First Use of UHPFRC in Thin Precast Concrete Roof Shell for Canadian LRT Station

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[*] Ductal® from Lafarge North America, is the registered trademark for a new generation of ultra-high performance, fiber-reinforced cement-based materials that provide strength, ductility, durability, and aesthetics.

Fig. 1. The Shawnessy Light Rail Transit (LRT) Station is an excellent example of the successful melding of emerging technology, inventive design and manufacturing savvy. (Courtesy of Tucker Photo.)

A very thin architectural shell was selected for the roof structure of the new Shawnessy Light Rail Transit (LRT) Station in Calgary, Alberta, Canada. Twenty-four unique, thin-shelled precast concrete canopies measuring 5 × 6 m (16 × 20 ft) and just 20 mm (¾ in.) thick, supported on single columns, provide an attractive light-filled shelter for commuters. This unprecedented structure was made possible with the design flexibility of a new generation of ultra-high performance fiber reinforced concrete (UHPFRC) materials that offer a combination of superior technical characteristics including ductility, strength, and durability without using mild reinforcing steel, while providing highly moldable products with an excellent surface quality. The UHPFRC compressive strength was 150 MPa (22,000 psi) and flexural strength was 18 MPa (2600 psi). This article reveals the many advantages of this innovative technology, and presents the material's mechanical properties as well as the challenges faced in structural design, manufacturing, and erection.

Today, hundreds of light rail transit (LRT) stations are being planned, built, and expanded across North America. In designing these commuter facilities, architects and engineers are faced with numerous considerations, including cost, durability, sustainability, public safety, and design limitations.

Precast concrete solutions can provide superior finishes, tight construction tolerances, speed of construction, lower maintenance requirements, and increased economic value to these transit projects. However, this new UHPFRC technology can challenge existing paradigms surrounding precast concrete systems, as evidenced in the LRT station project that is the subject of this article.

Notwithstanding the obstacles posed by the limitations of existing codes and conventional manufacturing methods, original projects continue to take advantage of new technologies whenever the opportunity for design innovation presents itself to the engineering community. The Shawnessy LRT Station, constructed in 2004 in Calgary, Alberta, Canada, is an excellent example of the successful melding of emerging technology, inventive design, and manufacturing savvy.

In this article, the authors divulge the properties of a new generation of ultra-high performance fiber reinforced concrete (UHPFRC) materials used in an unprecedented application. For the Shawnessy LRT Station, the design, modeling, and novel manufacturing processes created an original precast concrete structure by combining function with innovation (see Figs. 1 and 2).

Originally conceived in a steel design, the canopies were changed early in the design process to a precast concrete solution for economic, durability, and aesthetic reasons. With an architectural design evoking images of the first-conceived steel system, the weightless appearance and airy environment created by the Shawnessy LRT Station surprises many people. Upon closer examination, commuters realize that the canopies are not constructed of steel or metal, but with sleek precast concrete having a high quality surface finish and a once unimaginable structural thickness of only 20 mm (¾ in.).

The primary goal of building precast concrete canopies over the LRT station platforms was to provide protection for commuters from inclement weather and to enhance the architectural appearance of the station within the adjacent residential community. Going well beyond its primary service function, the final solution pushed the envelope of precast concrete design possibilities by taking advantage of a new generation of UHPFRC materials.

The station is comprised of two platforms for inbound and outbound trains. In addition to the UHPFRC canopy system, the platform slabs, exit ramps, and screen walls were also built with precast concrete, providing an all-precast superstructure. The platform slabs and exit ramps were manufactured with high performance concrete (HPC) that provided a dense, "bug hole" free surface that is durable and able to withstand weathering effects, de-icing agents, and pedestrian traffic. Screen walls shield commuters from the freight rail line immediately adjacent to the inbound platform.

Each precast platform deck with exit ramps is about 104 m (340 ft) long × 3 m (10 ft) wide. The canopies are bolted together to create a roof that is about 76 m (250 ft) wide × 5 m (17 ft) wide, which covers most of each platform. For this project, the material's compressive strength was 150 MPa (22,000

Table 1. Shawnessy LRT Station project schedule and costs.

Precast conceptual design	May to August 2002
Prototype development	September to December 2002
FEM and final design	January to April 2003
Manufacture of full-scale prototype canopy system	April to June 2003
Third party testing of full-scale prototype	April to June 2003
Production of precast elements	August to December 2003
Erection	September 2003 to January 2004
Station open to public	June 2004
Total construction cost: $2,600,000 ($3.6 million Canadian)	
UHPFRC precast concrete: $775,000	
HPC and regular precast concrete: $265,000	

Table 2. Precast concrete components for the LRT station.

Precast concrete component	Number	Dimensions	Weight, kg
UHPFRC			
Curved half-canopy sections	40	5.1 m × 3 m × 20 mm thick	1800
Flat half-canopy sections	8	5.1 m × 3.8 m × 20 mm thick	2200
Columns	18	3.7 × 0.3 m (bottom) 305 × 355 mm (top)	1300
Columns	6	4.4 × 0.3 m (bottom) 305 × 355 mm (top)	1550
Tie beams	20	205 mm × 230 mm × 5.5 m long	600
Lateral and rear struts	72	150 × 150 mm	330
Rain troughs	24	20 mm thick × 6.0 m long	175
HPC			
Platform slabs	72	5.1 m × 3.0 m × 205 mm thick	7268
Exit ramp slabs	12	3.5 m × 3.0 m × 205 mm thick	4988
Regular concrete			
Screen walls	36	4.0 m × 3.0 m × 205 mm thick	5700

Note: 1 m = 3.2808 ft; 1 mm = 0.03937 in.; 1 kg = 2.205 lb.

Table 3. Concrete strength test results.

Property	Mean value after 72 hours of thermal treatment	Standard deviation
Compressive strength, MPa (psi)*	150 (22,000)	6.2 (900)
Flexural strength, MPa (psi)†	18 (2600)	3.4 (500)

*24 sets of 75 × 150 mm (3 × 6 in.) cylinders.
†24 sets of 40 × 40 × 160 mm (1.6 × 1.6 × 6.3 in.) prisms.

psi) with a flexural strength of 18 MPa (2600 psi).

Constructed during the fall of 2003 and the winter of 2004, the Shawnessy Station forms a part of the southern expansion of Calgary's LRT system, which serves about 120 million boarding passengers annually. The total construction cost was $3.6 million (Canadian).

