FLOOR VIBRATION ASSESSMENT AND TUNED MASS DAMPER DESIGN FOR A COMMERCIAL OFFICE BUILDING

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EXECUTIVE SUMMARY

Complaints about the floor vibration in one area on the second floor of a commercial office building have been persistent since the building opened in the early 1990s. Following an initial vibration survey carried out by a local acoustics firm, a follow-up vibration survey of the space was performed as a precursor to the design and installation of tuned mass dampers to mitigate the vibration in the area of concern. The raised access floor provides little cushioning of occupant footsteps resulting in higher-than-typical forces being applied at the floor's primary resonance frequency of 5.8 Hz. Four tuned mass dampers (about 1300 lbf each) are installed to increase the effective damping of this mode beyond the low inherent damping of 3%. The walking-induced vibration levels are reduced by about 70% near the fundamental floor mode and are now below the accepted limits for an office-type occupancy. Additional vibration mitigation can be achieved by incorporating vibration isolation into the floor system where most of the traffic occurs.

1. BACKGROUND

Some occupants of the three-story office building (Figure 1) have reported annoying levels of vibration in one bay on the second floor of their building. The three-story building, designed in 1992, is a braced structural steel frame with a floor system comprised of metal joists supporting a 3.5-in. thick slab on a non-composite metal deck. The joists are supported on steel beams that frame into the steel pipe columns. An 18-in-high access floor is used as an air distribution plenum. The access floor system, manufactured by Tate Access Floors, Inc., has support posts spaced at 2 ft on center each way that are glued to the floor slab. The corners of four floor panels screw into each support post.

Figure 1 Administration Building

Floor vibration has been a problem since the building opened. At one point, sand bags were placed on the floor to add mass (inertia) in the hopes that the response would be reduced. No significant benefit was observed and the sand bags were eventually removed. Recently, an acoustics firm was engaged to measure the vibration levels in the area of concern and to recommend a mitigation plan. The Acoustics report was provided to building management and the architectural firm that designed the building in April 2015.

The area of concern within the building is the 28-foot by 28-foot interior bay located between Gridlines 6 and 7 (east/west) and Gridlines D and E (north/south) as shown in Figure 2[1]. The floor structure consists of 18-inch deep joists (18LH08) that span 28 ft in the north/south direction and are spaced at 4 ft on center in the East/West direction. The joists are supported on W24x68 girders on the north and south sides.

The acoustics firm measured vibration levels at four locations within the bay during their site survey. The vibration levels at the center of the bay [see Figure 3 from Reference (a)] exceed the criteria per Reference (b) for office spaces at three distinct frequencies: 2.5 Hz, 6.3 Hz, and 25 Hz. The results show that walking-induced vibration is the dominant source of the vibration felt by the building's occupants. The findings also clearly indicate the atypical nature of the floor system dynamics at the site. The very low frequency of 2.5 Hz is a very low frequency if it represents a structural resonance frequency. The as-built structure would have to be significantly

[1] The clouded area showing the area of concern was marked on the drawing by the client.

different from that shown in Figure 2 for the 2.5-Hz vibration to represent a resonant floor mode. The response near 6.3 Hz is at a frequency most likely to coincide with a structural mode of the floor based on the as-drawn construction. The maximum response is measured at 25 Hz where people tend to be less sensitive to vibration; however, the magnitude of the measured vibration is extremely high and, according to the data, should be quite noticeable. Short of a significant stiffening of the floor structure, it is unlikely that any one mitigation strategy will successfully address the vibration at these three frequencies and the acoustics firm has suggested a multiphase approach for dealing with the vibration at the site.

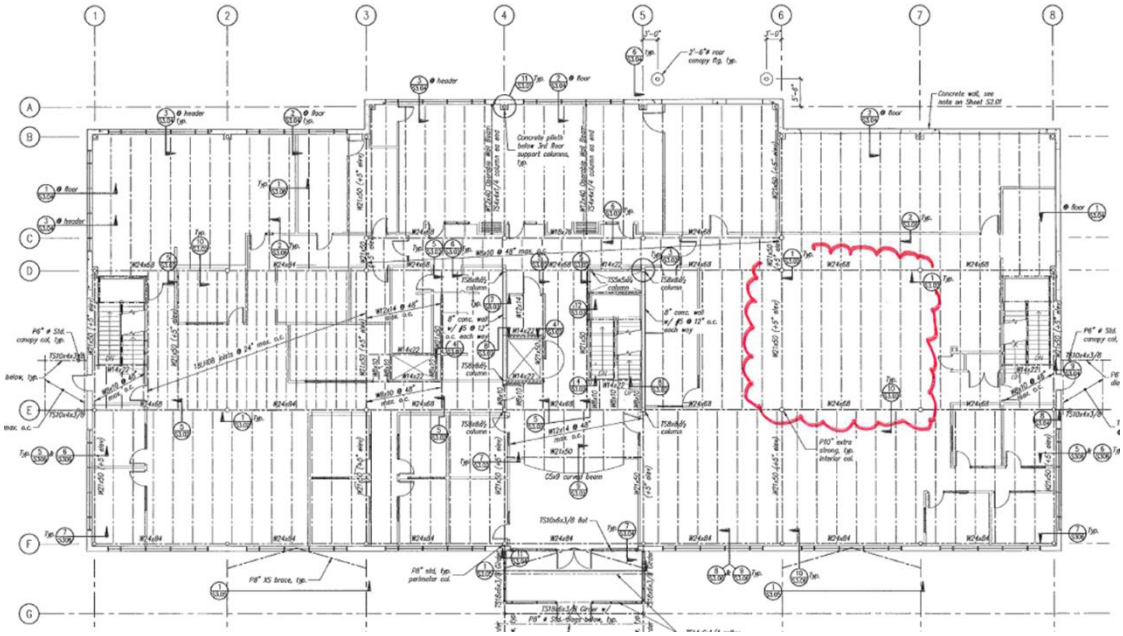

Figure 2 Second Floor Structure With Area of Vibration Concern Identified

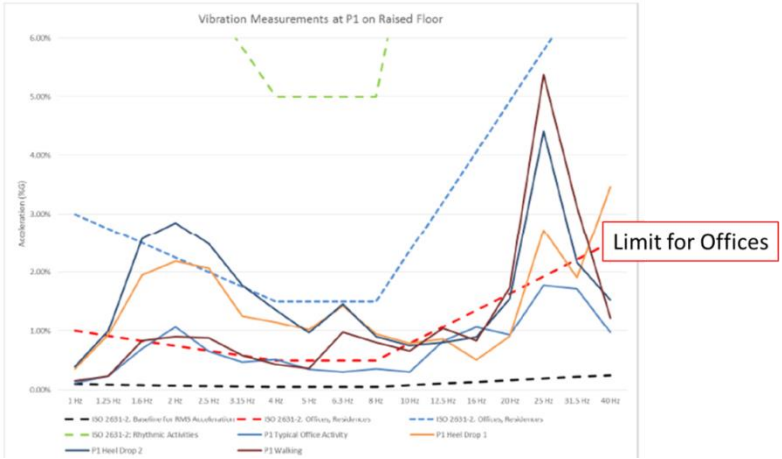

Figure 3 Floor Vibration Measurements

2. WALKING-INDUCED VIBRATION OF FLOOR SYSTEMS

Walking-induced vibration is a common source of vibration complaints in buildings when vibration is reported. According to information summarized in AISC Design Guide 11 (DG11) [Reference (b)], the normal walking pace falls between 96 and 122 steps per minute, which corresponds with a frequency range between 1.6 Hz and 2.2 Hz. Each footfall generates a downward-acting force on the floor and the floor deflects downward and rebounds with each step. Normally, this response is not noticeable; however, if the floor system is unusually flexible and/or a person's walking pace happens to coincide with a dominant floor resonance frequency, the floor structure can dynamically magnify the deflection by a factor of about 15 to 20 times the typical deflection, which can be quite disturbing to others working nearby if it occurs frequently enough.

Typical office building floor systems do not have resonance frequencies below 2.5 Hz; they tend to fall in the 4 Hz to 10 Hz range. Steel structures tend to be on the low side of this range and poured-in-place reinforced concrete structures tend to be on the high side. So, how can the higher frequency resonant mode of a floor be excited by the lower frequency of a normal walking pace? Each footfall causes an abrupt application of a force to be applied to the floor. Successive abrupt applications of a force at a given frequency result in forces at that frequency and at harmonics (integer multiples) of that frequency. In other words, a person walking with a step frequency of f_w is applying forces to the floor at f_w, $2f_w$, $3f_w$, and so on. As a general rule, the magnitude of the force diminishes with each higher harmonic; however, even a smaller force can excite a higher frequency resonant mode of a floor system if one of the harmonic frequencies (f_w, $2f_w$, $3f_w$, …) happens to be close to the floor's resonance frequency. Access floor systems can exacerbate this mechanism. The lack of resilience in the thin carpeting and the stiff access floor structure, combined with loose panels give rise to a "bang," "bang," "bang" with each step that magnifies the forces in the higher walking harmonics.

There are no vibration limits imposed by the Building Code in the design of buildings. Engineers are merely asked to *consider* the effects of vibration. Few engineers have a technical background in vibration and hence, cannot perform a rigorous vibration assessment of a structure. To make matters worse, the real-world response of a structure is virtually impossible to predict because of the sensitivity to variables that the engineer has no knowledge of (*e.g.*, friction in a bolted connection or the stiffening effect of non-structural partitions). DG11 was written to provide engineers with simple formulas and guidelines for addressing vibration in buildings although the merits of this approach is debatable. DG11 also presents limits of acceptable vibration for various occupancies. DG11 recommends the maximum vibration be limited to 0.005 g between 4 Hz and 8 Hz, where people are most sensitive to vibration. The problem with this criterion is that it applies at a single frequency. Walking-induced vibration generates vibration over a narrow, but continuous band of frequencies.

