Vancouver Convention Centre Expansion Project

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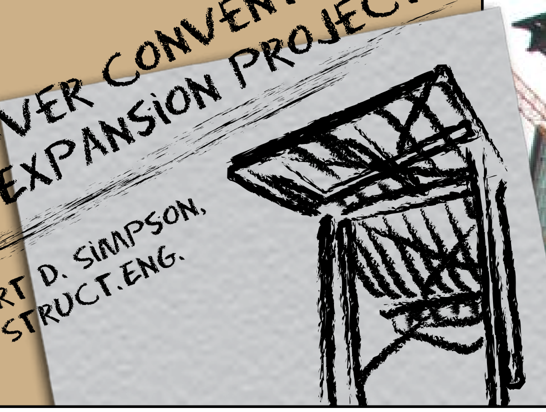

“Tools of the trade” have changed for Structural Engineers! While materials for structures have remained relatively constant over the decades, our ability to create innovative solutions has improved by magnitude shifts every few years. The latest change is with Building Information Modeling (BIM), a technological advancement that has again transformed the design process, particularly for some unique and complex buildings. Glotman Simpson took full advantage of 3D modeling, design, presentation, and delivery of documentation via electronic communication, only using paper copy for minor information and for backup, for the Vancouver Convention Centre project.

VCEC roof framing prior to roof deck installation showing supplementary diaphragm cross bracing.

Early in design development, Glotman Simpson proposed the use of BIM for the structural engineering solutions for the project. While the good old-fashioned pencil was used for “napkin” design, it quickly became apparent that the next step of 2D plans and sections would be prone to difficulty and misunderstandings. Architectural design by the collaboration of Downs / Archambault Partners, Musson Cattel Mackey Partnership and LMN Architects, utilized AutoCAD® 3D modeling to assist in massing and layout. The structural designers also proposed implementing steel detailing software, Tekla, to provide structural modeling at the design stage. By employing Tekla early in the project, the structural design information became the springboard for shop drawings and shortened the tendering and shop drawing period considerably. With early implementation, the structural engineer was freed of conventional limitations and the design evolved with greater precision and speed. As an example, 3D conceptualization provided a genuine understanding of the building that allowed experienced engineers, utilizing approximate and shortcut methods, to estimate preliminary steel quantities within 5% ofthe final built configuration.

Free to develop complex structures without the burden of sketching limitations, the engineer is then challenged to ensure that design of the structure remains true to analysis principals throughout the project. Increased complexity leads to an exponential increase in considerations necessary for consistent assumptions that create a safe and complete design. Gone are normal simplicities such as assumed lateral supports, diaphragm continuity or stiffness, or small displacement theory and, as a result, all relevant structural actions need to be considered and verified when designing a complex structure on a grand scale.

Configuration and Statistics

The new Vancouver Convention Centre consists of 1.4 million square feet (130,000m^2) of suspended structure in a multi-story building over a marine deck at the foreshore of Burrard Inlet in Vancouver. The marine deck designed by Westmar Worley Parsons, built upon hundreds of 36-inch (900-mm) diameter steel pipe piles, varying in length up to 180 feet (55 m) into the ocean, became the foundation for the building structure and the floor of the exhibition hall and truck loading. The marine deck measures 550 by 1120 feet (165 m x 341 m) and had to be separated into two sections to control thermal movements. Once created as a movement joint, the gap needed to be wide enough to allow seismic displacements of up to 14 inches (350mm). The building structure straddling the thermal joint was therefore split into two buildings, and required a wide expansion joint to accommodate the marine deck movements plus additional building displacements.

Designed to accommodate exhibition activities, conventions, meetings, ballroom activities, retail, restaurants, and public spaces such as the seawall bikeway and park-like open space, the building design presented diverse and interesting challenges. 15,000 occupants can be expected at one time in the exhibition hall alone. The ballroom is Canada’s largest at 55,000 square feet (5,100 m^2), accommodating up to 5,000 people for dinner! Public space around the building provides about three acres of park-like plaza and walkways including the Thurlow plaza, which will accommodate up to 10,000 people. Parking for 443 cars is provided in an interstitial floor within the building, plus a further 102 spaces in a nearby separate concrete structure.

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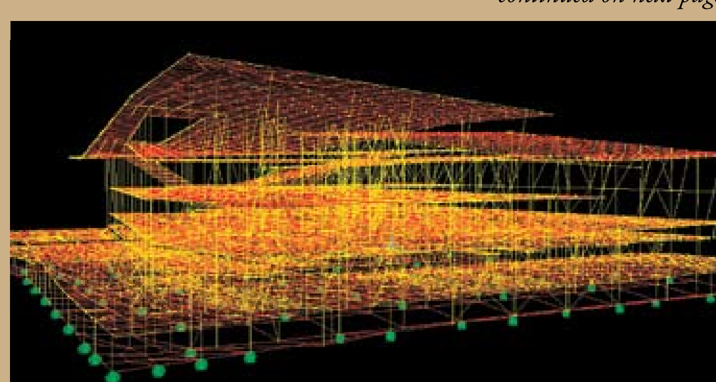

SAP2000 model was translated into Tekla software to create a steel “design” model for use in tendering the project to steel contractors.

