Dynamic Features of Precast Waffle Slabs in Cleanroom Design

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ABSTRACT

Comparing with traditional cast-in-place waffle slabs, precast waffle slabs have the intrinsic merits of better quality control, shorter construction time, and thus a reduced construction cost. One major concern of their utilization in cleanroom design is whether the dynamic performance of the slabs would meet the desired vibration criteria. In this paper, different types of slab-column connection have been modeled to characterize the wave propagation on the fab level when subject to mechanical and walker excitations. In addition, we have investigated a mock-up facility constructed with precast slabs. The facility has a similar configuration to a typical VC-D cleanroom [1]. Its midbay stiffness, mobility, and transfer functions were identified via instrumented hammer tests. The field data showed good agreement with the finite element simulation results. In the end, we present the vibration evaluations of a generic precast waffle fab, particularly its horizontal performance, to further verify the applicability of the precast design.

Keywords: precast waffle slab, vibration criterica, dynamic feature

1. Introduction

Precast concrete technologies are widely used in civil constructions nowadays. The primary advantage is a faster construction speed, as the preparation of concrete slabs can be carried out simultaneously with other construction steps, e.g., the foundation work and column erection. The concrete slabs are generally on the critical path, so this schedule change results in a substantial economical gain. Also the slabs may be installed on-site in cold temperatures, reducing the risk of weather-related concrete pour delays. Meanwhile, since concrete slabs are cast and cured in-house, a better quality control can be readily achieved.

The application of precast concrete slabs in the construction of cleanroom and other high-tech research facilities, however, is rather limited to date. These facilities employ vibration-sensitive instrumentation, much of which has stringent vibration requirements. Consequently, the facility design must follow certain micro-vibration criteria [1-3]. For example, the fabrication level in current wafer foundry design often proposes a vibration level of 4.5-6.4 µm/sec (or 180-250 µin/sec). A general approach is to build the facility as “strong” as possible to achieve a sufficiently high floor stiffness and natural frequency. Historically, the majority of the operating cleanroom and high-tech facilities adopts conventional cast-in-place slabs in order to ensure rigid connections between the slabs, columns, beams, etc. in the structure.

This paper explores the applicability of precast slabs in cleanroom and high-tech facility design. First, the differences in the designs featuring precast slabs and cast-in-place ones are identified. Second, a simple 5×5 bay finite element (FE) model is built to characterize their dynamic performance. Third, vibration measurements are reported from a mock-up facility constructed with precast slabs. The facility was built with configurations similar to a VC-D cleanroom. The test data collected are correlated with FE predictions. Last is a generic study of full-size Fab design using these components, in order to evaluate their performance in the horizontal directions.

2. Precast vs. Cast-In-Place Slabs

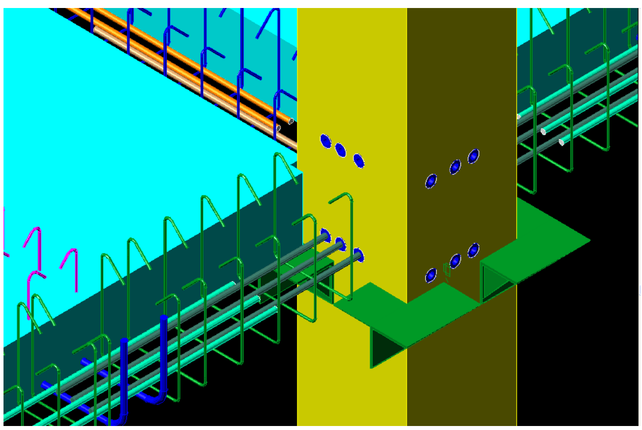
All the precast waffle slabs, along with other precast components, are cast and wet-cured either in the factory or some temporary houses near the construction site. During the construction, the slabs are transported to the site and installed at the desired positions (Fig. 1a). The next step is to assemble the rebar and pour concrete between the precast slabs to solidly tie them together (Fig. 1b). This modularity and assembly process is the major structural difference between the use of precast and cast-in-place slabs.

(a)

(b)

Fig.1. Photos taken during a cleanroom construction, showing (a) the assembly of precast slabs on the Fab level, and (b) the concrete pouring between the slabs. (Courtesy of Ruentex Construction)

As better illustrated in Fig. 2, the precast slabs are indeed "sitting" on the columns, and not poured integral with them. Thus, the connections of the floor slab and the columns are not as rigid as the cast-in-place ones. When vibration waves in the precast slab floor propagate to the column lines, the top of column might not rotate the same as the floor, i.e., the connection behaves somewhere between an ideal "rigid" and a "pinned" connection. On the other hand, in the case of cast-in-place slabs, the connection to the columns is always deemed rigid.



