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Josep Ignasi de Llorens

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Recent developments in architectural fabric structures in North America

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C.G. Huntington
Huntington Design Associates, Inc., Oakland, CA, USA

18.1 Introduction

The birth of the modern North American fabric structures industry can be dated from 1970, with the opening of the United States Pavilion at Osaka, Japan's Expo '70. Among its epochal transformations, Osaka demonstrated the ability of fabric structures to use a new structural system, the low profile air-supported roof, to create architecturally exciting long-span construction. The digital analytical tools used to evaluate the simple form of Osaka evolved quickly to facilitate the design of the more complex tension-structure forms that followed close on its heels, and the project's success encouraged David Geiger to team with Dupont and Owens Corning Fiberglas to create the polytetrafluoroethylene (PTFE)-coated fiberglass material that brought permanence and fire safety to fabric construction. The firm Geiger Berger, formed by Geiger and partner Horst Berger to engineer the Osaka roof, was brought to prominence by the project, and went on to revolutionize fabric structure design over the ensuing 20 years.

By the late 1970s, modern fabric construction's critical elements were already in place and included a wide range of forms; long-span capability; reliable digital analytical tools; and membrane materials providing durability, fire safety, and translucency. I joined Geiger Berger in 1978, shortly after completing graduate studies in structural engineering at the University of California at Berkeley. This was a heady time for the firm, with the architectural press awash in images of the firm's newly erected fabric tension structures and air-supported roofs, and work underway on the Jeddah Hajj Airport Terminal (Figure 18.1), which was the world's largest fabric roof at the time of its completion (Berger, 2005). By that date, Geiger Berger had completed a handful of additional tension structures of widely divergent form, and had built on the experience of Osaka to design air-supported roofs with the longer spans required for contemporary stadium applications.

In 1978, many limitations in design capability, materials, and application of fabric structures remained in both North America and the rest of the world. In considering recent developments in fabric structure design, it is useful to begin by identifying the issues that were outstanding at the conclusion of this first blossoming of fabric tension structures in the 1970s, and then evaluating what progress has been made in addressing them in the ensuing 40 years. Tensioned fabric structures remain a young technology, and it should not be surprising that enormous advances have been made

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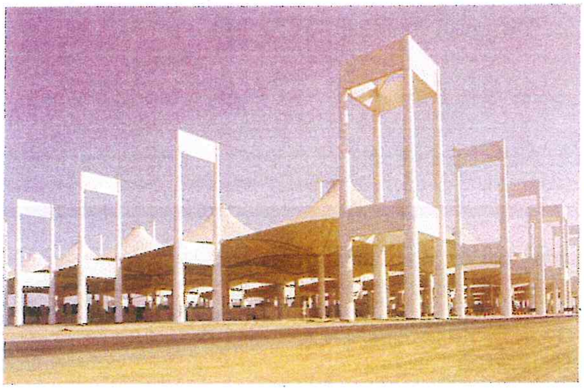
Figure 18.1 Engineering of the Jeddah Hajj Airport Terminal roof pushed the limits of computing power available in the late 1970s in order to analyze the behavior of the vast roof.

over the course of the past several decades. Those of us working in the field in the 1970s were largely young, optimistic, and confident in our ability to move the technology forward, and having witnessed the technology's rapid advances in the years following Osaka, we expected quick resolution of the outstanding material and design issues, with a continuing increase in both the breadth and quantity of fabric applications. The world of our future, we imagined, would be freckled throughout with fabric structures of every imaginable shape and size.

Many of these early expectations, perhaps unrealistic, have gone unmet as critical material and design issues remain unresolved, and the growth of fabric structure application has found limitations. The coming decades, however, will bring with them fresh-thinking engineers, architects, and materials scientists, who will seek and find solutions to the issues that presently limit the use and application of architectural fabric structures. We can expect, additionally, that the specialist architects, engineers, and contractors who currently dominate fabric structure work will begin to work in a more cross-disciplinary manner to create new materials and designs that enable us to realize more of the potential of architectural fabric structures for effective daylighting, efficient energy use, broad application, and diversity of form.

Fabric structure specialist practitioners and academics make frequent pilgrimages to international conferences where foreign colleagues are consulted and local works are visited. Large fabric structure projects frequently employ international teams of designers and builders, who exchange and develop ideas together. These activities and others lead to the rapid transfer of fabric structure technology across international borders. In considering the development of fabric structure design in recent years, therefore, it is no longer possible to draw strong distinctions between the fabric structure technologies used in different parts of the world. While fabric structure technology is international, though, the regulatory, cultural, climactic, and architectural contexts in which fabric structures are built have substantial geographic variation, and these differences are reflected in the discussion of North American practices that follows.



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The section of this chapter that follows will examine the changes in the primary technologies that are driving the evolution of fabric structures today: materials and analytical tools (including formfinding, analysis, and patterning software). Next, we will consider how these technologies have impacted fabric structure design and performance, in areas that include form diversity, energy use, application, reliability, and access to technical and construction expertise. The chapter concludes with listings of North American fabric structure resources, including trade bodies, literature, education, and consulting and construction expertise.

18.2 Fabric structure technology

The evolutions in fabric structure design that took place in North America in the 1970s focused on the creation of a new material with paradigm-changing properties, and the development of analytical techniques that made it possible to determine the form and structural behavior of membranes with complex or unique form. As with most technologies, the pace of change in fabric structure design has slowed as the technology has matured. Materials and analytical tools remain the primary fields of development, though, and North American scientists, designers, and builders remain at the center of this ongoing evolution.