VCEC Rendering. Courtesy of Downs / Archambault Partners, Musson Cattell Mackey Architects, LMN Architects.

Green Roof

Objectives for the building design included a planted green "landform" covering the 250,000 square foot (23,000 m^2) folded-form roof. The chosen design was 7 inches of lightweight growing medium, which would compact to 6 inches during normal consolidation and result in a load on the roof structure of 49 pounds per square foot (240 kg/m^2). Field measurements taken during installation ensured that variations in soil depth did not cause a design concern. On long-span structures, added roof loading can cause significant increases in the gravity supporting structure and also in seismic-force-resisting systems. It was determined that each incremental inch of soil thickness would add roughly $600,000 of additional structure to the building. Therefore, it was important for the design team to establish an appropriate value point for the growing medium, where additional thickness provided diminishing returns in terms of plant life and variety. Still, the green roof proved to be an overall cost advantage when considering alternative solutions for such a highly visible roof.

VCEC's 36-inch columns, sloped roofs with green roof systems and clear glazed perimeter walls.

Long Span Multi-Level Building

Multistory stacking of large-volume spaces made for a challenging design at the conceptual stage, requiring special structural solutions. In one area on the third suspended level was the 180- by 320-foot (55 m by 98 m) ballroom situated above the similarly sized parking level, which is above the 310- by 785-foot (94 m by 239 m) exhibition hall. Immediately adjacent, and tying into the floor levels, was a five-story building consisting of three levels of long-span meeting rooms and foyer space over two levels of parking/retail and office. Upper levels of the building are 23 feet (7 meters) floor-to-floor and the exhibition hall required a clear height of nothing less than 30 feet (9 meters).

Fortunately, a few columns could be permitted within the exhibition hall in 90- by 120-foot (27 m by 37 m) bays; however, the meeting rooms, ballroom, and foyer had to be clear span. The key solution for planning was steel trusses the full depth of floor levels and, in a number of cases, multiple floor levels. Deep trusses could be arranged to allow door openings through the walls as required for architectural layout. Considerable coordination in planning was required to facilitate functional use of the building and fundamental structural needs. Trusses became four stories high at some locations, to allow openings at intermediate levels and variable locations. The side walls of the ballroom vary in height up to 70 feet (21 m), and when added to the depth of the parking levels the trusses extend as much as 86 feet (26 m) deep. Spanning over the exhibition hall, and forming the floor of the ballroom level, is a story-deep two-way truss system with Vierendeel openings to allow for car parking within the depth of the structure. Sloped and stepped roofs resulted in disconnected diaphragms, requiring tie forces through drag lines coordinated with truss and brace lines. The trusses provided excellent inter-story stiffness for building integrity; however, care was needed to ensure that the seismic bracing system could function effectively and allow the necessary seismic energy dissipation.

In the midst of this complexity, a simple solution was developed. A basic grid pattern of 45 feet (14 m) by 30 feet (9 m) became the theme for the structure – almost. Trusses running north-south at 45-foot (15 m) spacing became the primary grid system and coordinated nicely with the 90-foot (27 m) grid of the exhibition hall below. Consequently, every second wall truss would have good support on the foundation structure. In the east-west direction, the 30-foot (9 m) grid was more flexible due to the continuous truss support, and therefore allowed for variations in the functional layout. All edges of the building are askew to the grid, causing anomalies at some locations. Still, the architectural massing and space planning followed the basic grid, which allowed for a very efficient structure considering the clear spans and loading requirements for the project.

This gnarly column is a junction of full height wall trusses forming the primary framing system.

The floor framing of the building was a combination of composite beams and open web steel joists supported primarily by trusses, but also by heavy long-span girders in locations where story-depth trusses could not be permitted. Floor deflection and vibration were a significant concern, requiring a concrete slab thickness of 3½ inches (90 mm) above the 3-inch (75-mm) composite steel floor deck. The floor slab was reinforced in two directions to allow for wheel loads from hand carts and light vehicles, and also to provide for better seismic diaphragm resistance and integrity.

Seismic Resistance

Eccentric braced steel frames provide lateral load resistance and seismic energy dissipation. To arrange bracing for a large-format truss structure, it was essential to work with the primary truss load paths for both vertical and lateral loading. There were very few options for lateral brace locations, mainly around the perimeter of the exhibition hall and through the mechanical spaces that run along the north side of the exhibition hall. Thus, it was clear where braced frames would have to go. By strategically selecting locations of lateral resistance in

Eccentric braced bay seismic resisting system with bases cast into foundation slab.

proportion to the associated mass of the building, the resisting system was balanced to the building mass, minimizing torsional motion of the building.

