Vertical Integration

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A Michigan construction firm creates a unique spatial relationship between its corporate offices and the rest of its facility.

HERE'S A THOUGHT: WHEN A CONSTRUCTION COMPANY LOOKS INTO BUILDING ITS OWN FACILITY, does it keep things simple, given its in-depth knowledge of the building process—or does it challenge itself even more than when it's building for a client?

In the case of Michigan firm Lamar Construction Company, the answer is the latter. When building its new headquarters, which opened in 2007, the company chose to place its corporate offices not in front of its shop, garage, and warehouse facilities, but cantilevered above them, thus tasking the building team (of which it was a member) with creating a satisfying work environment in a challenging structural context.

As the architect sought to realize Lamar's unconventional vision, early discussion with the structural engineer established some guidelines that would impact all aspects of the office design. Two 16-ft-deep, 112-ft-long cantilevered trusses were envisioned that would support the office from a vertical circulation shaft. These trusses would architecturally define perimeter office units as well as primary traffic aisles.

Designing for Constructability

From the start, the design team planned for lateral drift of the office space to be controlled through the torsional resistance of a concrete support shaft. However, two constructability consider-

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ations shifted the design in the direction of using of a full-height steel frame embedded within the concrete shaft walls.

The primary benefit of the steel frame was to help distribute truss reaction forces into the shaft. With some connection forces being well over 1,000 kips in magnitude, the steel frame (covered with shear studs for composite behavior) could develop reaction forces far greater than a traditional anchor bolt design in a thin concrete wall. During construction, the steel frame acted as an armature, supporting the formwork for the concrete shaft. It also provided a means to maintain both position and alignment of connection members throughout the casting of the walls. This alignment was critical because it allowed for precise launching of

A steel frame sheathed in concrete provides the structural support for the massive cantilevers.

the truss, which was designed and fabricated with approximately 3 in. of pre-dead load upward camber at the cantilever end.

An additional construction challenge was presented by shipping and lifting considerations that dictated the use of field welds to complete the connection of a W14×370 brace member. The field welds required qualification in conformance with the American Welding Society (AWS) D1.1 *Structural Welding Code* and around-the-clock field welding. In advance of the work, procedures were prepared and a mock-up of the joint was welded in the field to identify conditions that could delay field welding and to verify that the procedures prevented lamellar tearing due to the jumbo sections and high restraint. After welding of the mock-up, the erector delivered the welded joint to the laboratory for qualification testing. The final preparation involved constructing suspended blinds at the connection locations in order to protect welders from the harsh Michigan winter conditions while they performed their work.

Designing for Comfort

Understanding the building's pedestrian traffic flow was the main consideration in designing the truss. Early dynamic analyses suggested that all of the possible engineering solutions would likely provide satisfactory vibration characteristics for both lateral and torsional motions. Vertical vibration, however, presented some concern. Although anticipated accelerations were low, it was determined that even the most reasonable truss designs would yield vertical vibration frequencies akin to those produced by fast foot traffic.

In order to increase the building's natural frequency such that it would not be excited by these normal walking rates, the structural stiffness had to be substantially increased. Adding stiffness meant adding bulk to the members and their connections, which would in turn add both cost and visual obstructions to the project. The building had been initially conceived as a relatively light structure, so there was little opportunity to improve its vibration characteristics from that perspective.

The team's solution, outlined in the following section of this article, was to design for vibration levels above that of normal walking frequencies and to make provisions for tuned mass dampers (TMDs) to be installed only if deemed necessary. No one on the team wanted to use TMDs as an initial design solution, but they recognized their benefits as a back-up system. This would save the owner the initial economic and aesthetic ramifications of unexpectedly massive trusses, while still ensuring a vibration-free workspace.

With this approach in mind, a preliminary TMD design was provided that promised to control uncomfortable vibration under worst-case projections. The office floor system was then designed to be framed with a pair of concealed chambers that would accommodate the mounting of TMDs (if they proved to be necessary) to the bottom chords of the cantilever trusses.