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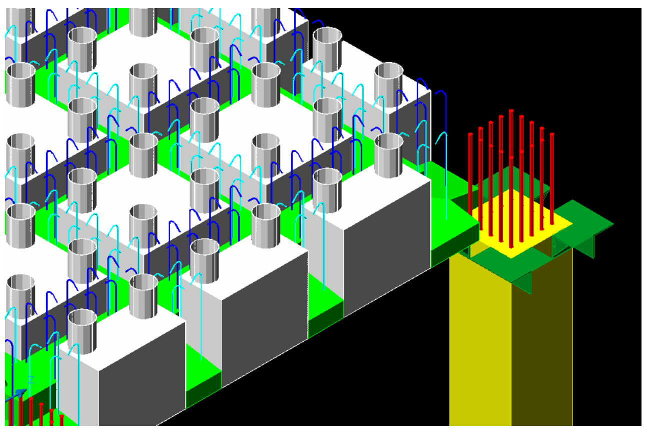


(b)

Fig.2. The connection of precast slabs to interior columns, showing (a) on the subfab level, and (b) on the top Fab level. (Courtesy of Ruentex Construction)

In the following sections, we assume precast slabs are pin-connected to interior columns, and compare their vibration performances with those of rigidly connected ones. This would replicate the least conservative modeling scenario, and assure a conservative design. In realty, precast slab floor would have a better vibration performance than the model predicts, since it is partially restrained.

3. Simple Fab Model

A 5×5 bay FE model has been built to study the dynamic performance of a waffle slab floor. It is a prototype of an operating VC-D cleanroom.

The simple model consists of two levels: The top Fab level is constructed with waffle slabs, which can be effectively represented by a grillage of beams; the subfab level is a one-way joisted slab with interior beams underneath (Fig. 3). (In practice, a structure such as this is entirely contained within a shell structure, which provides the required containment and environmental controls.) The top level supports the cleanroom and its vibration-sensitive equipment; the lower level houses support equipment. The two levels shown are supported with evenly-spaced columns, essentially connected to the piles in the foundation. The foundation is made of large concrete footings, strong enough to be simplified as solid constraints. The steel frame structures above the Fab level, the shell, are excluded from the model, due to their negligible vibration influence on the Fab level.

The original design (denoted as Design A) adopts conventional cast-in-place waffle slabs. With the midbay stiffness and the natural frequency identified from the FE model, the vibration velocity amplitude due to mechanical excitations is predicted as 3.4μm/sec (or 135μin/sec), and the velocity amplitude due to walker excitations (assuming a 68 kg (150 lb) walker at 100 paces/min) is 2.9 μm/sec (or 115 μin/sec) [4,5]. Both of the amplitudes meet the VC-D criterion (6.4 μm/sec or 250 μin/sec).

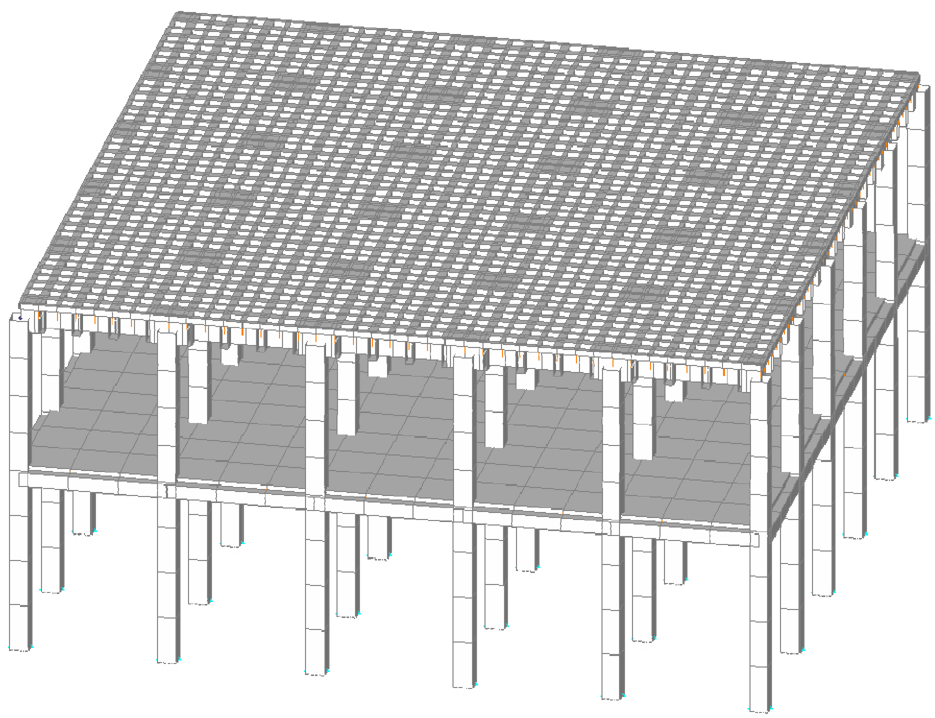


Fig. 3. The 5×5 bay FE model, featuring a VC-D cleamroom design. Constraints are not shown.

