

BC Place Seismic Upgrade

Project Highlights

Originally opened in the 1980's with an air-supported roof, BC Place Stadium is a 54,000 seat sports and entertainment facility which has undergone an extensive revitalization program, including the addition of a new post tensioned cable-supported fabric roof. The new cable supported roof replaces the original building roof which consisted of an air-supported fabric roof. The original air-supported roof was not designed for winter snow loading and as such incorporated a winter snow melt system to melt winter snow. The cable supported roof was designed to support winter snow in order to allow the decommissioning of the snow melt system which was both financially costly and environmentally costly due to associated green house gas production. The cable supported fabric roof was chosen because of its relatively lightweight design making it suitable for support on the existing stadium bowl structure. However the resulting increase in structural loading consisted of approximately 18,000,000 kg of roof dead load and 7,000,000 kg of snow load to be supported. Upgrades were undertaken to the vertical load carrying system to accommodate the increased vertical static loading.

At the same time as the stadium revitalization was occurring the building owner BC Pavilion Corporation (PavCo) engaged GENIVAR to undertake a seismic assessment of the existing stadium and report on anticipated capacity and potential upgrade to the facility. This review focused on accommodating the additional seismic demands introduced from the mass of the new roof and commensurate snow loads as well as the increased lateral demand of the existing building as prescribed by modern building codes. Significant changes in seismic design criteria had occurred between the design and construction of the original stadium and the National Building Code of Canada 2005 which was the basis of the seismic assessment and subsequent analysis.

The existing stadium bowl is comprised of 8 discrete segments with a total of 54 radial sway frames restrained out-of-plane by 42 circumferentially-oriented shear walls. The bowl segments are surrounded by 8 additional ramp structures. The bowl segments and ramp structures all separated by expansion joints. The expansion joints were designed into the existing structure both for constructability purposes and for initial shrinkage related movements and ongoing thermal movements.

Based on a review of the original building drawings it was determined that the detailing of reinforcing within the existing cast-in-place concrete elements of the stadium was substantially better than would have been expected in a building of its age. The level of reinforcement continuity and confinement was found in most cases to be very close to current code requirements for ductility.

This first step of the seismic assessment consisted of a conventional review of the facility. Based on that review deficiencies were observed and a conventional upgrade approach was developed. This conventional approach consisted of upgrading existing shear walls for shear to develop ductility, introducing soil anchors at the foundations to limit sway effects, and upgrading existing horizontal diaphragms in order to transfer lateral loads to vertical shear elements. This approach was documented and a cost estimate was provided. There were two main concerns with this approach. The first concern was the amount of intrusive intervention that would be required in the existing facility in order to undertake the upgrades. The second concern which was somewhat associated with the intrusiveness of the upgrades was the significant cost associated with the proposed upgrades.

The negative aspects of the conventional upgrade option as well as the positive aspect of the high level of reinforcing detailing found in the building structure lead to the consideration of an alternate

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and somewhat more sophisticated approach. A final factor in favour of this approach was discovered during design of the new stadium roof and associated upgrades to the existing stadium vertical systems. During the previous analysis it had been determined that the fundamental frequency (frequency of oscillation) of the roof structure was approximately 2 seconds. This compared to a fundamental frequency of approximately 0.6 seconds for the much stiffer base building structure. This helped to minimize lateral effects of the increased loading of the new roof. The alternate approach was loosely based on FEMA requirements with intent to try to utilize existing building structural systems and elements to the maximum extent possible. In order to do this the design team determined that a detailed understanding of the response of the stadium during an earthquake was required.

The first step in the process was to undertake a push over analysis of a select frame and a select shear wall. This analysis provided valuable preliminary information to the design team relative to capacity and response of these elements. This information was utilized to inform the following more sophisticated analysis.

