Lateral Thinking, Both Ways, for Both Objectives

While there are significant precedents for structural expression as an architectural theme with regard to the way a building or other structure resists the vertical loads of gravity, we have not yet fully explored the potential for expressing the way lateral forces of earthquakes are resisted.

Structuralism as an Architectural Theme
A classic case of elegance in architecture combined with elegance in engineering terms would be a bridge by Robert Maillart. From standard architectural texts (Gideon, 1941) to books written by engineers (Billington, 1979), Maillart’s arch bridges have been well presented to a large audience.

But as with most other examples of structuralism in architecture, the well-known example of Maillart’s works only have to do with vertical gravity loads, not lateral seismic loads.

The Design Challenge: Design a Building With “Maillart Bridges On Their Sides”
So, long story short, I set for myself the challenge of imagining a Maillart bridge turned on its side and then explored both the architectural and engineering aspects of what resulted when you try to make that into a building.

Lateral Thinking
This is an example of what could be called “lateral thinking, both ways, for both objectives.” It is lateral thinking both in the sense meant by the originator of that phrase, Edward De Bono (De Bono, 1967), and in the seismic sense of resistance to horizontal forces. De Bono has explored innovative visual and mathematical ways of opening the mind to the discovery of creative solutions by thinking around a problem rather than jumping to the most obvious conclusion. One of his sayings concisely explains his approach: “You cannot dig a hole in a different place by digging the same hole deeper.”

The other mode of lateral thinking is the literal one, thinking about and visualizing how a building or other structure will perform when loaded laterally by an earthquake.

“Both objectives” refers to the two reasons why one would want to incorporate lateral thinking into a building’s design:
1. To produce new forms of interesting aesthetic effect;
2. To achieve efficiency in seismic design, which, for sites where approximately one-third of the world lives (GSHAP, 1999), is a much more difficult structural problem than dealing with gravity loads.

Differences in Lateral and Vertical Loads
In simplified form, the differences between lateral and vertical loads can be reduced to a few key factors that must be considered and which enter into the design concept illustrated here.
The motion of the ground in an earthquake inertially generates seismic loads in the structure, and because that ground motion is complex, so are the effects on the structure. The key aspect relevant to the design issue here is that the ground moves in various directions (including vertically but those accelerations are significantly less severe than the horizontal), thus the structure feels lateral forces in various directions. Gravity forces on a structure are only exerted in one direction, down; an earthquake generates forces that must be resisted in any horizontal direction.

We can typically analyze a structure along one of its primary axes, with the seismic loads acting first one way and then back the opposite way; then do the same for the other axis. These are the typical governing cases, as compared to the various off-axis forces resulting from other directions of ground motion impulses. This is diagrammed in the accompanying illustration. The implication of this is that the structure’s horizontal resistance must be balanced in plan: You can’t take a structure designed to resist one-way (gravity, downward) loading, turn it on its side, and obtain a stable structure. The “Maginot Line” approach of providing resistance only in one direction doesn’t work for earthquakes.

There are of course other differences between gravity forces and seismic forces. Along with the fact mentioned immediately above, two others are listed in the table below.

Table 1: Comparison of Gravity and Earthquake Effects

<table>
<thead>
<tr>
<th>Gravity</th>
<th>Earthquake</th>
<th>Architectural Implications of Seismic Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. One direction</td>
<td>Multi-direction</td>
<td>Resistance to lateral forces must be balanced in plan</td>
</tr>
<tr>
<td>2. Elastic design</td>
<td>Inelastic design</td>
<td>For large earthquakes, it typically is not feasible to provide enough strength to resist the forces elastically; some inelastic behavior—cracking, permanent bending, etc.—is necessary.</td>
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<tr>
<td>3. Static</td>
<td>Dynamic</td>
<td>Ground motions and resulting forces vary by the split-second; frequency and damping characteristics of the way the structure “gives” affect the magnitude of the forces</td>
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In the design explored here, these three basic seismic factors have been integrated as follows.

**Multi-directional Resistance**

The typical building has walls that only resist in-plane lateral forces; for forces in the out-of-plane direction, the walls merely add to the problem (their mass adds to the load), and they must hang on to floors and the roof (structural diaphragms in that horizontal role) for support. Meanwhile the walls oriented the other direction do all the work. The building must be designed for the worst case on both axes, “throwing away” half the total resistance (not being able to mobilize the strength of the out-of plane walls).

The design produced here takes a “Maillart bridge on its side” as its basic structural unit and then designs it as a lateral-force-resisting element that can resist loads either along its own axis or for loads imposed perpendicular to it. This in itself is a great achievement in engineering elegance, accomplishing more with less.
Inelastic Design
The second consideration in Table 1 has to do with the fact that “ductility” is a central concern in earthquake engineering and is explicitly recognized as a requirement in every building code in the world that contains seismic regulations. (IAEE, 2000) Seismic forces in a large earthquake are so large and difficult to resist that it is not economical to provide so much strength via “bunker” construction that a building will come through the event without a crack, that is, remain elastic. Ductile behavior—cracking, permanent deformation of steel frame members or reinforcing steel, etc.—is explicitly designed into buildings by structural engineers. But ductility is also damage: We need to control where the ductile behavior, i.e., damage, occurs.