An alternative to the DG11 criterion is presented by the International Standards Organization (ISO), Reference (e). This standard uses the root-mean-square (RMS) vibration computed over a range of frequencies (1/3 octave). The bandwidth of the frequency range increases with the center frequency, so at a center frequency of 1 Hz, the bandwidth is about 1.23 Hz and at 10 Hz, the bandwidth is 12.3 Hz. This approach effectively captures how people perceive vibration at closely-spaced frequencies. The ISO standard defines a vibration level associated with a person's ability to just perceive vibration, which is often used as the vibration limit for hospital patient and operating rooms. The vibration limit recommended for office spaces is four times the perception threshold, or 0.002 g_{RMS} between 4 Hz and 8 Hz. As a simple comparison of the two criteria, a single frequency vibration with an amplitude of 0.005 g has an RMS magnitude of 0.0035 g, which is a bit higher than the ISO limit of 0.002 g.

3. ON-SITE VIBRATION SURVEY

Accelerometers are used to measure the time history acceleration response of a structure. The portable data acquisition (DAQ) system consists of a Windows-based laptop, a USB-powered four-channel 24-bit

data acquisition module (Data Translation DT9837A), and the four single-axis accelerometers identified in Table 1. A sampling frequency of 1000 Hz is used to digitize the analog acceleration data stream, which provides a useful frequency bandwidth out to about 500 Hz. The frequency range of interest is well below 100 Hz based on typical floor vibration frequencies, so the 500-Hz range is more than adequate for building vibration measurement applications.

Table 1 Accelerometers and Channel Assignments

Channel	Accelerometer	S/N	Sensitivity
1	PCB 333B52	46982	1.044 V/g
2	PCB 333B52	46983	1.040 V/g
3	PCB 393B04	32502	1.003 V/g
4	PCB 393B04	32503	1.009 V/g

The duration of the data acquisition period is adjusted based on the purpose of the data being collected. Each acquisition period produces an ASCII text file containing the raw time series data with one column of time values for each sample (at 0.001-sec intervals) and four columns of acceleration values (in g's). Each column of acceleration data corresponds to the channels listed in Table 1. The time series data are then processed to evaluate the time domain characteristics, the frequency content, or the DG11 and ISO vibration criteria.

A typical site survey involves several data acquisition periods at various locations on the floor. One of the objectives is to identify the primary vibration modes of the floor system. Heel drop tests are performed to apply a transient shock to the floor, which excites the floor across many frequencies simultaneously. Analysis of those data shows peaks at discrete frequencies which can be associated with one or more resonance frequencies of the floor structure. Once the primary resonance frequencies are identified, an appropriate walking pace is selected to maximize the floor's response to walking-induced vibration. Data are recorded while walking back and forth in the area at that pace (using a smartphone metronome app to set the pace) and then analyzed to assess the floor's response relative to the DG11 and/or ISO vibration criteria. In relatively high traffic areas, it is worthwhile to record ambient vibration that represents the normal traffic. These data are also evaluated relative to the vibration criteria.

The initial effort on this project involves a site investigation to verify the structure is constructed per the design drawings, to measure the floor vibration response to impulsive excitation (to determine the floor's resonant modes), and to measure the walking-induced vibration for comparison with the original findings. We performed the site survey on July 27, 2015 with the objectives to (a) identify the dominant floor resonant mode(s), (b) to identify the as-built structural members and spacing, and (c) to quantify a baseline vibration levels for comparison with the post-mitigation response at the conclusion of the Phase-1 effort.

3.1 STRUCTURE VERIFICATION

Measurements of the structural member dimensions, thicknesses, and spacing are obtained under the bay in question to confirm that that the as-built structure is consistent with the structural drawings made available for this project. It is possible that changes in the structure could have been made after the drawings were issued leading to a more flexible structure than that represented in the drawings.

The thickness measurements of the girder flange and web and joist chord were obtained with a Defelsko Positector Ultrasonic Thickness Gauge (UTG). The measured dimensions of the girder are shown in Figure 4. The flange and web thicknesses are consistent with a W24x68 per the documented dimensions (b_f = 8.97 in, t_f = 0.585 in, t_w = 0.415 in). Measurements show that the bottom chords of the joists are constructed from two angles with 2-in-long legs. The thickness of the angles is 1/4" (*i.e.*, L2x2x1/4). The cross-sectional area of an L2x2x1/4 is 0.938 in^2. The overall depth of the joists is 18 in. and the distance between the center of gravity (*i.e.*, the center of axial force) of the top and bottom chords is 16.83 in. The ultimate bending moment capacity, ϕM_n, of this joist and the corresponding maximum uniform distributed load, w_u, are estimated per the Load and Resistance Factor Design procedure as

$$\phi M_n = (0.9)(50\,\text{ksi})(2)(0.938\,\text{in}^2)(16.83\,\text{in}) = 1421\ \text{kip}\cdot\text{in}$$

$$w_u = (1421\,\text{kip}\cdot\text{in})\left(\frac{8000}{(12)(28\,\text{ft})^2}\right) = 1208\,\text{lb/ft}$$

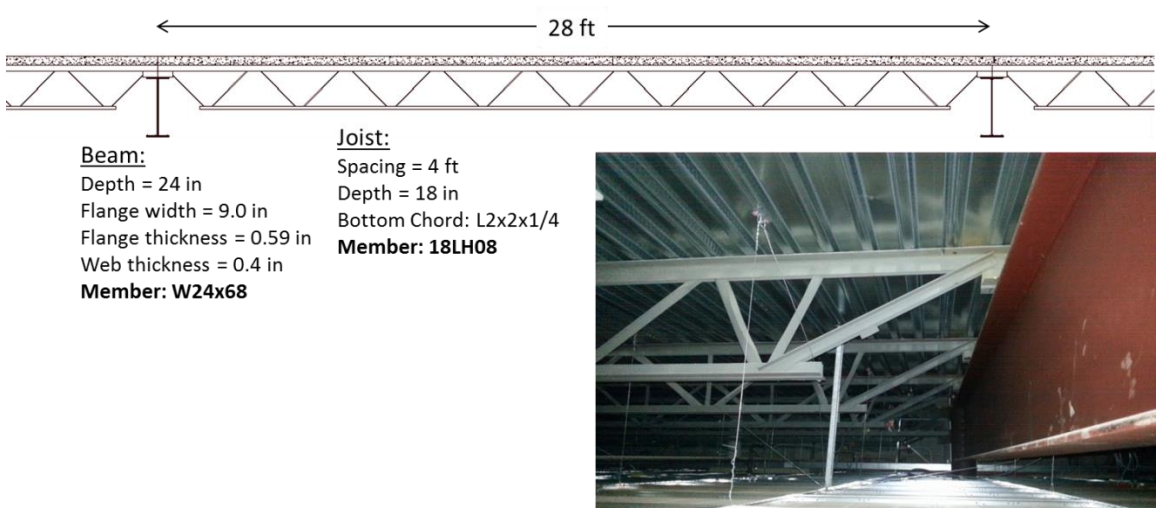

Figure 4 As-Built Floor Structure

The Vulcraft joist design catalog defines the maximum factored uniform load-carrying capability of an 18LH08 joist as 1176 lb/ft for a clear span of 28 ft. The calculated load-carrying capacity of the joists at the site is slightly higher than the documented strength (as it should be); hence, the joists at the site are consistent with the 18LH08 joist identified in the contract documents. The measured joist spacing of 4 ft is also consistent with the contract documents. The as-measured structural members in the structural bay of interest agree with those sections called out in the contract documents.

3.2 VIBRATION MEASUREMENTS ON PRIMARY FLOOR STRUCTURE

Two different measurement configurations are employed during the site visit. Initially, the four accelerometers are attached directly to the structural steel members supporting the bay of interest as shown in Figure 5. Channel 1 is located at joist midspan, on the joist closest to the center of the bay and measures the acceleration in the vertical direction. Channel 2 is attached to the bottom chord of the same joist at the north end, but measures the acceleration parallel to the joist span direction. Channels 3 and 4 are positioned on the centerline of each of the supporting girders at midspan and measure the acceleration in the vertical direction.

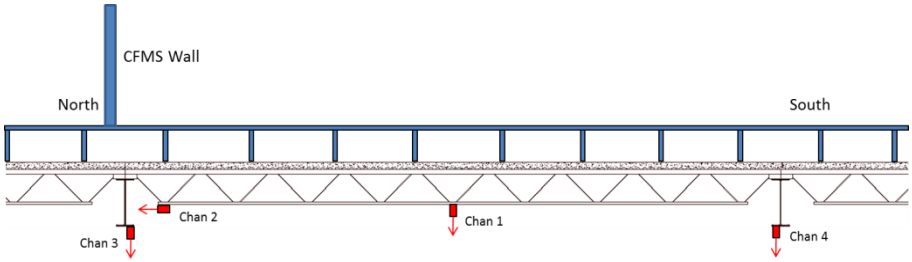

Figure 5 Vibration Measurement Locations on Floor Structure

A series of heel drop tests are conducted on the second floor at two locations: one at midspan of the south girder and the second at midspan of the joist nearest the center of the bay. The access panels were removed at both locations to allow the heel drop test to be performed on the slab rather than the access floor.

The vertical acceleration time series for five successive heel drops at the south girder are plotted in the left-hand side of Figure 6. The frequency content in the structure's response is shown in the right-hand side of the figure. The Channel 4 accelerometer is located immediately below on the girder where the heel drop test is performed, so it is not surprising that the maximum response is recorded with that accelerometer. The peaks in the frequency domain plot correspond with resonance frequencies of the structure. Dominant peaks at the south girder occur at 5.8 Hz, 11.8 Hz, and 14.1 Hz. As expected for this floor system, the lowest resonance frequency is 5.8 Hz. The 5.8-Hz response measured here corresponds to the 6.3 Hz peak. The acoustics firm's results are documented at the discrete and more coarsely spaced frequencies corresponding to the 1/3 octave bands. In the present analysis, the frequency resolution is 0.24 Hz; hence, the resonance frequency is 5.8±0.12 Hz based on this method of analysis.

