CANADIAN CONSULTING ENGINEERING AWARDS | 2011

The BOW

SPECIAL PROJECTS

MMM GROUP | MAY 2011

PROJECT HIGHLIGHTS

The BOW

Project Highlights

The BOW project in downtown Calgary is, at 58 storeys, the largest office space in Calgary and the tallest building in Canada outside of Toronto, With construction costs estimated at $1.4 billion, the high-rise office tower contains 158,000 m2 of office space, 100,000 m3 of concrete, 39,000 t. of structural steel and over 84,000 m2 of glass. The BOW project represents the first time that a triangular diagrid system has been applied to a curved building design in a North American skyscraper.

The BOW's aerodynamic crescent shape reduces wind resistance, down draft and urban wind tunnels. Its unique design maximizes natural light and occupants' views, and creates open, centralized spaces, including a sky garden system. The tower's form and mass were developed to adapt and utilize Calgary's climate, including seasonal sun paths, rainfall, wind, temperature and humidity. The building faces southwest, allowing the sun's heat to be absorbed and recycled through the building in all seasons.

As a key contributor to ensuring the structural integrity of the BOW, MMM Geomatics provided geomatics services for numerous aspects of the landmark building's construction. The team introduced leading-edge geomatics methodologies and technologies never used before in Canada, including in real time building monitoring and layout of steel members using GPS techniques. Additionally, MMM's strategy of employing a network of Nivel 220 inclination sensors for building monitoring is a practice employed by a number of the world's most challenging skyscraper construction projects, including the Burj Dubai.

To ensure the functionality of such a complex and innovative design, MMM Geomatics was responsible for establishing and maintaining a precise exterior control network for the BOW. As well, the external control network was augmented through the installation, coordination and maintenance of a network of rooftop, 360-degree prisms on neighbouring buildings.

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Project Highlights

MMM's survey methodology included accommodation of building tilt since typically during construction of a skyscraper complex such as the BOW the structure will temporarily lose its exact verticality and building shift and movement will occur. To accommodate building tilt, innovative survey methodologies for the establishment of building control and for precise survey layout of the structure were developed and utilized for the project.

MMM survey responsibility included the plumbing of the structural steel elements that provided the framework for the building. This process involved the real time layout and reporting of the instantaneous displacement from design location of the various structural components. Further, MMM provided detailed topographic and legal surveys of the BOW site and proposed connections to adjacent buildings. The MMM team was also responsible for the layout deck of screed offsets, project gridlines and the establishment of working level benchmarks for all trades.

With leading-edge technologies such as a Nivel 220 inclination sensor network, visionary advances in geomatics methodology, such as real time building monitoring and layout of steel members utilizing GPS, and rigorous quality control and quality assurance procedures, MMM Geomatics enabled the BOW skyscraper to soar to new heights. MMM's leading edge approach and ultra-precise data translated into proven results and, with its structural integrity assured, the BOW project unfolded on schedule and with confidence and success. The innovations MMM Geomatics applied to this challenging, complex project put the BOW on the map not only as a landmark on Calgary's skyline, but also as a milestone engineering achievement.

FULL PROJECT DETAILS

PROJECT SUMMARY

The BOW project is a 58-storey high-rise structure currently nearing completion in downtown Calgary and it will be the tallest building in western Canada. It will be the first time that a triangular diagrid system has been applied to a curved building design in a North American skyscraper.

As a key contributor to ensuring the structural integrity of the BOW, MMM Geomatics provided geomatics services for numerous aspects of the landmark building's construction, including the establishment and maintenance of the precise exterior control framework.

MMM brought to the BOW project leading-edge geomatics methodologies and technologies never before used in Canada, including monitoring of the building in real time and layout of steel members using GPS techniques. Additionally, MMM's strategy of employing a network of Nivel 220 inclination sensors for building monitoring is a practice employed by some of the world's most exciting skyscraper construction projects, including the Burj Dubai.

Throughout the project duration, streamlined and efficient workflow has proceeded without error or delay regarding checking, layout, and as-built of all structural steel. MMM is proud of its important role in providing innovative and precise geomatics services in support of this exciting new addition to the Calgary skyline.

