Evaluating and Modifying Existing Building Structures for Vibration-Sensitive Applications

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ABSTRACT
Designing a vibration-sensitive facility, such as a laboratory building, as part of a tenant-improvement or renovation project can introduce significant challenges. Often in these projects, the existing building structure has not been designed to meet the vibration requirements of planned sensitive instruments or research, and therefore mitigation measures must be implemented to achieve the desired criteria. This paper will discuss structural dynamic evaluation, analysis, and design for vibration-sensitive facilities, with a focus on specific issues associated with tenant improvement and renovation projects. Via a series of case studies, various strategies for reducing vibration on an existing structure will be presented, including pre and post mitigation measurement results for each case. These case studies will help to illustrate conditions where certain approaches, including structural retrofits, the use of tuned mass dampers, the use of non-structural elements, and other strategies, may or may not be effective or feasible.

Keywords: Building Vibration, Laboratories, Structural Retrofit, Tuned Mass Damper

INTRODUCTION
When designing a vibration-sensitive facility, such as a laboratory or sensitive manufacturing facility, achieving the required criteria is challenging enough in a new construction project, requiring careful coordination between the architect, lab planners, structural, mechanical, and process engineers, and others. Designing vibration-sensitive spaces as part of a tenant-improvement or renovation project, where the building structure and equipment may not have been designed with the planned sensitive research or equipment in mind, can introduce additional challenges. In some cases, the existing vibration conditions in such projects are less than ideal because the facility was originally designed for office, retail, or some other less-sensitive application. Given the scarcity of land available for new development in desirable urban, transit-adjacent areas, the prevalence of developer-driven research parks, and the potential cost-savings from re-using existing facilities, these challenges are becoming a fact of life for many prospective sensitive facilities.

This paper will discuss structural dynamic evaluation, analysis, and design for vibration-sensitive facilities, with a focus on specific issues associated with tenant improvement and renovation projects. Various strategies for controlling vibration and improving the performance in existing facilities will be presented via a series of case studies.

WALKER-INDUCED VIBRATION
There are many vibration sources that are of potential concern for a sensitive facility. This includes vibration generated by building mechanical, electrical, process, and other equipment, vibration due to turbulent flow through associated mechanical and process piping and ductwork, and vibration sources exterior to the building such as nearby roadways or trains. For the case studies presented in this study, however, the primary vibration source of concern is people walking on the floor. Walker-induced vibration is often the most significant concern for vibration-sensitive spaces located on suspended floors.[1]

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[1] Exceptions to this include very stiff suspended floors designed to very stringent vibration criteria (e.g. semiconductor fabrication cleanrooms and imaging suites), where continuous vibration generated by building equipment and piping often exceeds walker-induced amplitudes as well as slabs-on-grade, where the very high damping provided by the continuous subgrade below tends to mitigate significant vibration impacts from typical walkers. While many of the concepts discussed in this study are somewhat applicable to these floors, our focus will be on walker-induced vibration.

Floor vibrations are generated when a person walks on the floor because the load due to the walker varies with time. It consists of an initial pulse as the heel strikes, then a plateau as the weight transitions to the front of the foot as the person moves forward, then a drop-off as the foot is lifted to take the next step. For vibration-sensitive facilities, floor vibrations due to walkers are typically evaluated in the frequency domain, in large part because most criteria for vibration-sensitive instruments, as well as the typical generic VC criteria intended to represent various classes of sensitive instruments[1], are defined as a function of frequency. Figure 1 shows an FFT velocity spectrum measured as a person walked repeatedly at 100 paces per minute (ppm) through a 14.3m x 10m structural bay. A characteristic of any repeated-impact spectrum is that it will exhibit response peaks at the impact rate and integer multiples thereof, as well as a major peak at the fundamental resonance frequency of the structure being impacted (in this case, the floor). In this case, we see a peak at the pace rate of 1.67 Hz, and the x2 through x4 multiples. The x4 multiple in this case approximately corresponds to this floor's fundamental resonance frequency of 6.7 Hz.

Importantly, the highest vibration amplitudes generated by a person walking on floors of the type discussed in this study tend to occur at the fundamental vertical resonance of the structural floor bay[2] where the walker and receiver are located. The typical deformed shape at the fundamental resonance of a conventionally framed, rectangular floor bay – extracted from a finite element model of a floor structure – is shown in Figure 2. The highest amplitude response occurs at the least stiff portion of the bay – the point furthest from all the surrounding columns, or the "midbay". Lower resonance frequencies may be predicted via modeling that encompass more than one bay; however, field studies have shown that those modes generally are not excited by typical walkers.[2] Higher modes can be excited by walkers, however amplitudes at those frequencies tend to be significantly lower. Reducing the walker-induced vibration amplitudes occurring at the fundamental resonance frequency of the bay, particularly at the midbay, was therefore the primary focus of the case studies discussed below.[3]