For project cost breakdown, project schedule, and structural components, see Tables 1 and 2. The precast concrete incorporated into the Shawnessy Station project included UHPFRC, HPC, and conventional concrete components.

Based on the experience of previous projects,[1] the use of this new technology can lower overall construction costs and labor requirements, improve construction safety, reduce maintenance, and increase a structure's life span.[2] The mechanical properties and design flexibility of UHPFRC facilitated the designer's ability to create a very thin, elegantly curved, off-white shell structure.

UHPFRC MATERIALS TECHNOLOGY

UHPFRC offers a unique combination of high strength and ductility in a highly moldable product with excellent surface characteristics. This material is formulated of constituent materials including portland cement, silica fume, quartz flour, fine silica sand, high-range water reducer, water, and steel or organic fibers. The technology is covered by one of many patents in a range of ultra-high performance concretes, all under the material's trademark.

For the LRT station canopies, the contract document specified a premix formula capable of producing a minimum compressive strength of 130 MPa (19,000 psi). The formula selected was one of several in the premix product range and provided a mean compressive strength of 150 MPa (22,000 psi). Concrete compressive strength for this structure was 150 MPa (22,000 psi) and flexural strength was 18 MPa (2600 psi). Table 3 summarizes test data results from production of the 24 canopies.

By omitting mild steel reinforcement, the ductile behavior of this material is a first for concrete, as UHPFRC has the capacity to deform and support flexural and tensile loads, even after initial

Fig. 2. Night-time photo of the Shawnessy Light Rail Transit (LRT) Station in Calgary, Alberta, illustrates the commuter-friendly ambience and durable function of a novel UHPFRC design. (Courtesy of Tucker Photo.)

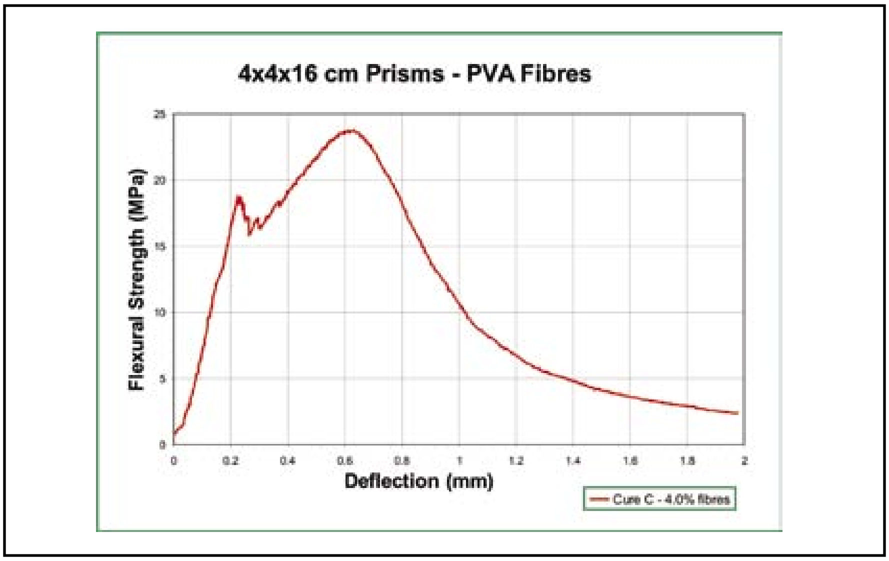


Fig. 3. Load-deflection curve for prism loaded in four-point bending.

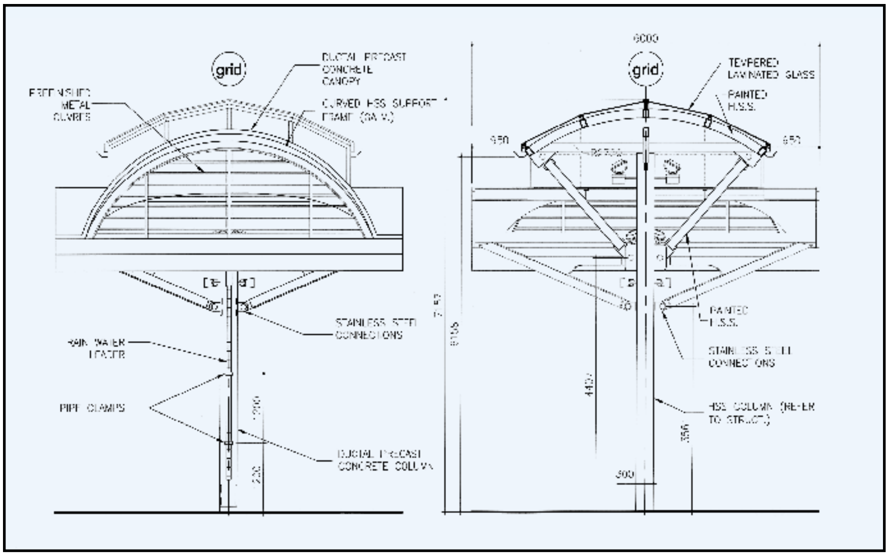


Fig. 4. Dimensions and section elevations of front and back views of precast concrete canopy and support strut.

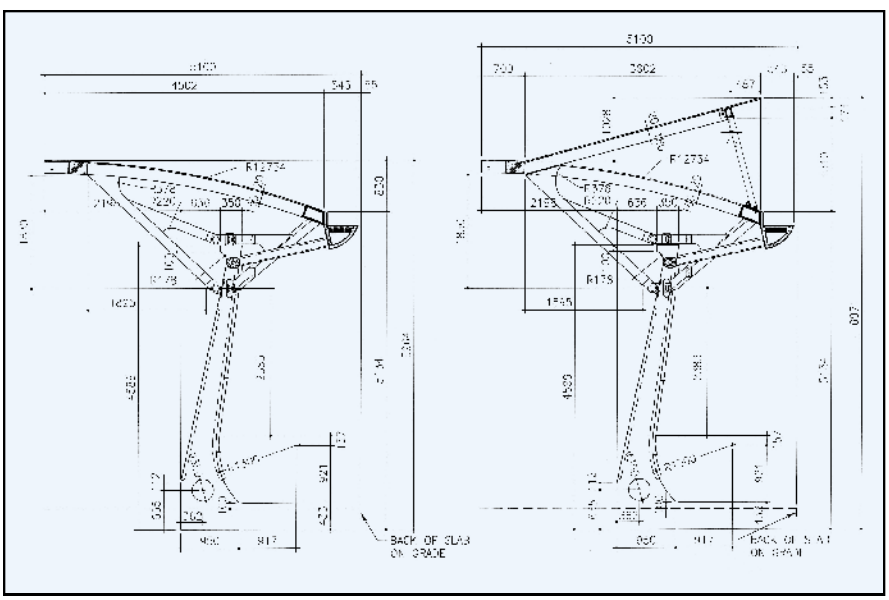


Fig. 5. Elevation and dimensions of side view of precast concrete canopy structure.

cracking (see Fig. 3). These remarkable performance characteristics are the result of improved micro-structural properties within the mineral matrix; in particular, an increase in toughness and control of the bond between the matrix and the fibers.