The next step was to undertake a comprehensive probabilistic seismic hazard analysis. This resulted in the selection of applicable earthquake records to be utilized in the stadium analysis. While the hazard analysis was being undertaken a full computer model of the existing stadium and new roof structure was prepared. This model incorporated a significant number of non-linear elements to allow simulation of structural element property changes to be anticipated during and earthquake. Once this model was prepared the design team undertook a series of time history analyses based on the earthquake records selected in the probabilistic seismic hazard analysis. Results of these analyses were studied and adjustments to the model were made to account for unanticipated effects.

As a result of these analyses it was determined that earthquake energy could be dissipated through a combination of foundation rocking at shear walls and linking the building segments with viscous damping devices. Foundation rocking was analyzed through a full structural and geotechnical analysis of the foundation to soil interface and dynamic interaction at the interface. The viscous damping devices were studied for magnitude of force and movement and optimized to take advantage of movement at the expansion joints. The viscous damping devices had the secondary benefit of providing additional load paths for seismic forces resulting in increased redundancy in the structure.

Having completed the analysis the design of the viscous damping devices was completed along with detailing of connections of the devices to the existing concrete structure. Connection design was undertaken in a manner which allowed minimal disruption to the existing facility resulting in significant savings in schedule and cost.

As a result of the advanced seismic analysis, thoughtful design and optimized construction approach it was determined that the final cost of the sophisticated approach to the seismic upgrade of BC Place stadium resulted in a total cost in the range of 20% of the initial code based approach.

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New Application of Existing Techniques / Originality / Innovation

A comprehensive Probabilistic Seismic Hazard Analysis was completed for the seismic analysis of BC Place Stadium. This resulted in the selection of earthquake records in order to carry out nonlinear response history analyses of the existing structure. On the basis of those analyses it was determined that an advanced upgrade approach to increasing seismic capacity of the existing structure was feasible with minimal upgrade to existing stadium structure elements being required. This advanced upgrade approach utilized a combination of existing shear wall foundation rocking and the incorporation of viscous damping devices at existing expansion joints in order to dissipate seismic energy and limit demand on existing structural elements and systems.

Project Objectives, Solutions & Achievements

After thirty years of successful operation with an air-supported roof, BC Place Stadium was about to undergo a monumental transformation including the incorporation of a new cable-supported retractable roof. An integral part of this redevelopment was a full review and assessment of the stadium's lateral load resisting system. GENIVAR in conjunction with EQ-Tec Engineering undertook this review in order to assess the suitability of the existing lateral load resisting system for the proposed redevelopment.

As part of the stadium revitalization, the base building needed to undergo structural upgrades to accommodate the new roof, as the stadium now supports an additional 18,000,000 kilograms of structural dead load and an additional 7,000,000 kilograms of design snow load. The new roof itself is of leading edge design and by design is quite flexible. It is supported on radially sliding bearings which are free to rotate in the radial direction resulting in a fundamental period (period of motion) of approximately two seconds. In comparison the existing base

structure is much stiffer with a fundamental period in the range of 0.6 seconds. On that basis the new roof design vastly reduces roof storey shear contribution to the base building relative to its mass compared with a stiffer more conventional roof assembly. Nonetheless, the added mass did contribute to an increase of the overall base shear of the building in a seismic event and the effects of this needed to be mitigated. Any modification to the lateral load resisting system, however, would inevitably affect the response of the building as a whole, and the potential effects of the roof-related modifications had to be considered in the review of the base building. At the preliminary design phase of the project it was equally important to ensure that the new roof interface with the base building incorporated a capacity design methodology as any potential over-strength in the base building below could create an overstress in the roof assembly above. A careful balance was therefore required to ensure that the building could sustain the new loads imposed on it, but that any modifications resulting from this added load would not adversely affect the roof already under construction. In addition, it was of paramount importance to minimize the impact of any retrofit solution on the existing building and its infrastructure to avoid costly and time-consuming modifications to the base building.

The project schedule was as ambitious as the new roof design, and the complex detailed analysis and design phase of the lateral load resisting system modifications was completed as upgrades to the building's gravity system and new roof construction were already underway. Wind loads governed the original design of the original lateral system of the building, with four shear walls extending up to provide lateral restraint of the original roof.