HIGHLIGHTS

- Precision layout of complex building elements and features, including rigorous quality control and assurance procedures, enables this landmark project to proceed without delay and with confidence
- Design, establishment and maintenance of a suitable and properly monumented control network satisfies stringent layout requirements and allows a demanding project schedule to stay on course
- Employment of sophisticated, state-of-the-art survey technologies such as precise digital inclination sensors are key to the success of a project as dynamic, complex and difficult as the BOW
- Leading-edge methodologies such as monitoring of building dynamics and correction of GPS-derived positions for building tilt, both in real time, are unprecedented in a Canadian skyscraper project

1.0 INTRODUCTION

The BOW, designed by Foster + Partners for Encana, is a 158,000 m^2 (1.7 million sq. ft.) office building comprised of 100,000 m^3 of concrete, 39,000 t. of structural steel and over 84,000 m^2 of glass. The tower's aerodynamic crescent shape reduces wind resistance, down draft and urban wind tunnels. Its unique design maximizes natural light and occupants' views, and creates open, centralized spaces, including a sky garden system. The tower's form and mass were developed to adapt and utilize Calgary's climate, including seasonal sun paths, rainfall, wind, temperature and humidity. The building faces southwest, allowing the sun's heat to be absorbed and recycled through the building in all seasons.

The BOW, with construction costs at an estimated $1.4 billion, is the largest office space in Calgary and the tallest building in Canada outside of Toronto.

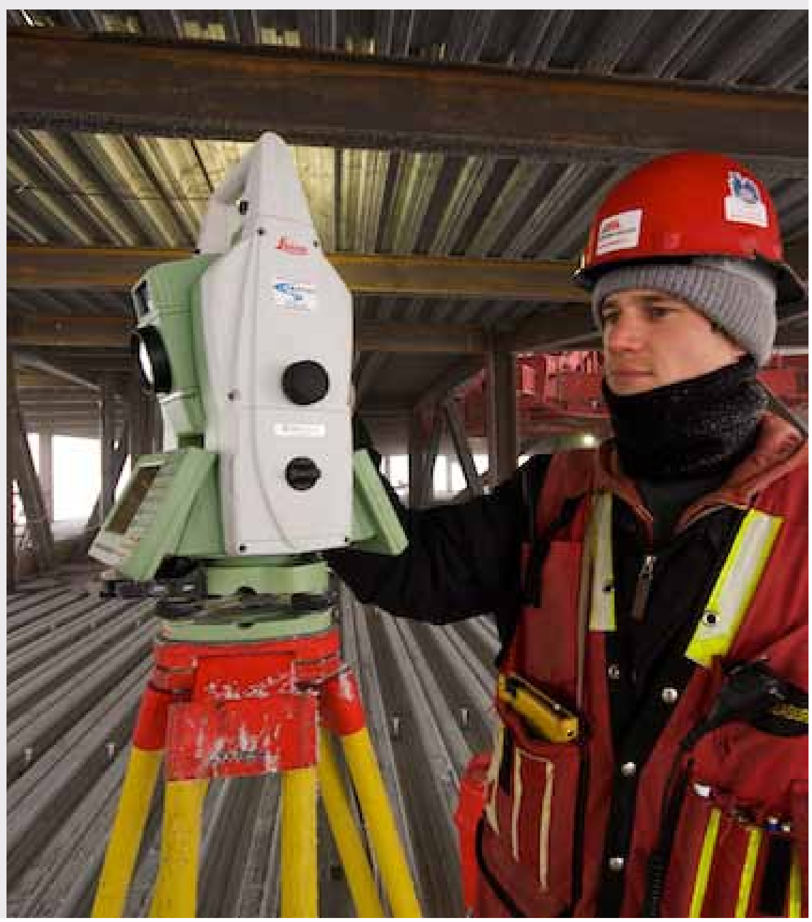
To ensure the functionality of such a complex and innovative design, MMM Geomatics was responsible for establishing and maintaining a precise exterior control network for the BOW. As well, the external control network was augmented through the installation, coordination and maintenance of a network of rooftop, 360-degree prisms on neighbouring buildings.