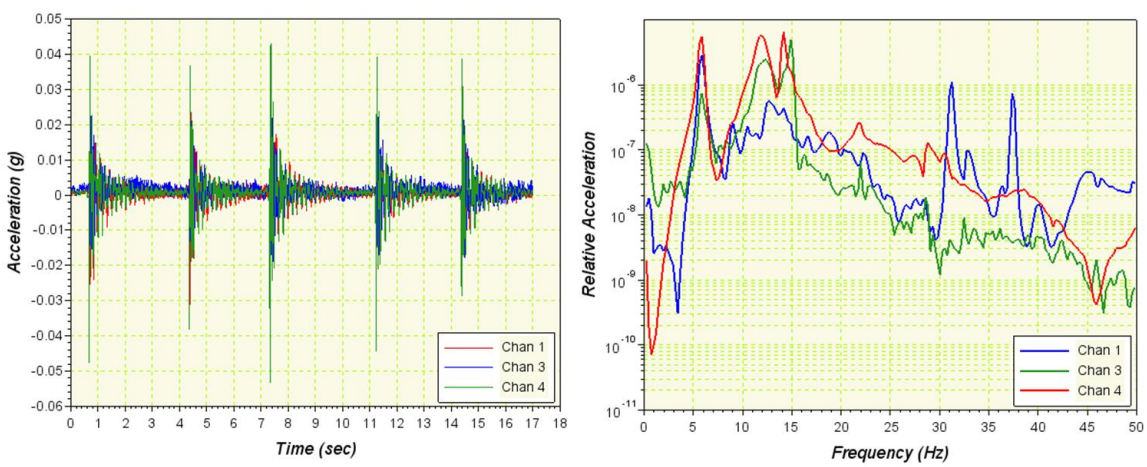

Figure 6 Heel Drop at South Girder: Acceleration Time Series (left) and Frequency Content (Right)

The next highest response is recorded at Channel 1 (joist midspan). The dominant resonance frequencies observed here fall at 5.8 Hz, 31.3 Hz, and 37.4 Hz. The data show a high response near 25 Hz, but there is no corresponding peak in the present data that suggests 25 Hz is a resonant mode of the floor. The acoustics firm has suggested this frequency could be associated with the access floor system. This is a reasonable observation as none of the present measurements are made on the access floor. Another possibility is that the 25 Hz response could be associated with the slab flexure as it spans between the joists. The current measurements only record the joist and beam responses.

The second series of heel drop tests is performed on the floor slab at about joist midspan, more or less immediately above the Channel 1 accelerometer. The time series for three successive heel drops is plotted in the left-hand side of Figure 7 and the corresponding frequency content is shown in the right-hand side of the figure. Somewhat surprisingly, the response of the south girder is slightly higher than the response of the joist itself. This suggests the flexibility of the girders plays a significant role in the vibration response of the floor system. The north girder response (Channel 3) is much lower than that of the south girder. The non-structural cold-formed metal stud (CFMS) wall, depicted in Figure 5, runs along and parallel with the north girder which stiffens this area of the structure. These relative magnitudes of response provide valuable insight into the structural mode shapes that correspond to the resonance frequencies for the floor system. No new resonance frequencies are identified in the second heel drop test.

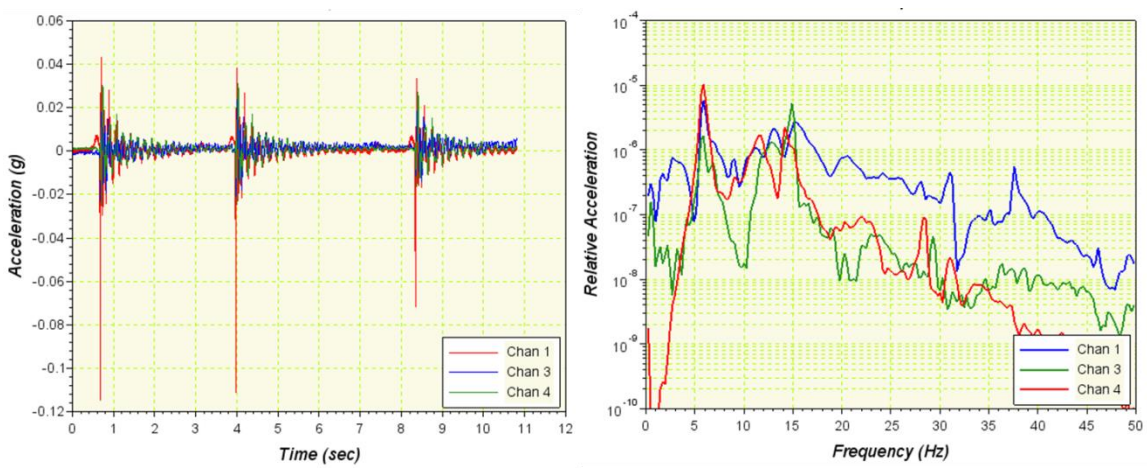

Figure 7 Heel Drop at Joist Midspan: Acceleration Time Series (left) and Frequency Content (Right)

One of the transient responses recorded at the joist midspan (Channel 1) shown in the left-hand side of Figure 7 is extracted for the more thorough time series correlation analysis shown in Figure 8. The red curve in the plot is the actual transient response data and the blue curve follows the damped sine formula shown in the figure. A least squares analysis is performed to identify the equation parameters (A, t_0, f, and ξ) that achieves the best agreement between the data and the equation over the time range shown. The data and the least squares best curve fit are very close (comparing peak/trough spacing and amplitude decay), which implies that the four equation parameters obtained from the least-squares fit are very close to those in the data. The frequency, f = 5.8 Hz, and the damping factor, ξ = 0.03, are the most relevant parameters, and in this context represent the resonance frequency and damping factor, respectively, for the lowest floor vibration mode. The estimated frequency parameter agrees with that obtained from the frequency domain analysis obtained above.

The response of the three vertical-oriented accelerometers to walking-induced vibration is shown in Figure 9, where the pace frequency of 116 steps per minute is deliberately selected (and achieved by listening to a smartphone metronome app while walking through the space) so as to maximize the possibility of exciting the floor's resonant mode. The acceleration time series is shown in the left-hand side of the figure and the frequency content is displayed in the right-hand side. Peaks in the frequency domain plot are clearly visible at many of the walking harmonics. The joist-mounted accelerometer is particularly responsive to the fundamental pace frequency of 1.9 Hz. The relative magnitude of this quasi-static (*i.e.*, at a frequency well below the fundamental resonance frequency) response is surprising. The south girder is most responsive at the floor's resonance frequency of 5.8 Hz (*i.e.*, 3×1.9 Hz). The north girder is least responsive. The joist also responds at the higher walking harmonics of 4×1.9 Hz (7.6 Hz) and 5×1.9 Hz (9.5 Hz). The access floor system is contributing to the walking-induced vibration

environment by enhancing the dynamic force magnitudes of the higher walking harmonics. It is doubtful that the vibration response at these harmonics would be so large if people could walk directly on the slab.

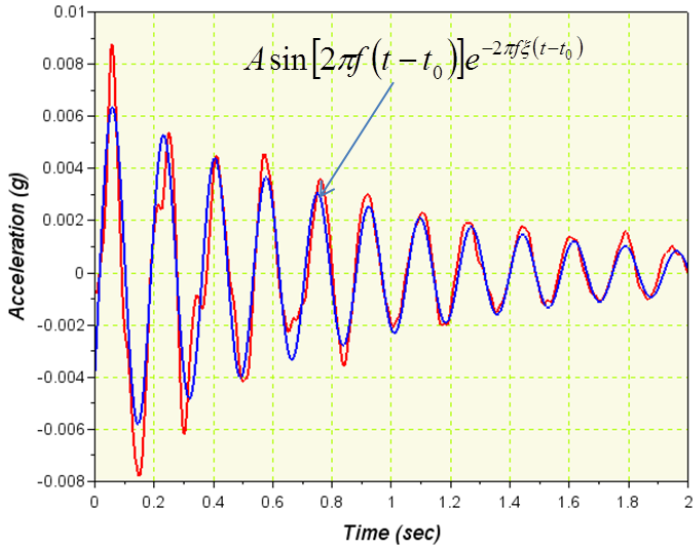

Figure 8 Damped Sine Curve Fit to Heel Drop Transient

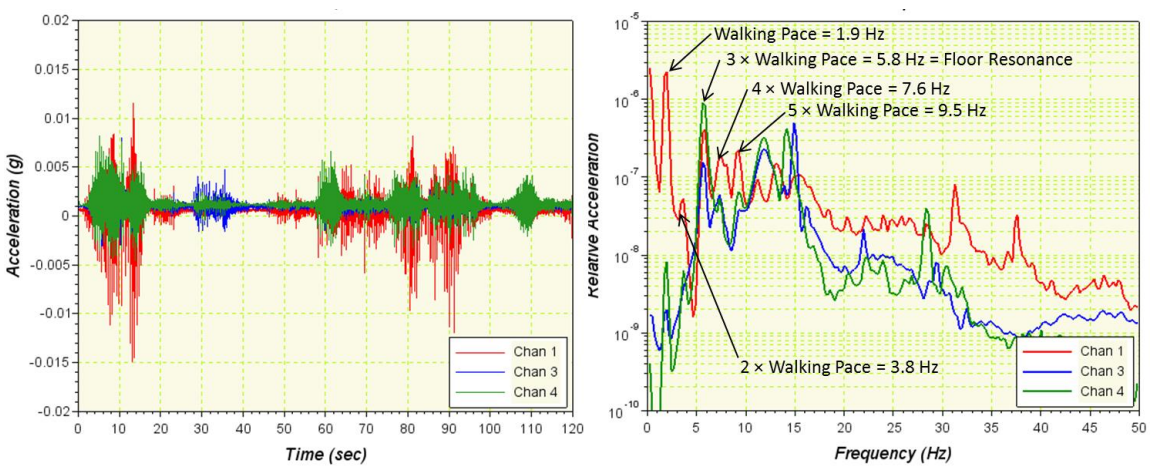

Figure 9 Time Series Acceleration (Left) and Frequency Content (Right) While Walking

The 2-Hz vibration reported by the acoustics firm is most likely the walking pace frequency of the staff taking the data or others who might have been walking around the space as the data were being collected. In any event, the data obtained in the present effort confirm that the 2-Hz vibration is not a structural mode of the floor system, but does represent the elastic response of the floor to downward forces generated while walking. Of the three dominant responses observed in the data (Figure 3), The 2-Hz vibration is caused by people walking on the floor and the "6.3"-Hz vibration is the resonant mode response of the floor system (actually at 5.8 Hz). The 25-Hz vibration is not observed at the locations instrumented for the present investigation.

