Longchamp Stair Optimization and Vibration Study

128-132 Spring Street, New York

By Victoria Arbitrio, P.E., SECB

Opened in May 2006, La Maison Unique, Longchamp's flagship store in an area of lower Manhattan known as SOHO ("South of Houston Street", pronounced how'-ston), has a special feature that catches the attention of everyone who passes; shoppers are drawn not only by a glimpse of the luxury items visible through the store window, but by the ribbons of steel and leather-brown rubber that create a sculptural landscape to lure shoppers from the street. This 55-ton steel stair synchronizes architecture and structure to form an elegant, fluid path up to the second floor.

The Longchamp stair includes twenty-three, 11-inch wide, 1.25-inch thick ribbons of rubber-covered steel that create the treads of a stair cascading from the atrium skylight, 60 feet above the street. This stair distills the architecture down to the structure, forming a set of rolling waves to transport customers up to the second floor where the main area of the store is located. Vertical plates form the stair risers – they vary in depth and curve to match the waves of the ribbons. (See *Figure 1*). From the street level floor, the stair switches back on itself with two intermediate level landings before reaching the second floor, forming a "Z" in plan.

The structural challenge was to design the stair for a comfortable level of vibration, and to optimize the time and materials required to build it. Structural parameters which control vibration are mass and stiffness. In composite slab floors, one addresses a vibration problem by increasing the stiffness of the steel beams rather than increasing that of the slab and, therefore, the mass of the system remains almost unchanged. With increased stiffness and constant mass, the fundamental frequencies are increased beyond the range which is classified as uncomfortable. For the Longchamp stair structure, the structural elements were also the architectural feature; the structural elements were sculpted in curves by the architect to achieve the slender form of the stair. To maintain these forms, the stiffness of the system and the overall mass were inherently tied. Several thicknesses of steel were investigated to optimize the