18.2.1 Materials

The first structure to employ the PTFE-coated fiberglass fabric developed by Geiger, DuPont, and Owens Corning was the University of La Verne Campus Center, completed in 1973 (Figure 18.2). Owens Corning had predicted a 20-year lifespan for the material, which was in excess of that typically provided by the dominant material on the market: vinyl-coated polyester. The prediction seemed bold when first spoken about an unproven material, but it has proven conservative. The La Verne

Figure 18.2 The University of La Verne Campus Center, completed in 1973, made the first use of the new PTFE-coated fiberglass fabric. Its original membrane is still in service today, with only modest loss in fabric strip tensile strength.

membrane is still in place more than 40 years after its original construction (Huntington, 2004).

PTFE-coated fiberglass materials put to rest old questions about the potential for permanent and durable fabric architecture. The new material also provided excellent fire resistance (including the ability to meet building code requirements for noncombustible construction), and its PTFE coatings (similar to the Teflon used to create easily cleanable cookware) gave it the ability to shed surface soiling and retain its crisp white color over decades of use. The new material, though, brought with it new challenges. The fiberglass used for the woven scrim, while very strong, is also brittle and subject to damage if creased in handling. The material's susceptibility to damage increased erection costs, and made it impractical for use in membranes that were to be erected seasonally, or unrolled or unfolded in normal use. More important, the stiffness of the PTFE coatings rendered the material unable to redistribute tensile forces at a point of overstress or damage, and hence vulnerable to tearing failures that may propagate across the width of the material under certain conditions.

Newer materials have been developed that address the issues associated with PTFE-coated fiberglass. They are discussed in detail elsewhere in this volume, and will only be noted briefly here. W.L. Gore of the United States developed (and later sold to Sefar of Switzerland) a fabric composed of woven PTFE that replaced the fiberglass scrim used at La Verne and elsewhere. The material, named Tenara, retains the durability and cleanability of PTFE-coated fiberglass, while offering the possibility for much greater light transmission (up to 38%). The PTFE scrim, furthermore, is much less brittle than fiberglass, which gives the material much higher tear strength and reduced vulnerability to damage from creasing. The latter property brings with it exciting new possibilities for use in deployable structures, where the membrane is unrolled or unfolded as required to suit varying environmental or use conditions. The material tends to creep under sustained load for a period of several weeks, but this can be addressed by retensioning of the membrane where necessary. The high cost of PTFE-coated PTFE fabric has limited its inroads into the market, but it is a valuable addition to the palette of materials available to fabric structure designers where high translucency or operability is required.

Foil, primarily in the form of ethylene tetrafluoroethylene (ETFE), is another newer membrane material that brings with it new design possibilities and an alternative to woven fabrics. ETFE is closely related chemically to PTFE, and essentially transparent, though its light transmission can be reduced by the printing of ink on the material in a process known as "fritting." ETFE, though, "has been embraced more in Europe than North America," notes Steve Neidig of USA Shade, a state that he attributes to a greater focus on associated fire safety issues in America. In order to exploit some of the new possibilities of ETFE construction, Birdair recently "borrowed" ETFE specialist Benoit Fauchon from its European affiliate. Birdair can now obtain its ETFE from several sources, including St. Gobain Performance Plastics in the United States, and Fauchon notes several developments that are increasing the range of application for the material, including foils that are thicker (currently limited to about 0.300 mm) and wider materials (currently limited to about 1.5 m). New foils add chlorine for greater clarity, and are available with pigments of any color, and a wide range of digital printing.

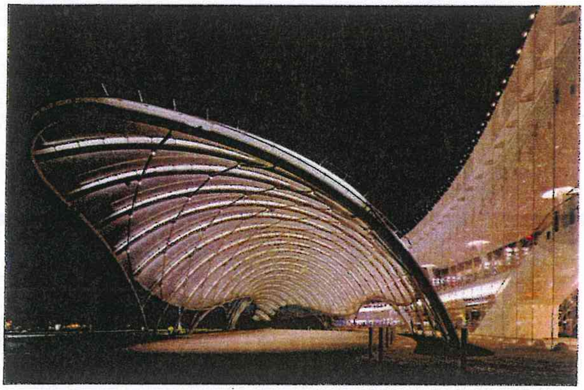

Figure 18.3 The entrance canopy for the Empire State Casino provides an eye-catching use of inflated ETFE foil lenses.

FTL and Birdair recently teamed up to create the ETFE-clad entrance canopy to the Empire City Casino at Yonkers Raceway in Yonkers, New York. The double-layer foil lenses are supported on curved round tube frameworks to create a voluptuous roof form (Figure 18.3). Fritting of the ETFE and LED lighting gives the canopy a singular appearance under both daylight and artificial night lighting. The tendency of the material to creep under load generally restricts its use to multilayer inflated lenses in roof applications, which contributes to the high cost that has also limited its use.

