National Concert Hall in the Palace of Arts, Budapest

Ferenc Gonda, M.Sc., Eng., Deketto Statikus Iroda Kft., Budapest, Hungary

Introduction

Only a few steps from the Danube River in Budapest, the greatest architectural investment into the city's culture in the past hundred years resides. The new 70 000 square meter Palace of Arts (*Fig. 1*), rising from an irregular, five-sided site, houses three momentous cultural institutions in Hungary: the Ludwig Museum, the 1700 seat home of the National Philharmonic Orchestra, and the 500 seat Festival Theatre. The complex is served by a three-level underground parking lot for 621 cars.

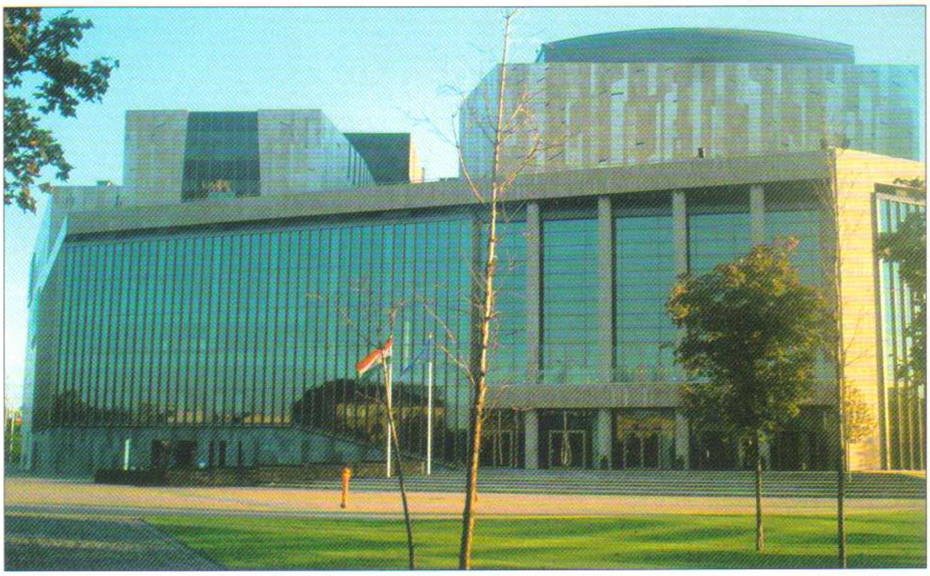
Fig. 1: The Palace of Arts, Budapest; entrance to the National Concert Hall (right)

The Palace of Arts

The structure of the house uses a variety of materials, taking advantage of the inherent usefulness of each. Floors were typically designed and built of cast-in-place reinforced concrete flat slabs, taking advantage of concrete's inherent mass, the local labor and fabrication, and the initial quick start of in-situ construction. Higher in the building, as in the Museum, floors were made of pre-cast concrete beam and slab construction. At the top of the structure, structural steel was used to span the larger distances needed at the roofs. The pre-cast concrete and the structural steel were erected quickly without shoring, but needed time for fabrication made available during the initial cast-in-place concrete work.

To minimize noise transmission between various venues housed in the building, superstructures of the different venues are physically separated into three structures: Museum, Hall and Theatre. The boundaries between the three structures are divided by double wall construction, the walls separated by 5 cm airspaces.

The Concert Hall

In the center of the cultural arts center sits the National Concert Hall, home of the National Philharmonic Orchestra. It is a classic shoebox shape, 55 m long, 23 m high and about 30 m wide. Together with reverberation chambers, the hall's volume is 40 000 m^3. The orchestra level, which seats 825 patrons, has three viewing areas: main floor, rear parterre, and box seats. Three wrap-around seating tiers, stacked above each other, offer seating at the rear and sides of the hall. All seating areas are raked to give optimum sightline viewing.