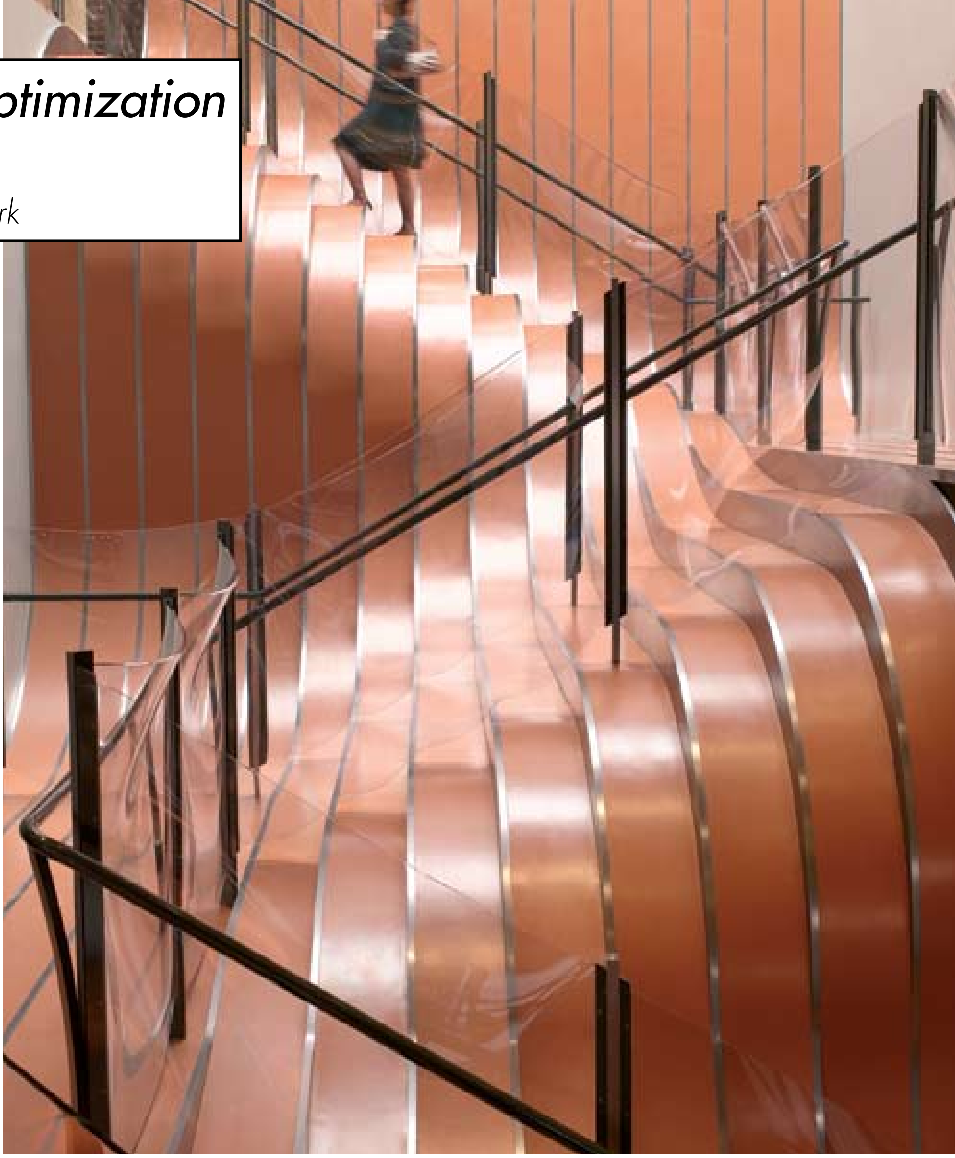

Figure 1: Stair (which mimics a waterfall) zigzags from street level to main retail space on the second floor.

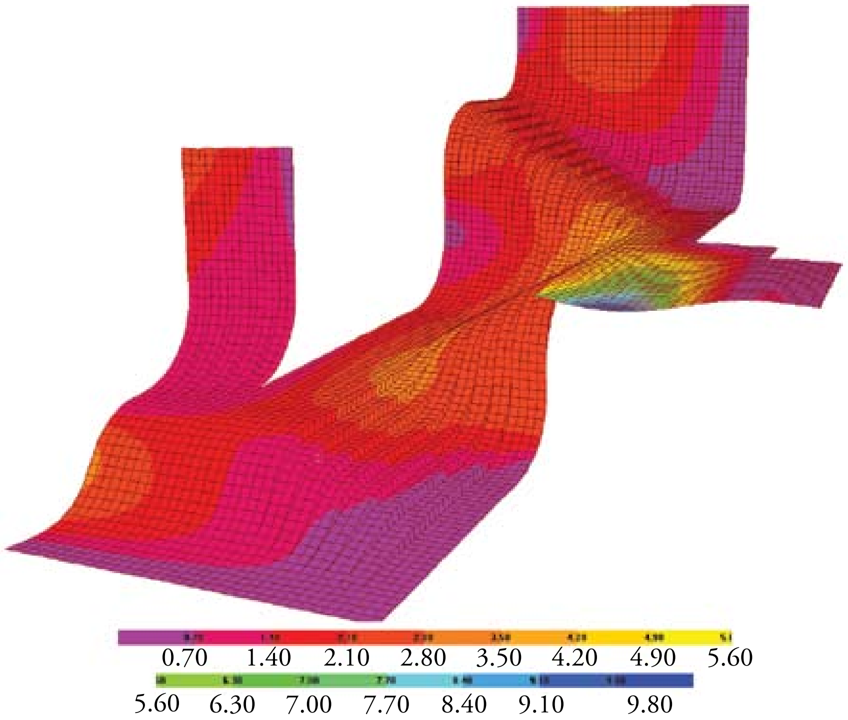

Figure 2: Maximum deflection in millimeters.

continued on page 12

Construction: Looking south at the second floor on left and upper mezzanine and cantilever on the right.

Construction: Erecting the top flight at second floor.

Construction: Upper mezzanine and cantilever, suspended over the construction photographer.

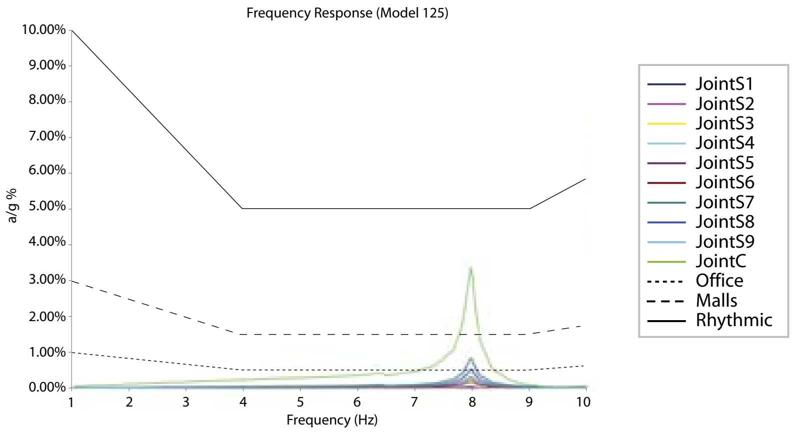

Figure 3: A curve for each control point shows the response frequency vs. acceleration at point of maximum deflection for the original stair structure.