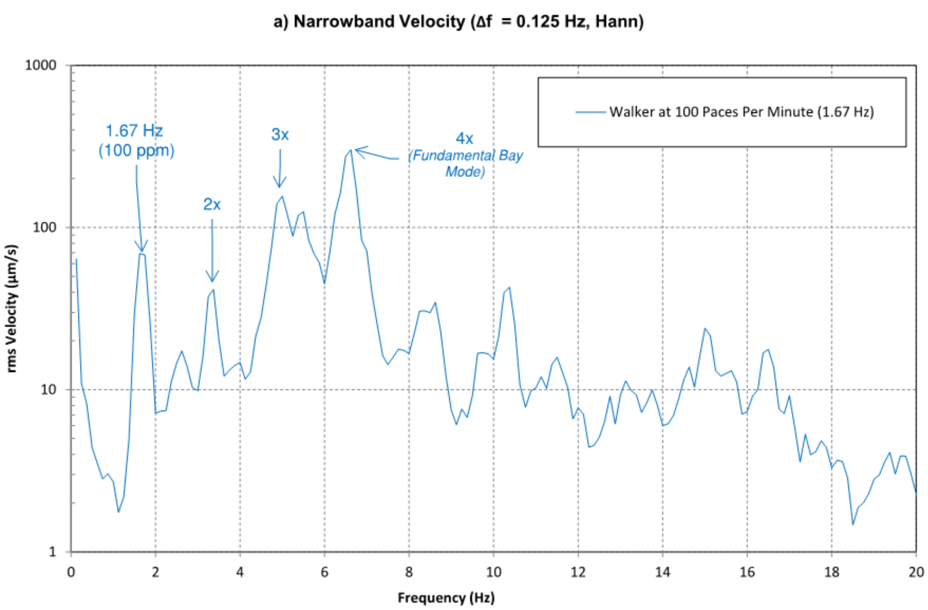

Figure 1: FFT spectrum of a person walking at 100 paces/min (ppm) through a 14.3 x 10m structural bay with a 6.6 Hz fundamental resonance frequency. Integer multiples of the walker pace rate, corresponding with peaks in the vibration spectrum, are indicated.

[2] The structural floor bay is defined as the portion of the structural floor that is bounded by the surrounding columns – typically four columns in the case of a rectangular or square bay.

[3] Prediction of footfall-induced vibration, which is an important step in the design of a new structure or modifications to an existing structure, is beyond the scope of this study.

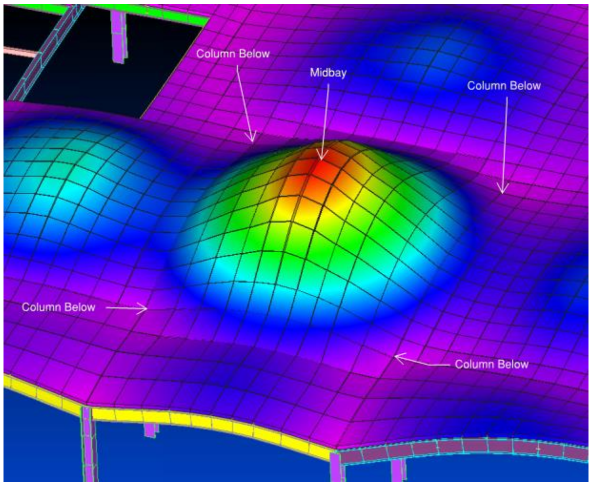

Figure 2: Isometric view of finite element model of a typical structural floor, showing the deformed shape of a typical floor bay at its fundamental resonance frequency

BUILDING MODIFICATION CASE STUDIES

In this section we will present case studies involving vibration-sensitive applications that were to be added to existing building structures originally designed with another application in mind. In each case, vibration measurements were conducted within the existing building prior to construction of the new facility, and then repeated once the renovation or tenant improvement – including any structural retrofits or other modifications installed for vibration control purposes – were completed.

Vibration measurements will typically be presented as RMS velocity in one-third octave frequency bands – which is the format of the standard VC curves often used as design criteria for sensitive facilities.[1] In some cases, narrowband FFT vibration spectra and/or the measured dynamic stiffness spectra will be presented as well to further illustrate the change in dynamic performance before and after the building modifications were completed. In most cases, results from a single structural bay may be shown for illustration purposes, however the sensitive areas and any mitigation measures installed typically extended over multiple bays supporting sensitive equipment.

Case 1 and 2 - Fit-Out Only

In most cases, a tenant improvement or renovation project involving vibration-sensitive spaces begins with a measurement survey to document the existing conditions. In the case of a tenant improvement project, this often involves measurements conducted with the building in “core and shell” conditions, with only the bare building structure and envelope in place and minimal architectural, mechanical, furniture, or components – which we will define generally as “fit-out” – installed. This additional fit-out will tend to contribute additional damping to the structure, which can reduce the maximum amplitude generated by a typical walker. In some cases, full-height partitions above and below the floor can contribute some added stiffness to the floor structure in addition to damping, further reducing the vibration amplitudes. Therefore, it is typically expected that the walker-induced amplitudes measured at a given location in core and shell conditions will be at least somewhat lower when the fit-out of the building is complete.

This is exemplified in Case 1, a multi-story tenant improvement of a core and shell building for biotechnology laboratories. The structural floor in this case was a composite 62mm thick lightweight concrete slab over 76mm metal deck supported on steel beams. Typical structural floor bays were framed with 10m span W24x68 girders supporting 6.9m W16x31 beams spaced 3.4m on center.