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Revitalized Stadium



Radial Viscous Damping Device at Ramp Wall

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Buckling Restrained Braces (BRBs) were installed to replace the top lift shear walls as an interface between the existing lateral system and the roof structure to ensure that the maximum roof storey shear could be quantified. The BRBs provided a ductile, capacity-design that avoided negative effects on the roof response resulting from overstrength in the existing shear walls below. In order to achieve a non-intrusive and cost-effective solution to the lateral upgrades of the base building below the new roof, ninety-six viscous damping devices were incorporated. These viscous damping devices were installed at existing building expansion joints throughout the building in order to provide redundancy of load paths for lateral seismic forces and to dissipate seismic energy during an earthquake. Meeting aggressive project milestones required flexibility on the design team's part, and advancing the design of damper connections and interface with the concrete structure during the analysis phase of the project. This was achieved by adopting a capacity design approach to the connections, and minimizing connection assembly types for ease of installation and interchangeability on site. Connection assemblies were also designed to accommodate a wide variety of as-built reinforcing placement in the concrete, thus ensuring that there was no need to await the results of time-consuming exploratory work prior to fabrication. Maintaining focus on the overall project milestones enabled the design and construction teams to work together to meet a challenging schedule without any compromise to building performance.

The combined efforts of the design team achieved the objectives of minimal intrusion on the building, improved capacity of the lateral load resisting system, and a seamless incorporation of the roof structure with the existing building below. All of this was achieved within a challenging and well-scrutinized public schedule in a manner that minimized costs to the owner by means of an innovative and elegant approach to structural analysis and design.

Aesthetic Aspects

Discussion on how to incorporate the damping devices offered several solutions with respect to aesthetics. The engineering team enthusiastically and successfully encouraged the client and project architect to showcase the dampers by leaving them exposed in public areas rather than concealing the dampers behind infill. Although the dampers are maintenance-free, the desire to showcase the technology incorporated in the revitalization of the facility, demonstrating the capabilities of consulting engineers helped guide the decision to keep the devices exposed.

Complexity

In consultation with EQ-Tec Engineering Ltd, an ambitious review was carried out in order to optimize the upgrade of the lateral load resisting system for the base building of BC Place. Prudence demanded that conventional designs be carried out in parallel, to serve as both a comparative to a more innovative approach and to ensure that project completion would be achieved in time for a publicized building opening. The ensuing analysis required extensive coordination with the roof design team, geotechnical consultants, and the general contractor to execute an intricate upgrade while minimizing any impact on the revitalization project already underway.

The base building of BC Place Stadium was constructed of eight principal bowl segments and eight additional ramp structures on the periphery of the building. These sections are gapped with expansion joints for serviceability considerations complete with sliding details of major structural component interfaces where building segments are not individually free-standing. The lateral load resisting system is comprised of 54 radially-oriented concrete sway frames and 42 circumferentially-oriented shear walls.

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Circumferential Viscous Damping Device at Expansion Joint – Level 4



Circumferential Viscous Damping Device at Expansion Joint – Level 4

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The eight ramp structures are also flanked by two radially-oriented shear walls each. A detailed review of the existing structure indicated a thorough detailing of concrete columns, beams and shear walls. This was encouraging, as the building had not been designed with present-day seismic detailing in mind.

While the frames were well-detailed and will withstand larger lateral loads than required by the governing code at the time of original construction, a noticeable concern was that circumferential concrete shear walls at the perimeter of the building were deficient in shear. In short, the most severely loaded shear walls were over-designed for bending in relation to their shear capacity, creating a brittle link in the lateral system. The 'conventional' approach to these upgrades would be to strengthen the wall webs to increase shear capacity and subsequently increase footing sizes to make these walls ductile. This approach, however, negatively impacts the remainder of the building as much higher design forces would have to be accounted for due to short period response of the building during a seismic event. This approach would also require soil anchors at the footings in order to keep lateral drifts down, prevent foundation uplift, and prevent pounding between building elements. While soil anchors might have relieved drift concerns and would ensure that the walls would be ductile (under much higher base shears); this approach makes the building much stiffer, attracting additional seismic loads not only to the primary elements but also of the infill components and equipment therein. Anchoring the shear walls would be problematic not only for the sake of expensive excavation and installation given confined spaces, but it would also cause great disruption in the building as many mechanical and electrical rooms are located in and around the shear walls at ground level. This further emphasized the need for an innovative approach to complement the existing building's dynamic characteristics and

minimize impact on the existing buildings systems.

