

# Long-Span Truss Structures for Low-Vibration Environments

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## INTRODUCTION

With the advancement of science and technology, vibration control becomes an increasingly significant requirement in facility design. Historically, waffle slabs have been widely used in the process floor design in semiconductor production facilities (Fabs), where a vibration level of VC-D ( $6.25 \mu\text{m}/\text{sec}$ ) is often required to host all sorts of vibration-sensitive fabrication tools [1]. In a less stringent vibration environment, for example, in hospitals and general optical labs, concrete joist slab with stiffeners could be a suitable design option. In both of the two approaches, the effectiveness of vibration control in floor structures would be substantially reduced when the column span becomes larger. As a result, it is technically difficult and financially inefficient to adopt conventional waffle slab or stiffened joist slab in a long-span facility design.

On the other hand, long-span truss structures are quite common in a number of industrial settings, for example, bridges, large factory buildings, etc. The truss design has been proven an efficient way of reducing structural weights, yet providing sufficient strengths and easily complying with all sorts of building codes (including the seismic ones). However, the long-span truss structures are often not considered as a viable design option for low-vibration environments. Heretofore, the approach has received little attention in the US (one of the few examples is a technological building described in [2]), but has been employed in Asia for over a decade for facilities engaged in semiconductor and flat panel (LCD/TFT) production, where large open spaces are of great value, and spans can reach over 30m.

The article presents the vibration analysis and test results of a long-span truss facility recently constructed in Asia. With  $5 \times 3$  bay finite element (FE) models, the midbay stiffness and fundamental resonant frequency of the process floor are evaluated. The mechanical and walker-induced vibration velocities of the floor are subsequently predicted and compared with the proposed vibration criteria. The model results are further substantiated with field data, which are measured at a number of locations randomly distributed over the process floor to represent the average-plus-one-standard-deviation level of the vibrations [3].

In addition, the article discusses the current state of the design and analysis philosophies, including space planning, "reverse engineering" of equipment loading, and structural optimization.

## FACILITY DESIGN

A typical large LCD/TFT facility (ground area over  $250\text{m} \times 100\text{m}$ ) has been recently constructed in Asia, featuring a large column span of 36m in one direction, and 9.6m in the other. The facility consists of five levels, among which Level 1 is the TFT process floor, supported on evenly-distributed columns spacing  $4.8\text{m} \times 6\text{m}$ , and Level 3 is the CF/LCD floor. The space functions and structural components are summarized in Table 1.

The building frames above Level 1 are steel trusses. The framing on Level 3 (top chords) and Level 2 (bottom chords), as well as other diagonal braces, are steel beams of different sizes (Figure 1). This design allows structural engineers to reduce the cross-sectional area of each individual member, and thus minimize the overall structure weight, while ensure sufficient strengths in the frame.

A concrete flat slab with cylindrical penetrations on a regular pattern, namely “cheese slab,” is assembled on top of the steel frames on two process floors. The cheese slab performs in a manner similar to a concrete grillage (i.e., a waffle without a topping slab), but tends to be less expensive to form in Asia. The light-weight cheese slabs on steel frames provide structural integrity as a diaphragm, as well as allowing equipment support.

Level	Space Function	Structural Components	Vibration Criterion
Level 3	Cleanroom – CF/LCD Process	Cheese Slab on Top Chord	VC-B (25 $\mu\text{m}/\text{sec}$ ) or VC-C (12.5 $\mu\text{m}/\text{sec}$ )
Level 2	Interstitial – Utility Distribution	Bottom Chord	
Level 1	Cleanroom – TFT Process	Cheese Slab	VC-C (12.5 $\mu\text{m}/\text{sec}$ )
Level 0	Subfab	Columns, Foundation	