MMM's survey methodology also had to accommodate building tilt. During the construction of a skyscraper complex as the BOW, the structure will temporarily lose its exact verticality and the building will shift and move. To accommodate this building tilt, innovative survey methodologies for the establishment of building control and for the precise survey layout of the structure were developed.

MMM survey responsibility encompassed the plumbing of the structural steel elements that provided the framework for the building. This process involved the real time layout and reporting of the instantaneous displacement from design location of the various structural components. Further, MMM provided detailed topographic and legal surveys of the BOW site and proposed connections to adjacent buildings. The MMM team was also responsible for the layout deck of screed offsets, project gridlines and the establishment of working level benchmarks for all trades.

MMM's contributions to the BOW were vital for ensuring safe, timely and structurally-sound construction of this highly sophisticated engineering and construction achievement.


THE BOW



2.0 SURVEY CONTROL

Accurate and timely survey control both on and off the BOW tower was necessary to keep up with expedited construction schedules. It provided a framework from which all surveys were based, building movement was monitored, and was key to layout and as-built of building elements. Throughout the various phases of the BOW tower construction, MMM established and maintained horizontal and vertical control networks as required to facilitate all subsequent surveys on site.

MMM conducted frequent and comprehensive check surveys on the horizontal and vertical control networks to assess control station stability and overall network consistency.

2.1 Horizontal Control Network

The primary purpose of the external control network at the BOW site was to act as a reference for, and provide an on-going accuracy audit of, the interior network employed on a daily basis by all the surveyors on site. In order to assess stability of the interior survey markers, MMM established an external, stable and precise network. The horizontal external control network consisted of 12 rooftop prisms, three external/framework control stations established by MMM, and two Pleiades Data Corp continuously operating GPS reference stations located in Calgary.

Framework Control

Framework control was established on nearby bridge structures of maximal structural stability. The framework control was the ultimate reference from which network accuracy and stability were assessed.

MMM installed three fixed-bracket markers compatible with both conventional and GPS survey equipment as framework control. They were installed at locations far enough from the BOW site to ensure stability. These markers were monitored to ensure disturbance had not occurred.

Rooftop Prisms

MMM placed and coordinated 12 Leica professional-grade prisms, tribrachs and carriers at strategic locations around the site. The setup allowed for the co-location of a GPS antenna on top of the prism. At three-month intervals, MMM performed a complete static GPS control survey involving simultaneous occupation of all rooftop prisms capable of GPS occupation and the framework control markers. The GPS surveying involved the overnight occupation of rooftop locations, followed by two 10-hour GPS static sessions completed over two days. The survey enabled the assessment of the stability and accuracy of the horizontal network.

Pleiades Data Corp

Pleiades Data Corp (PDC) is a partnership of several Alberta-based geomatics firms operating and supporting more than 25 continuously operating GPS reference stations throughout Alberta. MMM played a key role in the development of the data network. PDC reference stations continuously stream real time kinematic data and constantly record raw GPS phase and code data for precise post-processing applications. Data from two PDC Calgary stations provided additional baseline observations, more rigorous network geometry, and another layer of external control reliability.

PDC stations supplemented the external framework markers previously described. Static GPS observations were performed between the PDC stations, the external framework stations and the internal site control makers.

MMM's external control network provided an indisputable and highly usable reference network that enabled the project team to adapt to the demands of the BOW's dynamic site conditions.

2.2 Vertical Control Network

A vertical datum is a reference surface for heights. In Canada, it is currently realized through a network of monumented vertical control points with elevations derived by spirit leveling techniques. The datum is called the Canadian Geodetic Vertical Datum 1928 (CGVD28). On a local scale, the BOW project utilized a defined local vertical datum.

Typical vertical control stations are ground-based markers allowing for the transfer of elevations via spirit level observations. Sub-millimetre accuracies over short distances are attainable using spirit leveling techniques. Utilizing precise survey total stations, accuracies of a few millimetres over short distances are attainable using trigonometric leveling techniques. Both techniques were used extensively on the BOW project for the precise layout of building elements.

