UBC Botanical Garden: REVITALIZATION PROPOSAL

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University of British Columbia

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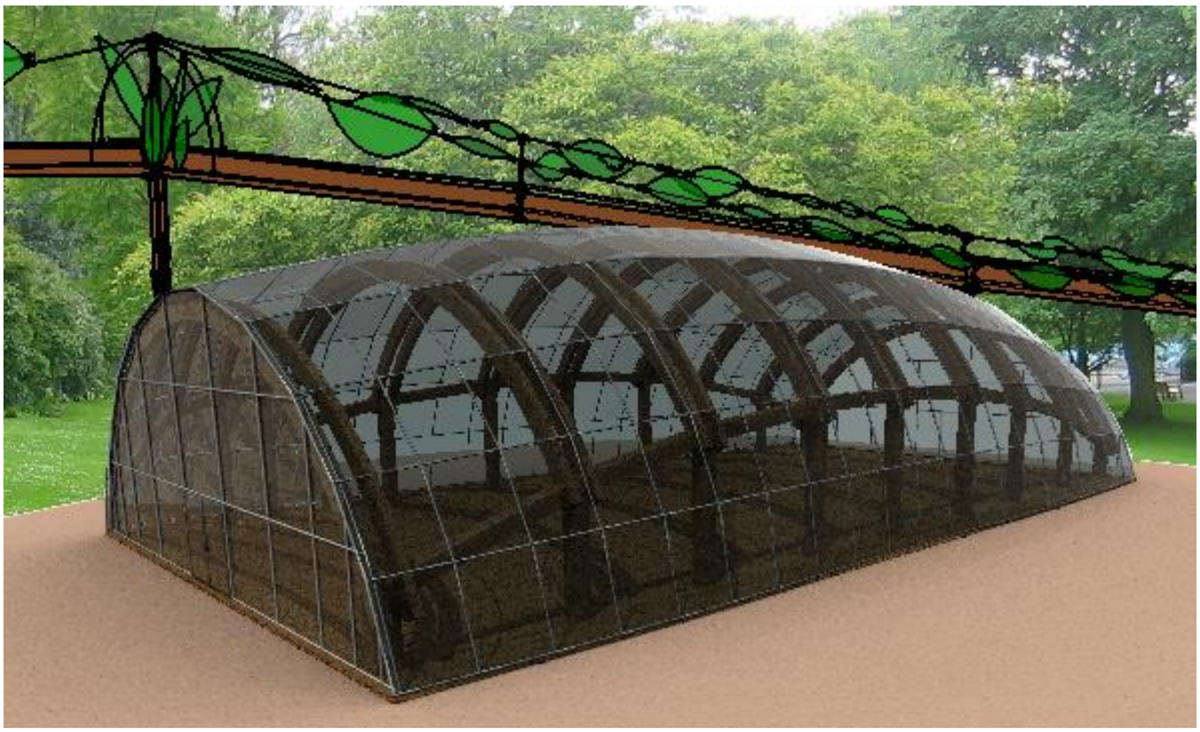

CONSERVATORY, GREENHOUSE CAFÉ, & OVERHEAD WALKWAY

APRIL 4, 2014

ubcbotanicalgarden
& centre for plant research

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Executive Summary

The following is a Detailed Design Report for "Phase 4: Relaxing and Learning" of the University of British Columbia Botanical Gardens (UBCBG) improvement works. The scope of work of our consultancy is limited to the structural design of the superstructure (a detailed design of the most critical frame), the construction management of the structure and envelope (a schedule, cost estimate, and renderings of the construction sequence), and the environmental considerations incorporated in the above mentioned design (an analysis of different materials and a rationale for their use).

The structural design consists of the analysis and design, complying with all relevant codes and guidelines, for the size and connections of all timber members to support a 15 x 30 metre footprint glulam structure. Each portal frame consists of glulam columns connected via a "circle of steel dowels" to a 15 metre-span glulam arch. Member dimensions and specifications can be found in the "Detailed Structural Design" section of this report.

The construction management portion consists of a construction plan for the designed components and full structure, including a project phasing plan, schedule (100 day project duration), and cost estimate (approximately $1.37 million CDN). A more detailed discussion of this can be found in the "Construction Management" section of this report

The environmental analysis consists of a discussion of materials in the design, construction processes, and operational issues and their potential environmental impacts. A more detailed discussion of methods and procedures used on our project will be elaborated upon in the "Environmental Analysis" section of this report.

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1.0 Introduction and Scope of Work

The UBC Botanical Garden (UBCBG) Redevelopment Plan is the main deliverable for CIVL 446 – a fourth year capstone project at the University of British Columbia (UBC). Having already completed the conceptual design stage of the project, our group was now tasked to work on the detailed design of a component of the conceptual design for the site. The site location will remain the same, with any future and potential construction taking place within the UBCB. This is located on the south-west corner of the UBC campus adjacent to SW Marine Drive. As stated in our proposal, our project focuses our design efforts into constructing a new Conservatory, greenhouse café, and overhead walkway for the UBCBG.

By developing these new structures and the overhead walkway, our group intends to attract new and older visitors to come visit the UBCBG more frequently, while also promoting a more sustainable philosophy for the UBC campus. For this project, the detailed design of the component was developed considering three separate civil engineering disciplines – structural, construction management, and environmental. Each of these disciplines were undertaken by considering the different criteria that were determined to be most critical. Included in this report is a detailed structural design and analysis of a component (one portal frame) of the proposed Conservatory, a section on the overall construction management (i.e. project phasing, scheduling, cost estimates) of the Conservatory, and an environmental analysis of the materials to be used in the construction of the Conservatory. Secondary conceptual design ideas such as the overhead walkway and greenhouse café are addressed, but were not the focus of detailed design and analyses.

2.0 Detailed Structural Design and Analysis of Select Components

Our detailed design for this engineering discipline is limited to the design and analysis of one portal frame and its associated connections. We chose to analyze the frame at the centre of the structure as we assumed that it will carry the largest load, and therefore is the critical section to design.

The structural system selected on this project is entirely composed of glulam wood members for the moment frames (using steel dowels as connectors), and sawn timber members for the cross beams. Our proposed design incorporates at least 80% of "beetle-kill" pine into the glulam which presents its own unique structural problems since there are no specific tabulated values for the strength of this particular species. In our design, it was assumed that "beetle-kill" pine has the same material behavior and characteristics of S-P-F glulam for the moment frames, and S-P-F sawn lumber for the cross beams. This assumption proves to be valid as long as the pine is harvested prior to the onset of deterioration and rotting of the wood. The reduction in properties of this type of wood can be minimized through the process of creating an engineered wood product which allows for relatively small, good-quality laminations to be glued together to create the full structural member.

The structural loads that were considered to act upon the structure were calculated by referencing the National Building Code of Canada (NBCC) and British Columbia Building Code (BCBC). In our analysis of the structure; dead, wind, snow, and earthquake loads were considered. SAP2000 was used as the primary structural analysis software in determining member forces in the proposed structure. Analysis of the SAP2000 revealed that our moment frame at the centre of the structure carried the largest forces as previously assumed. Compliance with structural standards was achieved following the provisions set forth in the 2010 Edition of the Wood Design Manual, which itself is based off CSA 086-09 for Engineering Design in Wood. The code provided a guide in determining the relevant limit states design of timber structures.

The proposed structural system is comprised of two main sub-systems, the gravity and lateral-force resisting system. Figure 1 shows the structural system modeled in SAP2000.

Figure 1: SAP2000 Model of Conservatory Structural System

2.1 Gravity System

The primary load-carrying system in the structure is the gravity system. It is a moment-frame system comprised of a glulam column on each end that support a curved glulam arch. The distance between the columns is the span of the short direction of the structure (15 metres). The connectors used are steel dowels, arranged in a circular arrangement to carry the bending moment efficiently into the columns and provide an aesthetic connection. Many options were considered in establishing the primary load path in this structure such as open-web wood joists, wooden trusses, and flat roofs. However, it was collectively decided that the glulam arches provide the most flexibility in providing an aesthetically-pleasing yet stable structure.

2.1.1 Arch

The overlying arches of the moment frame system are fabricated from long slender glulam members. Their primary purpose is to provide sufficient capacity to support the structure from loads which may act on it from the lateral or vertical directions and to also transfer bending moments induced by these acting loads. As opposed to regular horizontal beams, an arch member can carry a much larger capacity. They usually go under compressive stresses and can transfer forces to the base of the structure. Their secondary purpose is to provide a better aesthetic look to the structure as they span across the open area of the conservatory.

The constraints in designing this particular type of member posed an interesting challenge for the design. The slenderness of the member was a major factor in selecting a proper size for the glulam arch. Some of the efficiencies in the arches ability to transfer forces were lost in the transition points between beams and columns. In addition to the slenderness factor, an appropriate member size was required such that the circle of dowels connection could be designed correctly.