Occupants of the second floor feel the vertical motion of the floor as others walk through the space and between the cubicles. The fourth accelerometer, Channel 2, is oriented to measure the horizontal component of vibration and is located at the north end of the bottom chord of the midspan joist. One vibration mitigation option

is to attach dampers between the joist bottom chord and the supporting girder. As the joist deflects downward in response to people's movement above, the bottom chord of the joists translate horizontally toward and away from the girder. A bottom chord-mounted damper would provide an opposing force proportional to the velocity to reduce the motion. The magnitude of the horizontal displacement and velocity of the bottom chord that occurs as people walk on the floor is critical for evaluating the potential benefit that bottom chord dampers might provide. The displacement/velocity time history obtained from Channel 2 while walking on the second floor is plotted in Figure 10. The displacement should be a maximum when the velocity is a minimum and vice versa.

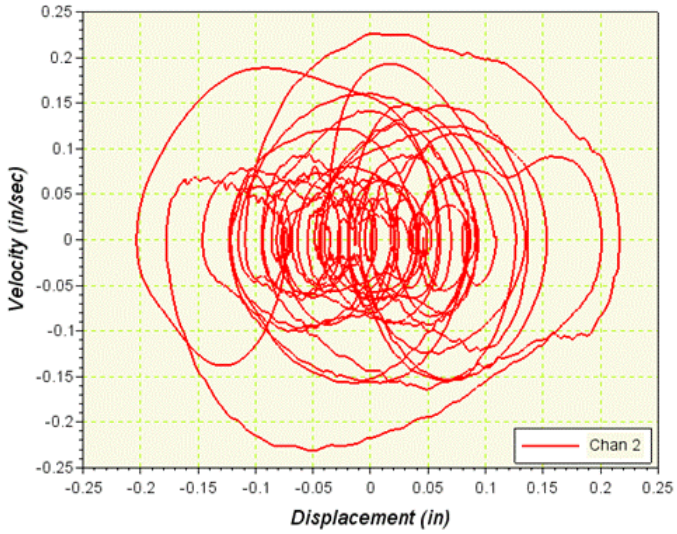

Figure 10 Horizontal Joist Bottom Chord Motion Due to Walking

3.3 VIBRATION MEASUREMENTS ON SECOND FLOOR WORKSTATIONS

The vibration measurements obtained from the structural steel members presented in the previous section are primarily intended to better understand the structural dynamics properties of the floor system. Additional vibration measurements are obtained at the workstations of occupants most likely to experience the floor's vibration as others walk through the space. These measurements are intended to document the vibration levels relative to established criteria for acceptable vibration in an office environment and to serve as the baseline for comparison with the post-mitigation environment. One of the primary reasons for acquiring data on the desks, rather than the access floor system, is to avoid localized anomalous acceleration responses produced by the access floor that people would not generally be aware of.

The second floor of the building in the area of concern is a typical open office plan populated with cubicles that have roughly 4-ft-high interlocking panels that support the desks/working surfaces. Two views of the area are provided in Figure 11. The main east/west corridor (left-hand side of Figure 11) is the high traffic zone and likely the source of most of the vibration. The cubicle area just to the north is where the maximum vibration levels are perceived. The workstation pictured in the right-hand side of Figure 11 (where the printer is) is not currently occupied because the vibration levels have been so annoying. The CFMS wall along the north boundary of the bay is also visible in this picture.

Figure 11 Second Floor in Area of Vibration Complaints: Main Corridor (Left) and Peak Vibration Area (Right)

A furniture layout for this area of the building in provided in Figure 12. The red arrows with "L" and "R" show the locations from which the left- ("L") and right-hand ("R") photographs in Figure 11 were taken. The green lines represent ceiling height non-structural CFMS walls in the area. The only CFMS wall that has a direct effect on the dynamics of the bay in question is the one that runs along the north boundary. The four accelerometers are repositioned from the steel structure below to the workstations identified in Figure 12. The new locations of Channels 1, 2, and 4 are almost directly above the previous locations of Channels 3, 1, and 4, respectively, discussed in the previous section. Most complaints come from the locations where Channel 2 and Channel 3 are now located. The person sitting where Channel 1 is shown is essentially sitting on the north girder and does not experience joist motion. Likewise, the person sitting where Channel 4 is shown is sitting on the south girder and, to a small degree, on the joist in the next bay to the south.

Vibration data are recorded while walking around the space (main corridors and between cubicles) at 116 steps per minute (1.9 Hz). The acceleration time series for the four channels are plotted in the left-hand side of Figure 13 and the corresponding acceleration spectra are plotted in the right-hand side of Figure 13. Peaks corresponding to many of the walking harmonics are visible in the spectra. The fundamental walking harmonic at 1.9 Hz is not nearly as prominent in these data (Channels 2 and 3, in particular) as it is in Figure 9 at the joist midspan. Other than the absence of a prominent walking pace spectral peak, the maximum response at all locations corresponds to the fundamental floor resonance frequency at 5.8 Hz. A relatively significant response in Channel 2 is seen near 25 Hz, which agrees to some extent with the original findings, except that the magnitude of the 25-Hz vibration was higher than any other response in the original data. Nevertheless, the presence of the 25-Hz response does suggest a cause/effect relationship with the access floor.

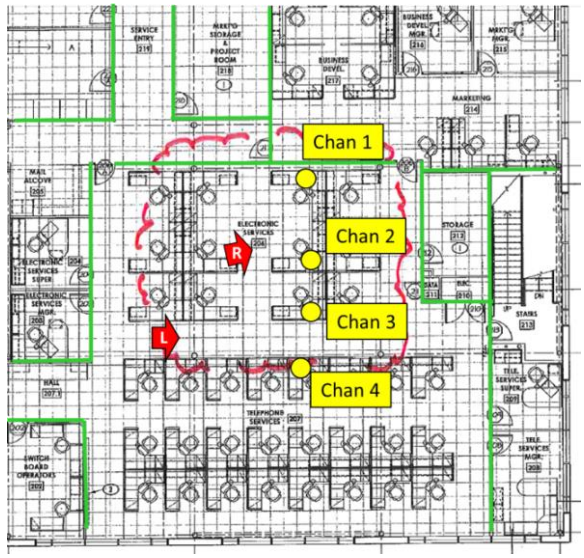

Figure 12 Furniture Plan, CFMS Walls, and Accelerometer Locations on the 2nd Floor

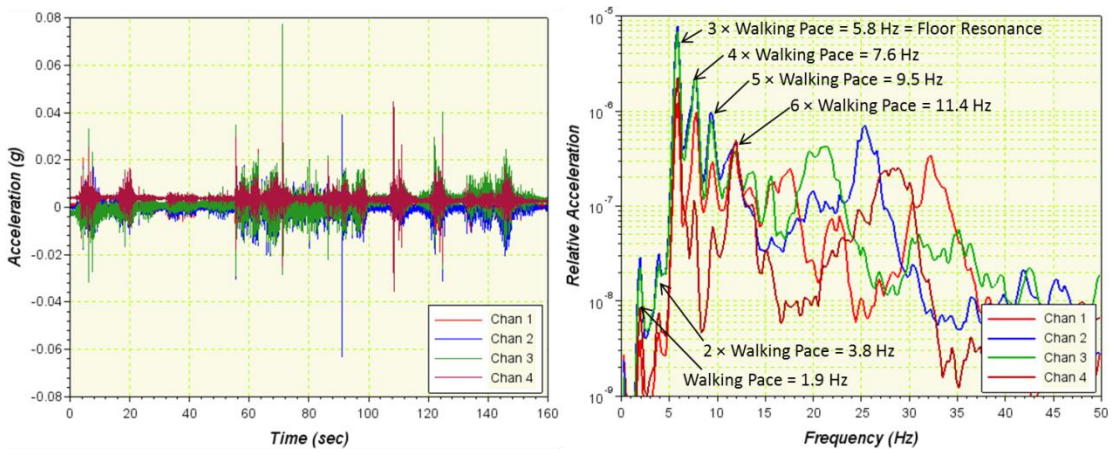

Figure 13 Walking-Induced Vibration: Time Series (Left) and Acceleration Spectra (Right)

Vibration criteria for an office-type occupancy are well documnted. The ISO standard accounts for multi-frequency response by considering the vibration in proportional bandwidths that increase in width with the center frequency of the band ($1.23 \times f_{ctr}$). The root mean square (RMS) vibration level in 1/3-octave bands is computed and assessed relative to the "Office" line plotted in the left-hand side of Figure 14. The 180-second long data series is analyzed in 1-sec-long data segments and the RMS acceleration is computed for a continuously-sliding 1/3-octave band and plotted in the figure as a single orange line. This time window is then shifted by 0.5 seconds and the next 1 seconds of data are analyzed. Each orange line represents a 1-sec snapshot of the vibration. This process results in over 360 lines (the orange "band"), from which the maximum response envelope is identified that bounds the total response history (the thick blue line). Where the envelope line crosses the "Office" line is where the vibration exceeds the preferred limit for an office. This occurs between 5 Hz and about 12 Hz. The "Perception" line represents the vibration level than most people can perceive as vibration. According to this interpretation, vibration can be felt from about 4 Hz to 30 Hz. The "Perception" standard is often used for hospital operating rooms and so is not considered a practical limit for office spaces.