Alternately, the waffle slabs could be precast (denoted as Design B). As mentioned previously, in the worst scenario, the waffle slabs are assumed to be pin-connected to the columns. The FE model gives a very close analysis result: a mechanical vibration of 3.6 µm/sec (or 140 µin/sec), and a walker vibration of 3.0 µm/sec (or 120 µin/sec).

The vibration features of the two configurations are summarized in Table 1. In the context of the dynamics of these facilities, the 4% difference is negligible.

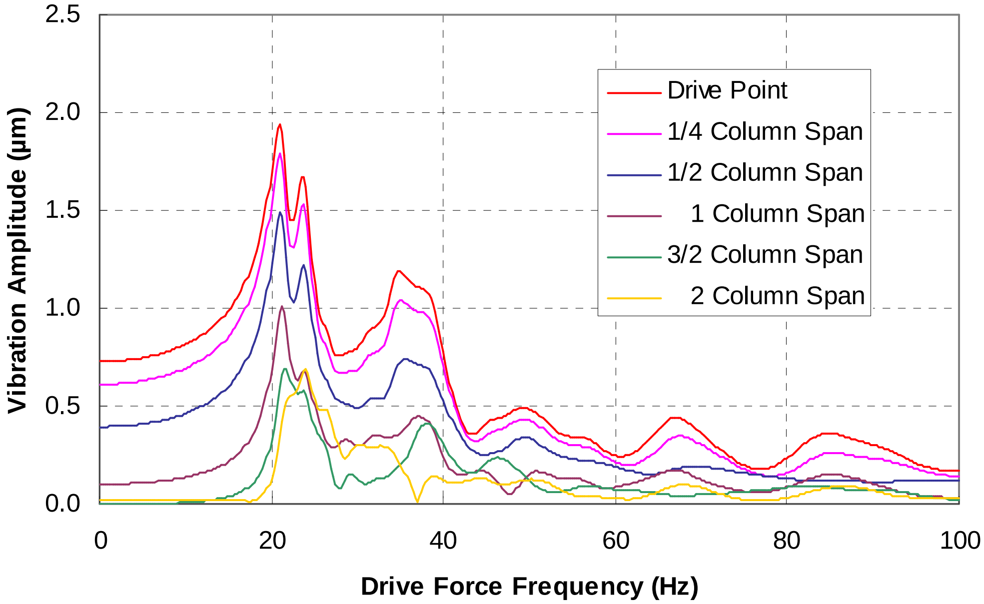
Table 1. The vertical vibration features of two slab floor designs.

	Design A	Design B	Difference (%)
Mechanical Vibration Velocity (µin/sec)	135	140	4%
Walker Vibration Velocity (µin/sec)	115	120	4%

Furthermore, a dynamic force of 150 lbf with frequency range (0-100Hz) is applied to the center of the floor in two designs. Figures 4 and 5 illustrate the vibration response in the frequency domain at specific locations, and Figure 6 depicts the attenuation with distance of the two slabs at selected frequencies. (It should be noted that the distance values in Figure 6 are normalized by the column span and the diagonal span, respectively.)

It is clear that the two slabs have very similar vibration features: their frequency responses are quite similar; they have nearly identical fundamental resonant frequencies around 21Hz (Figs. 4 & 5); their vibration attenuation curves are almost coincident with each other (except at 20Hz, which is close to their natural frequency, where a maximum difference of 0.36dB in vibration amplitude at the drive point is observed), resulting in similar mobility transfer functions of the two slabs in both column and diagonal directions (Fig. 6).

It is interesting to observe that the precast slab has a slightly larger vibration amplitude at low frequencies (<30Hz), whereas the cast-in-place slab greater at high frequencies (≥30Hz) (Fig. 6). This is due to the fact that the precast slabs would introduce additional damping at the connections. At low frequencies, however, these damping effects are not significant. The dominant factor would be the energy distribution ratio among the slabs and the columns when vibration waves propagate. In the case of precast slabs, pin-connections transfer less wave energy to columns (in the form of bending), while more energy remains in the floor. At high frequencies, the damping effects become more prominent, causing more energy to be dissipated at the connections, and remarkably attenuating the in-plane wave energy.