Insulated roofs have been a field of recent North American advancement. It is worth noting that La Verne, the original PTFE-coated fiberglass roof, was also an insulated roof. It employed a conventional 38-mm-thick glass fiber metal building insulation to achieve an R-value of 5, but the face sheet of the insulation rendered the roof opaque. In 1983, the Lindsay Park Sports Centre was completed in Calgary, Alberta, Canada, using a PTFE-coated fiberglass structural membrane, underslung with a 400 mm fiberglass insulation bed resting on a thin and transparent Tedlar film. The insulated roof suffered problems of condensation and dirt accumulation, though, and Birdair Structures recently completed a reroof of the structure, now called Talisman Centre (Figure 18.4), using a roof assembly with a 40-mm aerogel layer sandwiched between an outer structural membrane and an inner liner membrane of PTFE-coated fiberglass. The combined assembly delivers an insulation value of R-12 while retaining 2.5% light transmission. Aerogel roofs are a recent development, and we can expect further advances in both it and other insulating materials.

Designers of recent structures have been able to make use of materials with a broadened range of solar properties, as well as improved insulating materials, and highly durable fabrics suitable for deployable applications. Each of these new developments has brought with it cost, dimensional stability, or other issues, however, such that the two materials used for the vast majority of North American fabric architecture construction are exactly the same as they were 40 years ago: vinyl-coated polyester, and PTFE-coated fiberglass.

Figure 18.4 Talisman Centre in Calgary, Alberta, was reroofed using an aerogel fabric that provides effective insulation while maintaining significant translucency.

18.2.2 Analytical tools

The Osaka Pavilion and other early structures engineered by Geiger Berger were analyzed by modeling widths of fabric as cables of equivalent stiffness—an adaptation from the analytical methods used in Germany to analyze the Munich Olympic Stadium roof and other cable net structures. Geiger Berger and others soon adopted finite element analysis methods that modeled the fabric as membrane elements. This basic analytical engine has undergone only modest changes over the ensuing decades, with some state-of-the-art analysis software writers acknowledging that the basic analytical solvers in their programs have gone unchanged for many years.

The user interfaces of fabric structure design software, meanwhile, have evolved radically since the beginnings of the modern fabric structure era, a change that has occurred in parallel with the similar evolution of software in other fields. Analytical modeling of the early modern era required extensive manual input of geometry. Output was largely numerical, rather than graphic, and laborious review was required in order to verify analytical accuracy. At the same time, the cost and ease of analysis was burdened by the use of computers with far smaller CPU capacity than those of today's most meager personal computers. The analysis runs that Geiger Berger performed for the Hajj Pavilion in the late 1970s were made at great cost using time rented on the new Cray supercomputer. Engineers were nonetheless compelled to employ coarse analysis models and make use of lines of symmetry and other simplifications in order to limit CPU requirements.

With the proprietary membrane design software presently available, designers can employ mesh generation features to readily create complete and detailed models of large and complex structures, analyze them quickly on a desktop computer, and then review graphic output on the screen to pinpoint modeling errors before running a revised analysis. The cost of processing power and the difficulty of checking results using the old technologies made exhaustive verification of input a necessity. "I used to check everything very carefully before running the analysis," says Jim Ford, who markets his own suite of fabric design software and is a veteran of projects ranging from the first low profile air-supported roofs to the latest Brazilian World Cup stadiums. "Now, I create the model and run it immediately, because I can see any problems in the modeling on the screen right away."

An additional area of broad advancement in software is in the availability of post processors that summarize analysis output, indicate governing member forces, and provide building code design checks on cables and steel or other supporting elements. Engineers in years past could expect their work to include a laborious process of determining governing member forces for various load combinations, and then performing hand calculations or inputting these governing loads into separate software to perform member design and code checks. Currently available software automates this to varying degrees, with the most comprehensive software packages providing automated member and cable design checks in accordance with the appropriate governing code requirements.

18.3 Fabric structure performance

Evolutions in materials and analytical techniques have been manifested to varying degrees in the capability and performance of built structures. The range of fabric structure form and the breadth of applications employing fabric architecture have continued their early growth, fueled in part by greater access to technical expertise and the software and other tools of contemporary design. New technologies can sometimes run a step or two ahead of well-documented field performance, however, and the growth of the North American fabric structure industry continues to be impeded by insufficiently rare instances of tearing, ponding, connection failure, and other structural performance issues.

18.3.1 Diversity of form

If a membrane is stretched to a uniform level of prestress on nonplanar supports and not subjected to external loading, it will assume an anticlastic shape—one in which the curvatures about two perpendicular axes at any point on the membrane are of opposite sign. These opposing curvatures, characteristic of conical and saddle membrane forms, are required in order for the membrane to remain stable when the direction of membrane loading is subject to change. The only exceptions are air-supported or air-inflated structures, which employ synclastic curvature (curvature about perpendicular axes are of the same sign), and rely on air pressure to achieve stability under varying loads. Depending on the configuration of supports, the rate of membrane curvature (and the membrane's resultant stress state and stiffness) can vary substantially. In the extreme case, in which all supports lie in a plane, anticlastic curvature diminishes to zero.

In the early years of modern fabric construction, engineers focused on configuring supports so that anticlastic curvatures were significant over all areas of the membrane, and reversal of curvature under superimposed load (in which an area of the membrane adopts synclastic curvature) was minimized or avoided altogether. In making this

Figure 18.5 The amphitheater in Springboro, Ohio, uses minimally curved membranes to dramatic effect, while employing heat trace cables and drainage openings in the lower membrane to address extreme weather events.

choice, engineers understood that a membrane which has an anticlastic shape under prestress and a stable (if partially synclastic) shape under a full wind load will pass through an intermediate state in which an area of fabric has lost both curvature and tension, and is potentially unstable. With experience, designers have gained greater understanding of the membrane stresses and stability in these areas of curvature "pop through," and, in minimally curved forms, may apply a partial wind load to the structure in the analysis to test the extent of slack fabric that may occur at intermediate loading states. Similarly, where membrane slopes are minimal, engineers have learned to apply downward loads over only a portion of the structure, in order to test for areas of potential water or snow ponding. These changes, dependent more on evolution in engineering skill and judgment than on any advances in analytical technique, have allowed designers to select minimally curved or minimally sloped fabric roofs with greater confidence (Huntington, 2013).