By designing and analyzing the central moment frame of the proposed structure, it was assumed that all arched members for each bay would be fabricated to the same size. This may not result in an overly efficient design of the members, but they will still possess sufficient capacities and will be conservative for the areas carrying smaller loads. In addition, there may be reductions in production costs and a more consistent look to the structure in terms of aesthetics.

The governing criteria in the design which required optimization was the bending moment resistance of the structure and the slenderness of the member. Compared to the calculated factored bending moments on the span, the factored compression and shear forces were much lesser in magnitude and did not govern the optimization in our design of the arch members.

After completing the proper computations and optimization processes, it was determined that a 350x380mm glulam cross-section was required to satisfy the capacities required for the design loads. Since these arch members will span 18.5m in length, the main concern was to select a proper cross-section that satisfied the slenderness ratio. The effective length of the arches was reduced to 9.25m by introducing bracing joists along the middle of arches throughout the structure. This greatly reduced the size of glulam arch needed for our structural system. In determining the capacities of an arch member of this size, it was seen that the greatest efficiency of the member was in combined bending and axial resistance, followed by bending moment resistance. While the member is adequate in providing enough load capacity, its greatest efficiency was only 33%. From this value, it can be concluded that the member cross-section was not sized conservatively. Although a more optimal cross-section can be used, the primary reason for choosing 350x380mm is to provide continuity in size among the other members, such as the glulam columns and plywood box beams. This will result in a more appealing appearance to the connections. Detailed design calculations are included in Appendix A.

2.1.2 Columns

The columns are formed of nearly-square cross-section glulam members. Their purpose is to transfer the axial loads, bending moments, shear forces in-the-plane of the frame, and lateral loads to the foundation. An advantage of constructing the moment frames out of entirely glulam members is the similarity in mechanical properties and stiffness between the arch and column. Constraints in designing this member include: slenderness, the ability to carry design forces (similar to the arch but also including large forces in biaxial bending), and aesthetics of framing into the arch. An objective of our design was to design a repeatable column size which could be used throughout the structure to enhance constructability and meet all of the load combinations on various columns throughout the structure.

The governing criteria in the design that needed to be optimized was biaxial bending moment resistance and combined bending and axial resistance – shear and pure compression capacities were large relative to the load and did not govern our optimization.

A 365x380mm glulam cross-section of 4 meter length was selected as the optimum cross-section for the centre columns to meet both the design loads and provide an aesthetic column. The same cross section will be used for the adjacent columns but the lengths will change as the height decreases in the building. Given that the cross-section is nearly-square, the section properties are similar in both axes, allowing the section to adequately deal with biaxial bending. The architectural constraint is also met via the selection of a square cross-section which allows the same depth of arch and column to frame together providing optical "continuity" in size. The column loads, relative to the capacity, is at 86% in combined bending and axial resistance which is an efficient design in wood. A more efficient section could be designed for this frame, but it would not meet the constraints in adjacent frames where we will repeat this same size.

2.1.3 Connection (Circle of Dowels)

The connection of the glulam arches (a set of 2 lapping on either side of the column) is via a circular arrangement of steel dowels. Its purpose is to transfer axial, bending moment, and shear in-the-plane of the frame through the beams to the column. Constraints in designing this connection include: the geometry of the arch framing into the column, ability to carry the design forces, the angle of the grain in the connection, and the spacing of dowels relative to the edge of the beam and one another, and the net diameter (the lever arm). An objective of our design was to create a connection which has a ductile response, in the event of a structural failure, so as to provide warning to occupants. Advantages of this circle of dowels relative to other connection layouts (e.g. square bolt pattern, knife plates, and proprietary connectors) are that it allows transfer of forces with no eccentricity, ease of field-assembly, maximizes use of wood, and provides a unique aesthetic.

The governing criteria in the design are two failure modes: yielding of the connection according to the Johansen yield model and splitting of the member. A proprietary, formatted spreadsheet allows rapid calculation and checking of design criteria for multiple dowel layouts and allowed us to develop our optimum design to transfer the connection forces to the column.

Fourteen, one-inch ASTM A307 bolts will be arranged in a 275mm diameter circle located at the centre of the lap between the arch and column, as shown in Figure 2 on the next page.

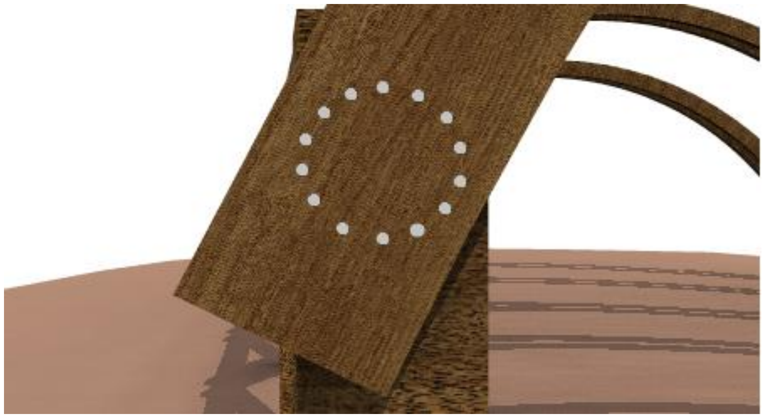

Figure 2: Circle of Dowels Connection.

The connection loads per bolt, relative to each bolt's capacity, is 97%, with the failure mode being via bolt yielding. This failure mode is desirable as it provides a ductile response in the event of a structural failure.

2.2 Lateral-force Resisting System

The primary-lateral load path in the structure is the series of box beams which frames perpendicular to the portal frames along the length of the building (30 metres). While the portal frames do provide some out-of-plane stiffness to resist lateral wind and earthquake loads, it is far insufficient due to the force orientation relative to the weak bending axis of the frames. The box beams act as truss elements and transfer these lateral forces in the most efficient way possible to the columns and eventually the foundations.

2.2.1 Box Beams

The box beams will be constructed of sawn lumber pieces with plywood or laminated veneer lumber side pieces. Their main purpose is to resist the lateral loads induced from earthquakes and horizontal wind loads. Since the box beams are mainly used for the lateral bracing, they do not experience large loads like the columns and arches, and therefore can be designed using a lower quality of wood to reduce material cost and waste. The lower quality of wood means that the designed box beams will be larger in dimension than the glulam column and arches, but will contain less material overall because of their hollow design. The box beams will be connected to the columns using a pin connection and therefore will not carry any moments transferred from the moment frame. Advantages of using box beams for the design of the lateral members are their low cost, onsite constructability and reduced material waste.

The governing criterion for the box beams was combined bending and axial compression, and defined the box-beams member size. The box-beams were designed as regular sawn-timber members with area, moment of inertia and section modulus all reduced to accommodate the hollow design of the members.

The box beams can be easily constructed on site to the exact dimensions needed with minimal materials. The box beams will be constructed using 2x4 (38mm x 89mm) sawn lumber pieces as the main skeleton of the beam and plywood sheets fixed to the skeleton using carpenter screws. The spacing of the moment frames is 3.75m on centre which is approximately equal to 1.5 lengths of plywood (4'x8' sheets). This means the box beams can be constructed using full sheets of plywood and will thus minimize waste. All of the box beams will be 365x400mm and will span 3.75m, between the moment frames. Using the same dimensions for the box beams throughout the structure will decrease construction and installation time and ensure that all members will be able to resist the maximum lateral forces exerted on the structure. The box beams were able to be designed to 98% capacity of the member which is very close to its ultimate capacity but still adequate for safe design. Figure 3 (below) shows the basic components of the box beams including the web (sheathing), web stiffener and flange (timber).

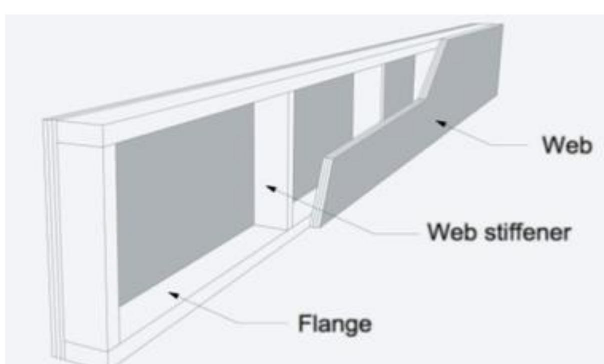

Figure 3: Box-beam Composition. (Timber Development Association (NSW), 2011)

3.0 Construction Management

Performing large-scale construction projects in such a sensitive environment poses many unique challenges. As the majority of the guests' garden experience occurs outside, and construction must occur concurrent to garden operating hours, it is imperative to reduce the visual and noise impact of construction on the surrounding areas. These issues can be mitigated through strategic site layouts and phasing of the project into smaller construction projects which occur in more contained areas within the UBCBG.

Our detailed design of the construction management portion of this project included the construction scheduling and cost estimating of the main structure of the Conservatory, including the site preparation, foundations, floor slab, structural framing, and the glazing. An overview of the project phasing and site planning is also detailed in the sections below.