Figure 3 shows walker-induced vibration amplitudes measured in the Case 1 facility at the same location with the same individual walker, walking location, and walker pace rate on two separate occasions under two conditions: core and shell conditions and at the conclusion of the tenant improvement work with all fit-out in place. Vibration amplitudes are shown from 1 to 160 Hz in one-third octave format, but only up to 40 Hz in narrowband FFT format – the latter to better illustrate the dynamics at the lower frequencies of interest. The fit-out in this case consisted primarily of typical fixed lab benches and case work, as well as mechanical ductwork and ceilings suspended below the slab. The fundamental bay resonance has not changed significantly between the two tests – which is as expected given that no additional stiffening elements were added to the floor structure. The highest vibration amplitude, however, is reduced by more than 2 times (> 6 dB), which is likely due in large part to the added damping provided by the fit-out. This is evident in the FFT spectrum on the right in Figure 3, where the sharp (high-Q) peak at the fundamental resonance at around 7.25 Hz measured under core and shell conditions has broadened and decreased significantly in amplitude once fit-out was completed.

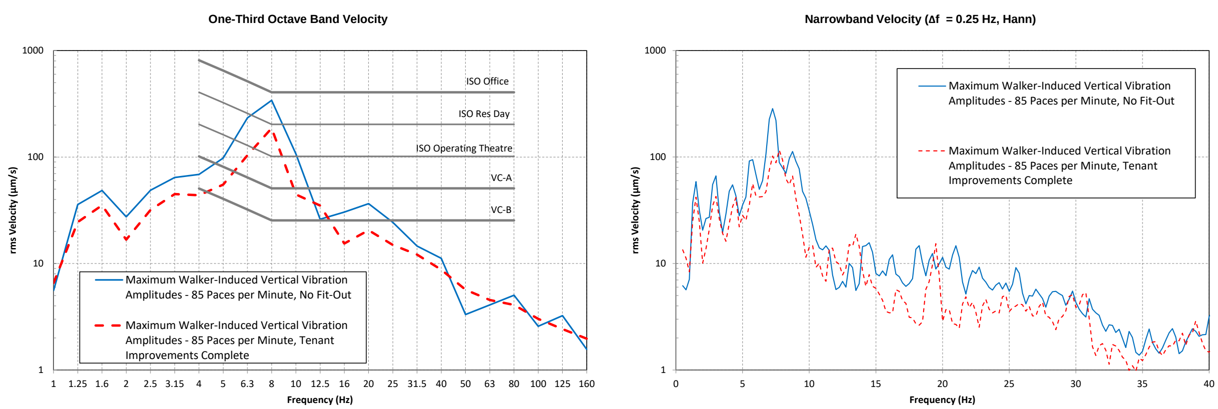

Figure 3: Walker-induced vibration amplitudes in typical wet lab – before and after tenant improvement works.

While the 6 dB reduction exhibited in Case 1 above is a significant improvement, some caution is advisable when evaluating the expected improvement that will be provided by fit-out alone. Many modern labs and sensitive manufacturing facilities include open layouts with minimal partitions, utilities, furniture, and no suspended ceilings. An example of such a facility is Case 2, which is an advanced medical technology manufacturing facility. Measurements were conducted in two bays on the same level with identical structural framing but differing fit-out. The structural floor in this case was again a composite system, with 76mm thick normal weight concrete slab over 76mm metal deck supported on steel beams. Typical structural floor bays were framed with W24x68 girders spanning 9.1m, supporting 12.2m W16x31 beams spaced 3.0m on center. One bay was essentially a bare structure, with no partitions, furniture, utilities, or ceilings installed below. The other bay, as well as the bay directly below, was fully fit out for vibration-sensitive manufacturing processes. In this case, the fit-out consisted primarily of the installation of a number of portable lab benches and ductwork suspended below, with no other partitions, ceilings, or utilities installed.

The walker-induced vibration amplitudes in the two Case 2 Bays are shown in Figure 4. In this case, note that the difference in amplitudes with and without fit-out is small – with a reduction of only around 2 dB. Measurements of the damping at the fundamental resonance frequency in each bay showed 1.5% of critical damping in the fit-out bay compared to 1.0% in the bay without fit-out – a fairly minor increase of only 0.5% due to fit-out. The result is a relatively minor difference in maximum walker-induced vibration amplitudes between the two cases – with maximum amplitudes that are within typical expected measurement variability.

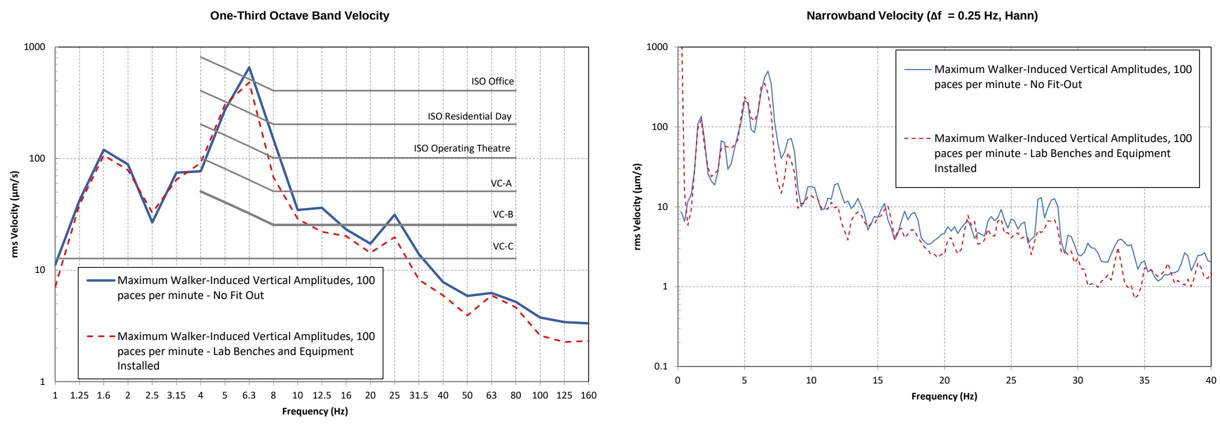

Figure 4: Case 2 - Walker-induced vibration amplitudes in identical structural bays – with and without fit-out.