To add mass for the acoustic performance of the hall, slabs and walls framing the hall are 30 cm thick concrete. The cantilevered seating tiers above the main floor are also heavy concrete construction. Heavy ceiling panels (290 pieces), 15 cm thick, are supported at the bottom chord of the roof trusses, which also support a heavy concrete roof (20 cm). The 4,5 m high roof truss space, sandwiched between heavy concrete above and below, contains large mechanical equipment. The concrete sandwich helps isolate noise and vibration from the equipment. For acoustical purposes, the auditorium is heavy and stiff, weighing-in at 16 600 tons.

To enhance acoustic performance, the hall's shape and volumetric ratios were narrowly chosen. Nearly 6000 m^3 of reverberation chambers, located behind 10 cm thick concrete doors facing the auditorium (*Fig. 2*), can be opened to the hall as needed. A 600 m^2 acoustic canopy shell, weighing 50 tons (*Fig. 9*), is suspended with rigging over the performance platform. The acoustic shell's effect can be fine-tuned by raising or lowering it in three separate parts.

Noise and Vibration Isolation

Noise and vibration from a nearby bridge was an early concern for the acoustic designers of the concert hall. To test the need for special structural isolation systems for the concert hall, two vibration test piles (15,5 m and 10,5 m deep) were installed, and vibrations from the bridge monitored. On the basis of vibration monitoring, it was determined that special structural isolation measures were necessary for almost the entire building. However, the auditorium needed more isolation than the rest of the building. Two lines of defense were set: the first around the entire building, and the second would further isolate the auditorium from the surrounding structure.

Part of the first line of defense against the ground-borne vibrations is a 10 cm isolation gap filled with loose, 120 kg/m^3 mineral wool, placed between the 65 cm diaphragm wall and the 30 cm basement walls of the building (blue line in *Fig. 3*). This gap protects the perimeter of the building from external noise and sound transmission. Protecting the bottom of

Fig. 2: Rear of the auditorium during construction

the building is a massive, 1,10 m deep concrete mat foundation. To further reduce vibrations from the bridge, groundwater – which can increase the ground's ability to transmit vibrations – under the building is kept well below the mat foundation by permanently pumping groundwater (1–3 m^3/day) away from the building.

The second defense line (red line in *Fig. 3*) forms a complete separation of the auditorium structure and the surrounding structure, creating a "box in a box". The auditorium is the inner box, surrounded by double wall construction. Between the walls of the auditorium and the walls of the surrounding structure is a 20 cm airspace filled with only 5 cm loose mineral wool. In addition to the double wall construction, the bottom of the hall sits only on special vibration isolation bearings under it. The double wall construction and the isolation bearings ensure that no direct structural contact is made between the hall and its surrounding structure, and hence, there is little opportunity for external noise and vibration transmission to the Hall.

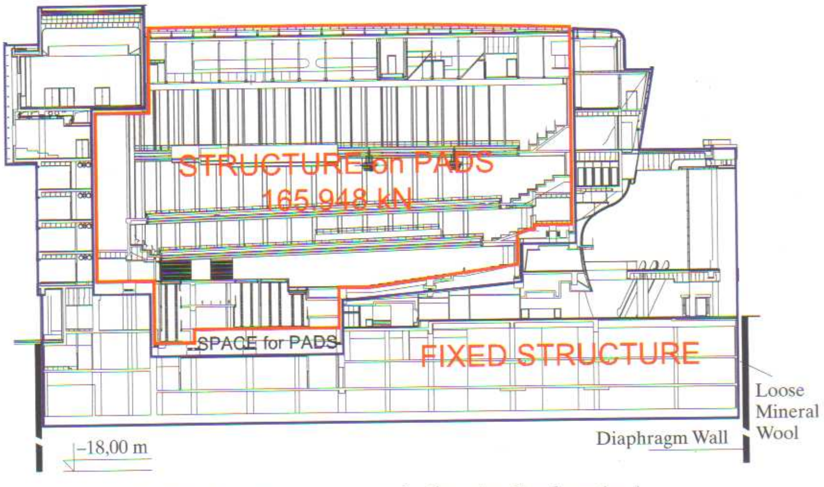

Fig. 3: "Defense lines" and the structure on pads (longitudinal section)

Isolation Pads

Gravity loads of the hall (166 MN) are taken at the base of the auditorium by 247 custom-made, rubber-and-steel isolation bearings. Each bearing takes an average 672 kN. Because the bearings have no lateral stiffness, bearings taking gravity loads can not also take the lateral loads. Lateral loads (wind, earthquake) on the hall must be taken at the auditorium base by an additional 88 bearings erected on vertical surfaces. There are a total of 335 gravity and lateral load resisting bearings.