With a carbonation depth penetration of < 0.5 mm (< 0.02 in.), there is almost no carbonation or penetration of chlorides or sulphides and the material possesses a high resistance to acid attack. The superior durability characteristics of the product are due to a combination of fine powders, selected for their chemical reactivity and relative grain size, with a maximum size of 0.5 mm (0.02 in.). The net effect of this mix design is maximum component compactness and a small, disconnected pore structure.

Following thermal treatment at 60º C (140º F) for 72 hours, the material becomes dimensionally stable, with a creep coefficient of 0.2 and no long-term shrinkage, thus making it very suitable for precast/prestressed concrete applications. The use of this material for construction is simplified through the elimination of mild reinforcing steel and the ability of the material to be virtually self-placing or dry-cast. The following list of properties is an example of the range of material characteristics for a formulation with organic fibers.

Strength

Compressive strength: 120 to 150 MPa (17,000 to 22,000 psi)

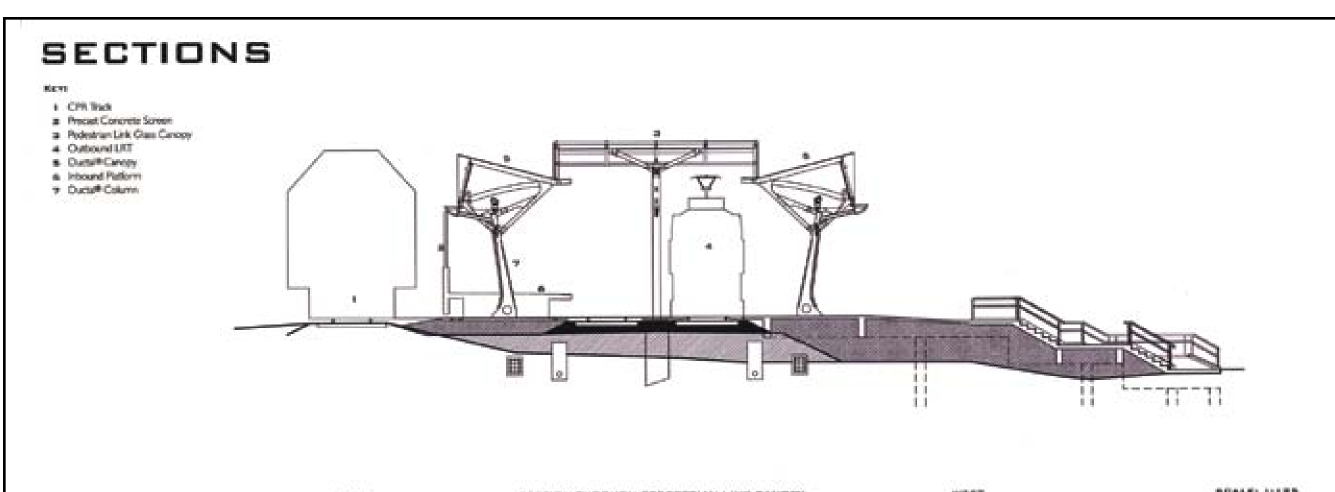


Fig. 6. Site elevation.

Flexural strength: 15 to 25 MPa (2200 to 3600 psi)
Modulus of elasticity, E: 45 to 50 GPa (6500 to 7200 ksi)

Durability

Freeze/thaw (after 300 cycles): 100 percent
Salt-scaling (loss of residue): < 60 g/m^2 (< 0.2 oz/sq ft)
Abrasion (relative volume loss index): 1.7
Oxygen permeability: < 10^{-20} m^2 (< 10^{-19} sq ft)
CI permeability (total load): < 10
Carbonation depth: < 0.5 mm (< 0.02 in.)

Materials were supplied to the precaster, Lafarge Canada Inc., of Calgary, Alberta, in a three-component premix. Powders were pre-blended in bulk-bags at a facility in Kansas. Chryso, of France, manufactured the superplasticizer, and Kuraray America Inc., of Japan, manufactured the organic fibers.

Currently, this material is only used in precast/prestressed concrete applications. Due to the mixing requirements, casting techniques, and shrinkage characteristics during setting and curing, further development work is required prior to its use in cast-in-place applications.

MODELING, DESIGN, AND CODES

After looking at the architectural conceptual renderings of the Shawnessy LRT Station, Lafarge proposed the construction of partial-dome-like canopies out of a new UHPFRC material. Reinforced with polyvinyl alcohol fibers and no mild steel reinforcement, this novel material would be shaped into a thin shell only 20 mm (¾ in.) thick. Since this would be the first use of this material for shell structures, the owner, the City of Calgary, requested that a full-sized prototype canopy be sent to the University of Calgary's Centre for Innovative Technology (CCIT) for extensive testing under the design dead and live loads for snow and wind uplift, as well as a determination of the prototype's response to dynamic loading (Fig. 15).

Stantec Architecture Ltd's (formerly CPV Group Ltd.) Structural Engineering Department carried out a finite element model (FEM) analysis of the structure under load combinations of dead load, wind, snow, and earthquake to determine whether the structure could be physically built. Their analysis also sized the members and performed a dynamic analysis utilizing the FEM to verify the overall stability and dynamic behavior of the structure.

Strudes Inc. of Montreal, Quebec, as a sub-consultant to Lafarge, carried out the detailed structural analysis and design of the canopy components and connections.[3] Fig. 4 shows the model's configuration of shell elements that represent one shell unit of the canopy with solid elements for connections to the struts. Beam elements were used to simulate the support struts and column. Fig. 5 illustrates how the model was composed of three shell parts and their supports tied together to form a single structural unit, configured as the final structure was built (see Fig. 6).

