both transient and resonant responses for different composite lengths are given in Table 5. The damping and response using high-performance Resotec are shown in brackets. Peak response is under 4th harmonic excitation due to footfall at 2.4Hz, 2.1Hz and 1.9Hz for the 100%, 40% and 10% composite, respectively.

Example 2	Frequency [Hz]	Total Damping [%]	Resonant Response Factor	Transient Response Factor
100% composite	9.5	3.0	4.1	1.9
40% composite	8.4	5.2 (7.5)	2.3 (1.7)	1.8 (1.7)
10% composite	7.6	9.1 (13.8)	1.5 (1.0)	1.9 (1.7)

Table 5 Example 2: Hospital floor, fully and partially composite beams

The responses considering both transient[2] and resonant response are summarised in Table 6. Although the SCI Guide on the vibration of floors in hospitals [9] does not consider transient vibration below 10Hz, this check is still applicable here because the high damping reduces the harmonic response such that the transient response might be critical.

Example 2, Summary	Frequency [Hz]	Total Damping [%]	Response Factor
100% composite	9.5	3.0	4.1
40% composite	8.4	5.2 (7.5)	2.3 (1.7)
10% composite	7.6	9.1 (13.8)	1.9 (1.7)

Table 6 Example 2: Dynamic performance, summary

It is clear that use of Resotec makes steel – concrete construction viable in this instance. A 40% composite design meets the requirements for day wards, and with careful planning of the space (location of corridors etc) it is likely that a non-composite design could be made acceptable for night wards or possibly theatres.

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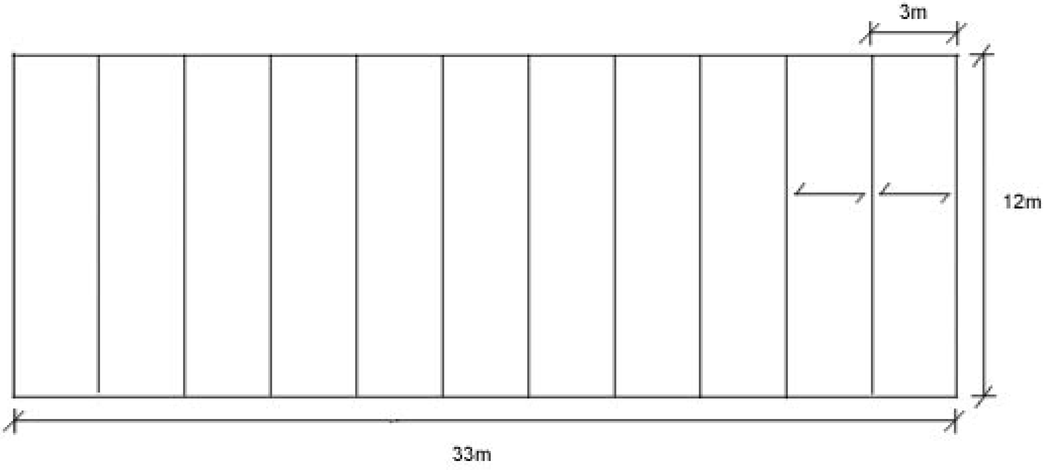
[2] Transient response factor based on walking frequencies up to 1.8Hz

Example 3: Light-weight office floor, 12m span

An office floor is designed with 12 no. 457x191x47 secondary beams spanning 12m at a spacing of 3m, forming a bay of 12m x 33m. The slab is 130mm thick C30 lightweight concrete formed on RLSD E60 Gauge 0.9 decking, as shown in Figure 20.



Slab Details:

Slab 130mm
LWC, Grade 30
RLSD E60 Gauge 0.9

Design Loading
LL 4kPa
Add DL 1kPa

Estimated Actual Loading
Dynamic LL - Add DL: 0.5 kPa

Figure 20 Example 3. Dimensions of 12x33m bay, details and loading of slab.

The floor was designed for an imposed dead load of 1kPa and a live load of 4kPa. For dynamic design purposes, the full imposed dead load plus 10% of the live load was assumed in line with the recommendations of [1], i.e. a total imposed load of 1.4kPa. The resulting total distributed mass for dynamic design was 350kg/m$^{2.}$

Dynamic analysis of the floor slab yielded a natural frequency of the first mode of 5.0Hz and the maximum response factor was 5.1 in multi-mode response to a footfall rate of around 2.3Hz. This response factor is below the SCI recommendation of 8 for a normal office. Nevertheless, when the floor was occupied for office use, complaints were made relating to perceived floor vibrations.

In the ensuing investigation it was determined that the actual loading on the floor was in the region of 0.5kPa, significantly lower than the assumed 1.4kPa. If this lower mass was used in the analysis, although the natural frequency increased to 5.9Hz, the predicted response factor increased to 8, which is more likely to attract criticism (Table 7). Therefore, the assumption of the floor loading affects the response both directly through the modal mass and indirectly by altering the frequency of the floor. Since higher floor loading increases the modal mass, an upper bound estimate of floor load may be unconservative.

Example 3:	Frequency [Hz]	Damping [%]	Response Factor
Assumed 1.4kPa UDL	5.05	3.0	5.1
Bare floor, 0.0kPa UDL	6.56	3.0	9.5
Realistic fitting, 0.5kPA UDL	5.90	3.0	7.3

Table 7 Example 3: Light office floor, fully composite beams

The potential for reducing the response factor of this floor to footfall induced vibration through the use of Resotec has been studied. In this case, the originally designed beams could be made 50% composite without compromising the static design criteria.

Making the beams 50% composite and introducing the Resotec product would reduce the frequency of the first mode of vibration from 5.9 to 5.4Hz. However, the damping in this mode is increased to 5.6% of critical with standard Resotec and as high as 7.5% with high-performance Resotec. Assessment of the dynamic performance based on these damping characteristics result in response factors of around 4.5 and 4.0, respectively (Table 8).

Example 3:	Frequency [Hz]	Damping [%]	Response Factor
50% Composite with Resotec 0.5kPa UDL	5.4	5.6 (7.5)	4.3 (3.9)
50% Composite with Resotec 1.4kPa UDL	4.6	5.6 (7.5)	4.5 (4.0)

Table 8 Example 3: Light office floor, 50% composite beams

This example shows that taking ‘design’ values for imposed dead load and 10% of the static live load may not be conservative in relation to floor vibration. Furthermore, the example shows how Resotec could substantially improve the dynamic performance of this type of floor without requiring any other changes to the design.

CONCLUSIONS

A constrained damping layer installed between the slab and steel beam in a composite floor can significantly improve the dynamic performance of the floor. Such a system has been developed by the authors and is now available as the commercial product Resotec.

Typically only the central 50% of the beam length is made composite, and the absence of shear studs over the end sections, which incorporate the constrained layer, results in cyclical shearing of the visco-elastic material between the slab and the beam as the beam vibrates. This leads to the dissipation of energy in the constrained layer and consequently increased damping in the floor as a whole. Damping of a fitted out floor is typically doubled, which significantly reduces resonant dynamic response. While constrained layer damping systems have been used before, this application is novel in that it does not require any additional structural components, weight or construction depth. Typically, the strength capacity of the partially composite beam is sufficient or nearly sufficient to withstand the demands that the fully composite beam was designed for; at worst a slight increase in section size may be required. Resotec therefore can realise a considerable cost saving over alternative methods for improving the dynamic response (such as increasing the mass or stiffness).

The Resotec constrained layer damping system has been extensively validated and is now available as a commercial product. The system has been successfully implemented in a central London development and at Derby hospital

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