The impact of fit-out on vibration performance also needs to be considered when evaluating a building for a renovation project. In these cases, existing elements – particularly partitions on the slab under test as well as full-height partitions located directly below the slab – could significantly impact the measurements of the existing conditions. If these elements are to be removed as part of the renovation – as is often the case for more modern designs that are intended to provide a more open architectural layout – the vibration amplitudes after the renovation could be significantly higher than those measured prior to the start of work. In these cases, follow-up vibration measurements after the demolition phase of the renovation is complete can be advisable to provide a more accurate documentation of the anticipated performance.

Case 3 and 4 - Conventional Structural Retrofits

In cases where vibration performance improvements due to fit-out alone are expected to be insufficient to meet project criteria, one common approach to further reduce vibration is to stiffen the floor structure. Walker-induced vibration amplitudes are generally inversely proportional to the stiffness and fundamental resonance frequency of the bay, and structural retrofits can be used to increase both.

Case 3 involved a portion of the 4^{th} floor of a building that was being fit out as a vibration-sensitive vivarium space for biology research, requiring VC-A (50 µm/s RMS) performance. The existing floor structure supporting the vivarium space utilized a one-way joist slab, with an 83mm lightweight concrete slab on a 76mm steel deck, framed with W21x44 joist beams spanning 12.8m and spaced of 2.4m on center, supported by W24x55 girders spanning 7.9m. Initial vibration measurements on this slab showed walker-induced amplitudes of up to around 2,000 µm/s RMS, around 40x (32 dB) higher than the VC-A criterion. Structural retrofits were proposed to reduce the vibration amplitudes, including tube-steel (HSS) elements welded beneath the existing steel beams supporting the floor, as well as an additional 100mm topping slab installed atop the existing slab. Photos of the topping slab and stiffening steel are shown in Figure 5.

Figure 6 shows walker-induced vibration amplitudes measured as part of Case 3. Measured vibration amplitudes at a single location on the floor are shown for three separate conditions: core and shell, core and shell with structural retrofits installed, and with the final fit-out complete. The results show that the structural retrofits reduced the maximum walker-induced amplitudes by roughly 10 times (20 dB), significantly increasing the fundamental resonance frequency of the floor as well. Notably, the added stiffness from the retrofits reduces the amplitudes at nearly all frequencies, including at low frequencies around the walker pace rate. Walker-induced amplitudes are further reduced around the bay resonance once the partitions, ceilings, casework, and other fit-out are installed – with the final conditions meeting the VC-A criterion.

Figure 5: Case 3 – Photos of topping slab (left) and tube steel stiffeners from below (right, with fireproofing applied)

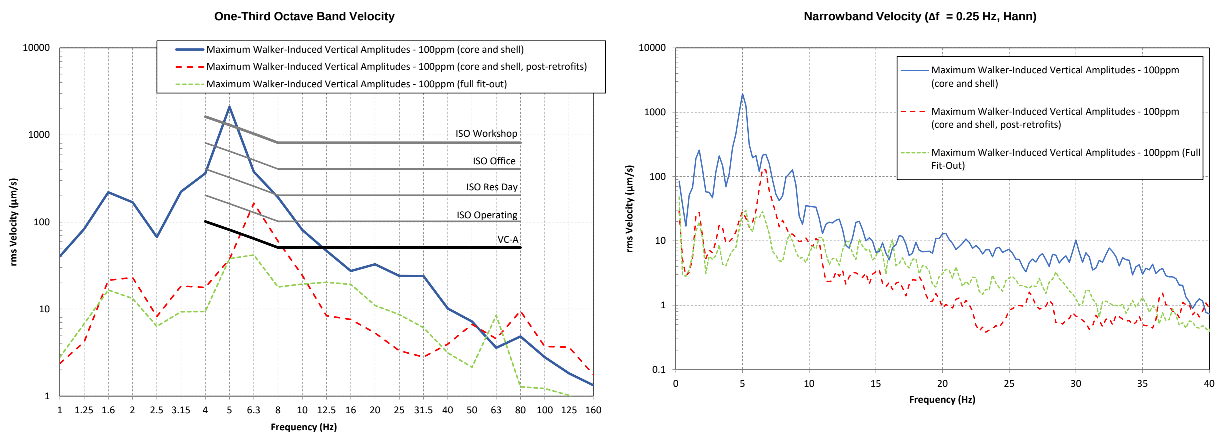

Figure 6: Case 3 - Walker-induced vibration amplitudes at the same location 4th floor vivarium space at various stages of completion. Walker at 100 paces per minute through the middle of the structural bay in all cases.