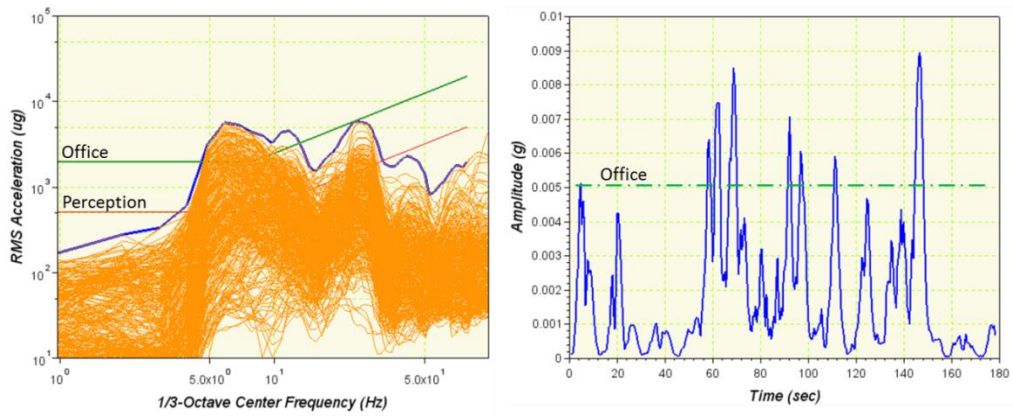

Figure 14 Channel 2 Vibration Response per ISO Criterion (Left) and AISC DG11 Criterion (Right)

The DG11 criterion essentially assumes the source of the excitation is harmonic (*i.e.*, operates with a single frequency) and specifies a peak g-level for different occupancies. An upper bound on permissible acceleration for office-type occupancies is 0.005 g. This criterion is not ideal for real-world data because most real-world sources of vibration, excluding rotating machinery, are fairly broadband in nature. Nevertheless, this criterion is used here for the sake of completeness. For this application, the Fourier transform of the time series is computed over the same 1-sec segments discussed above and the maximum response between 4 Hz and 8 Hz (the 5.8-Hz resonance frequency falls within this band) is plotted versus time in the right-hand side of Figure 14. There are several occurrences where the peak vibration exceeds the 0.005-g limit to a significant degree. Both criteria agree in the sense that the measured vibration exceeds the normally-accepted limits for vibration in an office environment and confirm the original findings for the site as well. The primary cause of the excessive vibration is direct excitation of the fundamental floor resonant mode by the third harmonic of the walking pace. There are additional contributors that tie back to the access floor construction and its tendency to amplify the forces at the fundamental walking frequency (about 2 Hz) and in the higher walking harmonics.

4. VIBRATION MITIGATION

The recent site survey confirms the findings of the original vibration survey and the qualitative assessment of the occupants in this area of the building: vibration levels exceed the commonly used limits for vibration in an office environment and vibration mitigation is warranted. There are a number of contributors to the vibration environment including the direct response of the floor system at the walking frequency and many of its harmonics, the third harmonic magnified by the fundamental floor vibration mode, and possibly higher-frequency modes at 11.8 Hz and 25 Hz. Joist bottom chord dampers are evaluated as a possible mitigation option for the lower frequency walking harmonics and tuned-mass dampers (TMDs) are evaluated to mitigate the vibration caused by resonant floor mode amplification of walking-induced vibration—the largest source of high vibration.

4.1 JOIST BOTTOM CHORD DAMPER

Joist bottom chord dampers are evaluated to determine if they can provide a broad-band benefit where the TMDs operate over a very narrow frequency band. The concept of the bottom chord damper is shown in Figure 15. Ideally, the damper only produces an axial force proportional to velocity and no force proportional to displacement. Joist bottom chords are not designed to support significant compressive forces as would be produced if a solid steel member were placed between the girder web and the joist bottom chord (force proportional to displacement). In this case, the force must be transmitted through a viscoelastic layer which will protect the joist chord from excessive compression forces.

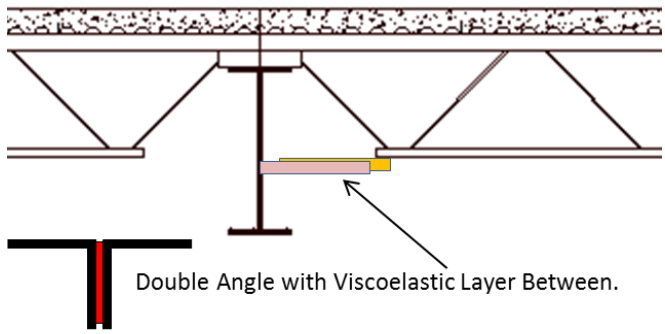

Figure 15 Joist Bottom Chord Damper Concept

A simple model of the floor system is created to assess the contribution of joist bottom chord dampers attached at both ends of the joist as a dynamic force is applied at joist midspan. A typical damper might have a damping coefficient of 270 lbf/in/sec. The maximum horizontal tail velocity of a joist is measured at around 0.25 in/sec (per Figure 10) while walking on the second floor. This velocity will produce a maximum force of only 67 lbf for a normal walking pace. The hope is that the joist bottom chord dampers might be able to reduce the quasi-static (much lower than the resonance frequency) response of the floor at the typical walking pace. The deflection of a joist to the force exerted by a person at midspan in the first walking harmonic, δ_P, and the opposing deflection produced by a joist bottom chord damper, δ_D, are given by

$$\delta_P = \frac{WL^3}{96EI} \quad and \quad \delta_D = \frac{F_D d L^2}{8EI} \qquad \frac{\delta_D}{\delta_P} = \frac{12F_D d}{WL} \approx 0.11 \tag{1}$$

The ratio of the quasi-static displacements provides a rough estimate of the benefit provided by the joist bottom chord dampers. Using the geometry of the joists at the site and estimated damping force determined from the measure joist bottom chord motion, joist bottom chords will only provide about a 10% reduction in the joist displacement (and Acceleration). As 90% of the motion would remain, the joist bottom chord dampers are not considered to be efficient enough to warrant their fabrication and installation cost.

4.2 TUNED-MASS DAMPER DESIGN

The heel drop test results provide valuable insight into the primary vibration modes of the floor system. A finite element-based structural dynamics model of the structure is required to provide additional insight into the floor's vibration characteristics that can then be incorporated into a lower-order model of the floor system for assessment of the TMD mitigation option. SAP2000 is used to model the east side of the second floor as shown in Figure 16. The stiffness and distributed mass along the north girder are increased to account for the presence of the CFMS wall and fully composite stiffness properties of the joists are assumed. No moment continuity between the girders and the columns or between the joists on either side of the girder support is assumed. A superimposed mass of 20 lbm/ft^2 is assumed to account for the occupants, the raised access floor, and the cubicles. The computed 1st mode resonance frequency is 5.85 Hz, which agrees with the measured frequency and the relative response amplitudes shown in the figure are in general agreement with the relative magnitudes measured during the heel drop tests.

Figure 16 Finite Element Model and 1st Floor Vibration Mode

A reduced degree of freedom structural dynamics model is developed from the finite element model for the purpose of identifying TMD properties and to predict the vibration mitigation obtained from the TMDs. A 5-degree-of-freedom (5-DOF) dynamics model is shown in Figure 17. Degrees of freedom q_1, q_2, and q_3 describe the floor deflection (q_1 and q_2 represent the deflection of the north and south girders, respectively, and q_3 represents the additional deflection associated with bending of the joists). Degrees of freedom q_4 and q_5 describe the motion of the TMDs relative to the floor. Based on the floor vibration survey, the north girder does not exhibit as much motion as the south girder and joist midspan; hence, the most effective locations for the TMDs is at joist midspan and at midspan of the south girder.

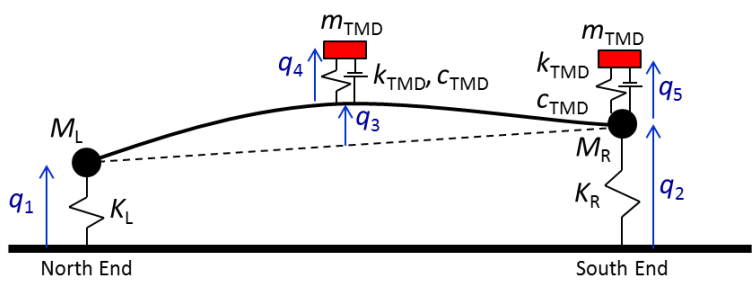

Figure 17 Five-Degree-of-Freedom Floor Dynamics Model

The mass of the TMDs, m_{TMD}, governs the level of vibration mitigation provided by the TMDs. The stiffness of the TMDs, k_{TMD}, is selected in combination with the mass to provide the TMD tuning frequency, f_{TMD}, per

$$f_{TMD} = \frac{1}{2\pi}\sqrt{\frac{k_{TMD}}{m_{TMD}}} \tag{2}$$

The tuning frequency that optimizes the vibration mitigation provided by the TMDs is slightly lower than the floor's resonance frequency depending upon the TMD mass and damping coefficient given by

$$c_{TMD} = 2\xi\sqrt{k_{TMD}m_{TMD}}\ , \tag{3}$$

where ξ is the percent critical damping. Typical achievable values for ξ fall in the range of 0.10 to 0.15.

The equations of motion are derived for the 5-DOF model shown in Figure 17 using Lagrange's Equations and provided as the coupled system of 2nd order ordinary differential equations shown in Equation (4) for a dynamic force applied at joist midspan. The spring stiffness at the north and south ends is derived from the flexural stiffness of a 28-ft-long W24x68 steel beam. The stiffness of the north beam and the lumped mass, M_L, is increased to account for the stiffening and mass effect of the CFMS wall at that end of the bay.

$$\begin{bmatrix} \left(M_L+\frac{m_{TMD}}{4}+\frac{L\mu}{3}\right) & \left(\frac{m_{TMD}}{4}+\frac{L\mu}{6}\right) & \left(\frac{m_{TMD}}{2}+\frac{L\mu}{\pi}\right) & \frac{m_{TMD}}{2} & 0 \\ \left(\frac{m_{TMD}}{4}+\frac{L\mu}{6}\right) & \left(M_R+\frac{5m_{TMD}}{4}+\frac{L\mu}{3}\right) & \left(\frac{m_{TMD}}{2}+\frac{L\mu}{\pi}\right) & \frac{m_{TMD}}{2} & m_{TMD} \\ \left(\frac{m_{TMD}}{2}+\frac{L\mu}{\pi}\right) & \left(\frac{m_{TMD}}{2}+\frac{L\mu}{\pi}\right) & \left(m_{TMD}+\frac{L\mu}{2}\right) & m_{TMD} & 0 \\ \frac{m_{TMD}}{2} & \frac{m_{TMD}}{2} & m_{TMD} & m_{TMD} & 0 \\ 0 & m_{TMD} & 0 & 0 & m_{TMD} \end{bmatrix} \begin{Bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \\ \ddot{q}_3 \\ \ddot{q}_4 \\ \ddot{q}_5 \end{Bmatrix} + \begin{bmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 \\ c_{21} & c_{22} & c_{23} & 0 & 0 \\ c_{31} & c_{32} & c_{33} & 0 & 0 \\ 0 & 0 & 0 & c_{TMD} & 0 \\ 0 & 0 & 0 & 0 & c_{TMD} \end{bmatrix} \begin{Bmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \\ \dot{q}_4 \\ \dot{q}_5 \end{Bmatrix} + \begin{bmatrix} K_L & 0 & 0 & 0 & 0 \\ 0 & K_R & 0 & 0 & 0 \\ 0 & 0 & \frac{EI\pi^4}{2L^3} & 0 & 0 \\ 0 & 0 & 0 & k_{TMD} & 0 \\ 0 & 0 & 0 & 0 & k_{TMD} \end{bmatrix} \begin{Bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \\ q_5 \end{Bmatrix} = \begin{Bmatrix} -1 \\ -1 \\ -2 \\ 0 \\ 0 \end{Bmatrix} \frac{F(t)}{2} \tag{4}$$

The damping matrix is formed as a composite. A uniform modal damping coefficient of 3% is assumed for the 3-DOF model of the floor alone (no TMDs) based on the measured damping coefficient discussed relative to Figure 8. The coupled damping matrix in physical coordinates is obtained using the modal matrix and the diagonal modal damping matrix via $[C_{Physical}] = [R^T]^{-1}[C_{Modal}][R]^{-1}$. The resulting 3x3 matrix of damping values is placed in the upper left 3x3 space shown in Equation (4). The additional damping terms are the discrete dampers, c_{TMD}, that are an essential part of the TMD and determined from Equation (3). The dynamic force applied in the model [right-hand side of Equation (4)] is applied at the most dynamically sensitive location at the joist midspan.