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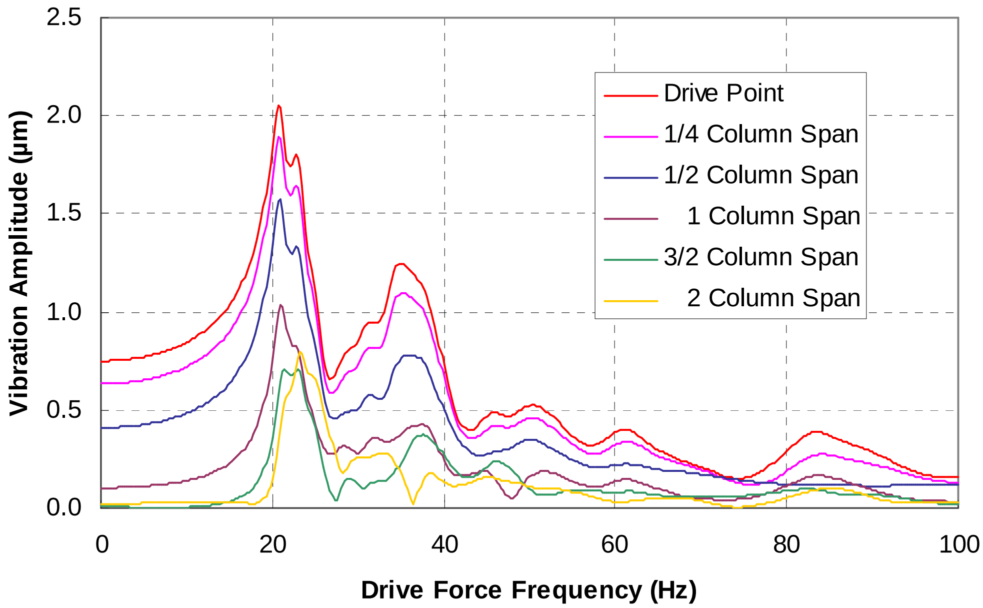
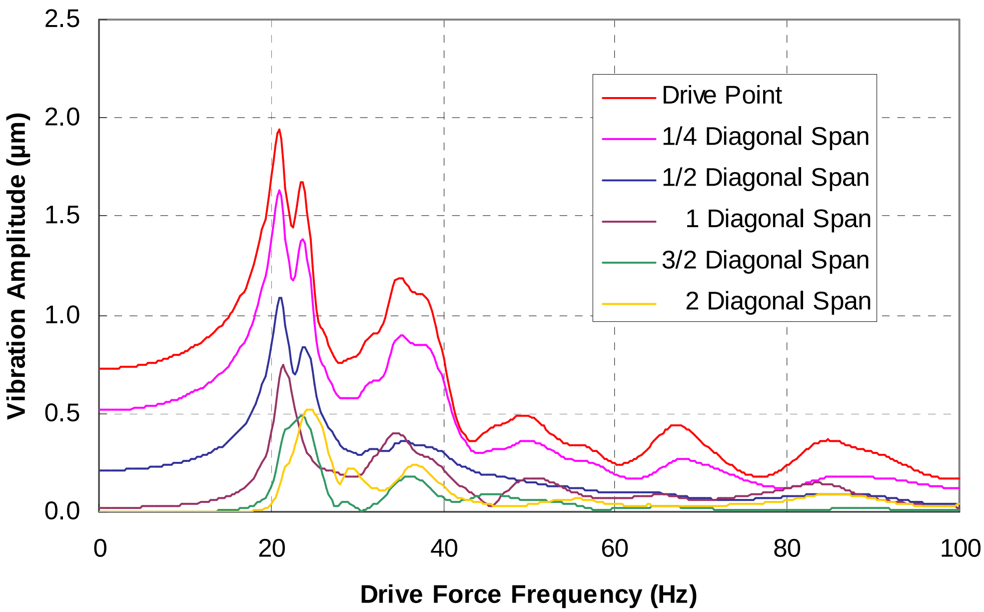


(b)

Fig. 4. The vibration amplitudes of (a) cast-in-place slabs (Design A) and (b) precast slabs (Design B) with different drive force frequencies, measured at distinct distances along the column line.