The bearings are made of soft natural rubber bonded in layers between layers of steel plates. For each bearing there are five 29 mm rubber layers with four 3 mm interior steel layers between each rubber layer and 10 mm external steel plates top and bottom (*Fig. 4*). Most of the 335 gravity and lateral bearings are 450 mm × 450 mm × 177 mm, but 19 of the bearings had to be made smaller (360 mm × 360 mm × 177 mm).

Bearing stress is kept very low on the rubber bearings, 0,33 kN/cm^2 to ensure a longer life for the bearings. The rubber bearings are elastically very soft and compress 8,26 mm (average) under the low stress.

The bearings have a vertical resonant frequency of 6,0 Hz, and the resonant frequency of the floor structure nearest the bearings was designed to a frequency of 13,0 Hz (double the bearing's resonant frequency). To maintain this high frequency, mass and stiffness had to be added to the structure. For instance, some slabs were increased to 30 cm thick, and the seating riser platforms were cast over the sloping structural slabs using additional concrete.

Fig. 4: Natural rubber bearings on the site

To minimize the number of isolation pads and the associated costs, any area under the auditorium that could be omitted from the auditorium structure above was placed with the surrounding structure below instead. The base of the auditorium is not a horizontal plane under the hall, but is at different levels, each different base level containing isolation bearings (*Fig. 3*). There are four levels: orchestra pit (–2 m), main orchestra level (+5 m), the rear parterre (+11 m), and the bottom of the reverberation chambers at the 2nd tier (+13 m).

Placing the bearings at four levels complicated the detailing of the concrete above and around the bearings. For instance, isolation bearings needing a 45 cm bearing width could not be placed directly under the center of 30 cm thick perimeter concrete walls. The resulting eccentricity between the load in the wall above and the bearing placed under it was taken by the surrounding structure, usually the nearby floor slabs.

Loads on the lateral-load-resisting isolation bearing pads are based on a 0,08 g relative acceleration applied to the building mass, based on the requirements for Budapest cited in Eurocode 8. The resulting lateral loads calculated from code equations are 12% of the gravity loads of the auditorium structure. To resist these lateral loads, 22 pairs of bearings are needed in both longitudinal and transverse directions under the auditorium, resulting in 2 × 22 × 2, or 88 lateral load resisting bearings.

Lateral bearings are placed under the perimeter walls of the auditorium in pairs, on either side of special upstanding and downstanding concrete lugs. Downstanding lugs from the auditorium structure above alternate with upstanding lugs from the surrounding structure below, interlocking with bearings between the lugs to transfer the loads between the two structures. The bearings are pre-compressed so they remain in compression during any expected lateral ground motion. The pre-compression load for each bearing is 650 kN, which compresses each bearing 7,6 mm. Horizontal resonant frequency of the lateral-load-resisting bearings is 2,7 Hz.

Fig. 5: Reinforcement of upstanding lug

Construction Works

The lugs downstanding from the auditorium structure were mostly made of pre-cast concrete (*Fig. 6*) to simplify and quicken construction, and meet the very stringent construction tolerances of only ±5 mm. Both upstanding and downstanding concrete lugs contained large quantities of carefully detailed reinforcement (*Fig. 5*).

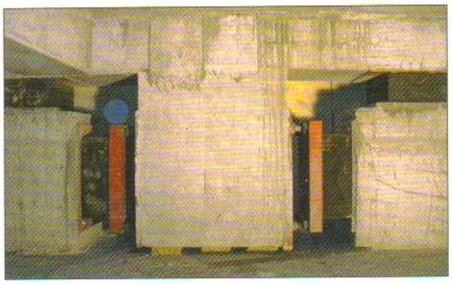

Fig. 6: Lateral bearings between lugs

One surface of a lateral bearing could be directly cast against the concrete lug on that side. However, a 68 mm thick steel plate was needed on the other side of the bearing to provide a strong, stiff surface for the jacking force during pre-compression of the rubber bearing (*Fig. 7*). The flat jack fit in the gap between the thick steel plate and the other concrete lug, exerting force onto, and compressing, the rubber bearing. To lock the pre-compression force in the bearing, the positions of steel plate and bearing were fixed with six M36 bolts.