3.1 Project Phasing

In order to spread out project costs and reduce total amount of construction occurring at one time, it is proposed that construction occur in three distinct phases:

- **Phase I:** Construction of overhead walkway.
- **Phase II:** Construction of Conservatory and Garden Café.
- **Phase III:** Renovation of at-grade pathways with permeable concrete.

This phasing system has been selected from least to greatest cost commitment for the major construction projects and the benefit each phase has on future phases.

Completion of Phase I will bring a visual anchor point for the UBCBG to SW Marine Drive in an effort to increase the amount of visitors, and improve accessibility and traffic flow to the Great Lawn from the main entrance. This improvement in number of visitors and traffic flow within the gardens is vital to the success of the Conservatory and Garden Café, as the current state of visitor attendance and walkway system are hindrances to the long-term financial success of the Garden Café.

As is described in the Site Planning section, Phase II relies on the existing pathway network within the UBCBG as a means of accessing the Great Lawn, where the Conservatory will be constructed. Having restoration of the pathway system occur in Phase III, after construction of the Conservatory is complete, allows for gravel to be laid in order to add new paths or widen current paths. Sequencing the pathway restoration to occur after the construction of the Conservatory also prevents premature degradation of the new pathway materials from heavy machinery driving on these routes.

3.2 Site Planning

Due to the sensitive environment within the UBCBG, careful site planning is necessary to ensure the impact of construction on the surrounding ecosystem is reduced as much as possible.

3.2.1 Phase I: Overhead Walkway - Stadium Road Construction Site

The majority of the overhead walkway runs parallel to Stadium Road, making Stadium Road and the adjacent paved maintenance and utility area the best means of access and material storage for Phase I of construction. This allows for all aspects of construction to occur on the periphery of the site and reduce the potential impact on guests. Site layout for Phase I of construction is shown in Figure 4.

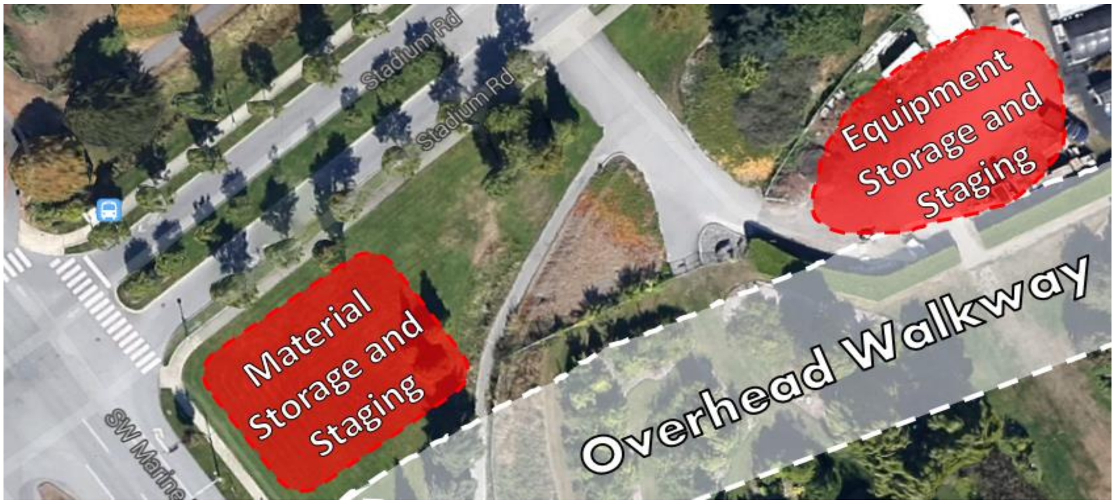

Figure 4: Phase I Site Layout at Intersection of Stadium Rd. and SW Marine Dr.

3.2.2 Phase II: Conservatory – Great Lawn Construction Site

The Conservatory is to be constructed on the southwestern portion of the Great Lawn, adjacent to the Garden Pavilion, as shown in Figure 5 below.

Figure 5: Phase II Construction Site Layout on Great Lawn.

This location is difficult for construction vehicles to access. There is no paved access from Stadium Road; any equipment accessing the site from Stadium Road would have to travel on soft soil along a sensitive marsh area. The preferred site access route is via W16th Avenue, using the existing pathway network to access the Great Lawn, as shown below in Figure 6.

Figure 6: Phase II Construction Access Route via W16th Avenue.

Having the main site access point on W16th Avenue limits traffic disruption along SW Marine Drive; traffic issues on SW Marine Drive due to construction may cause commuters to select another route, reducing the number of potential visitors who will see the new overhead walkway.

While using the pre-existing pathways for site access is extremely disruptive to garden patrons, establishment of an equipment and vehicle storage area, as well as mobilization of equipment on-site at non-peak hours can help reduce disruption to the guests' experience.

3.2.3 Phase III: Garden Pathway Redevelopment Site

As the goal is to fully renovate all the at-grade pathways with permeable pavement, it is very important that the renovation does not greatly impact UBCBG's ecosystem or the patrons. In order to accomplish this, we have chosen to go with cast-in-place permeable pavement that requires minimal site preparation and excavation. As the permeable pavement is applied like cast-in-place concrete and only requires a small crew with a small batch mixer, casting of sections of the concrete pathways can be accomplished in small sections in the early hours of the day and equipment can be moved out of the way when UBCBG is open to the public to mitigate impact on patrons.

3.3 Project Schedule

Due to the impact a large-scaled construction project would have on UBCBG and on the patrons of UBCBG, it was very important to develop a condensed construction schedule that could accommodate a building of this nature and size in a relatively short period of time. After various trials at balancing cost and scheduling, we came up with the following optimized schedule of around 100 days for the construction of the building, with the first 68 days being construction of the building itself and the final 32 days being site demobilization and clean up. A Gantt chart displaying the construction schedule for the Conservatory's structure and envelope is shown in Figure 7 on the next page.

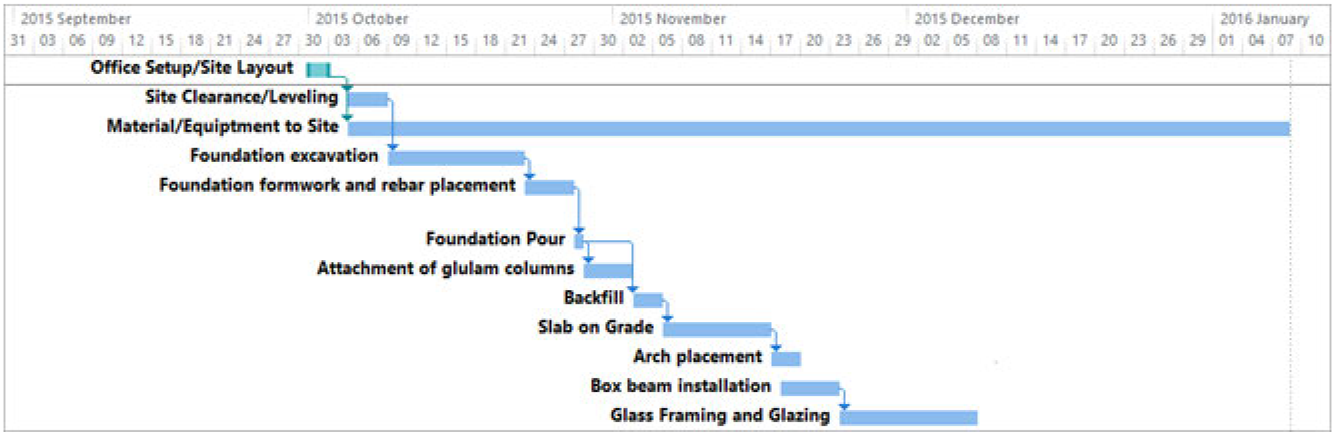

Figure 7: Gantt Chart Showing Conservatory Structural Construction Schedule.

In order to accomplish such a condensed schedule, some of the construction tasks were overlapped. For example, the first box beams are installed as soon as the second set of arches have been installed as seen in Figure 8 below.

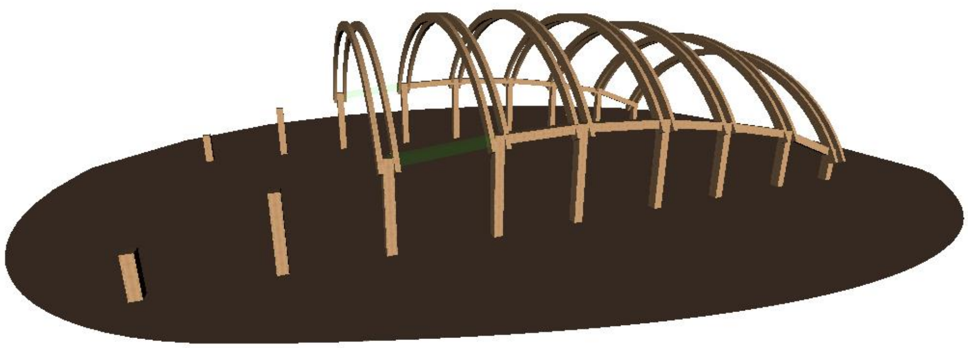

Figure 8: Overlapping of Construction Tasks (Box Beams between Last Installed Arch Set).

