



GARAGE STRUCTURE VIBRATION TRANSMISSION TO HUMAN OCCUPIED SPACES

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Abstract

Parking garages designed to be separate, stand-alone structures are often very limber, longer-span structures with low resonant frequencies. They exhibit vibration characteristics ill suited for office, residential, hospital or other human occupancies. Expansion or extension of the garage structure for a proposed human occupancy should recognize differences between occupancies or usages and incorporate acceptable floor vibration design parameters.

Three case studies are presented about investigations garage vibration, one for an office expansion above the parking level and two for continuous slab extension from garage to horizontally adjacent residential spaces. . Measurements were conducted to determine resonant frequencies of driveway and parking areas and to determine vibration amplitude spectra for ambient and vehicle pass disturbance conditions. Ambient and disturbed conditions are compared with human perception criteria (re: ISO 2631). Differences between garage driveway “sources” and parking “receiver” locations indicate transmission losses.

Apparent resonant frequency (narrow band) and 1/3 octave amplitude spectra for ambient and disturbed condition are shown. Garage plans and photos are incorporated.

Design implications for structural continuity between garage driveway and parking slabs and adjacent floor slabs for human occupancy are discussed with conceptual methods of reducing vibration amplitudes on receiver slabs for continuous and discontinuous slabs.

INTRODUCTION

Three concrete multilevel garage structures were evaluated for vibration disturbance characteristics that could propagate from driveways to vertically or horizontally adjacent human-occupancy spaces. Vibration spectrum analysis measurements were conducted on garage structural slab surfaces to obtain ambient and vehicle-pass disturbance conditions. Other than controlled events, there was no ambient activity on the measured slabs, although minor transient influences from other areas could

influence ambient levels. Structural responses to heel drop impacts were measured to determine apparent structural resonant frequencies. Simultaneous measurements were conducted on driveways and adjacent parking bays to determine losses for (a) continuous span and (b) separate spans of different length and resonant frequency. Original measurements were conducted for repeated vehicle passes in both directions, using automobiles and light trucks. For this paper, results for each location are logarithmically averaged to simplify presentation. In one garage, decoupled topping slabs and resilient underlayments of varying thicknesses were measured simultaneously with untreated driveway (no decoupled topping) to compare source to receiver losses. Results and conceptual design parameters are presented below.

GARAGE STRUCTURE DESCRIPTIONS

Garage structure plans and measurements locations are shown and described below.

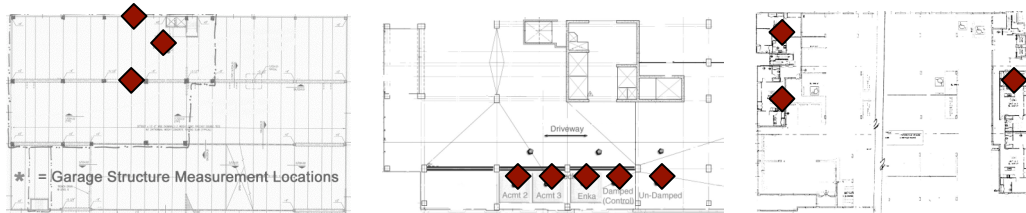


Figure 0,^{1,2,3} A, B & C– Plans: Garage 1 (left), Garage 2 (center) and Garage 3(right)

Garage 1 – Long span double tee-beam

An office structure was proposed to be built on top of an existing concrete parking structure. Steel column extensions would support a steel floor structure above. The existing structure has 11 m (36') long inverted tee beam girders supporting 17.1 m (56'-3") long double tee beams. The double tees are 3.65 m (12') wide and 750 mm (30") deep, with a continuous 70 mm (2.75") lightweight concrete topping on the double tees for total slab thickness ≈ 175 mm (7"). Apparent structural resonance from heel drop impact is 2.5 Hz with a prominent 5 Hz harmonic. The driveway occupies the mid-span of the beams (parallel to girders), with parking spaces on both ends of the tee-beam spans. Measurements were taken on tee beam deck at mid span, near girders and on a concrete column cap that steel extension columns will bear on.