ASCM Network

Alberta Survey Control Markers (ASCM) are located at approximately two-block intervals in close proximity to the BOW site. These markers are countersunk in a landscaped area or in a covered manhole. MMM selected and monitored nearby ASC markers. One of these markers, an HPN deep benchmark type marker, was selected as the primary vertical reference for the project.

External Vertical Control

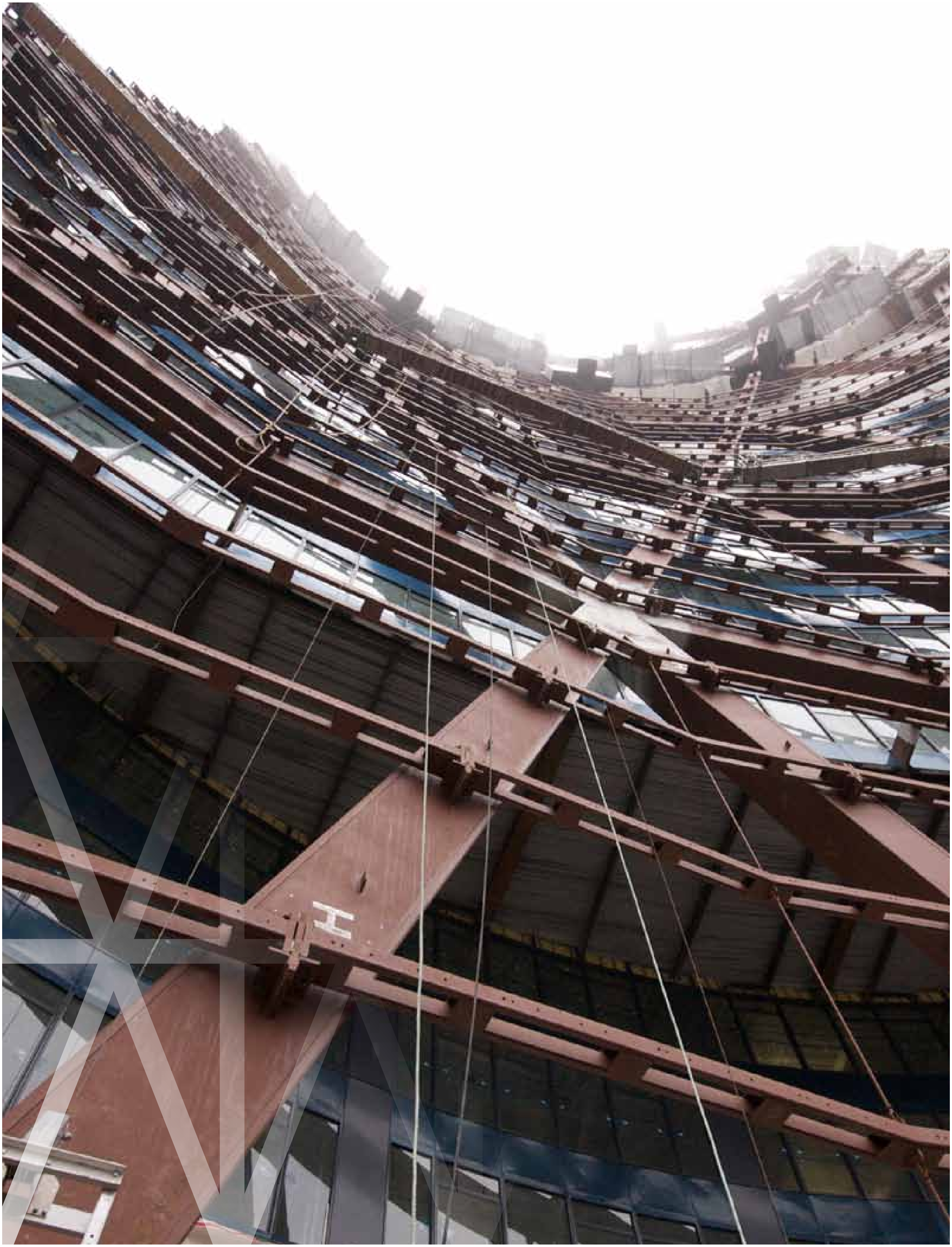
External vertical control was extended from the site wall targets to the ASCM network and to the framework control established by MMM. Multiple sets of conventional angles and distance observations were completed from ground stations surrounding the BOW site to all wall targets. Redundant observations over the course of several iterations spanning time and under varying atmospheric conditions were adjusted using the method of least squares to yield local datum coordinates of the ground stations. Conventional angle and distance observations were used to transfer elevations to the rooftop prisms from the wall target datum and ASCM network, enabling flexibility in the selection of setup location for layout activities while maintaining stringent vertical accuracy requirements.