The coupled differential equations must be solved numerically to evaluate the response of the floor with and without the TMDs. Numerically efficient modal superposition techniques cannot be used to solve these equations because the damping matrix, with the c_{TMD} parameters included, will not be diagonalized by the modal matrix. Equations (4) must be solved via direct numerical integration. The equations are implemented in SciLab 5.5.1 and the built-in **ode( )** solver is used to obtain the time series response of the structure to a simulated heel drop event. The response and heel drop pulse are converted into the frequency domain and divided (response/input) to obtain the frequency response of the structure with and without the TMDs. The comparison is shown in the Left-hand side of Figure 18 with f_{TMD} = 5.7 Hz and ξ = 0.15.

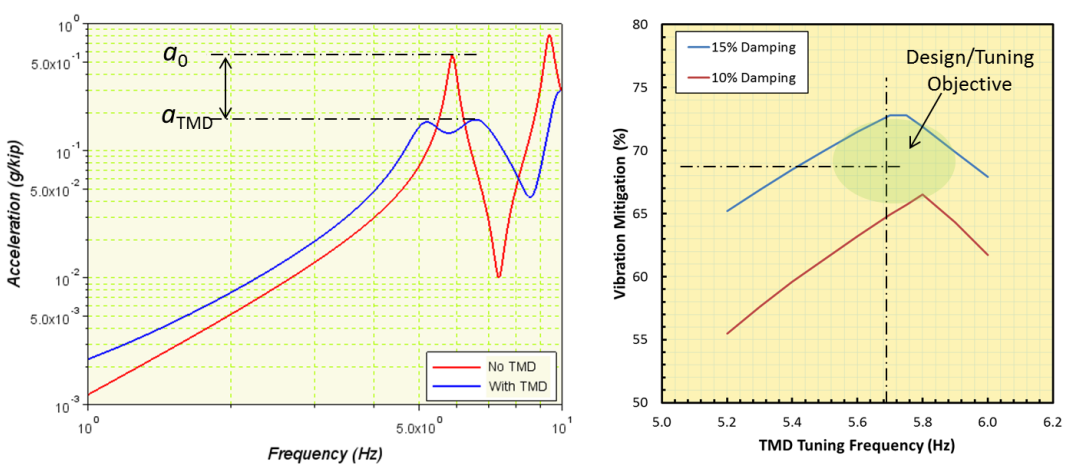

Figure 18 Frequency Response Characteristics (Left) and TMD Efficiency (Right)

The addition of the TMDs tuned very close to the floor mode resonance frequency produces two modes. One of the modes has the TMD mass moving in phase with the floor at the lower frequency and out of phase at the higher-frequency mode. The two peaks in the blue curve in the left-hand side of Figure 18 are the resonance

frequencies of these in-phase and out-of-phase modes. The vibration mitigation provided by the TMDs can be estimated from the difference in peak response of the floor without TMDs, a_0, and the maximum response of the floor with the TMDs, a_{TMD}, per

$$Mitigation\ Efficiency = 1 - \frac{a_{TMD}}{a_0}. \tag{5}$$

If the maximum floor acceleration in the vicinity of the original floor mode frequency is equal to the floor acceleration before the TMDs are added, the calculated Mitigation Efficiency per Equation (5) is 0%--no mitigation. If the maximum acceleration of the floor is 0 g after adding the TMDs (impossible), the mitigation efficiency is 100%. Hence, the Mitigation Efficiency varies between 0% and 100%. The mitigation Efficiency for two practical TMD damping factors is plotted for a range of TMD tuning frequencies near the ideal tuning frequency in the right-hand side of Figure 18. A green oval is drawn to indicate the range of tuning frequencies and resulting vibration mitigation than can be achieved with a TMD mass of m_{TMD} = 1300 lbm. The goal of the TMD design effort is to produce physical TMDs that provide this mass, tuning frequency (stiffness), and damping. The practical maximum vibration mitigation that is possible for a reasonable TMD mass falls between 65% and 70%.

A TMD can take many forms. The design objective is to provide the mass, stiffness, and damping properties required to achieve the vibration mitigation objective and to maximize the ease of installation. In this case, there is a raised floor and the slab below is essentially clear of any obstructions, so the TMDs can be simply placed on the slab under the raised floor. A side view of a typical TMD is shown in Figure 19. The TMD mass is in the form of ten 12 in by 19 in 1-inch-thick steel plates (64 lbm each) that slide onto the ends of the two flexure bars. The plates can be positioned to adjust the flexibility of the bars, which controls the TMD resonance frequency.

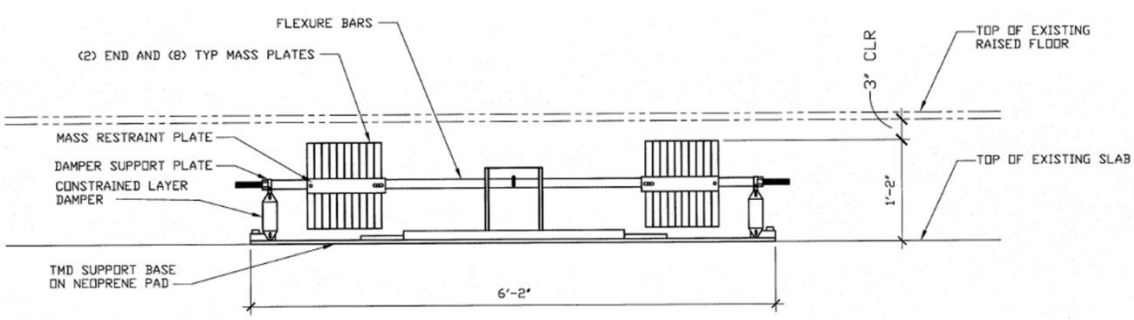

Figure 19 TMD Design Elevation

Constrained-layer dampers are attached to each end of the flexure bars to provide the desired level of damping. The constrained layer dampers are constructed from two 16-gage plates with a viscoelastic layer sandwiched between the two plates. The viscoelastic element is a 3-in wide by 0.5-in high by 0.5-in thick block of E-A-R ISODAMP C-1002. Damping is provided by shearing the viscoelastic material across the 0.5-in thickness. The damper also adds stiffness to the system which must be compensated for by increasing the flexibility of the flexure bar-mass system (*i.e.*, sliding the mass farther out along the flexure bars). This damper construction provides a typical damping factor of around 12% which is within the target design range considered in the right-hand side of Figure 18.

Four TMDs are fabricated per the design shown in Figure 19 by Johnston Products of Dallas. The four TMDs are placed within the bay in question as shown in Figure 20. This arrangement is consistent with that shown in the dynamics model in Figure 17. No TMDs are placed on the north girder because the CFMS wall effectively reduces the motion of that girder relative to the joist midspan and south girder. The nominal weight of the TMD is documented as 1600 lb; however, the sprung weight (effective TMD mass) is about 1300 lbf per TMD.

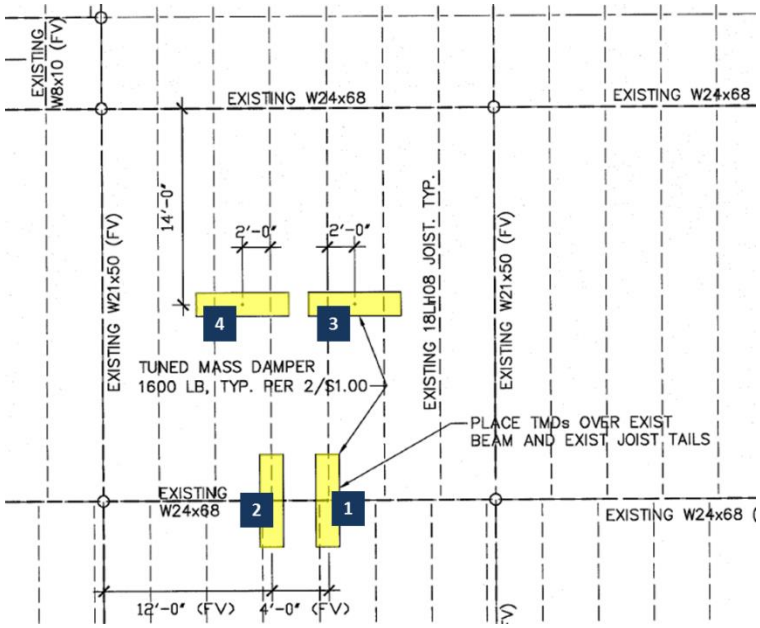

Figure 20 TMD Placement Within the Building

4.3 TMD INSTALLATION AND TUNING

The TMD components were delivered to the site on October 1, 2015 and installed on the floor slab as shown in Figure 20 on October 3 by a local general contractor, Jones and Roberts Company. TMDs 3 and 4 are shown in their installed locations in the left-hand side of Figure 21 and a close up of one of the constrained-layer dampers is shown in the right-hand side of Figure 21. Installation only required about 4 hours. The contractor also installed plastic pedestal head gaskets (manufactured by Tate Access Floors, Inc.) on top of floor pedestals supporting panels in the primary walking path. These gaskets can be seen in Figure 21 as the black "+" elements on top of the pedestals.