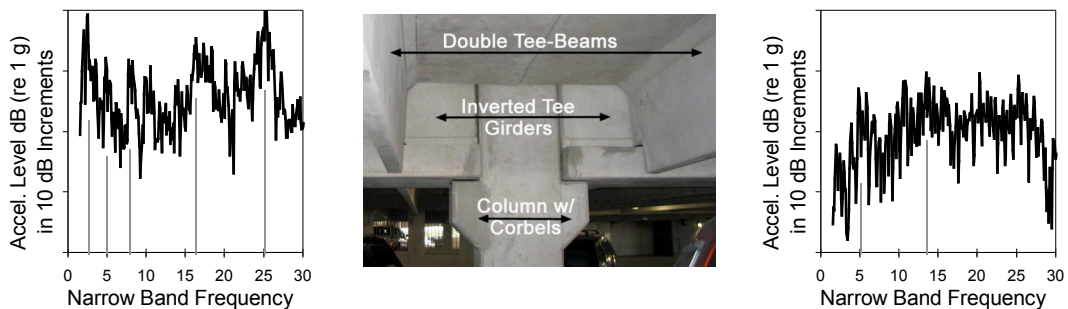


Figure 1, A & B¹– Apparent Resonant Frequencies: (A) Tee-beam deck and (B) Girder beam

Garage 2 – Medium span post-tensioned flat slab

An existing concrete parking structure was used as a proxy, to represent a proposed concrete structure, where the garage driveway and parking slab is to be extended laterally to accommodate residential condominiums on the same slab. The existing structure has columns spaced 8.83 m (29') parallel to the driveway. The driveway bay is 8.6 m (28'-3") wide, and the adjacent parking bay is 4.75 m (15'-7") wide. The post-tensioned (PT) flat slab is 190 mm (7.5") thick for driveway and parking. Apparent structural resonance (measured as response to heel drop) is 9.2 Hz on the driveway "source" and 13 Hz on the parking or "receiver" slab. The driveway lane and parking spaces are on separate bays, separated by columns. Measurements were taken on the driveway bay and in the immediately adjacent parking bay. Although the proposed future facility would have a parking bay between driveway and residential floors, the existing adjacent parking bay was used as a proxy for the future residential floor (on the next bay beyond parking). Concrete masonry units (CMU) were stacked along the column line to provide mass damping on the structure (to simulate) demising partitions. Simultaneous measurements were made on driveway (source) and residential proxy (receiver). Decoupled "receiver" floors were created by installing slabs of 25 mm (1") to 38 mm (1.5") gypcrete on 6-20 mm (1/4"-3/4") thickness nylon filament resilient underlayment. The decoupled slab surface responses were measured for comparison with no decoupled surface.

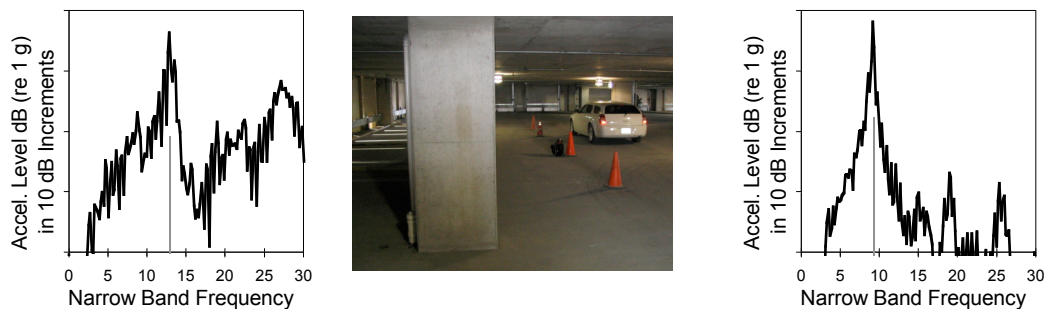


Figure 2, A & B² – Apparent Resonant Frequencies: (A) Parking bay and (B) Driveway bay

Garage 3 – Medium span post-tensioned flat slab

A concrete parking structure was constructed to accommodate wood frame residential apartments above, but also had two apartments each on the east and west outer bays. The garage has one column-supported level above a slab-on-grade level plus one upper slab above parking that the wood-framed apartments are constructed on. The column-supported concrete parking level is extended laterally one additional bay to accommodate two apartments on each end of the building (four total). The post-tensioned (PT) flat slab is 250 mm (10") thick on the east end, with column spacing 9.75 m (32'10") parallel to driveway by 11.57 m (38') driveway bay width and 4.87 m (16') adjacent apartment bay width. Slab thickness is 215 mm (8.5") with irregularly spaced columns. Apparent structural resonance (measured as response to heel drop) is 11 Hz for the 250 mm slab and 12.5 Hz for the 215 mm thick slab.

Walls were not yet constructed on the east end 250 mm slab when measurements were conducted, but CMU demising walls (no interior wood frame partitions) were constructed on the west end 215 mm slab. The driveway lane and parking spaces are on separate bays (column line between). Simultaneous measurements were taken in the driveway bay (source) and in the actual residential bays (receiver, with parking bay between). Simultaneous measurements were also taken on the residential bay (primary receiver) and at the same location on the structural floor bay above (secondary receiver) to determine vertical vibration transmission losses via columns.