3.4 Estimated Cost

A detailed cost analysis was done on the project to provide UBCBG with an accurate idea of what the Conservatory's structural system and glazing would likely cost. A cost estimate for the construction of the Conservatory's structural and glazing systems are summarized in Table 1 on the next page, while detailed spreadsheets of the cost estimate are included in Appendix B.

Table 1: Estimated Cost of Conservatory's Structural System and Glazing.

Component	Cost
Site Preparation	$23,413
Footings	$25,820
Groundwork	$75,700
Structural Framing	$87,751
Glass Ceilings and Walls	$1,158,000
Total	**$1,370,684**

The total construction cost for the Conservatory's structure and glazing will be approximately $1.37M, with approximately $1.16M of that coming from the vaulted glass ceilings and walls themselves. The estimated cost of the construction is based on crew labour cost data for BC from RS Means, market costs for construction materials, and other cost data from industry experience.

4.0 Environmental Analysis

The building will be designed in accordance to LEED Gold Standards. Renewable and recyclable materials will be used in the design, and the building will be constructed and operated efficiently in order to reduce harmful emissions. The building will be designed to have a long service life.

4.1 Materials

Selection of environmentally-friendly materials, or modification of common construction materials, is necessary to reduce the project's carbon footprint.

4.1.1 Wood

Wooden box-beams will be used in the building's transverse members connecting the frame. Beetle-kill wood will be used as much as possible in order to prevent the affected wood from going to waste. Any areas affected by the cutting of trees will be completely reforested. Timber will be sourced from the Lower Mainland to reduce emissions from transportation.

Glued laminated timber (Glulam) will be used in the building's frame. The production of glulam consumes electricity in the gluing and finger-jointing process, and releases greenhouse gases during transportation (AWC). However, glulam was chosen for the building because of its lesser impacts across the whole life cycle, rather than other materials such as steel or concrete.

4.1.2 Concrete

Concrete used in the foundation for the building will be treated with fly ash, and will use recycled concrete aggregate (RCA). Fly ash is a waste product in the manufacturing of coal and thus allows us to reuse a waste product in a useful manner and also displace some of the Portland cement in the concrete, which is a main source of CO2 emissions. Also, the use of RCA will allow us to minimize the hauling and transportation of aggregates from further in the Lower Mainland to UBC, and thus minimize transportation-related impacts.

4.1.3 Rammed Earth Floor

Rammed earth floor can be built using mainly the local material dug up from the building site. The rammed floor consists of a mixture of sand, clay, and gravel bound together by cement. This soil-based floor is inexpensive, has minimal environmental impacts and has the advantages of being soundproof and fireproof. Rammed earth floor is able to minimize the temperature fluctuations during different times of the day due to its insulating properties and thermal mass. This property is particularly beneficial for the Conservatory which incorporates a considerable amount of passive solar heating.

4.1.4 Glass

The glass walls and roof maximize the use of natural daylight within the Conservatory and significantly reduce the building's energy consumption. Heat is easily transferred through a single panel of glass, so the addition of a second panel of glass can increase thermal resistance of the glass walls by 50%. The thermal performance of the glass can be further improved by applying a low-emissivity coating. Low-emissivity glass reduces heat loss through the glass while allowing light to pass through. Double-glazed insulated glass with low-E coatings will be installed to reduce heat loss and prevent excessive heat gain through the walls.

4.1.5 Window Frames

Wood, plastic, and aluminum are three common materials used for window framing. Aluminum window frames typically last over 40 years, wood will last about 30 years, and PVC window frames last only about 25 years (Nottinghamshire Country Council, n.d.). Wood has the least environmental impact but can be expensive and requires regular maintenance to prevent it from deteriorating. PVC frames are energy efficient but contribute large amounts of hazardous pollutants throughout its life cycle. Aluminum frames are inexpensive, low maintenance, and have a relatively long lifespan.

Recycled aluminum will be used for the window frames. Recycled content can be used in both extruded and rolled aluminum without degrading the original properties. The embodied energy of recycled aluminum, including all the energy used from raw material extraction, manufacturing, transporting, assembly, and installation, are 80% less of that required for primary aluminum (McGraw Hill Financial, 2007).

Aluminum window frames conduct heat easily which causes a substantially high rate of heat transfer in and out of the building. To improve energy efficiency and avoid thermal bridging, thermal breaks can be used by adding an insulating barrier in aluminum frame.

4.1.6 Salvaged Materials

Using salvaged materials will reduce the amount of materials that need to be produced for the building, and lower the building's energy footprint. Paneling, doors, doorframes, furniture, or cabinetry could all be sourced from buildings in the region that are being decommissioned.

4.2 Construction

Several considerations will be made in an effort to reduce the environmental impact of construction.

4.2.1 Air Quality

Dust and particulate matter may be released into the air during construction. Proper site ventilation and dust screens can capture the particles in the air and prevent them from being blown around.

Care will be taken to ensure that all adhesives, paints, finishes, and sealants are compliant with the Volatile Organic Compound (VOC) limits listed in LEED's guidelines.

Before the building is opened to the public, an air quality test will be undertaken to ensure that it is safe to use.

4.2.2 Waste Management

A Construction Waste Management plan will be developed before starting construction. All waste will be gathered at a specific site, and will be recycled or re-used as necessary. Any materials that are not used will be directed to a nearby supplier for another construction project to use. Soil that has been dug up will be used in the rammed earth floor, and any remaining soil will be stockpiled and used for the various gardens. The building will promote recycling and composting of all waste to staff and visitors. Composted soil will be used by the UBCBG.

4.3 Operation

The building will have a detailed Operation Plan to optimize the energy use of the building.

4.3.1 Access

The UBCBG is conveniently located near a bus stop, so promotional material will encourage visitors to travel to garden via public transit. Additional bicycle racks will be placed near the entrance of the UBCBG to emphasize the importance of traveling by bicycle.

4.3.2 Water

Stormwater will be captured and treated on-site to be used on plants inside the building. High-efficiency toilets and sinks will be installed. Grey water will be used in non-potable applications, such as toilet flushing.

4.3.3 Lighting

Glass will be installed in the walls and ceiling to limit the energy needed for light. Monitoring systems will automatically turn on lights only if needed, and all lights will be shut off when the building is not in use.

4.3.4 Ventilation

Natural ventilation will be used as much as possible. Windows will be opened strategically to create a comfortable airflow through the building. A monitoring system could optimize the process and turn on electric ventilation system only when needed. Smoking will not be permitted near the building.

4.3.5 Metering

Meters will monitor the building's use of water and electricity. After several weeks of building use, the system will have a good idea of the building's water and electricity consumption, and it will optimize their use.

5.0 Overhead Walkway

The network of pathways currently on-site provides visitors access to all of the features and anchor points offered by the UBCBG. SW Marine Drive currently splits the UBCBG into two separate gardens; the North Gardens and the Asian Gardens. The two separate gardens are currently only connected by the Moon Tunnel which means visitors must backtrack to visit both areas which increases the amount visitors must walk to reach all features of the UBCBG. The Moon Gate and Tunnel are also not visible from SW Marine Drive; therefore, they do no advertise the UBCBG to passing traffic in any meaningful way.

The current pathways and trails in the UBCBG are not weatherproof and are subject to erosion from foot traffic and wet weather. The pathways sometimes become water-logged and do not aid in the collection of storm water in the wet season. Continually maintaining and fixing the pathways is an inefficient use of funds and can be stopped by investing in a new, more durable surface.

5.1 Recommendations

The addition of another piece of infrastructure that crosses SW Marine Drive will allow visitors to loop around the UBCBG while still accessing all the main areas and anchor points. An overhead walkway crossing SW Marine Drive near the entrance of the UBCBG will address all the issues of the current pathways. A unique and innovative design will advertise the UBCBG to the public and potentially increase visitor traffic.

The installation of a water collection system beneath the pathways is an option to help with storm water management. A collection system that can transfer the surface water runoff into a collection pool for irrigation and water features (ponds, streams) can be implemented at the same time as the pathways are being replaced. Although this may be a costly project, it will help reduce the amount of drinking water used for irrigation and water features and will also help decrease erosion of the pathways.

Phasing of construction is needed for this project due to its potentially high cost, long construction time, and significant areas affected by construction. The overhead walkway can be one stage of the project and the permeable pathways can be the next stage with the option of adding a storm water collection system. Splitting the overhead walkway and pathway restoration into stages allows the UBCBG to update its pathways while still allowing visitors to access most areas of the UBCBG during construction.

5.2 Proposed Design

The overhead walkway will be constructed near the entrance of the UBCBG as stated previously. Below is a conceptual design of the overhead walkway, and the loop created by adding the overhead walkway.