Final tuning of each TMD required the rest of the day and the morning of October 4. Tuning the TMDs requires placing accelerometers on top of the mass plates above the center of mass of the 10-plate mass and tapping the outer-most mass plate with a rubber-headed mallet. The transient response of the TMD mass is recorded with the DAQ system and the data are analyzed using the same approach represented in Figure 8. The length of the threaded bar shown in the right-hand side of Figure 21 that projects from the end of the flexure bars to the outer-most mass plate is used to set and maintain the position of the mass plates. If the measured resonance frequency is significantly higher than the target tuning frequency of 5.7 Hz, the length of the threaded bar is reduced and the mass plates are pulled farther out and the impact test is repeated. If the resonance frequency is significantly lower than 5.7 Hz, the length of the threaded bar is increased and the plates are pushed toward the center. Once the plates are positioned correctly, mass restraint plates are attached to each side of the TMD mass to prevent the individual plates from vibrating free of one another and causing a "clanking" sound.

The TMD tuning results for both sides of TMD 1 (see Figure 20) are shown in Figure 22. The north end of the TMD performs as expected with a final resonance frequency of 5.6 Hz (close enough to the 5.7 Hz target) and a critical damping factor of 12%. The south end TMD shows anomalous results with a much higher than desired resonance frequency of 7.4 Hz and lower than desired damping factor of 6%. Both sides of the TMD are identical and the south end result is considered to be temporary and should correct itself after it has had time to "wear in" over time.

Figure 21 TMDs 3 (Far) and 4 (Near) In Place (Left) and TMD Constrained-Layer Damper (Right)

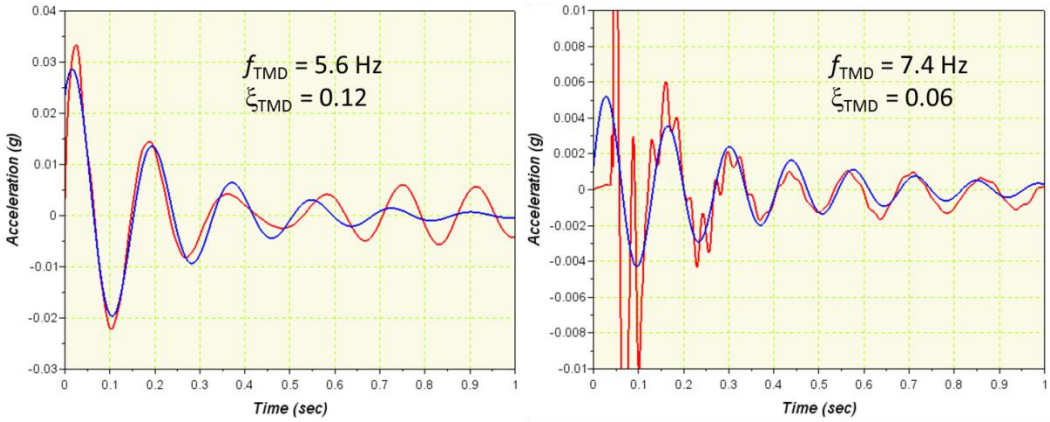

Figure 22 TMD 1 Tuning Performance, North End (Left) and South End (Right)

The tuning results for the remaining three TMDs are provided in Figure 23, Figure 24, and Figure 24. The results are very consistent with final tuned resonance frequencies falling between 5.6 Hz and 5.9 Hz and critical damping factors between 5% and 14%. On average, the TMDs satisfy the tuning objectives and the overall design objective and should provide 60% to 70% vibration mitigation per the performance assessment shown in the right-hand side of Figure 18.

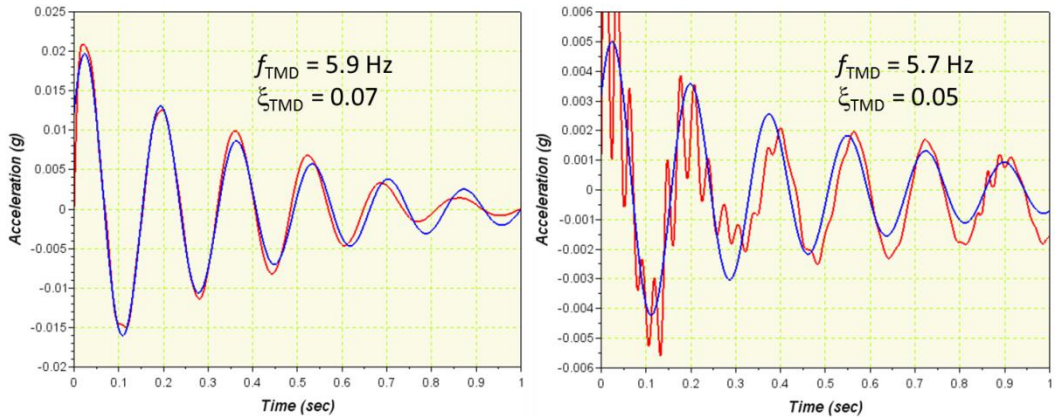

Figure 23 TMD 2 Tuning Performance, North End (Left) and South End (Right)

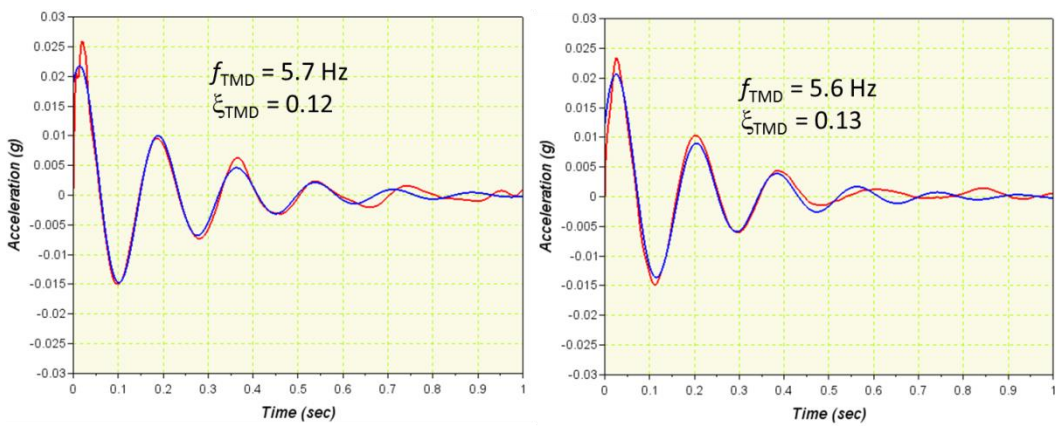

Figure 24 TMD 3 Tuning Performance, West End (Left) and East End (Right)

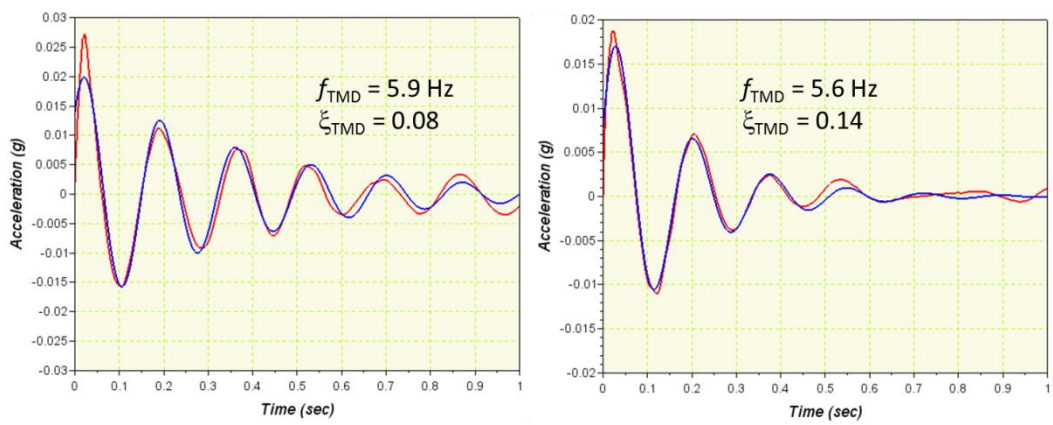

Figure 25 TMD 4 Tuning Performance, West End (Left) and East End (Right)

4.4 POST-INSTALLATION VIBRATION RESPONSE

Accelerometers are placed at the locations where the maximum vibration was recorded during the site survey on July 27. Channel 1 is placed where Channel 3 is shown in Figure 12 and Channel 2 is placed at the same location as shown in Figure 12. Once again, the cell phone metronome app is used to set a walking pace of 116 steps

per minute (5.8 Hz/3) and data are recorded while walking back and forth (north and south) within the high-vibration cubicle area. The data are evaluated with the ISO and DG11 criteria and are plotted in the left- and right-hand sides, respectively, of Figure 26. The RMS vibration level at 5.8 Hz (the TMD target frequency) has dropped below the 0.002 g_{RMS} limit to 0.0015 g_{RMS}. The peak vibration envelope does exceed the office criterion near 7.6 Hz, but this is not at the frequency where the TMDs were designed to mitigate. The 7.6 Hz vibration is the 4th walking harmonic (Figure 13) and is more pronounced in these data because the very brisk walking pace exaggerates the vibration response at the walking harmonics and the floor's resonance frequency.