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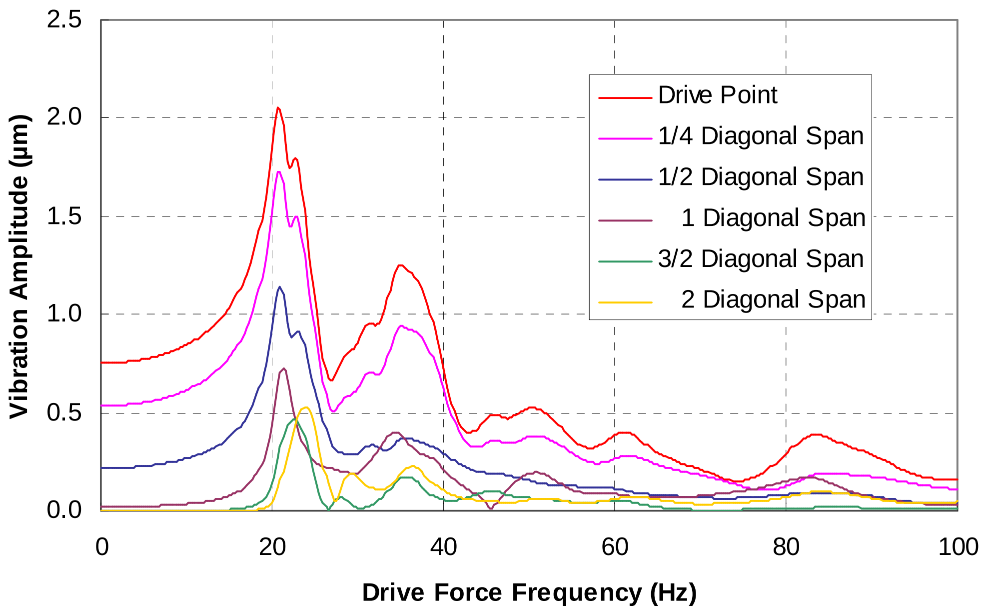
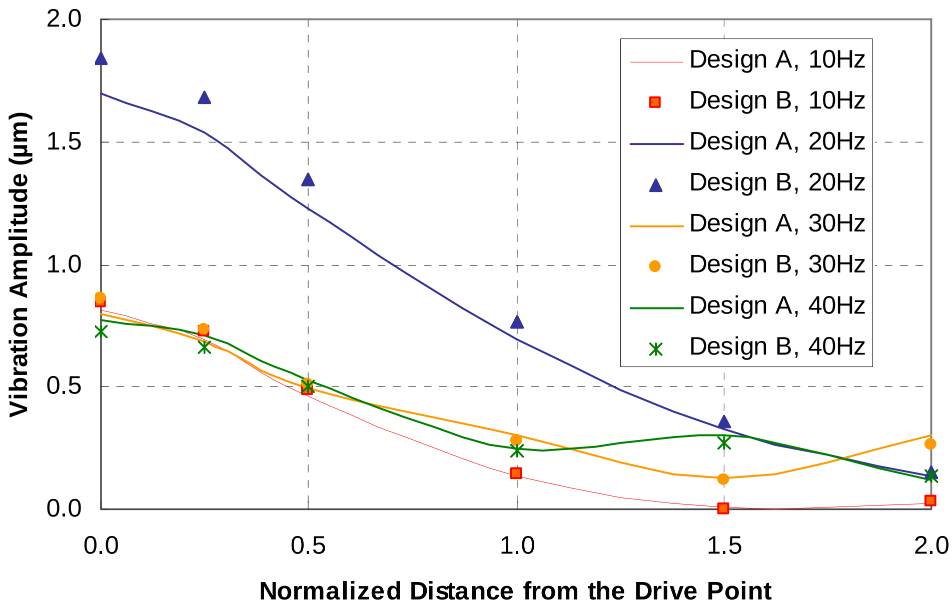
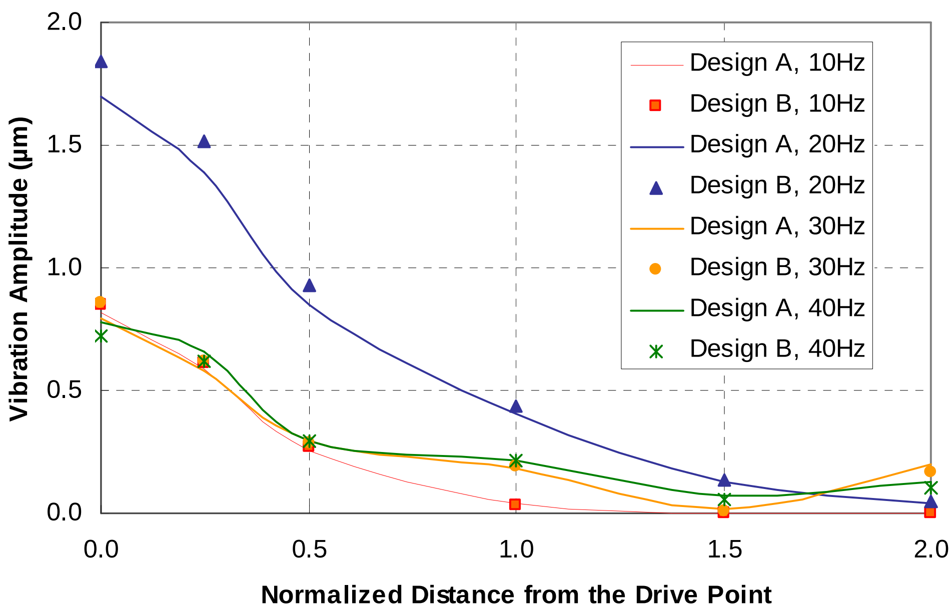