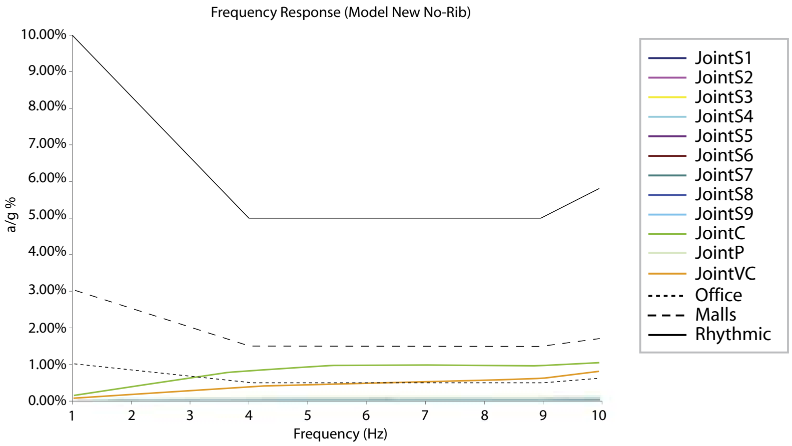

Figure 4: A curve for each control point shows the response frequency vs. acceleration at point of maximum deflection for the optimized stair structure.

ethereal appearance of the structure with the necessary strength, deflection, and vibration requirements. Other parameters were also studied, such as boundary or support conditions which affect the system's stiffness.

Design procedures are well understood for composite slabs, but complicated analysis must be performed if the structural system is not limited to regular composite beam framing, or if the vibration of beams and girders are coupled. Thus the project yielded two main challenges: 1) what is the best analysis to determine the vibration behavior of a system composed of continuous steel elements where mass and stiffness cannot be modified independently and, 2) what is a reasonable comfort criteria for vibration?

To address the first challenge, Gilsanz Murray Steficek (GMS) modeled the geometry of the structure imported from a 3D architectural model to generate a finite element computer simulation using shell elements (SAP 2000). Boundary/support conditions were modeled, then dead and live loads were applied to verify the elastic behavior of the structure and to identify a point of maximum deflection. This preliminary analysis calculated stresses to be within the limits of grade 36 ksi steel.

With the system accurately modeled, the structural engineers first executed a modal analysis to determine the vibration modes and frequencies where the structure moves when it is displaced from its equilibrium point. If the structure is excited near these frequencies, resonance occurs. Under resonance, and without damping, the response of the structure amplifies the effect of the excitation, generally resulting in vibrations outside of human comfort levels.

Next GMS performed a Steady-State Frequency Response Analysis (SSFRA). This analysis basically solves the stationary response of the structure if the system is loaded with a sinusoidal excitation where amplitude and frequency are variables, as is the case when a person climbs the stair. Nine control points were investigated located along the stair path, including the tip of the second mezzanine level cantilever where the maximum deflection was found to occur. (*Figure 2, page 10*). The excitation is the design weight of an aver-

Figure 5: View from above - construction work proceeded from the second floor, at top of photo toward the north (at left).

Design Team:

Architect
Atmosphere Design Group
Designer
Heatherwick Studio
Owner
Longchamp
General Contractor
Shawmut Design & Construction
Structural Engineer of Record
Building Structural Engineering Services
Structural Engineer for Stair
Gilsanz Murray Steficek, LLP

age person (157 pounds per AISC, Design Guide 11: *Floor Vibrations Due To Human Activity*) factored by a dynamic coefficient (α) which varies with the frequency of steps.