Figure 3, A & B³ – Apparent Resonant Frequencies: (A) 250mm and (B) 215 mm PT slabs

VIBRATION PERCEPTION CRITERIA

Vibration levels that are perceptible in office and residential spaces due to intermittent transient disturbances are undesirable, because they may startle or annoy occupants. Velocity level criteria derived from ISO 2631 are commonly used for floor vibration analysis and design.^{4,5,6} Results for the Garage 1 office development were compared with “Office” and “Daytime” perception levels. Residential floor results in Garages 2 and 3 were compared to “Perception Threshold” and “Night” criteria.

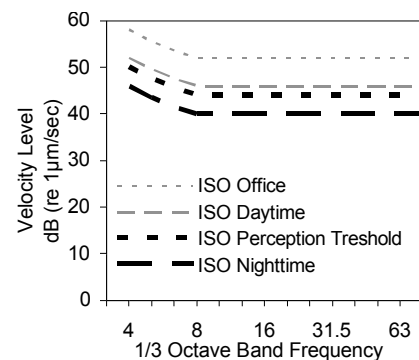


Figure 4, Vibration Criteria (re: ISO)

SOURCE AND RECEIVER VIBRATION LEVELS

The Garage 1 vertical extension project intent was to develop a method of preventing excessive vibration on the proposed floor above due to driveway slab excitation. The Garage 2 and 3 projects were intended to determine whether de-coupled slabs could attenuate driveway vibration at nearby receiver floors and to develop other attenuation measures, respectively. Parking bays adjacent to driveways were measured as proxy indicators of vibration on residential floor bays. Future reaction characteristics were projected for the Garage 1 vertical expansion. Residential floor reactions above and adjacent to vehicle passes were measured in Garages 2 and 3.

Garage 1 – Long span double tee-beam

The existing Garage 1 parking structure rises four stories above ground level. Vertical and horizontal vibration comparison shows that ambient vibration is below perception level in all directions. Vehicle pass vibration raises the vertical vibration level on the existing driveway slab well above ISO “perception threshold” and “office” criteria, but similar deck excitation above the girder beam results in much lower vibration amplitude. Prominent disturbance frequencies are in the 5 and 16 Hz 1/3 octaves.

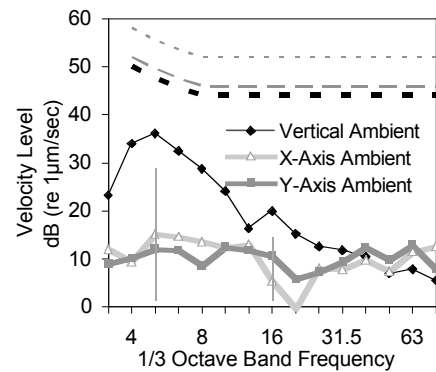


Figure 5 – 3-axis Vibration Comparison

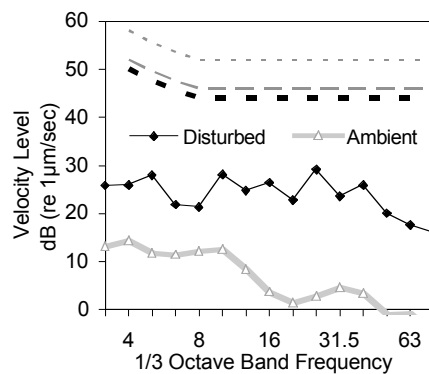
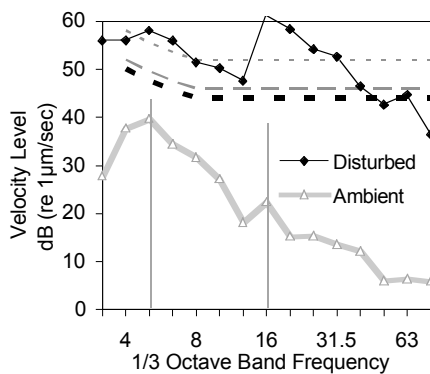


Figure 6, A & B – Ambient vs. Vehicle Pass: (A) Tee-beam Deck and (B) Deck above Girder

The proposed expansion was intended to be a steel beam and composite concrete deck with girder and beam configuration mirroring the existing girder and tee-beam garage layout. A resonant frequency above 5 Hz was recommended for the proposed office floor above the garage to de-tune the proposed office floor from the 2.5 Hz garage resonant frequency and prominent 5 Hz harmonic. The structural engineer was unable to achieve a feasible design with resonant frequency any greater than 3 Hz, due to the long span. A design revision was recommended with girder and beam directions reversed for the office structure, i.e. girders on long dimension and beams on short dimension. This resulted in a more economic structural design than the original proposal and achieved a design resonant frequency of 4 Hz for the office floor, with first harmonic of 8 Hz, which is non-coincident with the garage deck.