Acknowledging that the negative impacts of a conventional strengthen-and-anchor system, the design team focused on soil-structure interaction to attain a more comprehensive understanding of inter-storey drift associated with foundation rocking and the impact on the concrete sway frames in the transverse direction, as they would be subjected to higher loads than would be anticipated under a fixed-base design. In order to verify the response of the building with unanchored foundations, detailed non-linear push-over analyses were undertaken to verify the story drifts, and load sharing between the shear walls and sway frames out-of-plane. This also produced an overall capacity of the entire system when accounting for plastic soil deformation compared with results obtained from a fixed-base, linear response spectrum analysis. The push-over analysis was a critical component of the seismic upgrade project, as it was able to verify that the rocking foundation approach was viable, and efforts could be focused on providing supplemental damping and an energy dissipation mechanism in the form of viscous dampers, and their incorporation into the project schedule in lieu of the concrete and foundation works considered.

A comprehensive Probabilistic Seismic Hazard Analysis was completed for the purpose of earthquake record selection and scaling as well as carrying out nonlinear response history analyses. The selection of dampers was based on minimizing pounding between segments and utilizing the existing expansion gaps throughout the building. The presence of the dampers links the 16 structures of the base building together during a seismic event, adding significant redundancy between individual building segments in a manner that did not negatively alter the period of the structure.

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Circumferential Viscous Damping Device at Expansion Joint – Level 4



Circumferential Viscous Damping Device at Expansion Joint – Level 2

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This exceedingly complicated analysis and review of multiple time-histories was conducted in a timely manner to optimize the damping characteristics of the devices in addition to reviewing the demands on the structure and soil below simultaneously. While the detailed analysis was conducted, a broader analysis was also carried out concurrently in order to devise a range of damper characteristics anticipated for the purpose of tender and to initiate procurement and construction of the devices while the final details of the dampers were being completed. This higher-level parallel approach was key to the success of the project's completion on schedule.

Environmental Impact

The seismic upgrades were undertaken in concert with a broader revitalization of BC Place; fundamental to the design approach of the revitalization was to avoid construction waste and preserve as much as possible of the existing building while improving every aspect of its performance. The seismic upgrades carried out were no exception; it was recognized that pursuing a more typical option of adding soil anchors would require intrusive construction that would have required demolition of existing mechanical and electrical spaces (among others) in order to maneuver heavy equipment associated with the foundation anchors. This would not only create construction waste from temporarily removing portions of the structure and all of the infill in the path of the affected rooms/spaces, but also all of the electrical conduits/trays, transformers, and electrical busses in addition to mechanical works including steam lines, storm lines, fire suppression systems that were affixed to the shear walls and surrounding infill. None of these primary utility rooms, surrounding infill, or equipment stored therein was affected with the seismic damper installation.

Social and Economic Benefits

Minimizing new construction materials and avoiding removal and re-installation of mechanical and electrical works offered substantial cost savings with the approach taken. Moreover, the accelerated schedule of the revitalization project did not allow for the shutdown of core services in the building during construction, given that conventional concrete upgrades and foundation works would have incurred substantial costs on temporary measures to keep these systems in place without interruption. The installation of dampers avoided all of these costs by keeping existing equipment rooms in place and working around existing stadium infrastructure.

BC Place Stadium hosts events where the total number of spectators, building staff, and event providers can peak on the order of 60,000 people. GENIVAR and EQ-Tec Engineering, working in concert with the BC Pavilion Corporation, worked through a design that would not only upgrade the performance of specific structural elements associated with the new roof structure, but the stadium lateral load resisting system as a whole. Electing to pursue a more elegant analysis and upgrade to the lateral system of the entire facility exceeded the stipulations prescribed by the permitting authority; this approach was undertaken as part of a paramount and ongoing commitment to public safety.

