Structural Design for Vibration Isolation at Benaroya Hall

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Abstract: Vibration and sound isolation for the Seattle Symphony Hall was a major structural design concern. Concrete construction offers mass. Parking below the hall and double-wall construction create isolation. To save construction time, the hall’s seating tiers are precast concrete. Special isolation bearings are the only connections of the hall to the surrounding supporting structure. Structurally, the hall is an isolated “box within a box.”

A NOISY, VIBRATING, URBAN SITE FOR THE SYMPHONY

The new Symphony Hall occupies a city block in downtown Seattle. The Burlington Northern Railroad (BNRR) tunnel runs diagonally 60 feet below the steeply sloping, previously undeveloped site. An underground Metro Transit Station, the entire width of Third Avenue, runs the entire uphill length of the site to a depth of 50 feet. Both the station and the BNRR had to remain operational and undamaged. The structural challenges of the site are enough, but rail and transit systems both create unwanted sound and vibration for the Symphony. Controlling sound and vibration became the major criterion in planning for construction on this site.

STRUCTURAL PLANNING FOR THE SITE

Three methods were considered for bridging the BNRR tunnel: (1) massive concrete grade beams at foundation level, (2) a thick concrete mat at foundation level, and (3) framing above that “bridged” over to foundations alongside the tunnel easement. The tunnel affects other downtown sites, and we knew that Methods (1) and (3) had been successful. However, a thick mat foundation is the one solution that helps abate train vibration and noise. The 78-inch-thick concrete mat spans 60 feet over the rail easement and will dampen and reflect noise and vibrations. It is supported on each side by 6-foot-diameter piers, drilled to an elevation below the tunnel. The columns above strike a rectangular grid on the diagonal mat foundation, which was designed and optimized using a finite-element computer model.

The mass of the 6-inch slab on grade elsewhere at the basement was insufficient for acoustical performance, so a nonstructural, 12-inch-thick lean-concrete slab was cast under the 6-inch slab on grade. Lean-concrete, with minimal strength and low cost, has the same acoustical properties as structural concrete.

Concrete construction for the garage and the hall is used to add mass. Mass needed for acoustics adds thickness to concrete slabs beyond that required for structural optimization.

Early building plans and elevations were set considering needs for vibration and sound control. Parking below the hall creates spatial separation between trains and music, but created the need to shore the Metro Station during excavation. To avoid costly underpinning of the station, the excavation bottom was raised. It was decided that 30 feet of unexcavated soil was to remain between the station and hall so that (1) the soil could be soil-nailed together during excavation as a retaining structure to shore the station, and (2) a spatial separation would exist between buses and music.

A major structural item--installing special isolation bearings under the auditorium--is discussed separately below.

SPECIAL STRUCTURAL DESIGNS FOR ACOUSTICS

The “box-within-a-box” concept separates the auditorium from the surrounding structure. The auditorium is the inner box, surrounded by 8-inch concrete walls, termed the “inner walls.” These walls are the seismic shear walls for the inner box. An uninterrupted, 7-inch-wide joint separates the inner walls from the 8-inch concrete masonry (CMU) walls, termed the “outer walls.” The outer walls are the shear walls for the outer box. The outer box is the structure surrounding the auditorium. A reinforced masonry wall is more easily built adjacent to a concrete wall.

Other structural systems are designed to aid acoustical performance. Exterior precast concrete cladding panels outside the hall complete the double-wall construction. Additional concrete was added for mass to the roof of the auditorium, which supports a heavy plaster ceiling that acts as a double layer above the hall for sound isolation.
Auditorium balcony framing is precast concrete, including interior walls cast to odd shapes. The complex wall geometry was cleverly arranged by the architect to enable casting with the use of only a few forms. Precast concrete for auditorium framing saved construction time, yet gives the structure the mass needed acoustically. Figure 1 shows the auditorium balcony tiers during construction.

STRUCTURAL DESIGN FOR THE BEARING ISOLATION SYSTEM

Isolation bearings are installed under the auditorium for vibration and sound control. The need for bearings and the vibration-control-related bearing design were determined by Wilson Ihrig and Assoc. SWMB designed and incorporated the bearings as structural elements. Many of the soft, 40-durometer, natural-rubber bearings are needed. There are 308 gravity-load-resisting bearings, 15" by 15", and 224 lateral-load-resisting, precompressed bearings, 21" by 21". Placement of a lateral-load bearing during construction is shown in Figure 2.

All bearings are accessible for construction, inspection, or possible replacement in an 8-foot-high isolation level under the hall. Down-turned concrete girders in the isolation space ceiling run north-south, and up-turned concrete floor girders run east-west. Gravity-load bearings are compressed between the girders where they cross in plan. Lateral-load bearings are placed low against the sides of floor girders, and others are placed high on the sides of the ceiling girders to interlock the girders in two directions where they cross. Girders have unusual profiles, as they bulge up or down to intersect the lateral-load bearings.

The bearings compressed about \( \frac{1}{2} \) inch as load was added during construction. The large settlement could produce large errors in the calculated loads on each bearing from the highly indeterminant structure. To overcome this, auditorium walls were built with narrow vertical open strips, cast-in solid later. The strips divided the structure into less indeterminant sections and added accuracy to load calculations. Most of the gravity-load bearing compression occurred prior to prestressing the lateral-load bearings, which were already in place. This allowed realignment of the lateral-load bearings, which were precompressed successfully with flat jacks placed between bearing plates. Turning the bearing bolts to bear against the bearing plate finished the process.

Lateral-load bearings and “lugs” of concrete on the concrete girders were designed for a seismic load from 3/4g acceleration. To adopt the intent from base-isolated design, similar to our situation, 1g used for Seismic Zone 4 base-isolated structures was pro-rated to 3/4g for our Zone 3. This design intent makes the bearings and attachments much stronger and less susceptible to damage than other structural components, especially during smaller earthquakes.

FIGURE 1. Construction of the Auditorium balconies.  
FIGURE 2. Placement of a lateral-load-resisting bearing.