Garage 2 – Medium span post-tensioned flat slab

Garage 2 has many levels, with residential floors above. Vertical transmission to residential floors, above is less of a concern than in Garage 1, because shorter structural spans with columns between drive and parking areas yield higher resonant frequencies in the garage slabs. Horizontal transmission from the driveway to residential floors via the continuous structural slab could cause annoyance.

The structural engineer and architect considered using decoupled finish floor slabs in the residential units to isolate vibration. A test was arranged to construct mock-up decoupled slabs with varying thicknesses of finish slab and of resilient underlayment media. Simultaneous measurements were made on the driveway and on the receiver floor areas to determine and compare losses. Two areas with no decoupled slab, one damped with concrete masonry units (CMU) on the column line to simulate a demising wall and one with no damping were measured. Both had disturbance vibration levels above “perception threshold” level at resonant frequency.

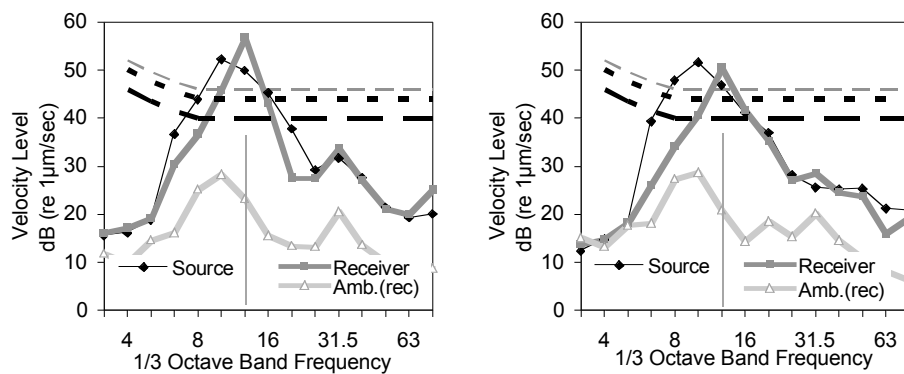


Figure 7, A & B – Ambient + Vehicle Pass on parking (receiver) vs. driveway (source):
(A) undamped slab and (B) slab with masonry damping on column line

Similar measurements on the de-coupled slabs also resulted in large amplitudes at the structural slab resonant frequency, although somewhat lower (below). A chart of vibration reduction (difference between source and receiver velocity levels) shows that the de-coupling provided negative loss (or amplification) at the slab resonant frequency, possibly due to inadequate damping.

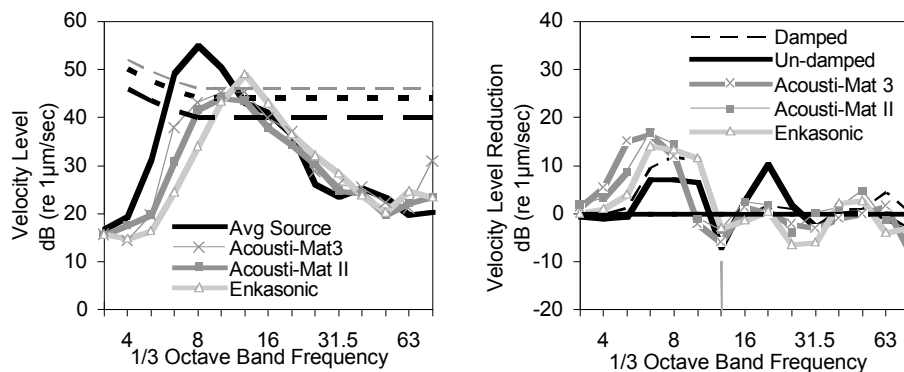


Figure 8, A & B – Vehicle Pass Vibration: (A) Level on de-coupled topping slabs and (B) Reduction on de-coupled slabs. Note negative reduction at slab resonant frequency.

Garage 3 – Medium span post-tensioned flat slab

Garage 3 also was designed and constructed with residential units above the garage, but only units on the same structural slab were of concern. Measurements were

conducted, however, to test horizontal and vertical transmission loss from driveway to adjacent residential floor areas. On the east end of the structure the slab is 250 mm depth and the apartments are in the immediately adjacent bay to the driveway. The west end residential, parking and driveway bays are 215 mm and one parking bay separates the apartments from the drive. In addition, column spacing is irregular.