Figure 9: Pathway Loop from Addition of Overhead Walkway near UBCBG Entrance.

Figure 10: View of Overhead Walkway Looking South.

5.2.1 Materials

The overhead walkway will be designed using local, environmentally-friendly materials that help accentuate the UBCBG's mission statement. Natural materials such as wood and stone will fit the theme of the UBCBG and aid in the aesthetic design of the overhead structure. The piers of the bridge will be made from glulam or another acceptable member made from beetle -kill pine. All of the smaller parts of the structure (i.e., railings, decking) will also be made primarily of wood beetle -kill pine and recycled steel.

Permeable concrete or another material approved for heavy foot traffic will be used to replace the walkways in the UBCBG. These products are generally available with recycled aggregate and can be poured in place relatively quickly. The amount of storm water infiltration may be decreased when compared to the existing pathways, but the durability of a permeable paver will provide the UBCBG with benefits in the long-term and will decrease maintenance costs.

Figure 11: Permeable Pavement for Heavy Foot Traffic Walkways. (Grey to Green, 2014)

6.0 Greenhouse Café

The Greenhouse Café will be located within the confines of the proposed Conservatory at the UBCBG. The café itself will be encased in a small glass shed, acting as a greenhouse within another greenhouse. This design allows proper viewing of the plants in the Conservatory while maintaining a safe environment for food services. As well this ensures no aromas will overpower the natural scents of the plants for visitors of the Conservatory. The café will be a light-service café, serving fair trade coffee as well as sandwiches, salads, and baked goods. All food available on the menu will contain organic vegetables and organic free-range meat products to further enhance the sustainable experience at the Conservatory and the UBCBG. The seating area will be small yet comfortable area with a few tables and benches with a seating capacity of approximately 24 people. The reason for such a small capacity is two-fold. First of all, the frequency of people visiting the UBCBG is relatively low so building a large capacity café at this point would not be justified. Secondly, the main attraction of UBCBG is the plants in the gardens. By having a smaller seating capacity for the café, it encourages the visitors to finish their meals quickly and get on with exploring the rest of the wonders of the UBCBG.

6.1 Alternate Design/Location

An alternative design/location that was considered involved separating the café from the Conservatory and locating the café as a standalone structure at the entrance, replacing the existing café in the process. The existing café is located within the gift shop and at the exit/entrance of the UBCBG, which is a great location; however, the lackluster selection and quality of food and beverages available does not help attract visitors. Furthermore, the low popularity of the café also reflects poorly on the quality of services offered by UBCBG. Therefore, a revamped café at this same location would both increase revenue as well as give the entrance/face of a much needed facelift. Another benefit of locating the café separate from the Conservatory is the fact that this would lead to the addition of two anchors to UBCBG and not just one combined anchor/attraction.

6.2 Recommendations

Our recommendation is to locate the café within the Conservatory really boils down to cost and space limitations. As UBCBG runs on a tight budget, locating the café within the Conservatory would save money as it would be a combined project under one roof rather than two separate projects at two separate parts of the UBCBG, requiring separate permits and access/site protection costs. In addition, the shortage of space available for buildings also led the team to go with the combined design in order to maximize space in UBCBG for the plants themselves, the true stars of the show.

7.0 Conclusion

In conclusion, our team did a detailed analysis of the structural design, construction management, and environmental considerations. We used our knowledge from our engineering education and information from the guest lecturers in CIVL 446 in order to put together this report.

This building is beautifully able to balance sustainability and strong structural design, and will bring more visitors to the UBCBG for years to come. We are very proud of the work in this report and for the future of the UBCBG.

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Appendix A – Conservatory Structural Design Calculations

A.1 Design Loads

Inputs				
Try a cross-section size	b	323	mm	
	h	180	mm	
	Tributary width	3.75	mm	
	Height	4	m	
	Length of beam	18.5	m	
Dead Load				
Roof Weight:				
Wood Design Manual Table 11.25-11.27	Sprinklers	30	N/m^2	
	Glass+ steel trim	90	N/m^2	
	Total pressure	120	N/m^2	0.016
Beam Self Weight:				
	Weight of glulam	4300	N/m^3	
Then UDL for beam component is		0.250	kN/m	
	In pressure	66.6672	N/m^2	
Thus total dead load	D is	186.67	N/m^2	
Dead load on beam	D is	0.70	kN/m	(central beams; tributary width = 7.5m)
	D is	0.35	kN/m	(end beams; tributary width = 3.75m)
Earthquake Load:				
Weight of Building	W	3.453	kN/m	
Moderately-ductile moment resisting frame	Rd	3.5		
	Ro	1.5		
Braced frames	Mv	1		
	Ie	1		
Building period	Ta	0.141	s	
Determine spectral acceleration points S(T)				
	Sa(.2)	0.94		
	Sa(.5)	0.64		
	Fa	1		
	Fv	1		
Then Sa(T)	Sa(T)	0.799		
	V	0.525	kN/m	
	Vmax	0.350	kN/m	GOVERNS
		1.313	kN	(middle)
		0.657	kN	(ends)
Base Shear	V*	0.350	kN/m	
Snow Load:				
	Is	1		
	Ss	1.8		
	Cb	0.8		
	Cw	0.75		
	Cs	1		
	Ca	1	(for middle of span)	
		0.5	(for ends of span)	
	Sr	0.2		
Central beams	S1	0.81	kN/m	(middle)
	S2	0.405	kN/m	(ends)
End beams	S1	0.405	kN/m	(middle)
	S2	0.2025	kN/m	(ends)
Wind Load:				
Case I	W1	1.425	kN/m	*(wind loading acting <-- on vertical members and downwards in arch)*
	W1-ends	0.71	kN/m	
Case 2	W2	2.19	kN/m	*(wind loading acting upwards on arch only)*
	W2-ends	0.72	kN/m	
Case 3	W3	1.29	kN/m	*(wind loading acting --> on vertical members)*
	W3-ends	0.64	kN/m	
Load Combinations:				
	1.4D		1.25D+1.5S+0.4W3	
	1.25D+0.5S		1.25D+0.5S+1.4W1	
	1.25D+0.4W1		1.25D+0.5S+1.4W2	
	1.25D+0.4W2		1.25D+0.5S+1.4W3	
	1.25D+0.4W3		1.0D+1.0E1+0.25S	
	1.25D+1.5S+0.4W1		1.0D+1.0E2+0.25S	
	1.25D+1.5S+0.4W2			