TABLE 1 – SUMMARY OF SPACE FUNCTION, STRUCTURAL COMPONENTS, AND VIBRATION CRITERION, BY LEVEL

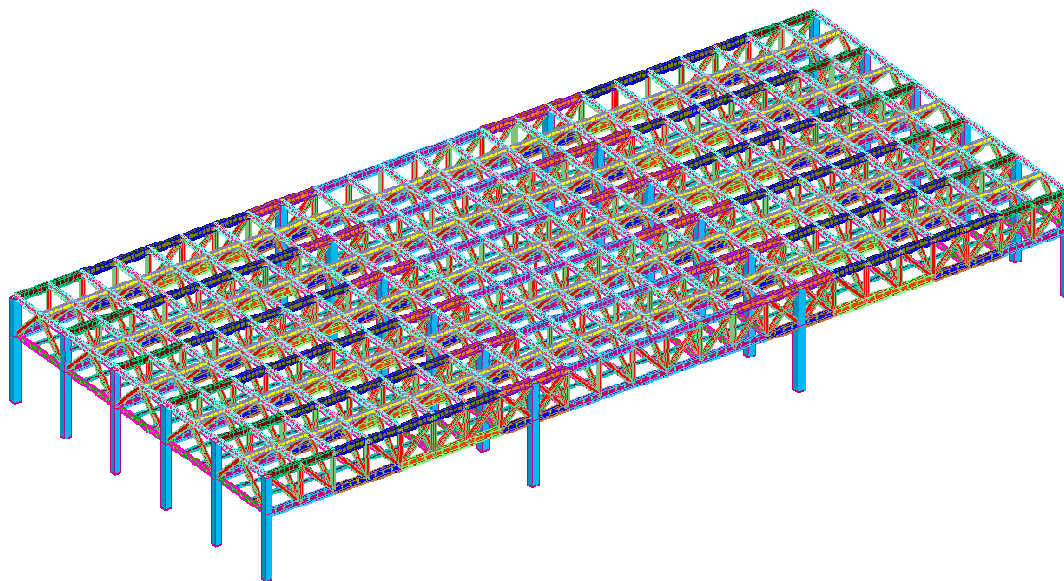


FIGURE 1 – THE STEEL FRAMING ON LEVELS 3 AND 2. DIFFERENT COLORS REPRESENT DISTINCT BEAM SIZES.

The tools employed on the Level 3 require a rather stringent vibration environment, i.e., the linear average vibration amplitude, in terms of one-third octave bands ranging in center frequency from 4 to 80Hz, must meet generic criterion VC-B (25  $\mu\text{m}/\text{sec}$ ) or VC-C (12.5

$\mu\text{m}/\text{sec}$ ) curves [4,5]. The specified limits are intended to apply to both vertical and horizontal (two orthogonal axes) vibrations.

## VIBRATION ANALYSIS

In the facility design, the vibration sources are often categorized into two groups: mechanical (pumps, fans, chillers, piping, ductwork, etc.) and human activities (footfall, carts, etc.).

For elevated floors, the mechanical vibrations ( $V_m$ ) can be estimated semi-empirically [6,7]:

$$V_m = C_1/k_v \quad \text{in vertical direction} \quad (1)$$

$$V_m = C_2/\sqrt{k_h} \quad \text{in horizontal directions} \quad (2)$$

where  $k_v$  is the static midbay stiffness in the vertical direction,  $k_h$  is the “global” horizontal stiffness for the elevated structure,  $C_1$  and  $C_2$  are empirical constants. It should be noted that the mechanical velocities derived from the above two formulas are the one-third octave band values at the respective resonance frequencies, and reflect quasi-stationary “background” vibrations.

The walker-induced velocity ( $V_w$ ) may be evaluated as [5,8]:

$$V_w = C_w/k_v f_n \quad (3)$$

where  $f_n$  is the natural resonant frequency of the floor, and  $C_w$  is an empirical constant. Note that human activities, due to their transient nature, could only excite elevated floors in the vertical direction. Technically, the walker-induced velocity is a function of weight, speed (pace), walk path, footwear type, and many other factors. Equation (3) is based upon the Ungar and White model [5,9], with regard to its dependence on stiffness and frequency, but the term in the numerator is based upon statistical analysis of field data and the resulting rms velocity amplitude is in terms of one third octave bands. The model describes the walker velocity in the most severe scenario, i.e., the receiver (research tools, accelerometer, etc.) are placed at the midbay on an elevated floor, and walker are passing by it at a relatively high speed (say 100 paces per minute).

In a relatively “stiff” floor (defined as the case where floor stiffness assuming rigid columns is significantly larger than the column stiffness), the mechanical vibrations will generally dominate the floor performance. Conversely, in a “soft” floor (where floor stiffness is less than the column stiffness), the walker vibrations usually predominate [10]. In the case of a long-span truss structure, the weight of a floor bay of the truss system is quite large, and the footfall force from a walker would be unlikely to motivate the effective mass of a truss bay [11]. Thus it is acceptable to disregard footfall with regard to truss response. On the other hand, the robotic equipment used for material handling tends to be quite large, generating dynamic forces much greater than those associated with footfall, and these must be considered.

Equations (1) through (3) indicate that the vibration velocities could be quantified with the floor stiffness, the natural frequency, and some empirical constants. The stiffness and frequency values are readily obtained from a  $5 \times 3$  bay finite element model (as shown in Figure 2). It predicts that the truss design would meet the proposed vibration criteria (VC-C and VC-B).