Case 4 involves the 2nd and 3rd floors of an existing core and shell building that were being fitted out to house vibration-sensitive optical tables to be used for advanced technology research and development. The instruments in this case, which included optical tables and high-magnification optical microscopes, required vibration criteria as stringent as VC-A (50 µm/s RMS). The existing structural floor in this case was a 64mm normal weight concrete slab over 50mm steel deck supported on steel beams. Typical bays were framed with 14.8m span W24x62 beams spaced 3.0m on center supported by 9.1m span W24x76 girders. Walker-induced vibration amplitudes within the existing core and shell building exceeded 700 µm/s RMS, well above the VC-A criterion.

Structural retrofits were implemented to reduce the floor vibration amplitudes, including WT stiffeners welded beneath all existing beams and girders, and an additional 100mm thick normal weight concrete topping slab was added. In this case, due in part to the relatively thin existing concrete slab, supplemental columns and a new girder were also required at the midspan of the existing beams to provide further stiffness. Example photos of the WT stiffeners welded to the underside of the existing beams, new columns, and new girders are shown in Figure 7. Notable, the number of structural bays that could be retrofitted was limited by the total mass of added concrete that could be added to the building without required seismic retrofits.

Figure 8 compares the walker-induced vibration amplitudes measured at a single location in Case 4 in the base core and shell conditions, as well as after structural retrofits and fit-out were complete. The combination of stiffening the floor and the added damping from fit-out in this case reduced the maximum walker-induced amplitudes by more than 14x (23 dB).

Figure 7: Case 4 – Stiffening steel and new columns and girders.

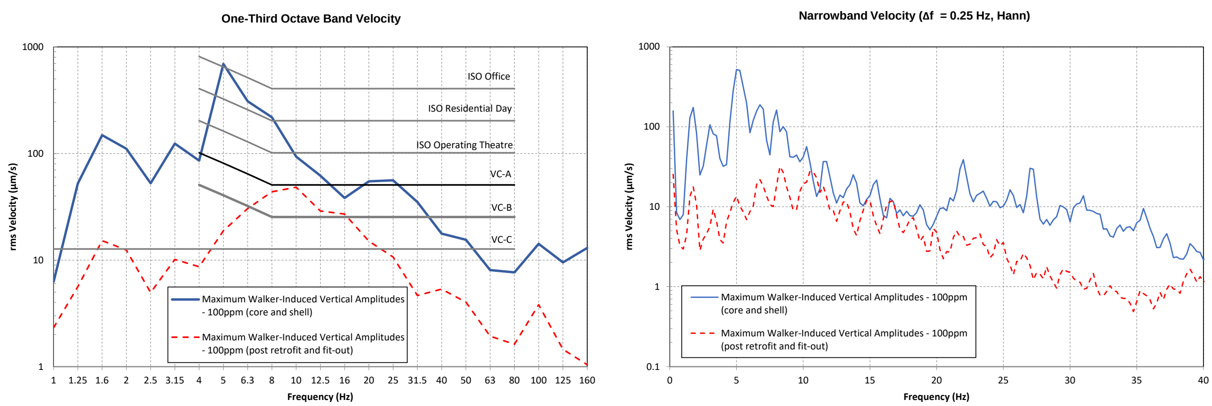

Figure 8: Case 4 - Walker-induced vibration amplitudes in 2nd Floor optics lab before and after retrofits and fit-out.

Case 5 – High-Strength Topping Slab

In some cases, many of the conventional approaches for stiffening the floor slab discussed above are not an option due to project limitations. This occurred in Case 5, which involved a 200mm thick concrete flat slab supporting subfab level of an existing semiconductor fab built in the 1990s, with typical structural bays that were 7.2m x 7.2m. Results from this Case have been summarized as part of prior presentations.[3] The floor, which was initially designed for gravity loads from equipment only, required upgrades to achieve the VC-B (25 µm/s RMS) vibration performance needed for new process equipment that would be installed as part of a facility upgrade. Existing floor bays contained service penetrations of various sizes, which impacted the existing vibration performance, however a uniform solution applicable across the over 400 individual structural bays involved was required. Structural retrofits including additional helper columns, added beams under the floor, and even additional diagonal braces or truss-like elements were considered and analyzed as potential solutions. However, these options were eventually rejected due to the very stringent space limitations associated with a manufacturing facility of this type.

Eventually, a retrofit was designed that involved the installation of a new concrete topping slab to help stiffen the existing structure. Due to space limitations, however, the maximum allowable depth of the new topping slab was only 50 mm. To achieve the required improvement in vibration performance using only this thin topping slab, an extremely high strength concrete with minimum compressive strength of 99.3 MPa was utilized. The Young's modulus of the concrete, which is critical to the stiffness of the bay and therefore vibration performance, was around 2x that of concrete used for the base building. Achieving this concrete strength required the use of a low water-to-cement ratio along with special high-strength aggregate, which is visible in the core sample from the topping slab shown in Figure 9. An adequate bond between the existing slab and new topping slab, which is critical for shear transfer for low-amplitude vibration, was ensured by scoring the existing slab prior to pouring the new slab.

Vibration spectra due to a typical walker in an example location on the floor, measured before and after the installation of the topping slab, are shown in Figure 10. The addition of the topping slab reduces the maximum vibration amplitudes by around a factor of 4 (12 dB), meeting the VC-B criterion. The plots show that the fundamental resonance frequency of the bay increases somewhat with the addition of the topping slab, likely due to the added stiffness. The results shown are typical of the bays that were retrofitted, though it's notable that walker-induced vibration amplitudes were reduced by a factor of up to 6x in selected bay, with amplitudes as low as 7 μm/s.