A.2 Column

Tabulated Values						CSA O86-09
Assume material is similar to SPF 20f-EX glulam						
Material Properties:						
Bending moment	fb		=	25.60	MPa	Table 6.3
Longitudinal shear	fv		=	1.75	MPa	Table 6.3
Tension perp. to grain	ftp		=	0.51	MPa	Table 6.3
Compression parallel	fc			25.20	MPa	Table 6.3
Modulus of elasticity	E		=	10300.00	MPa	Table 6.3
Performance factor in bending	phi_b		=	0.90		$6.5.6.51
Performance factor in compression	phi_c		=	0.80		
INPUT						
Loading:						
Sum of all loads acting on beam (excluding d from support)	Wf		=		kN	
Maximum bending moment on span (weak axis bending)	Mfy		=	87.25	kN-m	
Maximum bending moment on span (strong axis bending)	Mfx		=	67.20	kN-m	
Maximum factored compression parallel	Pf		=	39.00	kN	
Maximum factored shear	Vf		=	34.07	kN	
Shear load coefficient	Cv		=	3.69		Table 6.5.7.3b)
Member geometry:						
Length	L		=	4000.00	mm	
Unsupported length for strong axis bending	lux	L	=	4000.00	mm	
Unsupported length for weak axis bending	luy	L	=	4000.00	mm	
Depth	h		=	380.00	mm	
Width	b		=	365.00	mm	
Moment of Inertia about strong axis	Iy	h*b^3/12		1.54E+09	mm^4	
Moment of Inertia about strong axis	Ix	b*h^3/12		1.67E+09	mm^4	
CALCULATIONS						
Moment Resistance about strong axis:						$6.5.6.5
Section Modulus	Sx	Ix/(h/2)	=	8.78E+06	mm^3	
Curvature factor	Kx	1	=	1.00		$6.5.6.5.2
	Kzbg	if(1.03*(b*L/10^6)^(-.18)<1,1.03*(b*L/10^6)^(-.18),1)	=	0.96		$6.5.6.5.1
Bending moment resistance case 1	Mri	phi_b*fb*Sx*Kx*Kzbg*10^(-6)	=	194.74	kN-m	$6.5.6.5.1
Effective length	le	1.92*lux	=	7680.00	mm	Table 6.5.6.4.3
Slenderness ratio	CB	sqrt(le*h/b^2)	=	4.68		$6.5.6.4.3
	CK	SQRT(0.97*E/fb)	=	19.76		
Lateral stability factor	Kl	(1/3)*(CB/CK)^4,if(and(CB>CK,CB<50),.65*E/(CB^2*fb*Kx))))	=	1.00		
Bending moment resistance case 2	Mrii	phi_b*fb*S*Kx*Kl*10^(-6)	=	202.39	kN-m	$6.5.6.5.1
a) Bending moment resistance capacity for straight beam	Mra	min(Mri,Mrii)	=	194.74	kN-m	$6.5.6.5.1
Then the total bending moment resistance	**Mrx**	**Mra**	=	**194.74**	**kN-m**	
Design check for bending moment:		***OK***				
Efficiency		***0.345***				
Moment Resistance about weak axis:						$6.5.6.5
Section Modulus	Sy	Iy/(h/2)	=	8.10E+06	mm^3	
Curvature factor	Kxy	1	=	1.00		$6.5.6.5.2
	Kzbgy	if(1.03*(b*L/10^6)^(-.18)<1,1.03*(b*L/10^6)^(-.18),1)	=	0.96		$6.5.6.5.1
Bending moment resistance case 1	Mriy	phi_b*fb*Sy*Kxy*Kzbgy*10^(-6)	=	179.67	kN-m	$6.5.6.5.1
Effective length	ley	1.92*luy	=	23040.00	mm	Table 6.5.6.4.3
Slenderness ratio	Cby	sqrt(le*h/b^2)	=	8.11		$6.5.6.4.3
	Cky	SQRT(0.97*E/fb)	=	19.76		
Lateral stability factor	Kly	(1/3)*(CBy/CKy)^4,if(and(CBy>CKy,CBy<50),.65*E/(CBy^2*fb*Kxy))))	=	1.00		
Bending moment resistance case 2	Mriiy	phi_b*fb*Sy*Kxy*Kly*10^(-6)	=	186.73	kN-m	$6.5.6.5.1
a) Bending moment resistance capacity for straight beam	Mray	min(Mri,Mrii)	=	179.67	kN-m	$6.5.6.5.1
Then the total bending moment resistance	**Mry**	**Mray**	=	**179.67**	**kN-m**	
Design check for bending moment:		***OK***				
Efficiency		***0.486***				
Shear Resistance						$6.5.6.7
Member Volume	Z	b*h*L*10^(-9)	=	0.55	m^3	
Then the factored shear resistance of rectangular member	**Vr**	**phi_b*fv*.48*(b*h)*1*Cv*Z^(-.18)*10^(-3)**	=	**430.21**	**kN**	$6.5.7.2.1a)
Design check for shear:		**OK**				
Efficiency		***0.079***				
Compression parallel to grain Resistance:						$6.5.8
Slenderness ratio	Cc	max(L/b,L/d)	=	10.96		$6.5.8.2
Slenderness check		if(Cc<50, "OK", "NOT OK- PICK NEW DIM")		OK		
Size factor for compression parallel	Kzcg	if(.68*Z^(-.13)<1,.68*Z^(-.13),1)	=	0.73		$6.5.8.4.2
Slenderness factor	Kc	(1+fc*Kzcg*Cc^3/(35*.87*E))^(-1)	=	0.93		$6.5.8.5
Then the factored compression parallel resistance	**Pr**	**phi_c*fc*(b*h)*Kzcg*Kc*10^(-3)**	=	**1904.88**	**kN**	$6.5.8.4
Design check for compression:		**OK**				
Efficiency		**0.020**				
Combined bending and axial resistance:						
Euler buckling load about strong axis	Pex	pi()^2*.87*E*Ix/L^2*10^(-3)	=	9225.69	kN	$6.5.12
Euler buckling load about weak axis	Pey	pi()^2*.87*E*Iy/L^2*10^(-3)		8511.72	kN	
Then the factored combined resistance check	check	(Pf/Pr)+Mfx/Mrx*(1/(1-Pf/Pex))+Mfy/Mry*(1/(1-Pf/F	=	0.85		$6.5.12
Design check for combined bending and axial:		***OK***				
Efficiency		0.855				

A.3 Arch Beam

TABULATED VALUES						CSA O86-09
Assume material is similar to SPF 20f-EX glulam						
Material Properties:						
Bending moment	fb		=	25.6	MPa	Table 6.3
Longitudinal shear	fv		=	1.75	MPa	Table 6.3
Tension perp. to grain	ftp		=	0.51	MPa	Table 6.3
Compression parallel	fc			25.2	MPa	Table 6.3
Modulus of elasticity	E		=	10300	MPa	Table 6.3
Performance factor in bending	phi_b		=	0.9		$6.5.6.51
Performance factor in compression	phi_c		=	0.8		
INPUT						
Loading:						
Sum of all loads acting on beam (excluding d from support)	Wf		=			
Maximum bending moment on span	Mf		=	46.09		
Maximum factored compression parallel	Pf		=	31.62		
Maximum factored shear	Vf		=	19.73		
Shear load coefficient	Cv		=	3.69	For UDL	Table 6.5.7.3b)
Member geometry:						
Length	L		=	9250.00	mm	
Depth	h		=	380	mm	
Width	b		=	350.00	mm	
Moment of Inertia	I	b*h^3/12		1.6E+09	mm^4	
Lamination thickness	t		=	40.00	mm	
Radius of curvature	Rx		=	8400.00	mm	
Beta (angle enclosed by curve in radians)	Beta		=	0.56	rad	
CALCULATIONS						
Moment Resistance:						$6.5.6.5
Section Modulus	S	b*h^2/6	=	8.42E+06	mm^3	
Curvature factor	Kx	1-2000*(t/Rx)^2	=	0.955		$6.5.6.5.2
	Kzbg	if(1.03*(b*L/10^6)^(-.18)<1,1.03*(b*L/10^6)^(-.18),1)	=	0.834		$6.5.6.5.1
Bending moment resistance case 1	Mri	phi_b*fb*S*Kx*Kzbg*10^(-6)	=	154.46	kN-m	$6.5.6.5.1
Effective length	le	1.92*L	=	17760	mm	Table 6.5.6.4.3
Slenderness ratio	CB	sqrt(le*h/b^2)	=	7.42		$6.5.6.4.3
	CK	SQRT(0.97*E/fb)	=	19.76		
Lateral stability factor	Kl	if(CB<10,1,if(CB<CK, 1-(1/3)*(CB/CK)^4,if(and(CB>CK,CB<50),.65*E/(CB^2*fb*Kx))))	=	1.00		
Bending moment resistance case 2	Mrii	phi_b*fb*S*Kx*Kl*10^(-6)	=	185.27	kN-m	$6.5.6.5.1
a) Bending moment resistance capacity for straight beam	Mra	min(Mri,Mrii)	=	154.46	kN-m	$6.5.6.5.1
Size factor for tension perp. To grain	Kztp	24/(b*h*Rx*Beta)^(.2)	=	0.42		Table 6.5.6.6.1
b) Bending moment resistance capacity from tension perp. to grain	Mrb	if(phi_b*ftp*(2*b*h/3)*Rx*Kztp*10^(-6)	=	142.82	kN-m	$6.5.6.6.1
Then the total bending moment resistance	**Mr**	**if(Mrb<Mra, Mrb, Mra)**	=	**142.8**	**kN-m**	
Design check for bending moment:		***OK***				
Efficiency				***0.323***		
Shear Resistance						$6.5.6.7
Member Volume	Z	b*h*L*10^(-9)	=	1.23025	m^3	
Then the factored shear resistance of rectangular member	**Vr**	**phi_b*fv*.48*(b*h)*1*Cv*Z^(-.18)*10^(-3)**	=	**357.4**	**kN**	$6.5.7.2.1a)
Design check for shear:		***OK***				
Efficiency				***0.055***		
Compression parallel to grain Resistance:						$6.5.8
Slenderness ratio	Cc	max(L/b,L/d)	=	26.42857		$6.5.8.2
Slenderness check		if(Cc<50, "OK", "NOT OK")		OK		
Size factor for compression parallel	Kzcg	if(.68*Z^(-.13)<1,.68*Z^(-.13),1)	=	0.662		$6.5.8.4.2
Slenderness factor	Kc	(1+fc*Kzcg*Cc^3/(35*.87*E))^(-1)	=	0.5046		$6.5.8.5
Then the factored compression parallel resistance	**Pr**	**phi_c*fc*(b*h)*Kzcg*Kc*10^(-3)**	=	**895.6**	**kN**	$6.5.8.4
Design check for compression:		***OK***				
Efficiency				***0.035***		
Combined bending and axial resistance:						
Euler buckling load	Pe	pi()^2*.87*E*I/L^2*10^(-3)	=	1654.285	kN	$6.5.12
Then the factored combined resistance check	check	(Pf/Pr)^2+Mf/Mr*(1/(1-Pf/Pe))	=	0.330		$6.5.12
Design check for combined bending and axial:		***OK***				
Efficiency				***0.330***		