Floor Benchmarks

As the tower rose, it became abundantly clear from the numerous iterations of control network monitoring that over time the BOW tower site was experiencing significant vertical settlement. To ensure the floor-to-floor design spacing was maintained in the tower, MMM established a series of local benchmarks on the ground floor. The elevations of the ground-floor benchmarks were maintained and transferred upward via total station and precise measurement by steel chain (tape). The actual spacing between column splices was measured and compared to the design dimension in six-floor increments. Following the data analysis, benchmarks (punchmarks) were established on each level to accommodate for any surplus or shortfall. Additional benchmarks were established on the perimeter of the building steel with respect to building core elevation and differential settlement within the structure. The various super and non-super elevated benchmarks positioned strategically within the building and offsite proved essential to enable the construction of various building elements to proceed simultaneously despite being influenced by differential settlement of the structure.

2.3 Floor Control

On each level, MMM established a series of at least six horizontal control stations which were used for all subsequent layout on the floor for building elements such as edge-of-slab, curtain wall, elevator shafts and various project gridlines. These six stations were monumented points on the ground floor concrete and were subsequently transferred vertically via laser plummet and validated by an extensive survey and data QC process via least squares adjustment. The control established served as the primary horizontal reference for all future layout by all trades within the tower.



3.0 BUILDING DYNAMICS

From daily data analysis and continuous column plumbing surveys, MMM observations indicate building deviations from the plumb line to be as large 40-50 mm at the current level and condition of the building. As the structure continuously deviates from a neutral plumb state as it is influenced by natural and man-made forces, it is necessary to account and correct for this displacement to ensure that, with the absence of these various forces, the building will return to true verticality.

The period of the building movements varied and consisted of a combination of short-term, daily and seasonal durations. Both manmade and natural forces caused significant influence on the structure, causing building settlement, expansion and tilt. Natural forces included wind, causing building drag, and solar effects causing temperature-related variation in steel and concrete. Artificial forces, caused by differential raft slab settlement and crane loading, yielded unbalanced artificial loading on the structure. The combination of these factors resulted in the deviation of the structure from the vertical plumb line or "neutral" location.

Once building displacement became significant, standard survey layout procedures were modified to account for the movement. Simply stated, design coordinates for all building elements apply only when the building is located in a neutral position free of displacement from the plumb line. To overcome the significant challenge of building tilt in a structure as tall as the BOW, MMM had to envision and employ innovative techniques and technologies.

3.1 Structure Tilt

To accommodate the structure's deviation from the vertical plumb line, or "neutral" location, the tilt of the structure required careful consideration when developing survey methodologies for establishing the control network and performing any layout on the structure elements.

Continued structural monitoring relative to the fixed rooftop prism and framework control network indicated that building movement started to gain significance after the first 36 floors of the structure had been erected. Continued monitoring and maintenance of the rooftop prism network through conventional and GPS observations enabled meaningful data to be collected and analyzed. Routine observations to the rooftop prisms located on neighbouring buildings indicate little short-term movement of these structures during normal working hours.

The final desired result is a building for which elements such as columns are plumb when the building is free from tilt to an acceptable level. MMM's exacting monitoring ensures the safety and functionality of the building as it rises and into the future.

3.2 Vertical Movement

MMM conducted observations which validated and proved that both horizontal and vertical expansion of the tower was in line with the magnitude to be expected from the typical expansion of steel with change in temperature. Structural settlement was monitored and always considered, yet the effect was primarily neutralized by establishing the elevation of each floor based on as-built conditions.