The thicker-slab east end vehicle-pass floor disturbance from exceeds “perception threshold” but the thinner west end slab is only marginally touching the criterion. Both slabs have similar reinforcing and stiffness. Since resonant frequency is proportional to the square root of stiffness divided by mass,⁷ the deeper, more massive slab has somewhat lower resonant frequency and greater amplitude. The thinner west end is also farther from the source; allowing greater transmission losses.

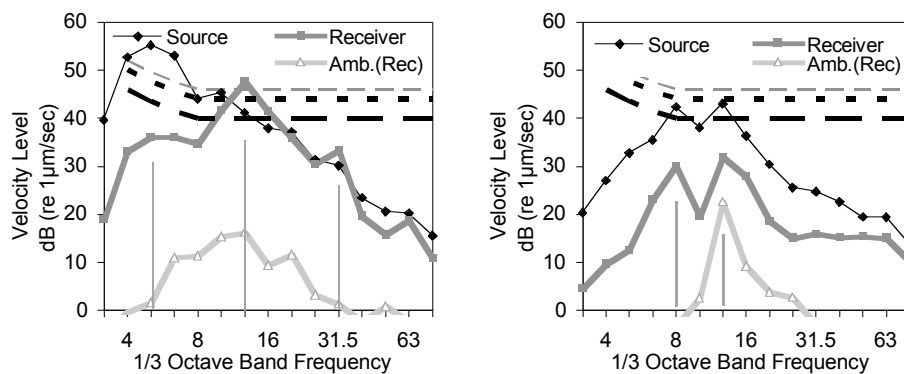


Figure 9, A & B – Ambient + Vehicle Pass on parking bay (receiver) vs. driveway (source): (A) undamped 250mm slab adjacent to drive and (B) damped 215 mm slab 1 bay from drive

Simultaneous measurements on garage level residential floor bays and identical locations on the structural slab above show vertical vibration reduction (via columns). Even at structural resonant frequencies, vibration reduction exceeded 10 dB; enough to assure that vehicle pass vibration would not cause perceptible disturbance levels on the floor level above the garage.

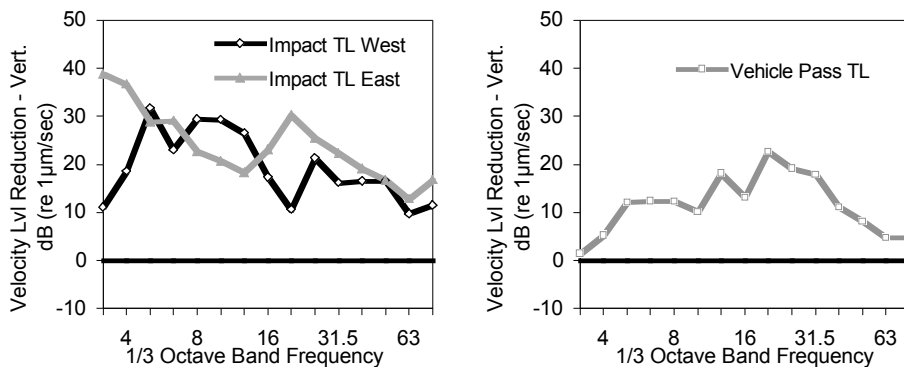


Figure 10, A & B – Vertical vibration transmission losses via columns to floor slab above: (A) Impact sources and (B) Vehicle pass on adjacent driveway bay.

SUMMARY

Human occupancy spaces subject to vibration disturbance transmission from garage structures should be analyzed for potential disturbance frequencies and amplitudes. Measures for isolation, damping and/or resonant de-tuning should be developed. The garage structures investigated in these case studies had very low frequency resonance on long span tee-beams and moderately low frequency on shorter flat slab spans. All of the structures exhibited pronounced resonant frequency amplification, possibly due to pre-stress and post-tensioned cable reinforcing. To prevent sympathetic resonant vibration on a floor structure above the long span, low frequency tee-beam deck, a generically different floor structure design with opposite girder and beam orientation and different resonant frequency was designed. For residential floors on same structural slab with garage driveway and parking, prominent vibration at the resonant frequency was difficult to suppress by de-coupling (isolation). Since the slabs were continuous and have same general span and depth parameters, de-tuning was not feasible. Damping is expected to provide some vibration reduction, but that will not be adequate in all cases to achieve the “perception threshold” design criteria. In conclusion, placing garage and human-occupied floors on connected structures should be avoided, either as vertical replications of structural system or on continuous slabs, because of the potential for undesirable and annoying vibration disturbances.

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