A recent project engineered by the author demonstrates one approach to a successful design that has both minimal curvature and minimal slope. At the amphitheater in Springboro, Ohio, architect Lorenz Williams sought a dramatic form with two overlapping membranes (Figure 18.5). The upper membrane is supported at three points, and therefore essentially uncurved in the absence of superimposed loads. By providing sufficient slope, however, it is able to drain under all load conditions. Some of this water drops onto the lower membrane, which has four support points configured in a manner that provides minimal curvature and slope. We incorporated a ridge cable to increase curvature and reduce the effective fabric span, but analysis pinpointed a region of potential ponding. Several 22 mm diameter drain holes were installed in this area to allow drainage in extreme rain conditions, with heat trace cables provided to create a path for water in the event of freezing rain or snow (Huntington, 2008a).

Mid-twentieth century concrete shell engineers adopted rational, mathematically definable forms such as the hyperbolic paraboloid in order to successfully analyze the forms using classical hand-analysis techniques. The preponderance of similarly simple forms in the fabric structures of the early modern era represented a carryover of this tradition. With the passage of time, however, designers have begun to take full advantage of the ability of contemporary digital analysis techniques to bring understanding to the structural behavior of today's more complex forms, which

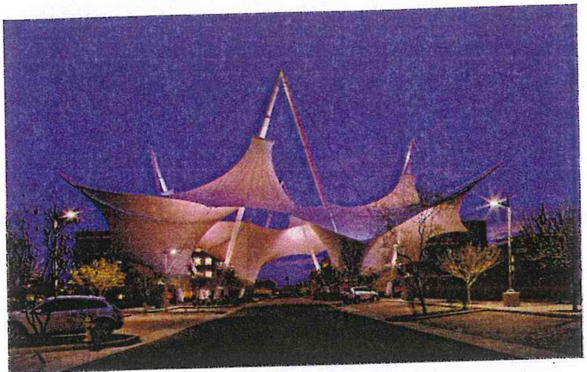

Figure 18.6 Structures like SkySong combine sophisticated engineering and a sensuous design sensibility to create complex forms with reversing curvatures.

sometimes reverse curvature or have zero curvature over significant membrane area. The New York firm FTL Design Engineering Studio has combined cutting-edge engineering with a voluptuous design sensibility to create a number of structures of complex and dramatic curvature. Among these is SkySong at Arizona State University, constructed by USA Shade, which combines upright and inverted cones, with transitions between forms that are shaped by lacy, curving trusswork (Figure 18.6).

18.3.2 Reliability

The growth of the North American fabric structure market was hobbled in the early years of modern tension structure design by old impressions of circus tents and camping tents, as unsophisticated, short lived, and flammable. These concerns have largely been laid to rest by the performance of modern fabric structures, which provide elegant design as well as excellent durability and fire safety. The reliability of modern fabric structures remains far from perfect, however, even in structures designed with state-of-the-art engineering skills and constructed by skilled and experienced builders. Some of the structural performance issues observed with fabric structures are listed below, with discussion of how they are being addressed in recent construction.

18.3.2.1 Tearing

In the PTFE-coated fiberglass fabrics first used at the University of La Verne, the stiffness of the coating prevents fibers from bundling at the ends of a tear to resist its propagation. As a result, the tear strength of PTFE-coated fiberglass is much less than that of vinyl-coated polyester fabric of similar strip tensile strength, and structures using it may bear the risk of broad damage resulting from localized overstress, detailing errors, or punctures from projectiles or other sources. The tearing properties of PTFE fabric—the material still most commonly employed on sophisticated, permanent structures—have unfortunately not been improved in the years since La Verne. Saint Gobain

Performance Plastics, the manufacturers of the Sheerfill brand PTFE fabrics that are used most widely in North America, has developed a fabric that uses a "multi-axial" Kevlar scrim that, in addition to high tear strength, has high shear strength. "The present high cost of the material prohibits its use in the majority of commercial structures," notes Saint Gobain's Michael Lussier, but it is employed for "high value structures in difficult environments." These include high-profile air-supported "radome" structures, which are otherwise prone to buckling under high lateral wind loads.

Until an economical material is developed that combines the durability, translucency, cleanability, fire resistance, and other qualities of PTFE fabrics with high tear resistance, designers must employ other means of ameliorating the effects of PTFE's low tear strength, including, of course, designing the rigid members that support the fabric so that they are not reliant on the vulnerable membrane material for their stability. Another strategy usefully employed by designers is to limit the size of fabric panels between the cables or supporting members that provide a termination point for tears.

18.3.2.2 Connection issues

Inherent in the design of membrane structures is the joining of flexible and relatively delicate fabrics to rigid and hard connection and supporting elements. Where these connections occur at acute membrane corners or other potential locations of stress concentration, the danger of fabric tearing becomes significant. Accurate membrane patterning, accurate determination of cable angles at membrane plate connections, the rounding or elimination of reentrant membrane corners, and the use of flexible and adjustable fabric edge clamping are measures that have reduced but not eliminated these risks in recent construction (Huntington, 2009).