Critical Test Loads

Around the base of the curved part of the canopy, a reinforced beam connects the curved element to flatter sections. The rear strut has reinforcing steel extending from the top to create a fixed connection between the cano-

Fig. 7. Thin, graceful precast concrete shells provide an uplifting and airy ambience for commuters. (Courtesy of Tucker Photo.)

Fig. 8. A single, slender column gracefully supports each precast concrete shell and serves as a conduit for communication, security, and electrical cabling. (Courtesy of Lafarge.)

py and strut. The model developed by Strudes was analyzed using the software SAP2000[4] to determine:

1. The boundary conditions to be applied in the physical test required by the owner and the critical snow and uplift load cases; and
2. The factored value, α, of the critical load to the factored dead and live loads so that the actual loading applied was an appropriate multiple of the live load, such that:

$$\alpha L = 1.25D + 1.5L - D \qquad (1)$$

where L is the live load and D is the dead load. Dead load is subtracted from the factored load as it already exists in the form of the panel itself. Thus, where the dead load increased the peak stress induced by the uplift loading, Eq. (1) was used. Where the dead load counteracted the effect of the live load, $0.85D$ was used in Eq. (1) rather than $1.25D$.

FEM was used to determine the critical load cases and the boundary conditions required on the edge of the prototype during testing to simulate the presence of neighboring panels in the full structural unit. Shell nodes representing less than 1 MPa (145 psi) were excluded from further consideration and the load case that produced the highest number of maximum stresses was taken as the critical case.

With the snow loading, the dead load always increased the peak stress induced by the live load. For wind loading, however, the dead load could either increase or decrease the peak live load stress. Stresses induced by critical load cases determined where the actual canopy should be instrumented during the prototype tests. The critical load cases identified in the modeling and the loading factor, α, for both the snow and wind loads were 1.75 and 1.7, respectively.

Strain gauges were placed in the canopies based on the results of the critical load cases. Dynamic analysis of the model showed the first mode of vibration to be a front-to-back sway at a frequency of 2.8 Hz. When compared with sophisticated computer-modeled calculations, that data confirmed that the 20 mm (¾ in.) thick canopy shell, without any mild steel reinforcing bars, exceeded the flexural tensile strength limit. The precast concrete solution surpassed the test criteria and easily carried full-factored live and dead loads without cracking.

Lightweight, Complex Shapes

An evaluation of the site context, community values, and transit guidelines identified the need for a visual lightness, while employing strong, durable materials for the canopies. UHPFRC's combination of superior strength properties and its ability to be cast into complex shapes facilitated the architect's creation of the attractive, thin off-white canopies, which provide shelter and natural light to the space below (see Fig. 7). Natural light is reflected off the smooth underside of the shell through louvered glazing, projecting an ambient glow to approaching commuters (see Fig. 8).

A single, slender column supports each shell and serves as a conduit for communication, security, and electrical cabling. Transparent screens constructed of glass and concrete act independently of the columns and canopies to provide protection and visibility at the platform level.

Extensive research and collaboration led to the achievement of a natural lightness in the design. Designed with

Fig. 9. Repetition of form provided formwork, precast concrete production, and erection economies. (Courtesy of Lafarge.)

this new technology, this system realized a reduction of materials used at a fraction of the depth and weight previously possible. Furthermore, the repetitiveness of the forms permitted re-use of the formwork during casting of the shells and columns (see Fig. 9).

In addition to the precast concrete components, the project's material palette is comprised of other highly durable materials including stainless steel, galvanized steel, and glass. While having greater internal energy than other materials such as wood, this LRT station will require less maintenance and should provide a longer service life.[5]

Both the function of the Shawnessy LRT Station and the nature of the site dictated a long, linear form running along a north-to-south axis [(see Sidebar, "Critical Community Support for Design of Station," pp. 62)]. Site constraints, above and below grade, restricted the width of the platform to an even greater degree, minimizing the overall footprint (see Fig. 10).

This walk-on LRT station is designed as a side-loading platform, staggered to improve passenger safety across the tracks. At-grade access is provided from an adjacent "Park and Ride" facility and bus terminal, offering easy access for buses and commuters. The area around the station is professionally landscaped (see Fig. 11).

In accordance with the National Building Code of Canada,[6] the structure was designed for various uniform balanced, uniform unbalanced, and concentrated snow and wind load combinations. Verification of the canopy modules was carried out with the assumption that each canopy is a free-standing structure.

Stress analysis was performed using "Stardyne Engine" from the STAAD 2002 program. The verification of the stresses was performed using Mathcad

Fig. 10. Site constraints, above and below grade, restricted the width of the platform, minimizing the overall LRT Station footprint. This walk-on station is designed as a side-loading platform, staggered to improve passenger safety across the tracks. (Courtesy of Lafarge.)

for elastic direct tensile stress limits of 3.5 MPa (540 psi) and a maximum crack width opening of 0.3 mm (0.01 in.) in accordance with the Association Française de Génie Civil (AFGC) Design Guidelines.[7]

In addition to the normal elastic analysis with FEM, a post-cracking elastoplastic analysis was performed, a necessary design check for materials that exhibit a pseudo-ductile behavior. The elastoplastic analysis provides member stress values after a stress redistribution due to plastic deformation.[8] When compared with sophisticated computer modeled calculations, the data confirmed that the canopy not only surpassed the test criterion of maximum allowable crack width opening of 0.3 mm (0.01 in.), but it carried full-factored live and dead loads without cracking.