(b)

Fig. 5. The vibration amplitudes of (a) cast-in-place slabs (Design A) and (b) precast slabs (Design B) with different drive force frequencies, measured at distinct distances along the diagonal line.



(a)



(b)

Fig. 6. The vibration contours of the two slabs at distinct frequencies, measured along (a) the column line, and (b) the diagonal line. Note that the distance values have been normalized.

4. Vibration Studies of a Precast Slab Building

A mockup precast waffle slab building has been tested with an instrumented hammer (Fig. 7). The building has a configuration similar to a typical VC-D cleanroom, except that it consists of only eight waffle bays, aligning in a 4 x 2 arrangement (Fig. 8).

Fig. 7. Setup of the instrumented hammer test.

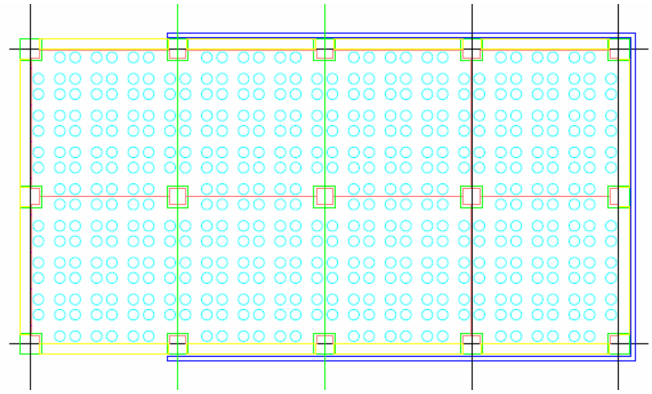


Fig. 8. The waffle slab level of the mockup building.

The main purpose of the test is to measure the vertical dynamic response, particularly the stiffness and resonant frequency, at the midbays and columns. Additionally, the mobility transfer function, defined as the vibration attenuation from the drive point to a receiver position at some distance, is also of importance, as a good way to check the slab continuity across the connections.

Figure 9 gives the average dynamic stiffness in the frequency domain at multiple midbay and column locations. Generally the columns are about 4-5 times stiffer than the slab. The average static stiffness of at midbay is approximately 5e+8 N/m.

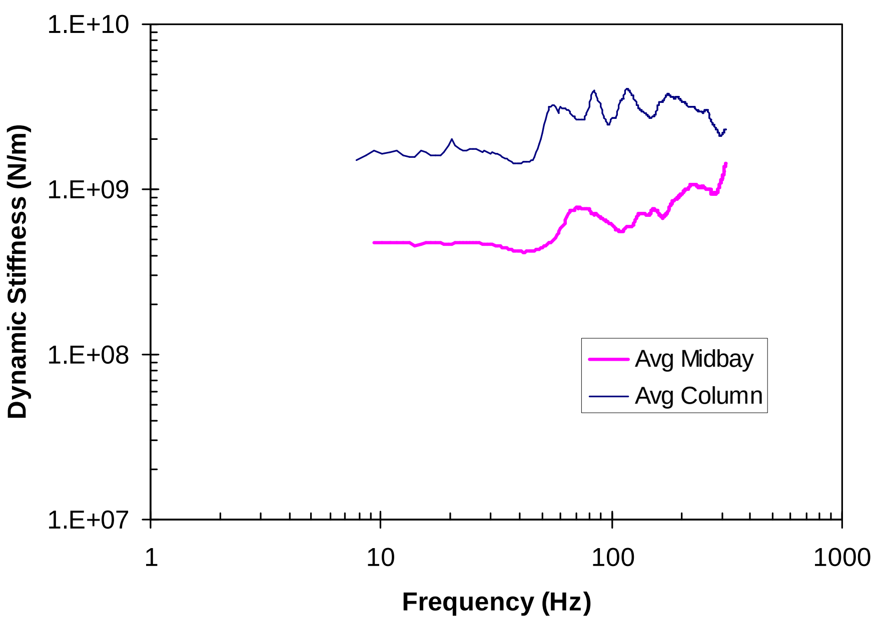


Fig. 9. The average dynamic stiffness measured.