A.4 Moment Connection-Circle of Dowels

Tabulated Values						CSA O86-09
Material Properties:						
Assume material is similar to SPF 20f-EX glulam						
Performance factor for Yielding	phi_y		=	0.8		$10.4.4.3.1
Yield stress of dowel (assuming ASTM A307)	fy		=	310		$10.4.4.3.3.3
Embedment strength of member 1/2 parallel to grain	fp	50*G*(1-.01*df	=	15.666	MPa	$10.4.4.3.3.1
Embedment strength of member 1/2 perp. to grain	fq	22*G*(1-.01*df	=	6.89	MPa	$10.4.4.3.3.1
Mean relative density of member 1/2	G		=	0.42		Table A.10.1
INPUT						
Loading						
Axial force in column (z-component of total force by SAP analysis)	N		=	24.16	kN	These values taken from the column in
Shear force in column (x-component of total force by SAP analysis)	V		=	19.64	kN	
Applied moment on connection	M		=	45.85	kNm	
Geometry						
Diameter of dowel circle	dc		=	275.00	mm	
Radius of circle	rad	(dc/2)/1000	=	0.1375	**m**	
Number of fasteners	nf		=	14		
Diameter of dowels (in mm)	df		=	25.40	mm	
Number of shear planes	ns		=	2.00		
Orientiation of fastener 1(measured relative to x-axis)	ang0		=	6.28	rad	
Angle of beam relative to horizontal	alp		=	13.74		
Member Section Properties						
-Member 1 is defined as the columns and member 2 is defined as the beam						
Thickness of member 1 (2 beams which sandwich column)	t1i		=	175.00	mm	>>Ref. beam sheet
Thickness of member 2 (column)	t2i		=	380.00	mm	>>Ref. column sheet
Member depth	d		=	380.00	mm	
Then the de value	de	(d-dc)/2	=	52.5	mm	
CALCULATIONS						
APPLIED LOAD PER FASTENER						
Vertical contribution:						
Axial load per fastener (y-direction)	n0	N/nf	=	1.726	kN	
Horizontal contribution:						
Shear load per fastener (x-direction)	v0	V/nf	=	1.403	kN	
Moment contribution:						
Polar moment of inertia	Ip	nf*rad^2	=	0.26469	m^2	
Force component tangent to radius of circle	Nm	M*rad/Ip	=	23.82	kN	
Check that bolt forces counteract applied moment		if(abs(M-nf*Nm*rad)<.01,"OK", "NOT OK")	=	OK		
Change in fastener orientation per rotation to next bolt	del	2*pi()/nf	=	0.449	rad	
Bolt Number 5 - Governing Bolt	**n**		=	**5**		$10.4.4.3.1
Does this bolt satisfy all design checks?		**YES**				$10.4.4.2a)
Mechanics to Determine Loading						
Inclination of load	a	ang0-n*del	=	4.5	rad	
Force in dowel due to moment (x-direction)	Nx	Nm*cos(a)	=	-5.3	kN	
Force in dowel due to moment (y-direction)	Ny	Nm*sin(a)	=	-23.2	kN	
Resultant force on dowel (x-direction)	Rx	Nx-v4	=	-3.9	kN	
Resultant force on dowel (y-direction)	Ry	Ny+n4	=	-21.5	kN	
Arctan result	ac	atan(Ry/Rx)*180/pi()	=	79.72	deg	
Angle of resultant	ar	if(and(0<ac,Ry>0),ac,if(and(0<ac,Ry<0),180+ac,	=	259.72	deg	
Angle relative to beam	ra	if(and(0<ar+alpha,ar+alpha<90), ar+alpha, if(ar	=	86.54	deg	
Force perp to beam	Fr	sqrt(Rx^2+Ry^2)*sin(pi()*ra/180)	=	21.8	kN	
Yielding Capacity						
Bearing angle to grain for member one(beam)	thi	ra	=	86.54	deg	$10.4.4.8
Bearing angle to grain for member two(column)	thii	IF(AND(0<ar,ar<=90),90-ar,IF(AND(90.01<ar,ar<	=	10.28	deg	
Embedment strength of member one	fi	fp*fq/(fp*sin(thi)^2+fq*cos(thi)^2)	=	6.97	MPa	
Embedment strength of member two	fii	fp*fq/(fp*sin(thii)^2+fq*cos(thii)^2)	=	9.10	MPa	$10.4.4.3.3
Yield cases from Johansen Model:						$10.4.4.3.3
	a) nua	f1*df*t1i	=	30,992	N	
	c) nuc	.5*f2*df*t2i	=	43,934	N	$10.4.4.3.2
	d) nud	fi*df^2*(sqrt((1/6)*fii*310/(fi*(fi+fii)))+.2*t1i/	=	15,413	N	$10.4.4.3.3
	g) nug	fi*df^2*(sqrt((2/3)*fi*310/(fi*(fi+fii))))	=	18,429	N	$10.4.4.3.4
Yield resistance of Bolt	**Nr**	min(nua,nuc,nud,nug)*0.8*2*1/1004	=	**24.66**	**kN**	$10.4.4.3.5
Efficiency of bolt	**Eff**	sqrt((Nx^2)+(Ny^2)/Nr	=	**0.966**		$10.4.4.3.1
Check yield capacity to resultant force		if(eff<1, "OK", "NOT OK")		OK		$10.4.4.2a)
Splitting						
Resistance due to member 1 on each side (beams)	Qsi	2*(0.7*14*t1i*SQRT(de/(1-de/d))/1000)		26.77	kN	
Check splitting capacity relative to the beam		IF(Qsi>Fr,"OK","NOT OK")		**OK**		
For member two (column)	Qsii	0.7*14*t2i*SQRT(de/(1-de/d))/1004		29.07	kN	
Check splitting capacity relative to the column		IF(Qsii>Rx,"OK","NOT OK")		**OK**		

A.5 Box Beams

Tabulated Values						CSA O86-09
Assume material is similar to SPF Sawn Lumber						
Material Properties:						
Bending moment	fb		=	11	MPa	Table 6.3
Longitudinal shear	fv		=	1.2	MPa	Table 6.3
Tension parallel. to grain	ftp		=	4.9	MPa	Table 6.3
Compression parallel	fc			7.9	MPa	Table 6.3
Modulus of elasticity	E		=	8500	MPa	Table 6.3
Performance factor in bending	phi_b		=	0.9		$6.5.6.51
Performance factor in compression	phi_c		=	0.8		
INPUT						
Loading:						
Sum of all loads acting on beam (excluding d from support)	Wf		=			
Maximum bending moment on span	Mf		=	87.25		
Maximum factored compression parallel	Pf		=	23.25		
Maximum factored shear	Vf		=	34.07		
Shear load coefficient	Cv		=	3.69	For UDL	Table 6.5.7.3b)
Member geometry:						
Length	L		=	3750.00	mm	
Depth	h		=	400	mm	
Width	b		=	365.00	mm	
Moment of Inertia	I	b*h^3/12		653983129	mm^4	
Lamination thickness	t		=	40.00	mm	
Radius of curvature	Rx		=	8400.00	mm	
Beta (angle enclosed by curve in radians)	Beta		=	0.56	rad	
CALCULATIONS						
Moment Resistance:						$6.5.6.5
Section Modulus	S	b*h^2/6	=	9.73E+06	mm^3	
Curvature factor	Kx	1-2000*(t/Rx)^2	=	0.955		$6.5.6.5.2
	Kzbg	if(1.03*(b*L/10^6)^(-.18)<1,1.03*(b*L/10^6)^(-.18),1)	=	0.973		$6.5.6.5.1
Bending moment resistance case 1	Mri	phi_b*fb*S*Kx*Kzbg*10^(-6)	=	89.54	kN-m	$6.5.6.5.1
Effective length	le	1.92*L	=	7200	mm	Table 6.5.6.4.3
Slenderness ratio	CB	sqrt(le*h/b^2)	=	4.65		$6.5.6.4.3
	CK	SQRT(0.97*E/fb)	=	27.38		
Lateral stability factor	Kl	if(CB<10,1,if(CB<CK, 1-(1/3)*(CB/CK)^4,if(and(CB>CK,CB<50),.65*E/(CB^2*f	=	1.00		
Bending moment resistance case 2	Mrii	phi_b*fb*S*Kx*Kl*10^(-6)	=	91.99	kN-m	$6.5.6.5.1
a) Bending moment resistance capacity for straight beam	Mra	min(Mri,Mrii)	=	89.54	kN-m	$6.5.6.5.1
Size factor for tension perp. To grain	Kztp	24/(b*h*Rx*Beta)^(.2)	=	0.41		Table 6.5.6.6.1
b) Bending moment resistance capacity from tension perp. to grain	Mrb	if(phi_b*ftp*(2*b*h/3)*Rx*Kztp*10^(-6)	=	1478.52	kN-m	$6.5.6.6.1
Then the total bending moment resistance	**Mr**	**if(Mrb<Mra, Mrb, Mra)**	=	**89.5**	**kN-m**	
Design check for bending moment:		***OK***				
Efficiency		***0.974***				
Shear Resistance						$6.5.6.7
Member Volume	Z	b*h*L*10^(-9)	=	0.5475	m^3	
Then the factored shear resistance of rectangular member	**Vr**	**phi_b*fv*.48*(b*h)*1*Cv*Z^(-.18)*10^(-3)**	=	**311.3**	**kN**	$6.5.7.2.1a)
Design check for shear:		**OK**				
Efficiency		***0.109***				
Compression parallel to grain Resistance:						$6.5.8
Slenderness ratio	Cc	max(L/b,L/d)	=	10.273973		$6.5.8.2
Slenderness check		if(Cc<50, "OK", "NOT OK")		OK		
Size factor for compression parallel	Kzcg	if(.68*Z^(-.13)<1,.68*Z^(-.13),1)	=	0.735		$6.5.8.4.2
Slenderness factor	Kc	(1+fc*Kzcg*Cc^3/(35*.87*E))^(-1)	=	0.9762		$6.5.8.5
Then the factored compression parallel resistance	**Pr**	**phi_c*fc*(b*h)*Kzcg*Kc*10^(-3)**	=	**662.4**	**kN**	$6.5.8.4
Design check for compression:		**OK**				
Efficiency		***0.035***				
Combined bending and axial resistance:						
Euler buckling load	Pe	pi()^2*.87*E*I/L^2*10^(-3)	=	3394.2352	kN	$6.5.12
Then the factored combined resistance check	check	(Pf/Pr)^2+Mf/Mr*(1/(1-Pf/Pe))	=	0.982		$6.5.12
Design check for combined bending and axial:		***OK***				
Efficiency		***0.982***				