Code Challenges for Emerging Technologies

One challenge facing engineers today is how to design structures with emerging technologies that are not supported by current design codes and standards. While UHPFRC is a material with ultra-high mechanical properties not addressed by existing design codes, there has been progress by several groups in recent years to develop interim guidelines to assist engineers. The following is a list, by country, of interim design guidelines for materials with ultra-high mechanical properties:

1. **France** — In March 1999, at the request of the Association of French Civil Engineers Scientific and Technical Committee, an interim design guide was prepared for use with UHPRFC for structures. The "Interim Recommendations" guide was published in both French and English in January 2002.
2. **Australia** — With the support of VSL (Australia), the University of New South Wales, Australia, published a "Design Guide for RPC Prestressed Concrete Beams" consistent with the design philosophy of the Australian Code AS3600-1994. This document provides design examples and material design guidance for compressive, flexural, shear, and torsion strength, as well as recommended flexural crack control limits, deflection control, fire performance, fatigue, prestress losses, and guidance on anchorage zones.
3. **Japan** — In September 2004, the Japan Society for Civil Engineers released "Recommendations for the Design and Construction of Ultra-High Strength Fibre Reinforced Structures — Draft." Included in this document are guidance on design rules, allowable material properties for design, testing, durability, construction methodology, and examples of completed Japanese bridge projects. The document will soon be available in English.
4. **United States** — In 2002, building upon UHPFRC research and development work begun at the Massachusetts Institute of Technology (MIT) in 1999, and in parallel with work commenced at the Federal Highway Administration (FHWA) in 2000 on the potential use of UHPFRC for bridges, the FHWA engaged MIT to prepare a study on the optimization of UHPFRC for highway bridges. This collaboration led to the release of a civil engineering report, CEE Report R03-01, "Model-Based Optimization of Ultra-High Performance Concrete Highway Bridge Girders." This report presents a model-based design strategy for a brittle-plastic composite matrix with an elastoplastic composite fiber reinforcement. The guide also gives a comparison between the model based on a maximum crack width opening and the LRFD design.

PRECASTER FACES BOTH MANUFACTURING AND ERECTION CHALLENGES

Innovative Production Techniques

UHPFRC is a new material with unique properties that are different from any other existing product. Manufacturing precast products using this material presented the industry with new challenges and opportunities for the precaster, Lafarge Canada Inc. of Calgary, Alberta. Recognizing that old methods were not adequate for the new requisites of UHPFRC production, a fundamental change in the conventional manufacturing process was required.

A precaster team of individuals with expertise in sales, engineering, production, and erection was established to identify the challenges posed by this new materials technology and to create the novel solutions necessary for successful production of UHPFRC. The Lafarge precast team identified six major questions, or manufacturing challenges:

1. Conventional concrete batching and mixing methods would not work because of the extreme accuracy required for measurement of ingredients, the requirement for high shear energy mixing, and the need to dissipate entrapped air in the plastic mix**.** *What modifications to traditional batching and mixing methods are required to successfully produce UHPFRC?*
2. Because of the material's high viscosity, conventional concrete finishing techniques could not be used. Therefore, casting the material into a horizontal form and finishing the top surface was not possible. *What manufacturing methods are required to produce precast concrete components with a consistent smooth surface?*
3. The material properties, particularly with a flexural strength of 21 to 48 MPa (3000 to 7000 psi), are influenced by the fiber orientation within the material's matrix. *What precast production methods will maximize the efficiencies of fiber orientation during placement?*
4. UHPFRC will shrink twice as much as normal concrete, in part because of the particle size distribution within the material's matrix, which by design eliminates the formation of an aggregate skeleton structure that restrains shrinkage in conventional concrete. *What processes will allow unrestrained shrinkage to occur during the initial set of the material — while maintaining the structural integrity of the UHPFRC — when the fresh concrete is still in a form that is essentially closed on all sides?*
5. Because the 24 canopy elements

were only 20 mm (¾ in.) thick and constructed with intersecting curves, it would be necessary to achieve precise tolerances to form the complex geometric shape. In addition, final product finish quality as well as material placement must be taken into account. *What quality control methods would have to be implemented to ensure success with such complex shapes?*

6. Since the UHPFRC needed to be placed in the form within 20 minutes from the time the product was mixed, placement by pumping appeared to have potential. *What pumping methods would efficiently propel a viscous material with very high fiber content?*

To address these challenges, the precasting team held a series of brainstorming sessions to generate viable solutions. Concepts were closely evaluated and tested against the existing global knowledge database on UHPFRC. An internal research and development (R&D) program was undertaken to provide answers to unprecedented manufacturing challenges that were not answered by any prior experience or research.

At first, some of the production problems appeared to be minor, for example, finding the best combination of mold surface and release agents. However, when the final solution turned out to be an epoxy coating on steel combined with bees wax as the dispersing agent, it became apparent that striking upon workable solutions was not always as simple as first imagined.

Fig. 11. At-grade access to the Shawnessy LRT Station is provided from an adjacent "Park and Ride" facility and bus terminal, offering easy access for buses and commuters. (Courtesy of Tucker Photo.)

Batching and Mixing

The key to producing UHPFRC is very accurate proportion control of ingredients and temperature. A high shear mixer is required to disperse water onto the cement particles without heating the mix through kinetic energy generated by the mixing process. It is necessary, moreover, to control the temperature of the raw ingredients because with such precise mixture proportioning required to produce UHPFRC, the amount of water or ice that can be added is insufficient to affect a significant temperature change.

All ingredients including the water had to be accurately weighed. There is a distinctive power consumption curve that a mixer demonstrates when mixing UHPFRC: the power consumption is initially low as the dry ingredients are blended and increases substantially when the water is added and dispersed. The power demand then drops as the superplasticizer takes effect. This power consumption curve was first identified during laboratory testing and was measured in production for control purposes to determine the mixing time and when to introduce fibers.

The temperature of the mix was measured using a laser targeted portable infrared thermometer, which gave instantaneous readings from a safe distance. Because the process of high speed mixing generates entrapped air into the mix that can lead to a weaker matrix and poor surface finish, it is necessary to slow the mixer at the end of the mix cycle to allow the entrapped air to escape.

Forming

Successful execution of the project depends upon design of the molds and procedures developed to use them. Traditional hand screeding and finishing of UHPFRC is not possible because of the high viscosity and high fiber content of