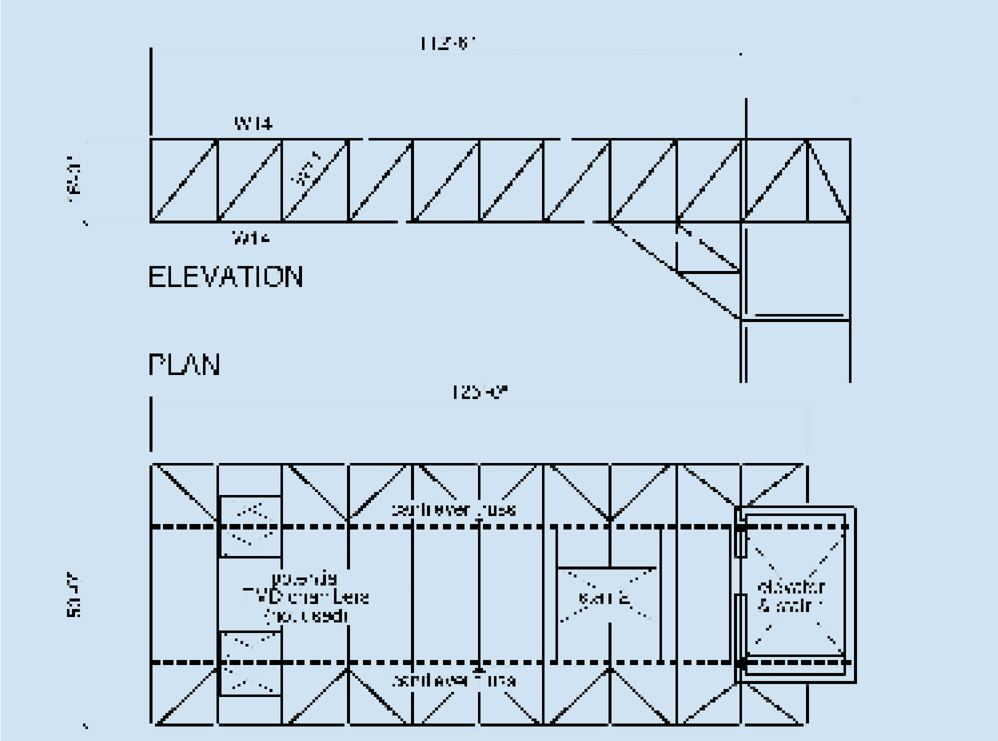
Dynamic Analysis and Testing

Based on the preliminary design drawings, a three-dimensional finite element model of the building structure was created using the SAP2000 software. The initial estimates of the structure's fundamental frequency showed that the building was not susceptible to wind excitations. However, the structure's first two modes of vibration were 1.5 Hz and 2.1 Hz, which made it susceptible to annoying vibrations from foot traffic.

The floor performance was subjected to three components of walking force, which resulted in a maximum vertical acceleration well above the acceptable limit. A number of modifications were made with the goal of increasing the natural frequencies to a range well beyond the normal walking range of 1.6 Hz to 2.3 Hz (representing slow to brisk walks), to prevent resonance or increase the structural mass to reduce the acceleration level.

The final design of the structure, after several modifications, resulted in natural frequencies of 2.6 Hz, 3.4 Hz, and 5.4 Hz for the vertical, lateral/torsional, and torsional modes, respectively. Even though the natural frequencies were outside the range that could be excited by the first two harmonics of normal walking excitation due to construction variations, assumptions made on modeling of the non-structural elements (in particular, the outside glazing), and the fact that finite element models generally tend to overestimate the natural frequencies, there was a high probability that the completed structure would have somewhat lower natural frequencies. The team recognized that such lower natural frequencies could result in vibrations above acceptable limits, thus the provision was made for TMDs as a fall-back option. It was determined that eight 2,000-lb TMDs would be able to reduce the vibration of the vertical and torsional modes to levels well below the perceptible range in the case that occupants experienced uncomfortable vibration.

To check the floor's structural performance and make preparations in case the TMDs were necessary, a series of dynamic modal tests using an electrodynamic shaker were conducted as soon as the concrete floor was poured and the outside glazing installed—but before the raised floor, partitions, and any interior finishes were installed. As expected, the



The offices are supported by a truss 16 ft deep that cantilevers 112 ft from a supporting tower.

natural frequencies were less than the analytical estimates. The main contributor to this discrepancy was found to be the consideration of the stiffness of the outside glazing. The measured natural frequencies were 2.7 Hz, 3.0 Hz, and 3.3 Hz for the vertical, lateral/torsional, and torsional modes, respectively. These values were outside the range of the first harmonic of walking excitation. A number of walking tests were conducted with the walker's pace synchronized with the vertical mode natural frequency. This resulted in acceleration levels as high as three times the acceptable limit. However, since the natural frequency was high (2.6 Hz), the person had to jog to keep up with the rhythm. As the floor was expected to be acceptable under normal walking scenarios, a series of random walks were also conducted with all resulting in acceptable levels of vibration.

A second round of dynamic testing was conducted after building completion, with a similar set-up to the first tests. The as-built natural frequencies were 2.3 Hz, 2.5 Hz, and 3.0 Hz for the vertical, lateral/torsional, and torsional modes, respectively. These values were well within the range of predicted natural frequencies by the analytical model after modifications based on the first round of tests.

Controlled walks at the speed of the measured natural frequencies were conducted, which only resulted in accelerations slightly above the acceptable limit (0.7% g) for the vertical mode excitation. However, since this constituted a brisk walk (135 steps per minute), the probability of such vigorous strolls is very low in an office space. More normal walks at an average speed of 120 steps per minute (2 Hz) resulted in vibration levels well below the perceptible limit. One important aspect of the building that contributes to the low level of vibrations is the limited width of the hallways, which typically allow only one person to walk through at a time, thus restricting traffic flow.

No TMDs

With a quantitative understanding of the building's performance and positive occupant feedback since the opening of the building in July 2007, the TMDs were determined to be unnecessary, and the floor chambers built to house them remain unused. But those chambers ultimately served the project well: They allowed the design team to confidently work beyond their range of experience to create a workspace of unprecedented character. MSC

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