Step frequency had a very important role in this stair design. The range of frequencies for the excitation due to people walking has been established between 0 Hertz to 10 Hertz, although the range of calibration for the excitation is between 3 Hertz to 9 Hertz. Special attention was paid to the vibration modes obtained in the modal analysis and the frequencies around them because, at those points, the excitation was expected to be amplified by the resonance of the structure. At the steady state, the frequency of the excitation and the frequency of the response have the same value, but a phase shift was introduced here by the transient state. The result of this analysis was a series of curves that related excitation/response frequency with acceleration of the control points. *Figure 3* shows the curves based on the original structural model and *Figure 4* shows the curves for the optimized model.

To address the second challenge of human comfort, the results were factored based on the condition that the real structure rarely achieves the steady-state due to human steps. The results from the SSFRA were normalized to peak acceleration in %*g*, where *g* is acceleration due to gravity, versus the frequency of the excitation/response. Those curves were compared with the recommended peak acceleration for human comfort for vibration due to human activities (Allen and Murray, 1993: ISO 2631-2, 1989). Vibration criteria are subjective, as they are based on personal perception. Vibration perceptions also vary with activity; a person seated or standing still will feel the vibrations more easily than a person walking, and the person walking will feel the vibrations before a person running or jumping. GMS used criteria for comfort equivalent to that generally used for indoor shopping malls.

The conclusion of this study was a set of configuration thicknesses-boundary conditions that achieved the selected comfort criteria, as well as the displacement-strength requirements mandated by code. Intermittent fillet welds were detailed based on the stress levels at the joints between the horizontal "ribbon" plates and the vertical risers. Designing and specifying each different weld was economical from both a material cost and a time perspective due to the total quantity of welds.

The stair was built off site, cut into transportable sections, then welded together with complete joint penetration welds on site. Section sizes were based on trucking dimensions. Erection began on the south wall, where the stair reached the second floor and proceeded north toward the first floor and the street (*Figure 5*).

The project has been a success. The engineering analysis maintained the architectural forms with a thin profile (*Figure 6*). Unhampered by distractions due to vibrations, visitors to the store are free to enjoy the marvelous topography of the stair structure as well as the retail offerings.▪

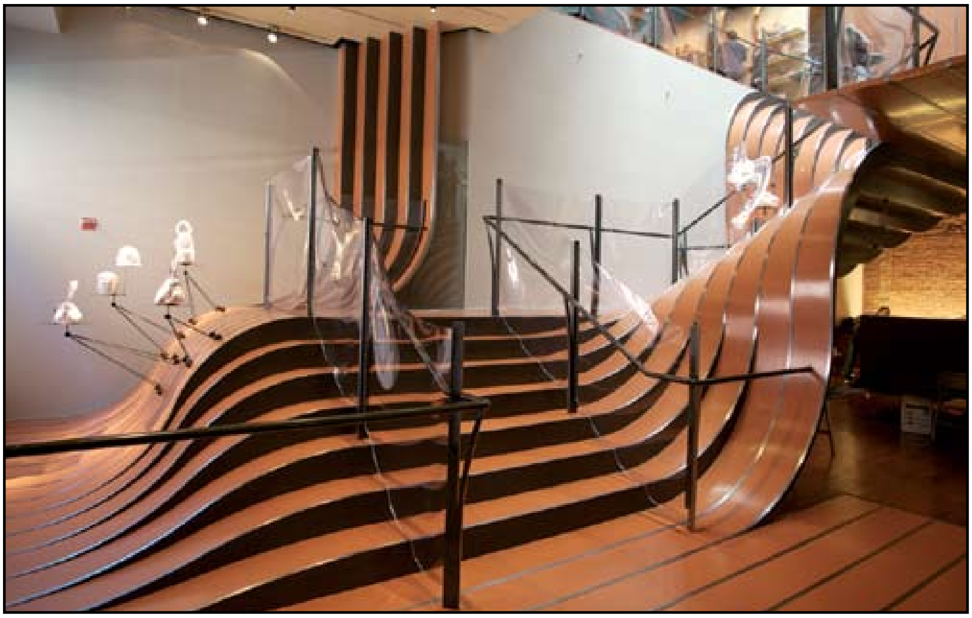

Figure 6: Lighting and product displays are cconnected to the 1.25" plates using high-strength magnets.

Victoria Arbitrio, P.E., SECB is an Associate Partner in the New York office of Gilsanz Murray Steficek, structural engineers & building envelope consultants. She is a member of SEAoNY, ASCE and a Past-President of NCSEA.