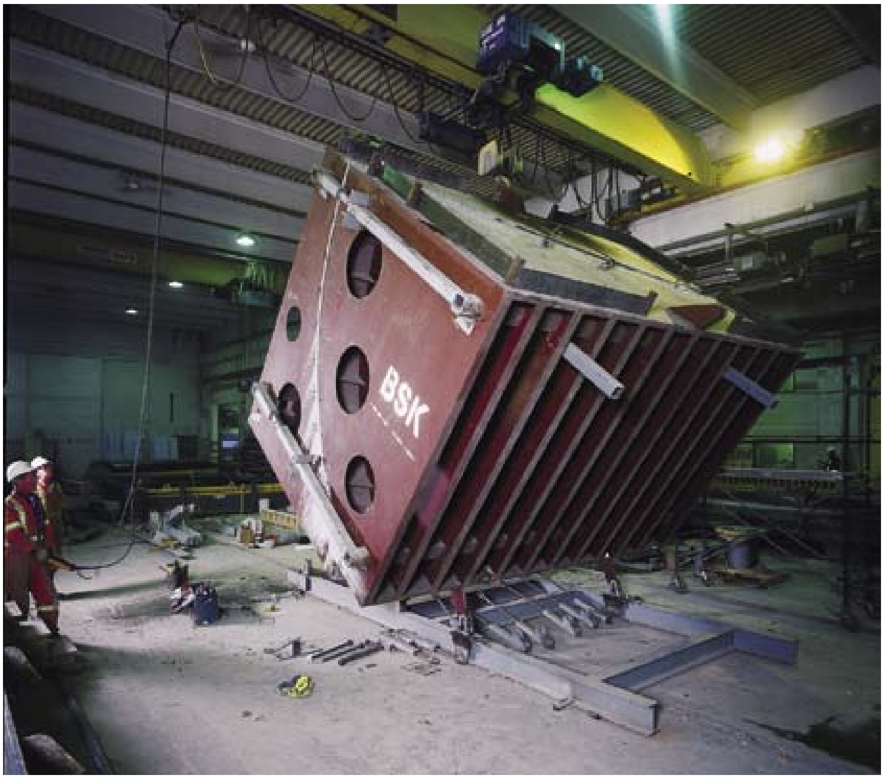


Fig. 12. The form is rotated 180 degrees to an upright position after the material gained enough strength. (Courtesy of Tucker Photo.)

Fig. 13. Top form is lifted from mold. (Courtesy of Tucker Photo.)

the plastic mix. The material also has no internal shear in the plastic state and behaves similar to self-consolidating concrete. This means that in order to manufacture the components with the desired surface finish, all exposed surfaces have to be formed.

The unusually slender, 20 mm (¾ in.) thick, canopies required the forms to be designed to limit live load deflections and to be manufactured to precise tolerances. This daunting specification can be exemplified by realizing that only a 3 mm (1/8 in.) form deflection (common in typical precast production) can increase the product thickness by almost 20 percent. Clearly, mold construction and deflections are of utmost importance.

The mold design also has to accommodate significant initial shrinkage of the UHPFRC at a time when the material has no internal tensile capacity. Attention to methods of release, orientation of mold, and product support are critical. As a result of the R&D program, it was determined that the best finish was obtained with the form in a near vertical orientation and by filling from the bottom by injection of plastic UHPFRC.

The canopy forms were made of plate steel. A three-dimensional model of the casting and form was generated by a computer model. Form deflections and stresses were analyzed by FEM to ensure the form would meet the required tolerance and deflection criteria. Electronic representations (DXF files) were then transferred to a CNC high-definition plasma cutting bed, which produced the diaphragm profiles.

The mold was assembled on accurate jigs, which controlled the location of the diaphragms. The rolled steel skin was drawn to the diaphragms and welded. The R&D program identified that sanding of the metal surface at weld locations, normally done in steel form fabrication, can create a substantial color difference on product casting. This problem is a result of the micro-particle size of UHPFRC, which is able to replicate the texture of the forming surface. To overcome this potential problem, the contact surface was coated with an epoxy based liner to provide a uniform finish.

It was determined that the form would

have to rotate after casting to orientate the product with the curve down, allowing unrestrained shrinkage to occur while at the same time supporting the casting. Since the form was already free to rotate, the next logical step was to use the form to turn the product right side up when the casting had sufficient strength. The steel form for the canopy was designed to rotate 90 degrees in either direction from the vertical.

The first 90-degree rotation turned the canopy shell upside down in the form. The top portion of the form was released to allow for unrestrained shrinkage as the UHPFRC set. Since the material did not have enough internal strength to support itself, the bottom form was used as a concave cradle to support the canopy shell while the UHPFRC set. Once the material gained sufficient strength, the top portion of the form was re-secured and the form was rotated 180 degrees to the canopy's upright position to allow for de-molding of the canopy element (see Figs. 12 to 14).

The form's center of gravity in both the filled and unfilled state was located as close as possible to an imaginary line that intersected lift and hinge points. This allowed the form and product to be rotated in a controlled manner using overhead cranes (see Fig. 12). The hinge point was designed with a vertical slot to prevent overlifting by the crane when the form reached the apex of the rotation curve.

The single plane curved canopies and the rain troughs were produced with molds that used displacement-casting techniques. These molds were designed to allow the correct volume of material to be placed into the form and then a backform was introduced that forced the plastic UHPFRC to conform to the mold shape.

The column forms were designed to be cast vertically to produce a uniform finish on all four sides. The vertical curve was computer modeled and the steel molds were fabricated using techniques that were similar to those used for the canopy forms. The molds were filled through a bottom injection port. Similar form fabrication techniques were used to manufacture displacement based forms for the single plane cross-over canopies.

Fig. 14. Demolding of the precast canopy element. (Courtesy of Tucker Photo.)

Fig. 15. Installation of the prototype canopy at the University of Calgary's Centre for Innovative Technology. (Courtesy of Lafarge.)

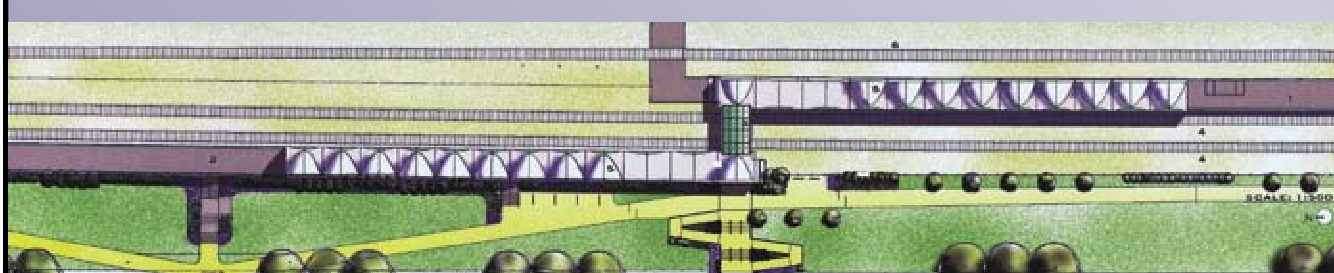
CRITICAL COMMUNITY SUPPORT FOR DESIGN OF STATION

by Enzo Vicenzino

Community involvement was an integral component in the design of the Shawnessy LRT Station. To encourage public communication and involvement in a potentially controversial project, consultation with the Shawnessy community was undertaken in February 2002 to develop a common understanding and vision for the Shawnessy LRT Station.