Meeting and Exceeding Owner's / Client's Needs

As previously noted as the advanced seismic analysis and upgrade option was being advanced a more conventional code upgrade incorporating additional shear capacity and upgraded building diaphragms was taken to an advanced level of preliminary design. This was done in order to verify the efficacy of the advanced upgrade. As a result of this it was determined that the advanced seismic upgrade had two distinct advantages. The first

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Radial Viscous Damping Device at Ramp Wall

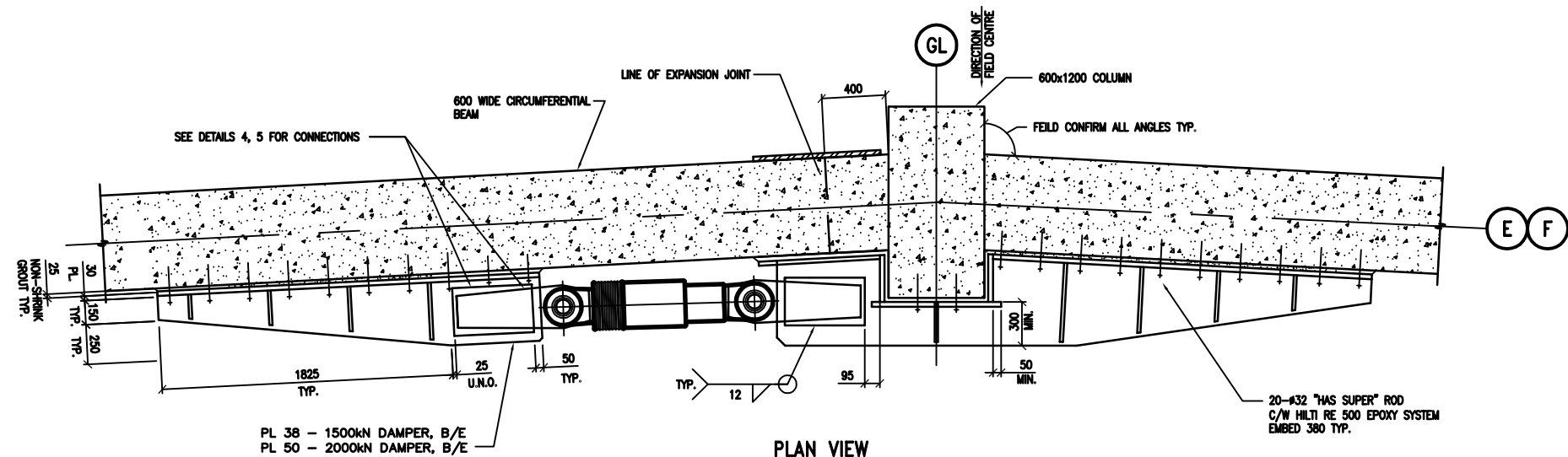


Circumferential Viscous Damping Device at Expansion Joint – Level 3

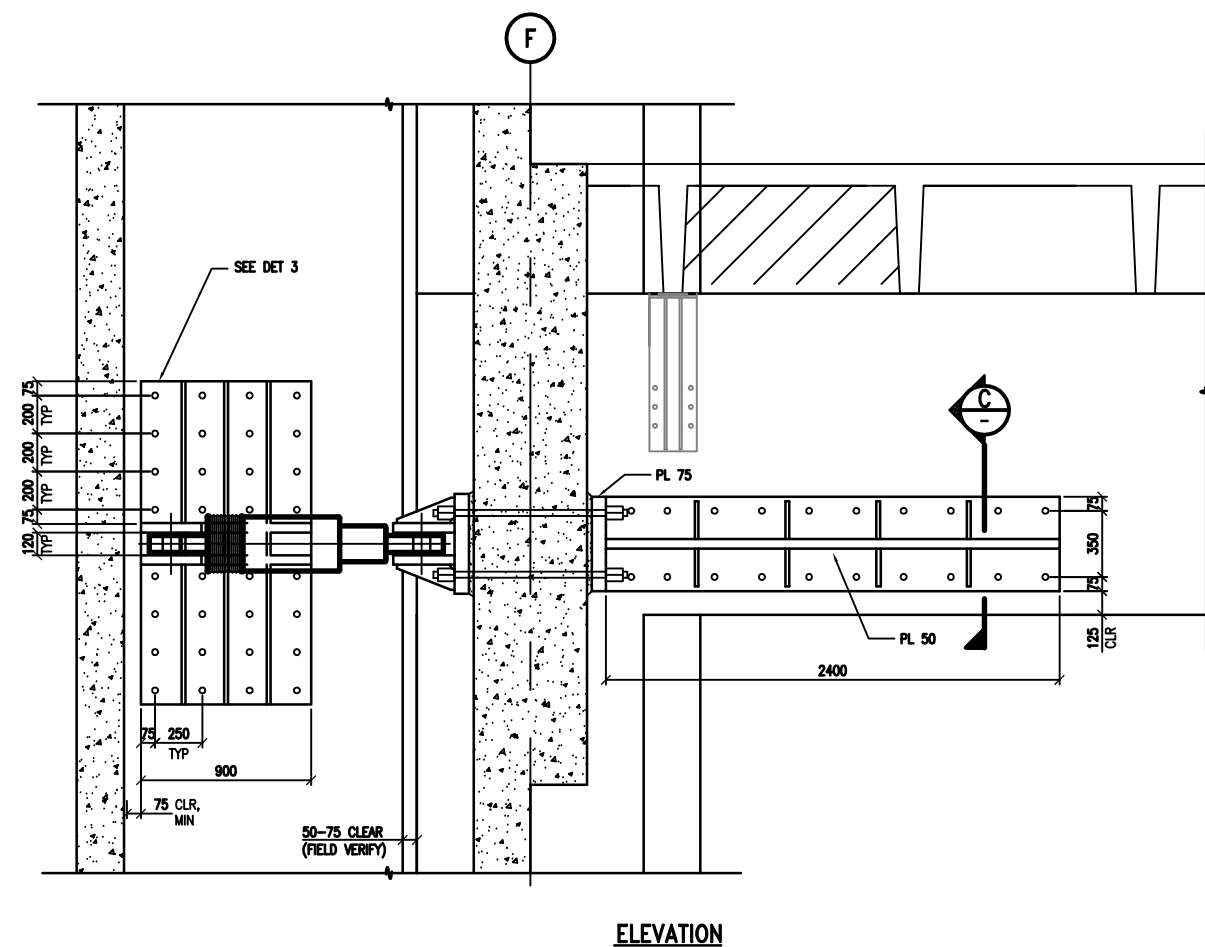
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of these was the advanced seismic upgrade resulted in minimal intervention within the building thereby reducing disruption within the facility. The second significant advantage of the advanced upgrade was the reduced cost relative to the more conventional approach.

Both options were taken to costing by the projects construction manager and the advanced seismic design approach resulted in an estimated cost of approximately 20% of the estimated cost of the more conventional approach.



1 DAMPER - TYPE 1 MOUNTING DETAILS
NOTE: NO COLUMN THICKENING CONDITION



B DAMPER - TYPE 3 MOUNTING DETAILS (AT RAMPS)



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PROJECT:

ISSUED FOR – REVISION:

0		2012/02/07	
IS	RE	DATE	DESCRIPTION

PROJECT NO:

DATE:

2012/02/07

ORIGINAL SCALE:

N.T.S.

DESIGNED BY:

A. PATTERSON

DRAWN BY:

JG.

CHECKED BY:

G. HUBICK

DISCIPLINE:

STRUCTURAL

TITLE:

BC PLACE
SEISMIC UPGRADE

SHEET NUMBER:

SHEET #: 1 OF 1

REV #

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