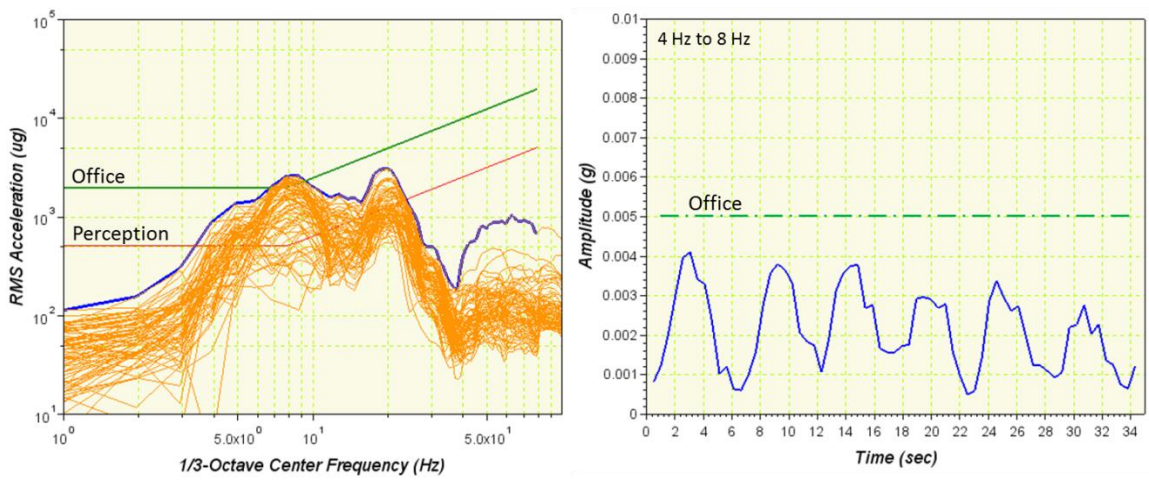

Figure 26 Walking Within Cubicle Area per 1/3-Octave Criterion (Left) and AISC DG11 Criterion (Right)

The AISC criterion (right-hand side of Figure 26) shows that the peak acceleration amplitude between 4 Hz and 8 Hz reaches a maximum of only 0.004 g and does not exceed the 0.005-g limit. The 7.6-Hz vibration noted in the ISO assessment is included in this DG11 assessment and does not exceed this criterion.

A separate data acquisition period addresses walking back and forth (east and west) along the main corridor (left side of Figure 11) where most of the office traffic occurs. The vibration assessment for the ISO criterion is plotted in the left-hand side of Figure 27 and the assessment relative to the DG11 criterion is provided in the right-hand side of Figure 27. As expected, the vibration levels are lower in the cubicle area because the additional footfall response of the joist is not present when the walking path follows the girder span direction rather than the joist span direction.

The worst-case vibration envelope in the ISO assessment falls below the office limit across the frequency spectrum, even at the 7.6-Hz walking harmonic. The vibration levels assessed relative to the DG11 criterion also fall below the office limit of 0.005 g and are 25 percent lower than the levels measured when walking is confined to the cubicle area. Satisfying the vibration criteria for an office-type occupancy does not imply that vibration can no longer be felt in the space. The measured vibration exceeds the "perception" line shown in the ISO assessment graphs, so the building's occupants in this area will still feel vibration.

The pre- and post-mitigation vibration assessments based on the ISO criteria are compared side-by-side in Figure 28, respectively. Before mitigation, the peak vibration at the floor's resonance frequency was 5694 μg_{RMS}. The peak walking-induced vibration at 5.8 Hz is significantly reduced to 1460 μg_{RMS} with the TMDs in place. This comparison suggests that the TMDs have reduced the vibration by 75%, which is the maximum benefit one can expect from TMDs. Alternatively, one could assess the vibration mitigation using the DG11 criterion where

the peak vibration dropped from 0.009 g to 0.004 g, for a 55% reduction in the vibration. A fair assessment for the mitigation provided by the TMDs falls in the 60% to 70% range, which is very good.

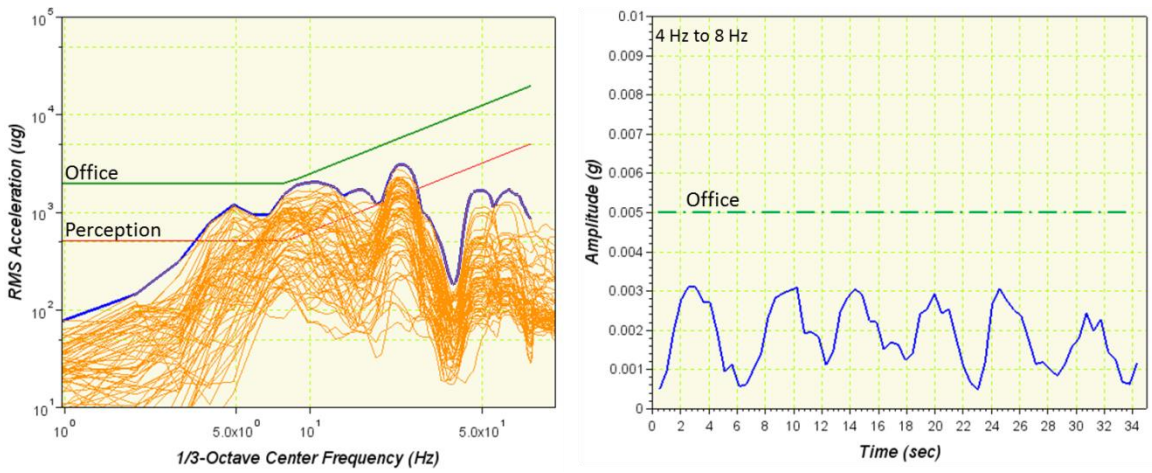

Figure 27 Walking Within Corridor per 1/3-Octave Criterion (Left) and AISC DG11 Criterion (Right)

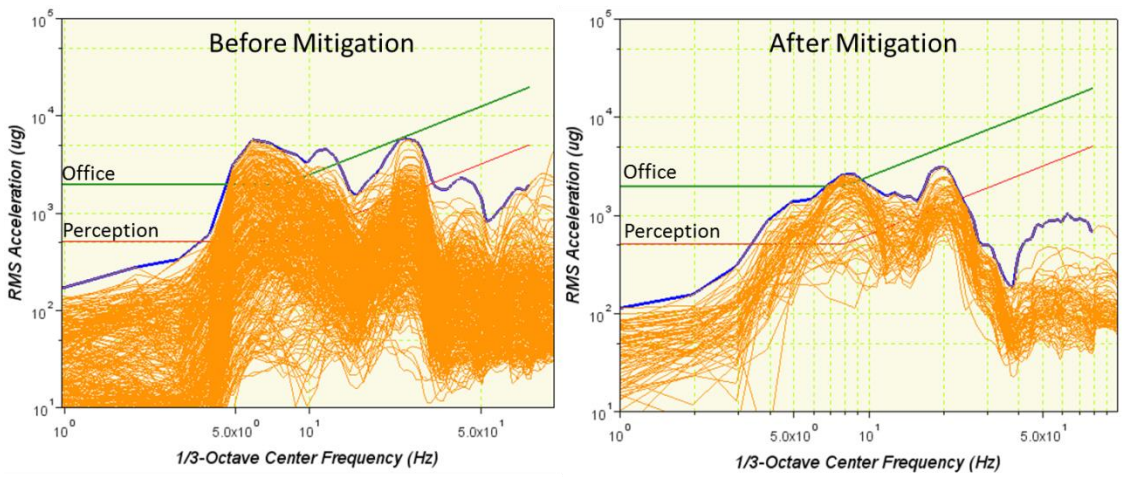

Figure 28 Comparison of Pre-Mitigation Environment (Left) and the Post-Mitigation Environment (Right)

5. CONCLUSIONS AND RECOMMENDATIONS

The vibration mitigation effort successfully reduces the vibration caused by the low-damped primary resonant mode by 60% to 70%. This floor system is very responsive to occupant activity as indicated by the original and more recent vibration surveys, and the significant reduction of the vibration provided by the TMDs does not address all of the vibration issues with the floor system. In spite of the significant reduction in vibration, the measured response still exceeds perception threshold (and always will), so people working in the space will continue to feel the floor vibrate. The perception threshold is used for hospital patient and operating rooms and is not the objective for any practical vibration mitigation efforts intended to address this floor system.

Vibration mitigation generally follows one or both of two approaches: (1) alter the dynamic forces (amplitude and/or frequency) applied to the structure and (2) alter the dynamic response characteristics of the structure (resonance frequency and/or damping). Altering the resonance frequency of the structure is very costly and may require structural changes that interfere with the functionality of the floor below. The TMD option selected by building management successfully increases the effective damping characteristics of the floor system. Hence, of the two top-level mitigation strategies, building management has implemented the most practical option associated with altering the structure.

Any further mitigation must focus on altering the forces that cause the vibration. People walk between 96 and 122 steps per minute, so there is no way to change the frequency of the dynamic excitation. Mitigation can only address the magnitude of the dynamic forces transmitted to the floor. The access floor system magnifies forces because there is no cushioning effect offered by the very thin carpet layer and the impact of loose floor panels on the support posts magnifies the forces in the higher frequency walking harmonics that are responsible for exciting the floor's resonant mode and for the 7.6-Hz walking harmonic that is currently responsible for the exceedance noted in Figure 26.

A vibration isolation concept is shown in Figure 29. The walking areas on the floor that people use to walk through the bay in question or to get to their workstations can be altered to incorporate a more resilient walking surface to absorb footfall energy. The current interior floor panel support posts can be replaced with edge post supports that are typically used around the perimeter of the floor. In this concept, the existing interior posts would be replaced with edge posts supporting the same floor panels, but at a lower elevation (say, 1 inch below the current access floor height. A viscoelastic pad could then be placed on the depressed floor panels to bring the finished elevation back to that of the adjacent panels. The carpet tiles would overlap the interface between panels as they do now, so there would be no outward sign of a difference. The resilient pad will cushion each footfall as people walk through the space which will significantly reduce the magnitude of the forces transmitted to the higher walking harmonics responsible for much of the remaining vibration.

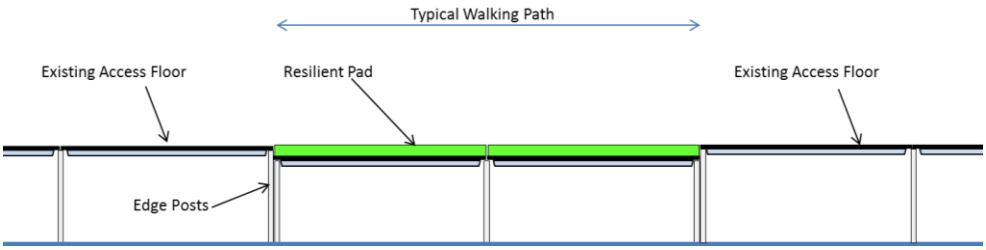

Figure 29 Vibration Isolation Concept in Typical Walking Areas

6. REFERENCES

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