Stantec Architecture Ltd. (formerly CPV Group Ltd.) created four designs and the community then selected two of the schemes for further refinement. The final design that was selected was a culmination of this very positive cooperative effort between consultant, client, and community and resulted in a unique and dynamic structure informed by, and responsive to, its context. The resulting design is a visual metaphor of tree-like structures that is inspired by the natural setting of the nearby, extensive community greenbelt.

The community's input established the importance of scale, massing, uniqueness, and density of development alongside the acknowledgment of the natural, cultural, and historical setting; this was a critical factor in the successful integration of the station and maintaining and enhancing the overall health and vitality of the community.



Injection Casting

It was not possible to find a commercially available pump that could successfully transfer UHPFRC because its high fiber content caused immediate plugging in conventional concrete and grouting pumps. The simplest solution was to construct a pressure chamber to contain the UHPFRC and apply air pressure above the material to force it into a piping system. The pressure chamber replaced the normal concrete bucket and was filled by direct mixer discharge.

The pressure chamber could also function as a vacuum chamber. Experimentation was done by applying a vacuum above the UHPFRC to draw any entrapped air out of the mix. This process produced only marginal improvement, as the material had already had its air removed in the mixer.

The process was discontinued because it was reducing the available pot life of the product. The pressure chamber, fitted with pressure regulators and safety blow-off valves, was designed to operate at a maximum of 0.1 MPa (15 psi), which meant that it

Fig. 16. Precast canopies enroute to the Shawnessy Station site. (Courtesy of Lafarge.)

was considered a low-pressure vessel.

The vessel top was sealed with a gasket and attached with a flip-away bolting system. A neoprene membrane was placed on top of the plastic UHPFRC in the chamber to create a barrier that prevented air from being forced into the mix. The bottom of the vessel had a simple ball valve. It was necessary to increase the piping size to 75 mm (3 in.) to reduce discharge time. To overcome the gravity pressure in the form, the pressure vessel was raised approximately 1 m (3 ft) above the form during the injection process.

Custom ports were designed to connect the filling tube to the form. The piping had to transition from the pipe diameter to a rectangular shape without reducing the cross-sectional area. A gate had to be built that would conform to the shape of the finished product and allow the filler hose to disconnect without leakage.

The design consisted of a plate connected to the transition trumpet that fit into a slot. A guillotine plate was driven into the slot that displaced the port plate and closed the form. This technique produced a casting that conformed to the form surfaces with no evidence of an injection nib.

Injection casting was used to influence fiber orientation in the precast concrete components. The long slender geometry of the fibers influenced their alignment in the direction of flow. Thus, the discharge from the hose caused the majority of the fibers to orientate themselves along the axis of the hose.

The same phenomenon occurs when UHPFRC flows between two closely spaced forming plates. FEM product design indicated areas in the casting that could benefit from a bias in fiber orientation. By carefully selecting the port location and casting orientation, the project team was able to control fiber alignment.

Displacement Casting

Displacement casting is another method that was used in the Shawnessy project to enhance surface finishes and influence fiber orientation. The process is done simply by depositing the precise volume of material needed in the shape of the final casting into the bottom portion of the form and then introducing the top portion of the form. This will displace the material into the shape of the casting. If the entry points of the secondary form are controlled, it is possible to move the plastic UHPFRP in directions that will influence fiber orientation and facilitate the release of entrapped air.

It was important to have alignment guides to control the exact positioning of the backform during the displacement process. Since considerable force is required, jack screws are used to generate the force necessary to displace the material. The simply curved canopy panels, rain troughs, and walkways were produced using this technique.

Product Handling and Jigging

A complete canopy on the Shawnessy project consists of right and left castings joined together with a bolted seam at the apex of the curve and a beam tension tie across the opening at the base. Once assembled, the unit is structurally stable. However, prior to assembly, the individual elements are very sensitive to the forces that occur during handling and storage.

Lift hooks and lifting inserts were eliminated from the precast concrete components. Instead, handling frames were fabricated with pins that would engage boltholes in the product. These holes served two purposes: initial handling and openings for bolt locations needed in final assembly. The frames were designed to accommodate vertical lifting forces without introducing any unnecessary stresses into the pieces.

An assembly jig was used to accurately locate the individual casting halves and allow them to be rolled together. The interfacing sections were "buttered" with epoxy and the stainless steel connection bolts were tightened at the apex of the curve and on the beam tension tie at the base to complete the assembly.

Transportation

The canopies were supported by struts in three locations when assembled into the final structure. To transport the assembled canopies, special

Fig. 17. Columns on the southbound platform. (Courtesy of Lafarge.)

Fig. 18. Temporary scaffolding to support canopies. (Courtesy of Lafarge.)

support frames were designed that provided similar three-point contact and enabled the transfer of these loads to the truck deck (see Fig. 16). Consideration was given to ensure that any flexing of the truck deck would not result in unexpected loads being imposed on the precast canopies.

Erection of LRT Station

The erection of the precast components for the LRT station began in September of 2003 (see Table 1). Due to scheduling and coordination requirements, the columns for the two station platforms were erected two weeks ahead of the remaining components. The nine columns on each platform were erected in one day (see Fig. 17).

After erection, the columns were aligned, the anchor bolts connecting the columns to the cast-in-place platform cross beams were tightened, and the gaps between the column bases and the cross beams were grouted with a high strength, non-shrink grout. After erection of the columns, temporary scaffolding was erected to support the canopies and position them at their proper elevation and alignment (see Fig. 18).

Because the canopies are supported at three points with a long moment arm to the column, each individual canopy had little resistance to torsion. Therefore, the design required a series of three canopies to be connected together to adequately resist torsion. Supporting the canopies on the scaffolding allowed a series of three canopies to be connected before any load was introduced into the system.

Pre-positioning the canopies before connecting them to the columns facilitated the required tight tolerances of the canopy system. Because the design is three-dimensional, the tolerances of the canopy system were very small and thus a shift in one plane could result in a larger movement in another dimension. By using conventional erection methods (connection of struts to columns followed by connection of canopy to struts), concerns arose about possible deflections of individual canopies after each canopy was erected.