No space is wasted in the mechanical rooms that run the 720-foot (219m) length of exhibition hall. Eccentric braced bays were threaded through the mechanical rooms at each 45-foot (14 m) grid to provide for even distribution of seismic resistance. It became necessary to invert one level of eccentric braces to accommodate access in the mechanical spaces; thus a unique brace configuration was adopted to engage a larger number of link beams for energy dissipation.

Leaning Columns and Spring Washer Brace

The leaning columns are a dramatic architectural statement along the north face of the building, overhanging the seawall and reaching the highest point of the structure over 100 feet (30 m) above. The columns lean toward the north at an angle of 15 degrees. For each unit of gravity load on the column, there are 0.25 units in lateral loading to be resisted in the building. The lateral force on each of the 12 leaning columns is greater than the design seismic inertia associated with the same gravity mass. Eccentric braced bay systems must be free of sustained lateral forces in order to function properly. Therefore, it was important to resist the leaning load with a system other than the seismic resisting system so that the eccentric braces would be free to sway and yield in both directions equally.

The basic structural concept of resisting the lateral load of the leaning columns is elementary; however, it becomes much more complicated when seismic displacements are involved. The seismic system must be allowed to move freely and yield in both directions without the brace system attracting seismic loading. Also, when the seismic system yields and extends the movement range, the column brace needs to allow the movement without significantly changing its load. Additionally, when displaced, the leaning column provides more P-Delta force per unit of movement than would be seen in a vertical column. Only two systems were feasible for satisfying the above-mentioned requirements: a balanced leaning column system and a spring tension brace system. The balanced column system might be technically feasible, but within the context of efficient building design, the introduction of additional leaning columns would not be suitable. Thus, a tension spring system was required.

Parking Vierendeel trusses with drive aisle passing through trusses at 45-foot bay lines.

Field welding of key joints where assembled sections are limited by lifting capacity.

Alternatives explored for the tension spring system included prestressing wire, coil springs, cupped spring washers, and redundant brace locations. While the prestressing wire showed promise, the difficulty in connecting and adjusting the wire was a significant limitation, and its axial flexibility was not sufficient to provide the desired free movement without becoming slack at one end of motion or overstressed at the other end. Coil springs could be implemented; however, the space required to accommodate a very large number of large coil springs was a deterrent.

The cupped spring washer solution was attractive, since very high forces can be achieved through a relatively small spring assembly. Cupped spring washers are placed face-to-face in pairs and assembled in series to provide for the large total required movement. Force and displacement limits of each spring assembly are determined from analysis of an individual spring washer, and the total required movement is determined by the collection of washers.

The force-displacement relationship for the cup washer is almost linear. The washers were compressed to the midpoint of their movement range, thus allowing 50% of the total potential movement in each direction from the neutral point. The number of washers in series was selected so that permitted sway was within the middle half of the spring movement range, thus allowing for ¼ of the washer design force at the greatest slack point and ¾ at the design movement. This would allow 25% of the total movement beyond design level without the system becoming slack or overstressed. In an exceptionally large seismic event, the system could theoretically become slack in one direction and "bottom-out" in the other direction. In each case, the system would assist the earthquake resistance and remain safe and intact. Tension rods are capable of resisting a force 2.5 times the design spring force, thus ensuring that the rods would not break if the spring assembly were fully extended. Additionally, post-seismic stability provided by the spring washer braces is important but not essential, because the building system can sustain the lateral loads without the diagonal spring braces.

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Installation of the system was performed by containing the cup washers inside preassembled 8-inch (200-mm) pipe "cans", with a large hole cut in one side for access and end plates for load bearing. The spring washers were compressed to the design service displacement of 50% total movement so that the assembly could be installed without a need to field apply large tension forces. In the field, the system was installed to a snug fit on all levels of the building, and the building was loaded with the roof soil before the spring washer assembly was released to act under sustained loading. To release the springs, a jack was applied to the assembly that took the load off the lock nut, which was then moved outside the potential movement range and the jack released. Braces were released in a sequence to ensure that no accidental torsion was introduced to the building. The axial movement of each brace was measured and recorded and compared with the expected value. The assembly was able to maintain the building position within tolerance without appreciable movement, proving that the anticipated forces were engaged within the spring assembly and braces.

Would We Do It Again?

Clearly, the 3D modeling technology implemented on the new Vancouver Convention Centre was critically important to the success of the structural design, and also to that of all design disciplines and the fabricators who followed. The challenge to the designer at the front end of the project is far greater when 3D modeling is used, and therefore requires the hands-on guidance of highly experienced technical design engineers to be a success. However, with the right people involved, a very complex building can be designed quite efficiently. The major benefit accrues to the owner and architect who enjoy the praise for a fabulous building. That is music to our ears!▪

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VCEC steel framed structure on marine deck.