3.3 Monitoring of Building Movement

MMM conducted control, layout and column plumbing surveys using normal survey procedures until the magnitude of building displacement became significant. Checks to external networks began to show significant displacement from the plumb line at approximately level 36 of the building.

Inclinometers/Tilt Meters

MMM employed inclinometer/tilt meter instrumentation used by the most innovative and complex skyscraper projects in the world. The Leica Nivel 220 inclinometer is a two-axis high-precision tilt sensor with a resolution of 0.001 milliradians. The device uses an optoelectronic principle to accurately measure tilt and temperature in real time, and allows for continuous data logging. Inclination is measured by the angles from the true horizontal line along two orthogonal axes. Once permanently fixed to the structure, the instrument is calibrated through three-dimensional positioning of the unit relative to the project coordinate system. Depending on the instrument's location, a displacement can be determined at any particular epoch and output to correct the horizontal position, essentially removing structure tilt.

Perhaps the most innovative approach MMM brought to the BOW project was the decision to utilize a series of six Leica Nivel 220 inclinometers, installed on the structure at a nominal 12-floor spacing to monitor and compensate for building tilt in real time. Commencing on the ground floor, inclinometers were installed on a steel column and precisely aligned to the BOW coordinate system, and were located as closely as possible to the building core. As the tower was erected, Nivels were installed as soon as the erection and torquing of steel above allowed. The inclinometers

logged tilt and temperature at a one-second data rate to a slave PC on the ground floor using a remote desktop connection. Daily, MMM plotted and analyzed tilt values and temperature for trends, spikes and anomalies. Normally, after any particular Nivel had been in continuous undisturbed operation for 7-10 days an average/normalized, X and Y tilt value were established for the specific Nivel, and it was brought into service. Any reading greater or less than the normalized Nivel values was translated into building tilt. Monthly values were analyzed and updated as necessary.

Computation of the Nivel corrections on any working level involved the summation of the orthogonal displacements derived from all Nivel sensors in the system. This process involved the computation of the X and Y displacements in nominal 12-floor chord segments; the structure would actually be curved rather than a straight chord between Nivels.

The final chord segment was derived from the tilt measured at the highest available Nivel and produced to the actual working level. The summation of the displacements derived for each segment provided the correction which was in turn applied to the surveyed GPS position, thereby accounting for instantaneous structure tilt.

MMM continuously monitored and validated the Nivel-derived building displacements via comparison with conventional survey measurements to external fixed control, thereby ensuring the quality of the column plumbing GPS surveys which relied heavily on the inclinometer system solution.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4.0 SURVEY TECHNIQUES

The following itemizes the survey techniques used in the BOW project.

4.1 Motorized Total Stations

MMM utilized three precision motorized Leica Geosystems total stations for all precise setting-out activities on site. In fact, MMM purchased the first sold-in-Canada Leica TS30 0.5″ total station for exclusive use on the BOW site. The accuracy of the TS30 is second to none and it was used for all applications where stringent accuracy was required. This included the establishment of on-floor control in the BOW coordinate system for subsequent use by all trades.

The precision total stations, located on neighbouring structures' rooftops, were used exclusively for the plumbing of columns below level 36. Above level 36, Real Time Kinematic (RTK GPS) techniques were used. All mega-diagonal steel members and nodes on the south side of the structure were positioned during night shift operations using precise total stations with automatic target recognition.

Additional setting-out activities were conducted for edge-of-slab/screed, project gridline layout, control surveys, and numerous as-builts of building elements as required by both the general and steel contractors.

4.2 Laser Plummets

A valuable technique used to transfer control upwards in the BOW tower was laser plumbing. This method involved the transfer of horizontal position from six stations on ground level up to each level of the tower. To compensate for building sway and the dispersive nature of the laser beam, laser plummets were relocated in vertical steps of approximately 12 floors. As required, the process involved overnight plumbing through a cut-out on each floor. The laser beam was projected onto a clear plexiglass at each location on the floor and a crosshair was established onto the decking or concrete, depending on the stage of construction. Ledcor Construction Limited (LCL) and MMM, with input from other trades, selected the laser plummet locations with careful consideration of network geometry and line of sight between control points which were positioned to avoid obstruction by steel columns and beams above. The coordinate values of the laser-plumbed control points were confirmed by measuring between the scribed crosshairs, as well as to external control. The laser technology provided accurate total station control points relative to the BOW coordinate system on all floors of the tower.