Figure 10 is a typical midbay mobility plot, from which the resonant frequency is estimated around 60Hz.

Figure 11 shows how the mobility values change in two adjacent bays. As expected, the mobility decreases with distance. More importantly, the decreasing trend continues across the column lines, and the attenuation is similar in both longitudinal and transverse directions. These results indicate that the precast waffle slabs have no apparent discontinuities between pieces.

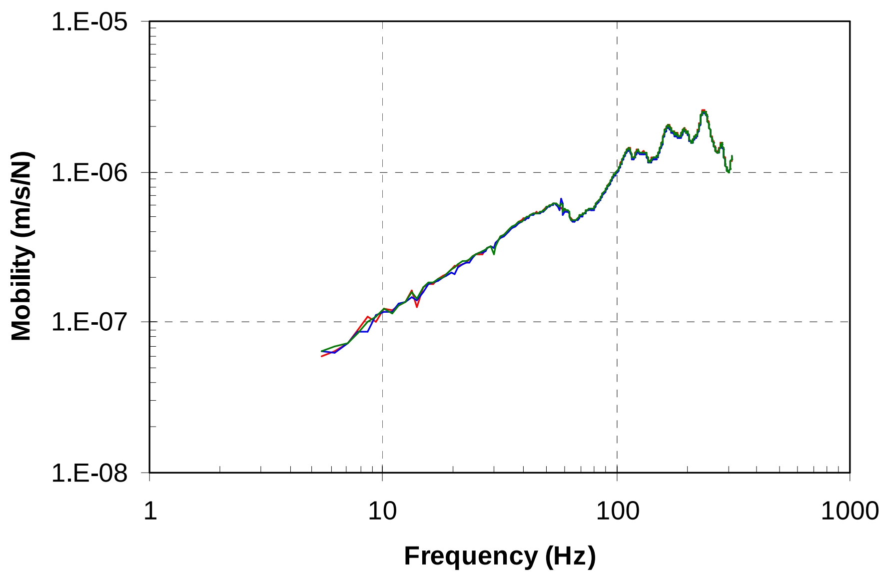


Fig. 10. Mobility values at a midbay (3 runs).

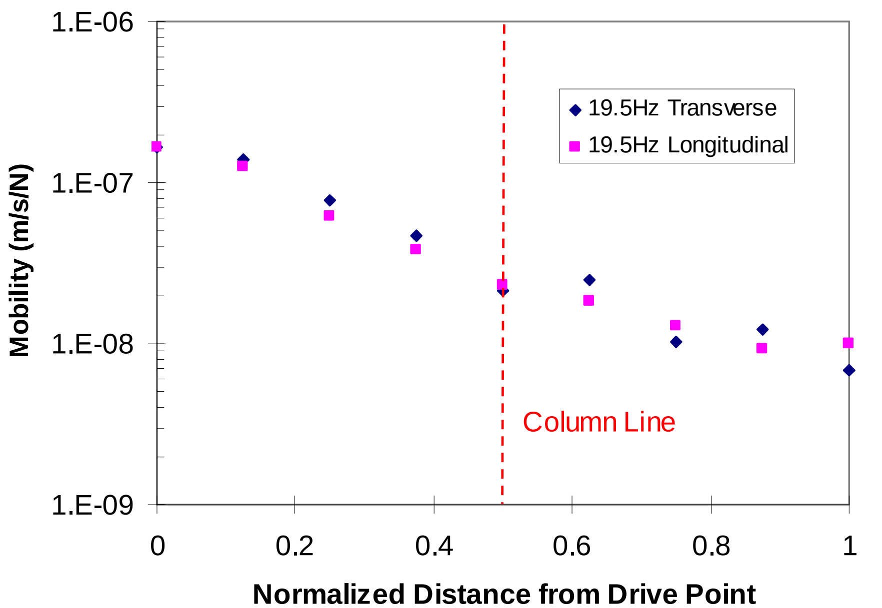


Fig. 11. A typical mobility transfer function measured across the column lines at 19.5Hz. Note that the distance values are normalized with the column span.

The field data have also been correlated with finite element analysis results.

As concluded in the previous section, the difference in the vibration performances of a pin-connection waffle facility (featuring precast slabs) and a rigidly-connected one (featuring cast-in-place slabs) would be minimal. Therefore, the measured data of the precast slab building have been intentionally compared with the FE results of a rigidly-connected slab model (Fig. 12). If the two sets of data showed good agreements with each other, the vibration similarity of precast slabs and cast-in-place ones would be further substantiated.