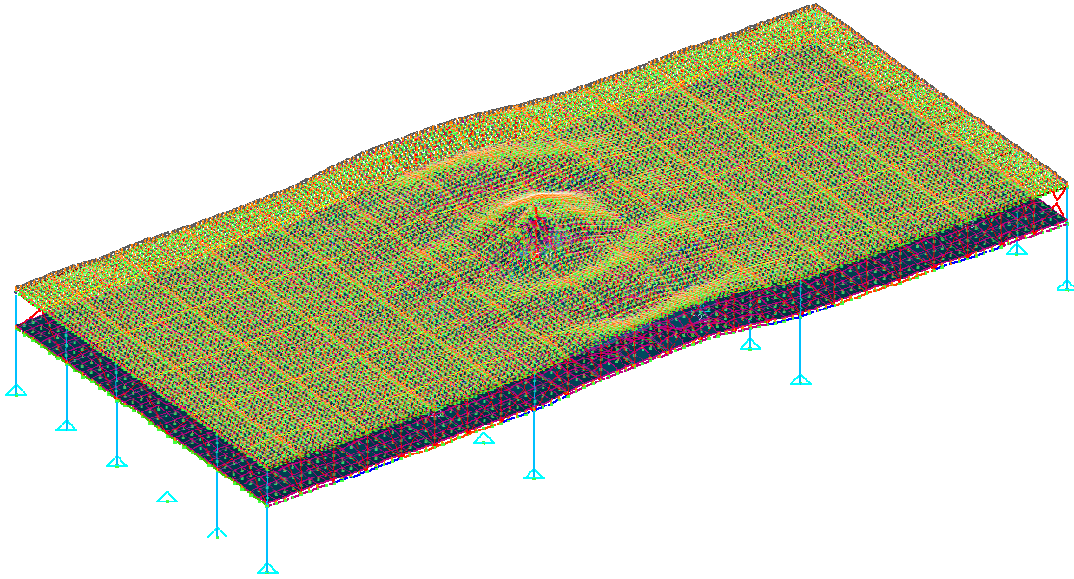


FIGURE 2 – THE STRUCTURAL RESPONSES OF THE PROCESS FLOOR WHEN SUBJECT TO A DYNAMIC MIDBAY LOAD (REPRESENTED BY A RED ARROW). THE FOUNDATION IS MODELED AS CONSTRAINTS.

## FIELD MEASUREMENTS

To further substantiate our vibration analysis results, a site visit to the facility has been made and the field vibration data were collected. The measurements were carried out at a variety of representative locations throughout the process floor, after the base-build mechanical equipment was in place and operating. The vibrations were sampled with a digital signal analyzer, using a measurement bandwidth of 0.25 Hz and a Hanning windowing function. The frequency range measured was 0 to 100 Hz.

The measurement data is reported in terms of one-third octave value and compared with standard VC curves. Figure 3 depicts two statistically meaningful representations of the field data (collected from 16 locations), among which the average-plus-one-standard-deviation level is the most characteristic [3]. Over the frequency of interest (4 to 80 Hz), the process floor is compliance with the VC-C criterion.

It has also been verified that walker does not contribute much in floor vibrations. Most of the vibration energy comes from mechanical sources, which can be either the air and liquid ducting and piping or the materials-handling robotics.