The peak in the frequency spectrum around the resonance frequency has a lower Q with the added topping slab, indicating that additional damping may have been introduced by the addition of the slab. The changes in dynamic performance are further illustrated by the dynamic stiffness measurement results at this location, shown in Figure 11. Note that the dynamic stiffness at frequencies well below the fundamental resonance frequency, which can generally be assumed to approximate the static stiffness, increases by around 3 dB. However, the dynamic stiffness at its lowest point (at the fundamental resonance frequency of the bay) increases by around 8 dB. In addition to added damping, this difference could be due in part to the repetitive floor structure in the subfab – where adjacent bays having the same thickness and column spans contribute to the dynamic response, due to similar or identical resonance frequencies. The application of the topping slab, which would have added a slightly different amount of mass to each floor bay depending upon the sizes of the individual penetrations, could result in greater differences in resonance frequencies between adjacent bays, resulting in a lower amplitude response at resonance. Regardless, the results show that the retrofit was successful in achieving the project vibration criterion.

Figure 9: Core sample of 50mm concrete topping slab installed for Case 5 showing high-strength aggregate (brown).

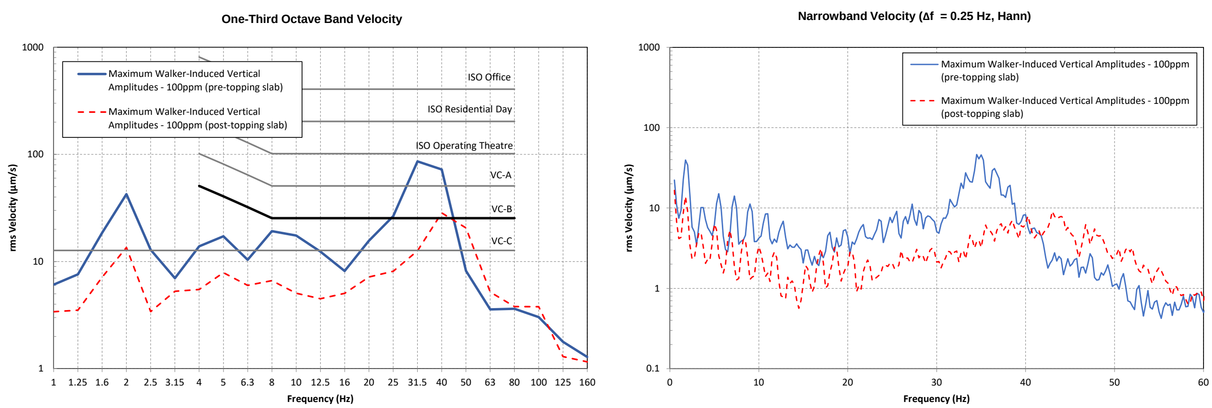

Figure 10: Case 5 – Measured walker-induced amplitudes before and after installation of high-strength topping slab

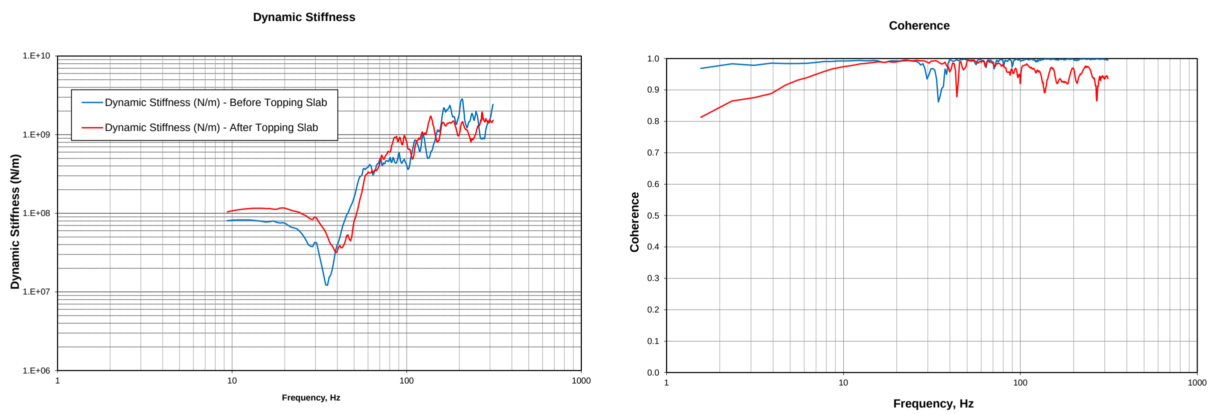

Figure 11: Case 5 – Measured dynamic stiffness and mobility before and after installation of topping slab

Case 6 – Structural Retrofits and Tuned Mass Damper Systems

Case 6 involved another tenant improvement project for a sensitive biotechnology lab facility. The building in this case had recently been constructed by a developer for use as a lab facility, however the vibration design of the floors was more appropriate for office occupancy. As part of the tenant improvement project, new lab spaces were to be constructed occupying six structural bays on the 2nd level. Typical floor bays were framed with 14.3m W24X55 beams spaced 3.4m on center, supported on 10m span W27X84 girders. The steel beams supported an 83mm lightweight concrete slab on a 50mm thick steel deck. Tissue culture research and sensitive instruments such as optical and confocal microscopes, flow cytometers, plate readers, and mass spectrometers were to be utilized in these labs, requiring the floor structure to provide VC-A (50 µm/s RMS) performance.