18.3.2.3 Ponding

In the early years of modern fabric construction, fabric structures were regarded as "special" structures, in which attainment of anticlastic form was deemed essential, and structural engineering specialists like those at Geiger Berger held far greater sway in the generation of overall form than did the engineers working in more conventional structural mediums. With the broader adoption of fabric structures in North American construction, however, has come a reversion to the more conventional model of the design process, in which architects create form, and structural engineers are tasked to "make it work." The increasing primacy of architects in tension structure design (not unlike that in the design of bridges and other design fields that are historically engineer driven), together with increasing reliance on specialist software for shape generation, has brought with it an increasing incidence of shapes with minimal curvature and, occasionally, slopes that are inadequate to prevent ponding of rain or snow. Good contemporary design practice includes increased attention to conditions that may result in sliding snow or other loading irregularities that will cause ponding. It also sometimes includes provision for interior drainage of the membrane, or even heat systems to facilitate the run off of precipitation, as discussed in Section 18.3.1

for the Springboro Amphitheater. Ponding conditions can be difficult to predict in complex or highly flexible membrane forms, however, and ponding-induced "bubbling" of membranes, or tearing failures, have continued to occur in some recently built structures.

18.3.2.4 Framed tent issues

Structures that employ fabric cladding supported by multiple bays of aluminum or steel rigid frames are commonly used in North America for applications that require economy and fast erection and disassembly. While this technology lies outside the scope of fabric tension structures that are the general subject of this chapter, they are a form of fabric architecture that has sometimes suffered serious structural performance issues, and therefore deserve mention here. The fabric panels in framed tents are typically a single bay (5+ m) in width, and installed along extruded tracks at the upper corners of framing members. These systems facilitate drawing both framing and fabric from a kit of parts to create a structure of the size required for a particular application, and their ease of erection and disassembly facilitates use in temporary structures.

The North American framed tent industry is highly competitive, and vendor selection is typically cost-driven. This, together with the reduced regulatory scrutiny associated with lightweight, temporary construction, has sometimes contributed to low design and construction standards and unreliable performance. Design loading is sometimes at fault, with structures that substitute small ancillary dead load on the roof for much higher building code-mandated live loads, or wind loads based on very short return periods. Temporary structures founded on asphalt or other ground surfaces often substitute staking into grade for anchorage to footings. While settlement due to excessive bearing pressure is rarely a safety or even a serviceability issue in these highly flexible structures, wind uplift failure of improperly designed or tested staking has led to overturning failure of some structures. Inadequate control of frame erection, including the omission of required bracing or bolts in framing connections, has also been at fault in the deficient performance of some structures.

18.3.3 Range of application

The first years of modern fabric construction in North America brought with them the creation of the low-profile air-supported roof and economical stadium-sized enclosures, as well as the use of fabric to cover a vast new airport terminal in Saudi Arabia. It is fair to say that the engineers working at Geiger Berger and Birdair saw these early successes as only the first steps in the evolution of fabric becoming a structural and form-giving material nearly as ubiquitous as timber or concrete. The ensuing decades have provided less pervasive growth in the use of fabric than the pioneers might have imagined, but some surprising successes as well.

An increasing focus on daylighting and energy use throughout the construction industry has coincided with the introduction of better-quality insulating fabrics, higher-translucency membranes, and the development of photovoltaically active membranes to create exciting new possibilities for the use of fabric in architecture. Among these are various membrane façade applications. Conventional vinyl-coated polyester and PTFE-coated fiberglass fabrics have been employed on various buildings as sunshades for daylighting control. Two of the most elegant have been designed by FTL Design Engineering Studio of New York. At the Mesa, Arizona Arts Center (Figures 18.7 and 18.8), south-facing windows are shaded by horizontal PTFE fabric eyebrows. Shading studies by BOORA Architects of Portland, Oregon, helped refine the geometry of the membranes to provide good shading of high summer light while allowing lower winter light to penetrate the building interior (Broderick, 2003).

North-facing windows at the Central Library in nearby Phoenix, Arizona (Figures 18.9 and 18.10), presented a different issue: intense summer morning sun in the adjoining interior offices and stack areas. Here, studies by Tait Solar demonstrated the value of a vertical shading system, and FTL specified a PVC-coated polyester mesh material to provide filtered light (Goldsmith, 2003). The fabric, Ferrari's Soltis 392, creates what FTL's Nic Goldsmith describes as an "opera net" effect derived from theatrical scrims. It reads as opaque when seen from the outside during daylight hours, but transparent in the evening when lit from the inside.

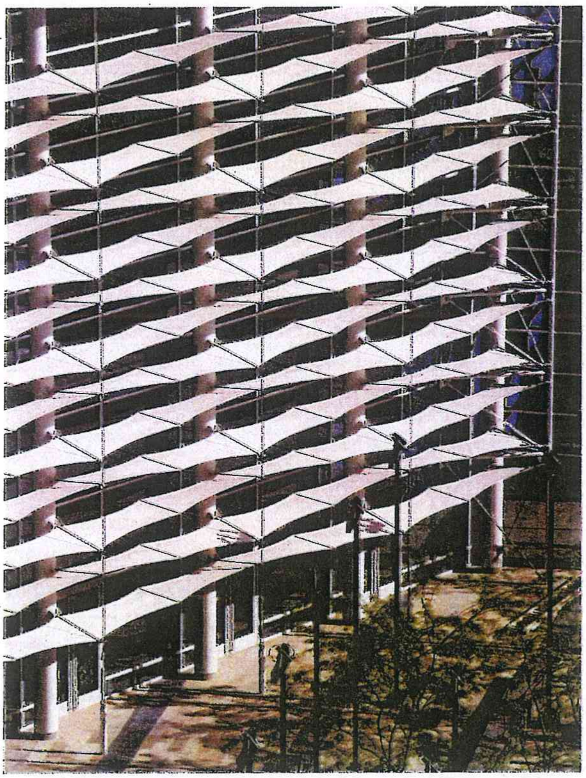

Figure 18.7 The visually dynamic façade of the Mesa Arts Center is protected by horizontal fabric sunshades that are configured to block summer sun while allowing lower winter light to flood the building interior.