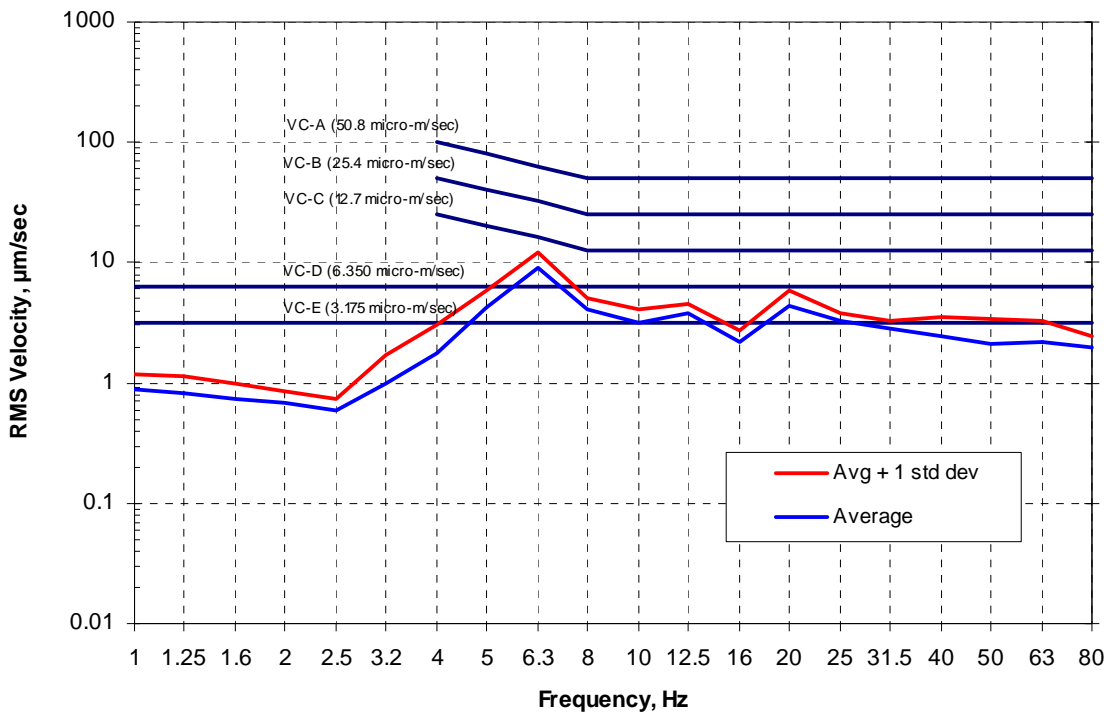


FIGURE 3 – THE STATISTICAL SUMMARY OF THE AMBIENT VERTICAL VIBRATIONS MEASURED ON LEVEL 3.

## TRUSS DESIGN SUMMARIES

### Reverse Engineering the Force Spectra

As noted previously, the floor's steady-state response to statistically stationary (non-transient) excitation from mechanical systems may be analyzed by means of the model defined by (1). On the other hand, the transient loads associated with robotic systems require a different approach. The dynamic forces exerted by these systems at other locations (usually the factory) may be estimated by a three-step "reverse engineering" process.

- When the robot is not operating, the mobility of the floor supporting it may be measured directly using an instrumented hammer system. (Mobility is the dynamic property, expressed as a spectrum, representing the frequency response function of velocity response to a measured force excitation divided by that force.)
- When the robot is operating, the velocity vibration of the floor supporting it is measured in a format compatible with the mobility spectrum.
- The force spectrum is calculated by dividing the velocity spectrum by the mobility spectrum.

The finite element model described before is used to calculate the drive-point and transfer mobility spectra associated with the robot's operating location. The derived force spectrum may then be used to calculate the floor vibration at the drive-point and transfer locations. Using this approach, required setback distances may be calculated between the robot and production equipment with particular sensitivities.

## Role of the Slab

The production level (Level 3 in this case) is supported on a concrete slab which, in turn, supports the production equipment. Measurements have demonstrated that if vibrations at the truss fundamental modes are excluded, the primary floor response (including that due to footfalls) occurs in the concrete slab alone, where it acts as if it is column-supported — the vertical truss elements behaving like columns and create “hard spots” simulating columns.

## Optimizing the Truss

Numerical studies have shown that the bending properties of the upper chord members add little to the bending behavior of the concrete slab. In other words, the slab's dynamic properties are dictated primarily by the stiffness and spacing of the vertical elements and the properties of the slab itself. This allows the upper chord elements themselves to be optimized based upon their loading and required performance in the truss system, without considering their interaction with the slab. This has allowed significant cost savings via reduction of cross-section area to that required for tension or compression.

## Design Philosophies

- Select truss spans. The traditional bay involves a long span (36m in the case) and a short span (9.6m). The resulting 3-D truss is designed as a two-way system.
- Size the slab thickness. The horizontal panel dimensions (4.8m in both directions in the case) effectively represent what would be column spacing in a conventional structure. The slab is designed based upon (1) and (3). There is some reduction in stiffness due to penetrations.
- Construct a finite element model of the structure, or some repeated module of the structure.
- Size the truss components. The vertical response due to the building's mechanical systems is represented by  $C_1$  in (1). The materials handling systems are modeled using the reverse engineered loads.
- The horizontal response due to the building's mechanical systems is represented by  $C_2$  in (2). The stiffness term in (2) is the lateral stiffness of the level under consideration. It will differ in the two principal directions, unless the building is square.
- Experience has shown that it is feasible (though expensive) to achieve stringent criteria on higher floors in the *vertical* direction, but it may not be possible to achieve those same criteria in the *horizontal* directions. Thus, it is customary to place the processes with the most stringent requirements at lower levels in the building, and those with the less stringent requirements on upper levels. If the same truss system was used at all levels, the vertical vibration environments would be similar from floor to floor, but the horizontal environment would increase as one moved upward from one level to the next.
- Lateral stiffness may be achieved by using shear walls, braced frames, or, preferably, creating a system of vertical trusses in which columns act as two chords.
- The example structure has two production levels. However, it is not at all uncommon to add another set of layers such that a third production level is possible.

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