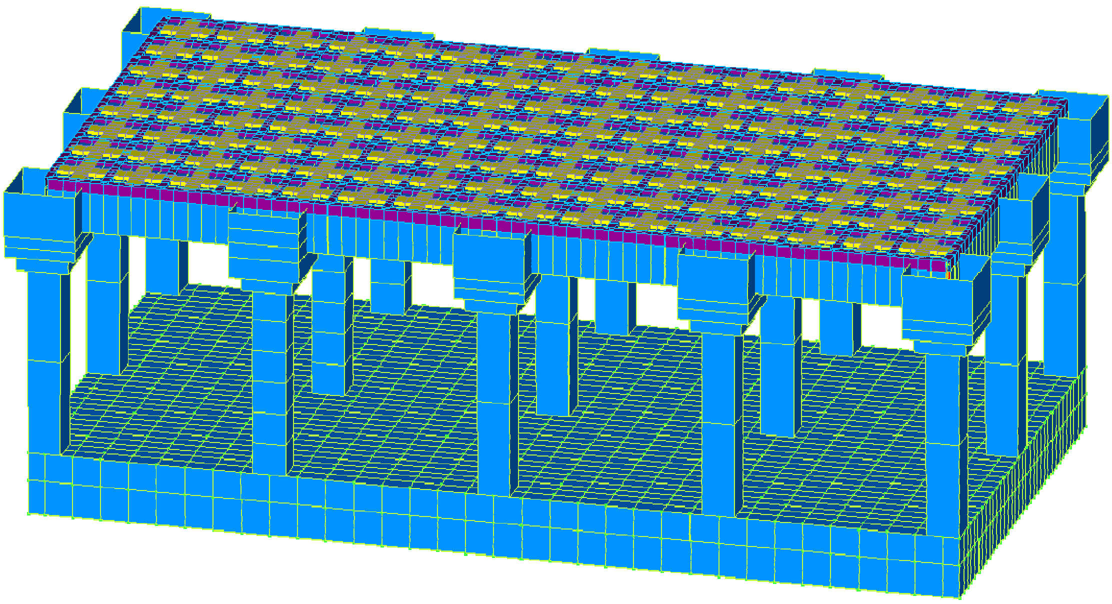


Fig. 12. The FE model built for the mockup building. Note that the waffle slabs are rigidly connected to the columns in the model.

Table 2 lists some midbay and column data from the records. The stiffness values are in good agreement, and the differences may be explained by variations in assumed foundation stiffness. Resonant frequency values from FEA, however, are lower than the measured ones. We believe this is due to the fact that the hammer can only excite either slab or column alone because of its relatively small impact capacity. On the other hand, the whole structure is excited in the FE analysis. If Dunkerle’s equation is applied to the field data, the combined frequency of the slab and column would be around 38Hz, which is quite close to the FE results.

Table 2. Comparison of field data and FEA results of the mockup building.

Location	Field Measurements		FEA Results	
	Stiffness (N/m)	Resonant Frequency (Hz)	Stiffness (N/m)	Resonant Frequency (Hz)
Midbay 1	8.8E+08	59	8.43E+08	35
Midbay 2	7.2E+08	64	8.43E+08	35
Column 1	2.1E+09	47	3.48E+09	32

5. Horizontal Vibration Performances

It should be pointed out that all the analyses above refer to the vibrations in the vertical direction. Most of the cleanroom and high-tech facilities also have the vibration requirements in the horizontal directions. It is therefore imperative to evaluate the potential impacts to the horizontal vibration performances as well before adopting precast slabs in facility design.

There are many design parameters which affect the horizontal performance, e.g., the dimension and layout of shear walls, the size of columns, the height of levels, the mass distribution within the building, etc. The selection of waffle slabs, on the contrary, would not have a prominent influence on the performance.

Again we start with analysis of an existing cleanroom, with distributed shear walls. It has been verified that the facility meets the vibration criteria in the horizontal directions and is now operating successfully. If we substitute the cast-in-place slabs used in the original design with precast ones, yet find the change in horizontal vibrations to be minimal, it is safe to conclude that using precast slabs in Fab design would also meet the horizontal vibration criteria.

Table 3 summarizes the corresponding vibration velocities evaluated before and after the substitution. The velocity values calculated [5] are almost identical. The waffle slab type has negligible effect on the horizontal vibration performance of the facility.

Table 3. Comparison of the horizontal velocities in the original design and precast slab design.

Direction	Original Design	Precast Slab Design	Difference (%)
Longitudinal	138	139	< 1%
Transverse	130	131	< 1%

6. Conclusion and Comments

All the numerical and experimental studies lead to a conclusion that the low-amplitude dynamic behavior of precast waffle slabs is comparable to that of cast-in-place slabs when used in cleanroom design. The resonance frequencies, point stiffness, and propagation characteristics are virtually identical.

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