Once again there were significant limits on the structural retrofits that could be installed as part of the project to help improve the vibration performance. New columns could not be installed due to contaminated soil beneath the building – excavation for new column footings would have required decontamination procedures, introducing significant project delays. Additionally, the labs were located directly above the main entry lobby and conference center for the building – and therefore dropping additional columns into these spaces was not preferred architecturally. Additionally, no additional concrete topping slabs could be installed in this case. Additional concrete would add significant mass to the building, triggering potential seismic upgrade requirements for the entire building. Additional damping benefits from the fit-out were assumed to be minimal, due to the open lab layouts with minimal partitions above and below most bays.

Stiffening of the existing beams and girders was feasible, however, and a retrofit design was devised that involved the installation of new WT and tube steel (HSS) sections welded to the underside of the existing members. However, stiffening the beams alone was not sufficient to meet VC-A. Modeling of the structure indicated that any further stiffening of the beams and girders would have diminishing returns without also stiffening the concrete slab and/or reducing the floor spans via the installation of new columns. Since these were not viable options for the project, an alternative of a tuned mass damper (TMD) system was considered instead to help further reduce walker-induced vibration.

TMD systems used to control floor vibration consist of a large mass, typically on the order of 2 to 10 percent of the mass of the floor bay, which is attached to the floor via a set of springs and dampers at the approximate location of maximum deformation at the frequency of concern – typically the middle of the structural bay, though not always. The system is designed and adjusted so when the floor is excited, the mass oscillates on the spring and damper system at the designed frequency – which is typically tuned to the fundamental resonance frequency of the floor bay. The oscillation of the mass dampens the vibration of the floor at resonance. Importantly, a tuned mass damper will only reduce the vibration amplitudes at the frequency it is tuned to. While vibration at the fundamental bay resonance is typically the worst case in terms of walker vibration, vibration amplitudes measured on the existing floors in this case exceeded the criterion at other frequencies as well – with amplitudes as high as roughly 200 μm/s at lower frequencies, predominantly at the walker pace rate and the first few harmonics. A TMD would not be expected to reduce these amplitudes. The TMD will also have minimal impact on the frequency of the floor resonance, meaning that a TMD installation alone would still result in a floor with a relatively low frequency resonance that is easily excitable by walkers. For these reasons it was advisable to combine any TMD installation with structural retrofits that increase the bay stiffness at least somewhat, rather than try to rely on the TMD to provide all the necessary attenuation. The retrofit design including additional steel and added TMDs is shown as a markup of the base building structural drawings in Figure 12 below.

There were several important considerations in implementing a floor vibration mitigation design involving TMDs, which are summarized below:

- The tuned mass damper must be adjusted to match the floor resonance with a high level of precision to be most effective. This tuning will generally be performed by the TMD manufacturer during installation, however the TMD must be designed to operate within a narrow range[4] of frequencies before shipment and installation. While the column spacing and framing designs for most bays were generally very consistent, the location of existing full height walls – as well as new full-height walls that would be installed as part of the tenant improvement – significantly altered the dynamics of each bay. Fundamental resonance frequencies for bays that were nearly identical structurally ranged from around 7 to 10.5 Hz. Predicting these resonance frequencies required very careful and detailed finite element modeling. These frequencies were then verified via measurements once the retrofits and most partitions were installed, with any adjustments communicated to the TMD vendor.
- In addition to impacting the fundamental resonance frequency, full-height partitions in the level below also impacted the fundamental mode shape within each bay. Figure 13 shows color contours illustrating the predicted deformed shape of one bay in the building (Bay 4, or the fourth bay from the left) which was to have a full-height partition below running north-south down the approximate middle of the structural bay. Note that the full-height partition serves to stiffen the middle of the bay, resulting in the highest deformation (the red area of the contours) occurring closer to the quarter bay – between the partition and the column line. Since the TMDs must be installed at the location of maximum deflection for the mode to which it is tuned for maximum benefit, this meant that the TMDs for this bay were shifted closer to the quarter bay rather than centered on the midbay as with other bays. Note that, as shown in Figure 12, similar considerations were required for the second bay from the left.
- The TMD installation involves adding significant weight to the underside of the floor structure. Two dampers were required in each bay in this case, each weighing approximately 1400 kg. The project structural engineer was required to confirm that the existing structure could support the new load, as well as work with the TMD manufacturer on the required details for attaching the TMD to the structure.

[4] The frequency range is generally dependent upon the specific design of the TMD and the amount of attenuation required

Photos of selected TMDs as installed on the underside of the structure are shown in Figure 14.

Walker-induced vibration amplitudes in a representative retrofitted bay are shown in Figure 15 under three separate conditions: core and shell, core and shell plus steel retrofits and partitions installed, and final fit-out with TMDs installed and operating. The results show that the structural steel retrofits significantly reduce the walker-induced vibration amplitudes – by around 2x (6 dB). The introduction of the TMD reduces the amplitudes further, to the point that the VC-A criterion is met. The narrowband FFT spectra show that the effect of the TMD is most pronounced around the resonance frequency of the bay, as expected. Some reduction in the amplitudes at other frequencies is evident as well, which could be due to the added mass of the TMD and/or added damping from further fit-out installed between the post-retrofit measurements and post-TMD measurements. The results show that the combination of added steel, TMDs, and damping from fit out were sufficient to achieve the project criteria.