4.3 Steel Chains

At project commencement, MMM purchased a 50 m calibrated steel chain. The chain included an official calibration certificate indicating the length of the chain under various temperature, tension and support conditions, as certified by Lufkin. The steel chain was compared with other MMM steel chains and total stations to ensure it was of the highest standard and suitable for project accuracy specifications.

In the tower, the steel chain was suspended through the vertical plumbing holes, and in 12-floor increments vertical control was transferred up the tower. A 20-pound weight was suspended from the bottom of the chain, which was secured 12 floors above. Corrections for tape elongation, temperature and tension were applied to the raw measurements. The chaining results were further validated and combined in a least squares sense to distances obtained by measuring up through the plumbing holes via precision total stations. The combination of the methods employed provided the validation and confidence required to ensure accurate elevation transfers up the tower.

4.4 RTK GPS

MMM employed Real Time Kinematic (RTK) GPS techniques to plumb the building columns from levels 36 and above. A major limiting factor and important error source that must be considered when using GPS techniques in urban environments is signal blockage and multipath from surrounding buildings. As the BOW's elevation increased, these effects were diminished as the building surpassed adjacent structures in height, and layout via RTK GPS proved highly effective and accurate. Under ideal conditions, Real Time Kinematic (RTK) GPS techniques can yield accuracies of +/-10mm+1ppm in the horizontal dimension and +/-15mm+2ppm in elevation.

As GPS is truly a "global" positioning system, coordinates obtained from GPS surveys in their raw form are based on the WGS84 world datum. The WGS84 datum is comprised of a reference ellipsoid, also known as the WGS84 ellipsoid, and a set of parameters defining the origin of the system relative to the centre of the earth. WGS84 coordinates are global coordinates in the form of latitude, longitude and height above the reference ellipsoid. In order to combine GPS observations with a local datum, it was necessary to translate the raw GPS observations and/or coordinates into the local BOW datum. Local datums are typically ground-based rectilinear systems in the form of Northing and Easting with an arbitrarily chosen origin and orientation. Using data from several measurement epochs, MMM developed and validated a set of transformation parameters involving scale, rotation and translation between the geodetic and local coordinate systems, known as a similarity or Helmert transformation.

4.4.1 Column Plumbing

Column centres were marked with a punchmark prior to erection and were then positioned utilizing RTK GPS techniques when safe to do so. The actual surveyed positions were compared to their corresponding design coordinates, allowing displacements to be computed. These displacements were relayed to ironworkers for column adjustments to design locations. MMM GPS survey procedures involved occupation of the column centre using nominal observation times of two minutes. Concurrently, structure displacement from the building's neutral position was determined using data from the precision inclinometer network. The displacements during each two-minute GPS occupation were applied to the raw GPS positions to determine the actual movements required to each column, thus accounting for the actual instantaneous deviation of the structure from the vertical.

4.5 3D Laser Scanning

At two of the future +15 walkway connections, MMM conducted 3D laser scanning surveys using a Leica ScanStation 2 high definition scanning (HDS) system. The surveys were conducted to aid in the design of the future walkway connections to adjacent buildings. The scanner provided phenomenal survey detail to the project in the form of survey point clouds and a 3D model of the proposed building interfaces.


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5.0 CONCLUSION

With leading-edge technologies such as a Nivel 220 inclination sensor network, visionary advances in geomatics methodology – such as building monitoring in real time and layout of steel members employing GPS – and rigorous quality control and quality assurance procedures, MMM Geomatics enabled the BOW skyscraper to reach new heights. MMM's unprecedented approaches and ultra-precise data translated into proven results. The BOW's structural integrity is assured, allowing the overall project to unfold on schedule and with confidence and success.

The innovations MMM Geomatics applied to such a difficult project put the BOW on the map not only as a landmark on Calgary's skyline, but also as a major Canadian engineering achievement.