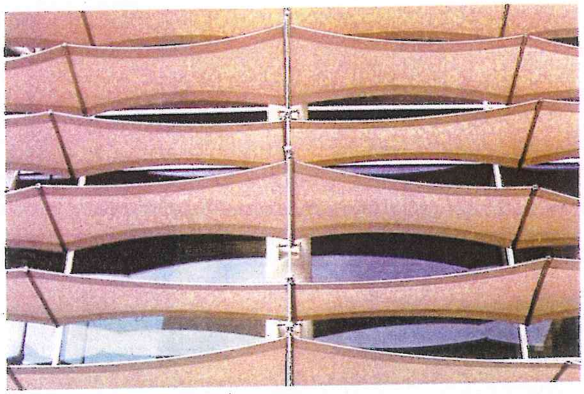

Figure 18.8 Mesa Arts Center sunshade close-up.

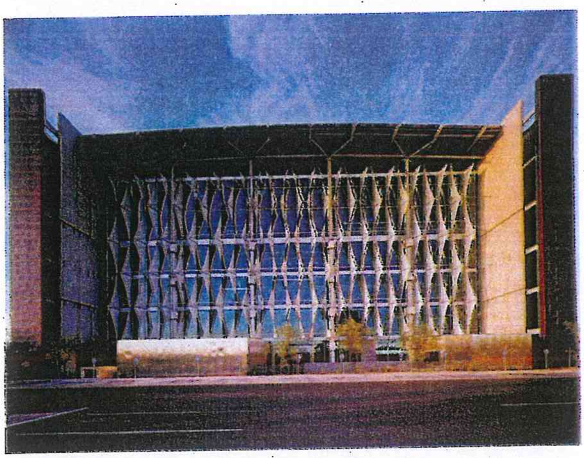

Figure 18.9 The vertical fabric mesh sunshades at the Phoenix Central Library provide dramatically different effects, depending on ambient lighting conditions. They appear nearly opaque in daylight, but have gossamer transparency at night.

The sunshades at Mesa Arts Center and Phoenix Central Library are placed perpendicular to the exterior wall plane so that conventional, translucent fabrics can be employed without eliminating outward views. ETFE now allows the retention of outward views when the membrane is placed parallel to the exterior wall plane, though no such North American application has the visual drama of the Beijing National Aquatics Center showcased at the 2008 Olympics. The high light transmission of ETFE now also provides an alternative to glass or polycarbonate skylight and glazing systems.

Façades do not experience snow or other sustained loading (other than prestress), and Birdair's Fauchon notes that this provides the opportunity to use ETFE in

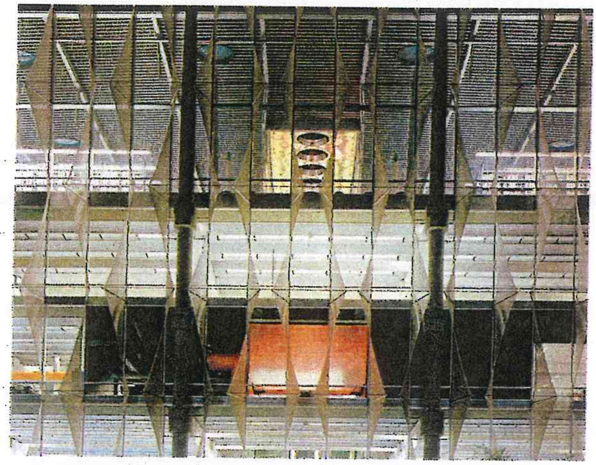

Figure 18.10 The vertical fabric mesh sunshades at the Phoenix Central Library provide dramatically different effect, depending on ambient lighting conditions. They appear nearly opaque in daylight, but have gossamer transparency at night.

single-layer applications for improved economy. This approach was taken in the recent renovation of BC Place in Vancouver, British Columbia, where Geiger Engineers teamed with Schlaich Bergermann & Partners to create a single-skin ETFE vertical clerestory between the top of the existing grandstand and the new perimeter compression ring above (Figure 18.11) (Campbell & Lynch, 2013).

North American designers, manufacturers, and contractors have also begun to integrate the use of photovoltaics (PVs) into fabric structure design. The author worked closely with solar power contractor SunPower to develop canopy systems that

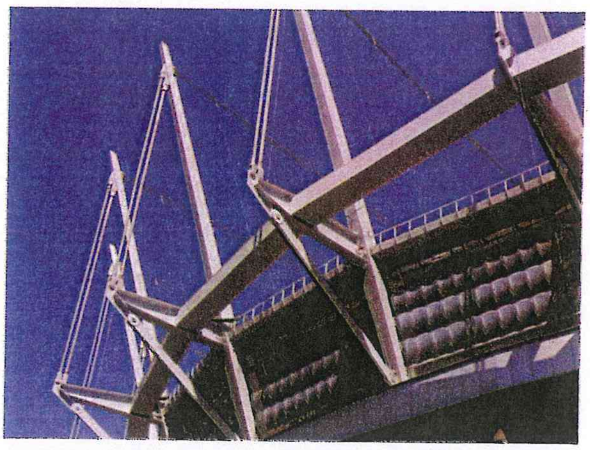

Figure 18.11 Single-layer ETFE film creates an effective clerestory below the new roof on Vancouver's BC Place Stadium.