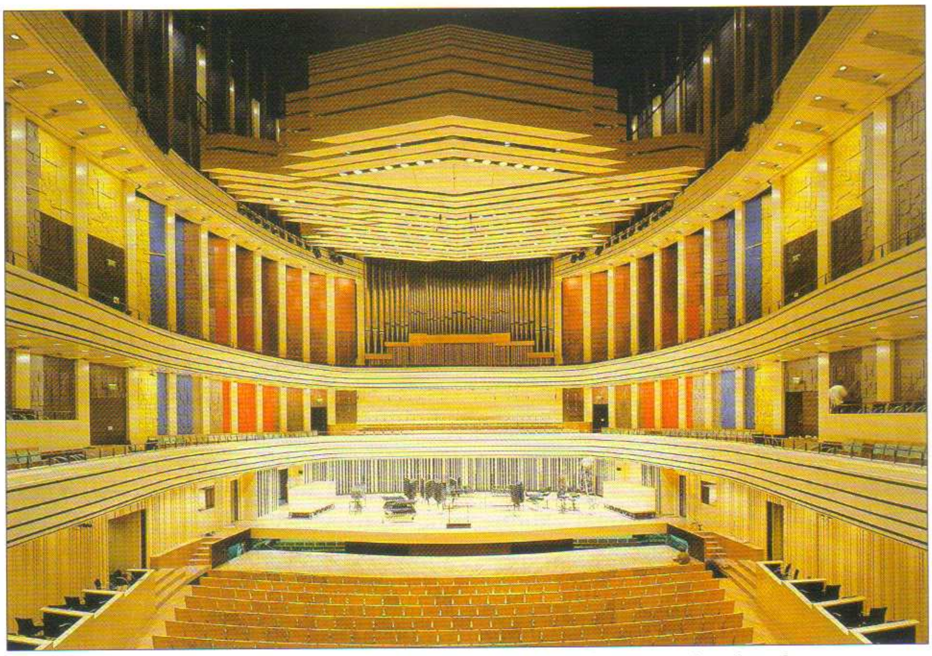

Fig. 9: "Inside" of the hall with acoustic canopy and reverberation chamber doors
(Photo by A. Polgar, Arcadom Rt)

The pre-compression procedure was made more difficult by the immensely tight headroom – 1,2 m to 1,6 m (*Fig. 8*).

Fig. 7: Lateral bearing on upstanding lug

As the hall was built, gravity bearings were compressed by about 8 mm due to the weight of the building; the entire hall moved down as the bearings compressed. To avoid shearing damage to the lateral bearings due to downward movement of the hall during construction, the lateral bearings were not pre-compressed until the construction of the "box" was complete and the gravity bearings totally compressed.

Fig. 8: Pre-compression

The diaphragm walls needed to be propped near the tops of the walls with a row of elastic pads bearing against the building structure. Using mineral wool was not enough near the tops of the walls near the surface terrain to be used as a bearing material.

Conclusions

The design for the new National Concert Hall in Budapest took great care to provide a vibration and noise-free acoustical environment for concerts, including isolating the Hall from noise and vibration from a nearby bridge. A "box within a box" system was used and the Hall was further isolated from the structure around it by using the latest technological advances in natural rubber isolation pads. This resulted in the perfect home for international concerts and recordings.

SEI Data Block

Owner:
Hungarian Ministry of Culture (NKOM)

Structural design:
Deketto Statikus Iroda, Budapest

Contractor:
Arcadom Rt., Budapest

Steel(t):	1900
Concrete(m³):	16 000
Total cost (EUR millions):	40
Service date:	March 2005