Had the canopy deflected, the erection and subsequent connection of the adjacent canopy to the previous canopy would have resulted in a misalignment of the boltholes for the canopy-to-canopy connection as well as presenting difficulties in maintaining uniform sight lines. Since the erection schedule required the canopies to be in place before the installation of the struts, traditional methods of hoisting the struts into place using a crane were impossible. A temporary three-legged assembly frame was erected on top of each column to provide an anchor for hoisting the struts into place after the canopies were erected (see Fig. 19).

On site, the canopies were lifted onto temporary supports and adjusted to their proper alignment and elevation. Once the canopies were installed on each platform, the struts were lifted into position using the assembly frame as support for the chain hoist. The struts were connected to the canopies and columns with stainless steel connections. Attachment was accomplished through pinning and welding the struts to the columns and to the underside of the canopies (sees Figs. 20 to 22).

The design required three canopies

to be connected to each other with a series of bolts along the ribs of the canopies (see Fig. 10). At every third canopy, an expansion joint was used to allow for expansion and contraction of the canopy roof system. Once the canopies were connected together, the scaffolding was removed allowing for uniform deflection of the canopy system. The precast components at the cross-over area were erected using the same methodology as the canopies on the platform.

CONCLUDING REMARKS

The successful use of UHPFRC in the Shawnessy LRT Station has demonstrated the tremendous potential of this innovative material in the world's first thin-shelled canopy system. But more importantly, this project has also demonstrated the advancement in precast concrete technology and the enormous potential of this innovative product for future generations of concrete construction. The UHPFRC used on the Shawnessy LRT Station project not only showcased the material's strength characteristics, but brought forth additional benefits, including:

- Greater durability properties, providing longer life use expectancies and less maintenance than other traditional construction materials such as steel and cast-in-place concrete.
- Conservation of materials — By using a high percentage of silica fume, which is a by-product of the ferrous silica industry, this allows the project to be recognized as using recyclable materials under certain sustainability programs and certifications.
- Reduction in global construction and life cycle costs through elimination of mild steel reinforcement, smaller construction components, and increased speed of construction.

Since the architect originally conceived the canopies to be made of steel, the actual UHPFRC canopies have demonstrated that thin-shelled systems can be produced with similar thicknesses to steel, but with much greater advantages.

While there are still several chal-

Fig. 19. Three-legged assembly cross on each column provided an anchor for hoisting the struts into place. (Courtesy of Lafarge.)

Fig. 20. Crane hoists thin-shell canopy over rapid transit rail lines to assembly frame. (Courtesy of Lafarge.)

Fig. 21. Crane set of canopy over assembly cross. Note chain hoist for lifting struts into position. (Courtesy of Lafarge.)

Fig. 22. Strut to mid-column connection. (Courtesy of Lafarge.)

lenges left to implementing UHPFRC materials technology, the real challenge ahead lies in finding the optimized shapes for each particular application. When the optimum shapes are determined, precasters and contractors can invest in the formworks necessary to produce these pieces. Thus, the true economies of these systems will eventually be realized in the standard mass production of optimized shapes.

UHPFRC's combination of properties — strength, durability, ductility, aesthetics plus design flexibility — facilitates the designer's ability to create new optimized shapes for construction. In general, this material offers solutions with advantages such as speed of construction, improved aesthetics, superior durability, impermeability against corrosion, abrasion, and impact — all of which translate into reduced maintenance and a longer life span for the structure.

Lastly, it is recognized that the technology of UHPFRC is still in its infancy and that the true benefits of this material have not yet been fully realized. It is expected that in the next few years, much progress will be made in the area of optimized solutions. Further project developments using this technology in other market segments will demonstrate and validate UHPFRC's true value (see Fig. 23).

This project won two awards in the 2005 PCI Design Awards Program — The Harry H. Edwards Award for innovation and carrying the industry to the next level of technology, and the Best Custom Solution. The jury comments were as follows:

"What is really unique with this particular project is the application of the material. This is an ultra-light, high-strength concrete (22,000 psi), and it allows concrete as thin as ¾ of an inch, which is incredibly thin. This low weight and thinness opens up almost unlimited possibilities for the use of precast concrete. It really pushes the envelope of design possibilities when you can get down to fabricating precast concrete of this thinness. The ultra-high performance fiber reinforced concrete opens up the possibility of many new markets, products, and customers. The ability to create precast concrete members that are ¾ of an inch thick

Fig. 23. Dramatic evening photograph of Shawnessy LRT Station exemplifies the remarkably ethereal ambience created for commuters as a result of innovative design, state-of-the-art manufacturing, and the latest materials technology. (Courtesy of Tucker Photo.)

leads precast concrete into markets that it has never participated in before. The capability of using injection moldings seems to be something that brings the precast concrete industry into a whole new field of technology, a whole new field of products and solutions, and a whole new field of customers and marketplaces. It should be fun to watch the precast concrete industry find applications and uses for this material."

CREDITS

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REFERENCES

1. Nowodworski, H., "Ultra-High Performance Concrete with Ductility: The World's First Long-Span Roof in Ductal® — The Joppa Clinker Dome Roof," CSCE (Canadian Society for Civil Engineering) Annual Conference 2002, Montreal, Quebec, Canada.
2. Acker, P., and Behloul, M., "Ductal® Technology: A Large Spectrum of Properties, A Wide Range of Applications," *fib* Symposium, Avignon, France, April 2004.
3. Adeeb, S. M., Nowodworski, H., Rosiak, K., Perry, V. H., Kroman, J., Tadros, G., Brown, T. G., and Shrive, N. G., "Modelling of the World's First Ductal Architectural Shell Structure," Paper Presented at the RILEM International Symposium, Chicago, Illinois, March 2004.
4. SAP2000, Computers and Structures, Inc., Berkeley, California.
5. Stantec Architecture Ltd. (formerly CPV Group Ltd.), Project Drawings and Specifications: *Shawnessy LRT Station*, Calgary, Alberta, Canada, 2003.
6. "National Building Code of Canada," Natural Research Council of Canada, Ottawa, Ontario, Canada, 1995.
7. "Ultra-High Performance Fibre-Reinforced Concretes," AFGC (Association Française de Génie Civil), "Interim Recommendations," Paris, France, January 2002.
8. Ulm, F. J., "Elastic and Elasto-Plastic Modeling of Shawnessy LRT Canopies," *Report*, Boston, MA, 2003.