Figure 18.12 At Springs Preserve Photovoltaic Park, fabric membranes above the parking area serve the dual functions of shading vehicles and providing a reflective membrane that improves the output of bifacial photovoltaic (PV) panels.

integrate bifacial solar panels with reflective fabrics to create integrated shading/power generation systems. At Springs Preserve Photovoltaic Park in Las Vegas, Nevada (Figure 18.12), overhead steel frameworks support solar panel arrays designed to rotate over the course of the day to maintain optimal orientation to the sun. The panels are spaced to allow penetration of sunlight through gaps in the array, and a portion of the light passing through is reflected off the fabric below and back onto the underside of the solar array, which employs "bifacial" panels that are photovoltaically active on both the top and bottom surfaces. The membrane fabricated and installed by tension structure contractor Eide Industries is a PVC-coated polyester mesh manufactured by Ferrari, as required to allow water drainage through the minimally sloped membranes. The mesh has less reflectivity than a solid membrane, but is still sufficient to provide an 18% increase in energy production over what would have been generated without use of the bifacial panels and reflective membrane (Huntington, 2008b).

Thin-film products, in which the PVs are integrated directly into the fabric membrane, have also begun to make inroads into North American construction. These membranes use silicon cells that are attached to the surface of a fabric to produce energy. The product was used at the Staten Island Children's Center (Figure 18.13), where a ridge-and-valley structure engineered by Weidlinger & Associates employs thin-film panels. The strain capacity of the PV is less than the prestress elongation

Figure 18.13 Thin-film photovoltaics (PVs) create opaque areas visible on the underside of the Staten Island Children's Museum membranes. These products do not yet have the efficiency needed for broad commercial application, but hold promise for the future.

of the PTFE membrane, and it was therefore necessary to attach the PV after erection and prestress of the membrane, using a mechanical anchorage system developed by Birdair, the builder of the structure. Current products are limited in their applications due to low photovoltaic efficiency, but research underway suggests greater future use.

Pvilion is an American firm that has developed "solar sails" that employ a thin-film solar fabric to create canopies over two- or four-vehicle solar electric vehicle-charging stations. A prototype system being developed at Google in Mountain View, California, for which the author is part of the design team, is expected to generate about 1.6 kW of power per station, sufficient to charge two electric cars per day.

The blossoming of the North American fabric structure technology in the 1970s and 1980s seemed to bring with it the enduring dominance of fabric in the long-span stadium roof market. The low-profile air-supported roof at Osaka led quickly to the use of the technology for new football and baseball stadiums. The first National Football League stadium topped by an air-supported fabric roof was the Pontiac, Michigan Silverdome, completed in 1975. The economy of the structural system made it quickly seem the only way to cover a stadium. By the time that repeated deflations of major roofs doomed the technology for use in major public structures, Geiger had created its successor, the cable dome, a system first employed on the roofs of gymnastics and fencing venues at the 1986 Seoul, South Korea Olympics. The market dominance of the cable dome was also short-lived, however, due to issues that included the difficulty of supporting large scoreboards, lack of viable insulation, and increasing demand for structural systems that allowed a portion of the roof to be opened and closed.

Fabric structure technologies have continued to evolve in response to the market demands of stadiums and other long-span structures, with significant successes beginning to emerge. The desire to gain the daylighting and other benefits of fabric, while providing operable stadium roofs, has been addressed in several instances by the installation of the fabric on a rigid, translating steel framework. The fabric clad "skylights" on structures such as Cowboys Stadium in Dallas, Texas (Figure 18.14), are

Figure 18.14 The translating center section of the Cowboys Stadium roof demonstrates the use of fabric in a versatile retractable-roof application, though the fabric functions more as cladding than a spanning element on the synclastic "skylight" form.

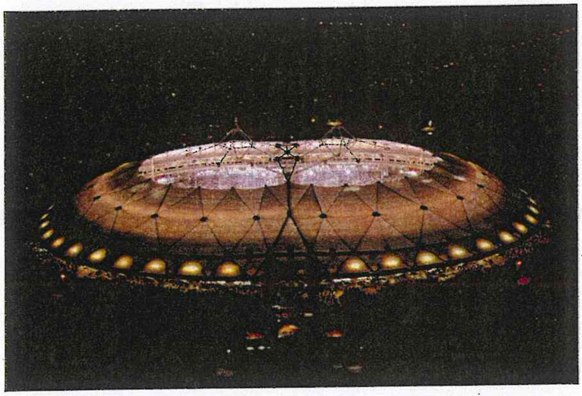

Figure 18.15 The graceful form of the La Plata Stadium roof provides a large center opening—a first step towards the use of the cable dome system with a retractable center section.

well-executed as well as being fast and reliable in operation, though they lack the visual lightness and daring of the most aesthetically satisfying long-span fabric roofs.