The design here provides for the ultimate receiving point of lateral loads to be the four corner cores. The “Maillart bridges on their sides” convey all loads to those points. We now have the opportunity to pack tremendous amounts of strength into these windowless pylons, but if the earthquake pushes them past their elastic limits (if the reinforced concrete cracks and spalls, the reinforcing is stretched permanently), this damage could be easily repaired while the building is still occupied.

Dynamics
Put a ton of weight on a bridge or a roof and there will be exactly a ton of load conveyed down through the structure, unchanging from one moment or one day to the next. In an earthquake, however, the building feels accelerations—it feels the effect of moving in one direction at one instant, then another direction at another instant. Its velocity changes abruptly (that’s how acceleration is defined in physics) as if the building were alternately stepping on the gas pedal and the brake, lurching around erratically.

How does that affect the design? We can “tune” the overall structure to have an inherent tendency to vibrate back and forth at a particular rate (fundamental period of vibration). Actually, we want to make it “out of tune,” that is, to avoid vibrating in sync with the motions of the ground. If the building tends to resonate with the earthquake, the forces can be several times greater than if it does not.

Again, the corner cores provide a strategic location for what are called “advanced technology devices” in the earthquake engineering field. Entire buildings and bridges in California and Japan rest on special bearings that can filter out the frequencies of damaging motion of the structure, and can add damping or “squishiness” to reduce the forces further.

The building volume that is contained within the four corner cores moves as one rigid unit, nicely braced by its “Maillart bridges on their sides,” while the seismic isolation devices at the bearing points at the cores absorb the impact of the earthquake and provide a cushioned ride. To my knowledge, there is no building in the world that uses such a “sideways” isolation scheme: The usual approach is to place isolation devices in the basement under the structure.

We can also introduce seismic isolators under the four cores in the conventional manner. This gives us a doubly-isolated building. The side structures of the building span vertically off the ground as well as laterally spanning to carry horizontal forces, and hence the building stands on the ground in only four places, at the cores. In practice, shake table testing and analytical
simulations would be conducted, for a given site (and thus a given “suite” of earthquake ground motions expected at that site in the future), to efficiently design the two sets of isolators work efficiently as a team.

**Aiming Higher: Earthquake-Proof, not Earthquake-Resistant**

“Earthquake-proof” is a forbidden term in earthquake engineering today, because as explained above, the typical design solution is to explicitly anticipate some ductile behavior (damage) and design it to occur in particular places so that the structure remains safe. In this design, however, we aim higher, and we use the term “earthquake-proof” by intent and unashamedly. The seismic goal is to provide such a high quantity of strength, via the “Maillart bridges on their sides” and corner buttresses, and with a double isolation scheme (sideways isolation of sides to cores, vertical isolation of cores to ground), that our building will undergo its maximum design earthquake with no damage at all. We’ve been settling for much less for too long.

**Aesthetics**

The schematic design illustrated here (Figure 1) visually speaks for itself, so I will only add two brief comments.

I initially found the “Maillart bridge on its side” to be a fascinating object as I rotated it in my mind, then sketched it. The sweeping curve of the arches that is beautiful when oriented vertically as in a bridge is also, I think, a beautiful thing arranged horizontally. The arch ribs are narrow bands, for obvious fenestration reasons to allow light and view from the inside looking out, and also to provide more visual interest when the building is viewed from the exterior.

The shape that results from this plan form, when roofed, results in the shell structure shown in exploded view. In practice, such roofs of significant span, while sometimes theoretically possible to design so that they produce no lateral thrust on their supports, in practice exert some outward lateral forces, if only because of asymmetric wind loads. Such horizontal forces, however, are easily resisted by the top-most “Maillart bridge on its side” and conveyed laterally to the corner structures. Not shown for clarity is the possibility of dividing into separate stories one or more of the lower levels of the interior space, but by intent I want to achieve a complete open-plan volume at least in the upper portion of the structure, if not to use the entire interior as one grand public space.
References


Turn a Maillart bridge on its side to resist lateral forces.
The "deck" is cut into strips for fenestration reasons
and to reduce weight.
Make the walls resist out-of-plane forces
so that the entire structure resists the earthquake
load at a given moment, rather than the usual
inefficiency where half the walls (the walls loaded out-of-plane)
must be supported by the diaphragm and in turn by
the walls that are oriented parallel to the ground
motion at that instant.
Locate the reactions at external buttresses to allow the
structure to span between them vertically and laterally.
Allow for isolation/damping devices where
these buttresses connect to the rest of the building.
Run the HVAC/elevator/stairs up the buttresses.
Provide lateral resistance to a roof's thrust.
Provide visual interest, viewed from either inside or outside
the building.

Figure 1: Perspective and Schematic Seismic Diagram