Appendix B – Conservatory Construction Cost Estimates

B.1 Site Preparation and Excavation

Site Prep and Excavation — including operator costs

item #	item description	QTY (m^3)	Crew Code	Crew Size	Productivity	Daily Output	Duration (days)	Worker-Hours	Unit Labor Pricing	Crew Pricing	Total Unit Labor Cost	Total Labor Cost	Equipment Unit Cost	Equipment Cost	Total Cost
1	Excavation and Site Prep	1608	B-3A	4 Labourers 1 Equip. Oper. 1 Hyd. Excavator, 1.15m3	0.046	163.00	9.87	73.97	$55.50	$1,677.82	$10.29	$ 16,551.71	$92.77	$6,862.16	**$23,413.87**

B.2 Footings

Formwork

item #	item description	QTY (m^2CA)	UOM	Crew Code	Crew Size	Productivity	Daily Output	Duration	Worker-Hours	Unit Labor Pricing	Crew Pricing	Total Unit Labor Cost	Total Labor Cost	Material Unit Cost	Material Cost	Total Cost
1	FOOTING FORMWORK (F1) 2 uses	85.68	m^2	C-1	3 Carpenters 1 Laborer	0.928	34.47	2.49	79.51	$63.33	$2,026.50	$58.79	$ 5,037.15	$10.75	$921.06	$5,958.21

Rebar

Item #	Item Description	rebar size	Volume of Concrete (m3)	Rebar/Concr	Tons of Rebar	10% extra	QTY (m-tonnes)	Crew Code	Productivity	Daily Output	Duration (days)	Worker-Hours	Unit Labor Pricing	Material Unit Cost	Material Cost	Total Cost	Notes
1	Footing (F1) pad	20M	33.264	25	0.832	0.915	20.25	4 rodm	16.797	1.91	0.48	15.4	$48.39	935	$ 855.30	$ 1,596.91	10% extra for lapping, splicing, and waste

Placing Concrete — including operator

Item #	Item Description	QTY (m^3)	Crew Code	Crew Size	Productivity (wh/m3)	Daily Output	Duration (days)	Worker-Hours	Unit Labour	Crew Pricing ($/day)	Total Unit	Total Labor	Material Unit Cost	Material Cost	Equipment Unit Cost	Equipment Cost	Total Cost	Notes
1	Concrete Placement for F1	33.26	C-7	9 1 Labour Foreman 5 Laborers 1 Cement Finisher 1 Equip. Oper. (med) 1 Equip Oper. (oiler)	2.093	34.41	0.97	69.62	$56.35	4134.79	$117.93	$3,997.08	$199.18	$6,625.59	$87.84	$6,115.51	$16,738.18	Assume 28 Day strength (35MPa) is 75% of ultimate strength, therefore use 41MPa Assume crane and bucket, greater than $4m^3$

Finishing

Item	Item Description	QTY (m^2)	Crew Code	Crew Size	Productivity (labor hr/m^2ca)	Daily Output (m^2CA/day)	Duration (crew days)	Worker Hours	Unit Labor Pricing (/Labor hr)	Crew Pricing (/crew day)	Total Unit Labor Cost	Total Labor Cost	Material		Equiptment		Total Cost
													Unit Cost	Cost	Unit Cost	Cost	
1	Total Footings Finishing	33.26	C-10B	8 3 Labourers 2 Cement Finishers 1 Concrete Mixer 2 Concrete Finishers	0.453	88.26	0.3769	15.07	$ 55.92	$ 2,236.93	$ 25.34	$ 843.07	$ 2.27	$ 75.61	$ 67.29	$608.64	$ **1,527.32**

B.3 Rammed Earth Flooring

Formwork

item #	item description	QTY (m^2)	Crew Code	Crew Size	Productivity	Daily Output	Duration	Worker-Hours	Unit Labor Pricing	Crew Pricing	Total Unit Labor Cost	Total Labor Cost	Material		Total Cost
													Unit Cost	Cost	
1	Formwork for Slab-on-Grade	90	C-1	4 3 Carpenters 1 Laborer	0.928	34.47	2.61	83.52	$63.33	$2,026.50	$58.79	$ 5,291.13	$10.75	$967.50	$6,258.63

Placing Concrete/Compacting Floor — including operator

Item #	Item Description	QTY	UOM	Crew Code	Crew Size	Productivity (wh/m3)	Daily Output (m3/day)	Duration (days)	Worker-Hours	Unit Labour Pricing ($/hr)	Crew Pricing ($/day)	Total Unit Labor Cost	Total Labor Cost	Material		Equipment		Total Cost	Notes
														Unit Cost	Cost	Unit Cost	Cost		
1	Loading excavated material into mixers and filling site to grade	1608	m^3	B-3A	4 Labourers 1 Equip. Oper. 1 Hyd. Excavator, 1.15m3	0.046	163.00	9.87	73.97	56	1,678	$10	$16,552			$93	$6,862	**$23,414**	
2	Concrete Placement, and Finishing (simultaneously with Item 3)	536	m^3	C-8	7 1 Labour Foreman 3 Labourers 2 Cement Finishers 1 Equip. Oper.	0.0136	550.00	0.97	7.29	$56	2685.91	$1	$2,618	$50	$26,690	$1,456	$10,610	**$39,918**	Assume 28 Day strength (35MPa) is 75% of ultimate strength, therefore use 41MPa
3	Floor Compactment	536	m^2	B-10F	1 Equip. Oper. 0.5 Labourer 1 Tandem Roller, 9 metric ton	0.0136	550.00	0.97	7.29	$45	179.00	$1	$174			$814	$5,935	**$6,110**	

B.4 Glulam Arches and Plywood Box Beams

Glulam Arches and Beams

double material cost for double length

item #	item description	# of Pieces	QTY (m^3)	Crew Code	Crew Size	Productivity	Daily Output	Duration	Worker-Hours	Unit Labor Pricing	Crew Pricing	Total Unit Labor Cost	Total Labor Cost	Material		Total Cost
														Unit Cost	Cost	
1	Glulam Arches	18	22.14	B-21B	1 Foreman 3 Labourers 1 Equip. Oper. (crane) 1 Hyd. Crane, 11 metric ton	0.8	6.00	3.00	14.40	$52.43	$1,707.34	$231.30	$ 5,122.03	$2,509.74	$55,576.94	$60,698.96
2	Glulam Columns	18	7.49	B-21B	1 Foreman 3 Labourers 1 Equip. Oper. (crane) 1 Hyd. Crane, 11 metric ton	0.8	6.00	3.00	14.40	$52.43	$1,707.34	$683.87	$ 5,122.03	$1,208.10	$9,048.43	$14,170.45

Box Beams

item #	item description	Qty (# of beams)	Crew Code	Crew Size	Productivity	Daily Output	Duration	Worker-Hours	Unit Labor Pricing	Crew Pricing	Total Unit Labor Cost	Total Labor Cost	Material		Total Cost
													Unit Cost	Cost	
1	Plywood Box Beams	16	B-21B	1 Foreman 3 Labourers 1 Equip. Oper. (crane) 1 Hyd. Crane, 11 metric ton	0.53	4.00	4.00	8.48	$52.43	$1,707.34	$426.84	$6,829	$378	$6,053	**$12,882**

B.5 Framing and Glazing

Framing and Glazing

item #	item description	QTY	UOM	Unit Cost	Total Cost
1	Framing and Glazing	965.00	m^2	$ 1,200.00	**$1,158,000**