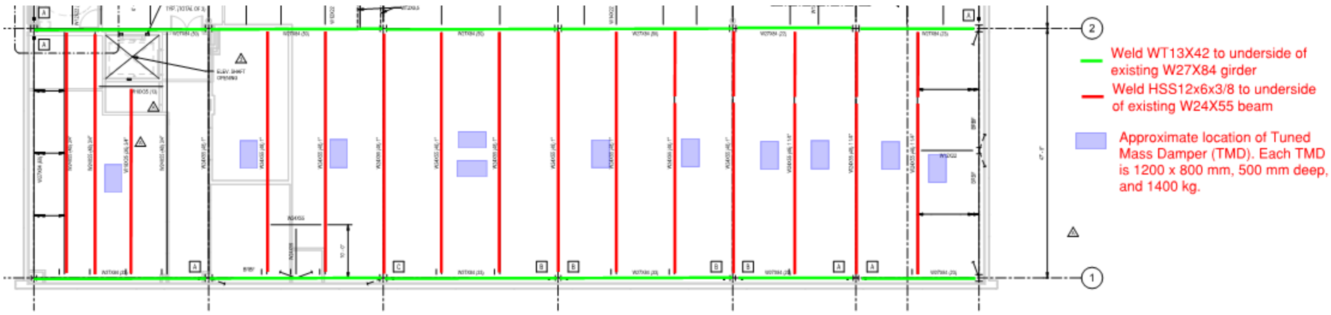

Figure 12: Case 6 – Level 2 structural framing plan showing location of new WT and HSS members and TMDs

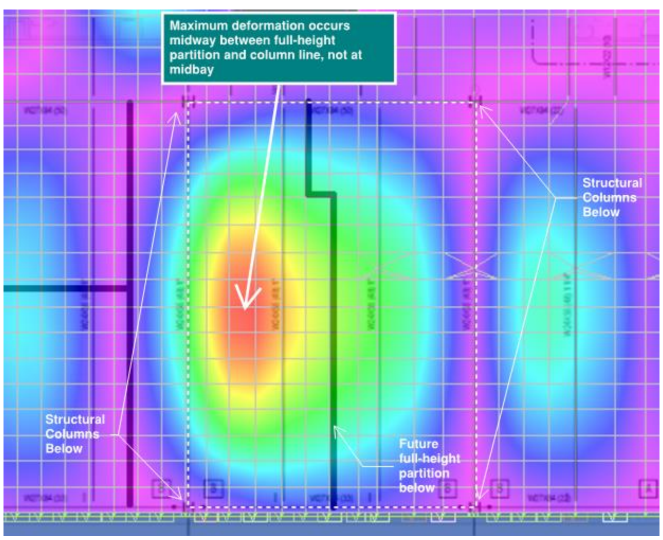

Figure 13: Case 6 – Deformed shape of fourth bay from the left at 7.2 Hz. Structural bay indicated as white dashed line.

Figure 14: Case 6 – Tuned mass dampers mounted to the underside of the floor structure.

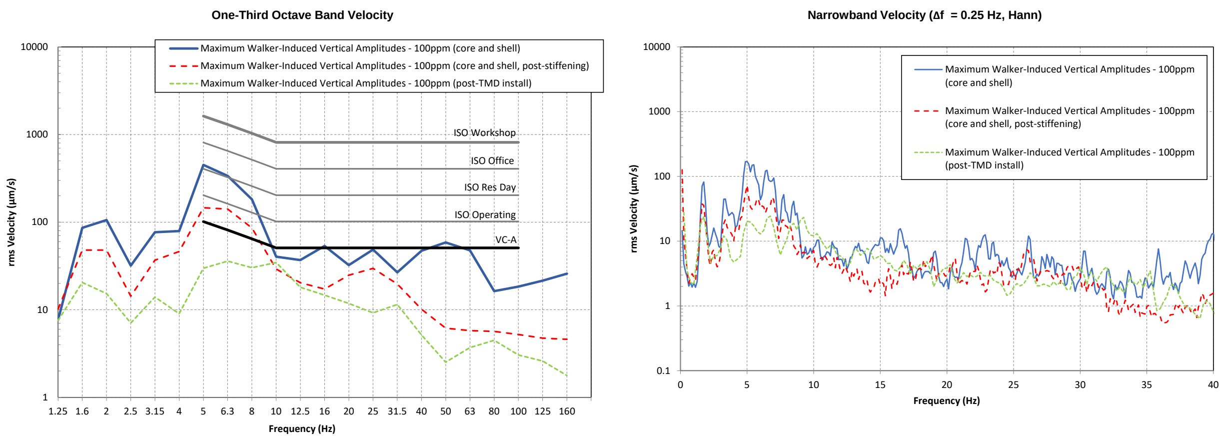

Figure 15: Case 6 – Measured walker-induced vibration amplitudes in a representative bay throughout vibration mitigation installation.

CONCLUSION

The case studies presented here show that buildings designed for more conventional occupancies can be upgraded for use in vibration-sensitive applications via several different methods. There are many considerations required when evaluating an existing building, as well as assessing potential options for reducing floor vibration where necessary. The specific approach for reducing vibration amplitudes in an existing structure will generally be dependent upon the specific project details and limitations, however the examples shown here show that in many cases these limitations can be overcome while still achieving the project criteria.

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