New approaches to long-span fabric roof design, as well as adaptations of earlier approaches, are also underway to satisfy the new demands for stadiums while preserving the unique visual character of the fabric tension structure. New York's Weidlinger Associates, in an ingenious adaptation of the original Geiger cable dome, engineered the roof over the stadium in La Plata, Argentina (Figure 18.15) with a cable dome that has a large oculus over the playing field. Further variations are on the drawing boards at Weidlinger, including concepts in which a retractable fabric roof will ride on top of the cable dome (Levy, 2013). Geiger Engineers recently employed a different cable-supported roof structure for the design of the replacement roof on BC Place Stadium in Vancouver, British Columbia (Figures 18.16 and 18.17). Here, the primary roof membrane is held stable by offsetting tensions in the overhead and underslung cables,

Figure 18.16 The BC Place Stadium renovation included the installation of a new roof with radiating overhead and underslung cables that support the fabric roof. The grandstand covers are fixed fabric panels, while the center section employs retractable TENARA pneumatic cushions.

Figure 18.17 The BC Place Stadium renovation included the installation of a new roof with radiating overhead and underslung cables that support the fabric roof. The grandstand covers are fixed fabric panels, while the center section employs retractable TENARA pneumatic cushions.

and the high-translucency TENARA pneumatic cushions employed for the central section of the roof retract or extend accordion-style as required for event and weather conditions.

Successful recent applications of fabric in architecture are most often those that take advantage of fabric's natural affinity for playful, voluptuous form, and those in which its intimate connection to daylighting can be used to advantage. Two recent projects of the author find this sweet spot for the application of fabric to architecture. At the marina in Stockton, California (Figure 18.18), fabric hypar canopies constructed by USA Shade provide shading against the sweltering Central Valley heat. Fabric provides a natural fit for the marina application, where it is both festive in mood and reminiscent of sail imagery. The marina docks float as required to accommodate tidal variations in water level, and normal dock flotation is insufficient to support the

Figure 18.18 Translucent PTFE-coated fiberglass fabric hypar "sails" provide ideal sunshades for the marine recreation environment at the new Stockton Marina berth covers. Tubular steel perimeter beams prevent inward collapse of the tensioned system, while light bracing cables resist lateral wind loads.

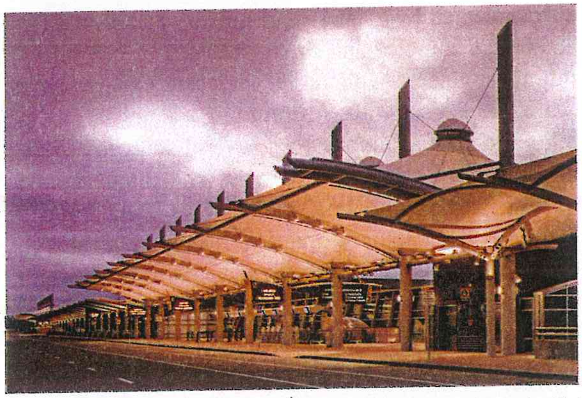

Figure 18.19 Visitors flying to the sunny city of San Diego enter into the light that penetrates the translucent fabric canopies at the newly refurbished airport terminal.

large reaction loads from the berth covers. Instead, the vertical guide piles for the docks were extended overhead to provide high and low support points for the hypars. The pile tops are linked by horizontal struts to equilibrate the large inward pull from the membranes, and light bracing cables stabilize the piles against unbalanced lateral wind loads (Fabric Architecture, 2010).

At an early design meeting for the roadside canopies at the San Diego International Airport expansion, a Port Authority official reminded the design team that "people fly to San Diego for the sunlight. When they leave the terminal to enter the city, they should enter to sunlight." This design directive guided the choice to use fabric for 600 lineal meters of canopy (Figure 18.19). The strict 8 m bay width in all of the canopies mirrors the structural module of the terminal structure behind it. In our design, the three sizes of canopy (ticketing pavilions as well as upper and lower roadway canopies) all employ simple curved, cantilevered struts, with overhead bracing arms back to the masts to reduce cantilever bending moment and resulting strut diameter. The larger ticketing pavilions are distinguished by raised peaks midway between the supporting columns, as befits their role as entry points to the terminal (Witcher, 2013).

18.3.4 Access to technology

The development of fabric structures in North America was severely hampered in its early years by limited access to analysis, design, and construction expertise. The technology was in some ways well established in North America by 1980, but there were only two North American contractors with broad fabric structure experience at that time, very few consulting engineering firms to compete with Geiger Berger in membrane engineering expertise, and very little college coursework or continuing education devoted to fabric structure technology. Both the growth of the North American fabric structure market and the technical sophistication of the work were constrained by these limitations in construction and technical expertise.

Today, unfortunately, there are still only a couple of fabric structure contractors in North America with the resources and experience to handle the largest projects, though they have been supplemented by a handful of midsized firms with good expertise and the resources to undertake complex and sophisticated projects. There are now a greater number of consulting engineers with fabric structure experience, and sophisticated membrane software packages with formfinding, analysis, member design, and patterning capability are now available from several sources. There has been limited progress in the incorporation of fabric structures into the academic environment, as university architecture and engineering departments face competing demands for core curriculum and elective coursework, and special topics such as the study of tension structures are typically relegated to occasional seminars.

The Industrial Fabrics Association International has proven an effective marketing organization for the North American fabric structure's industry, but the industry lacks a technical organization that, in the manner of the American Concrete Institute and the American Institute of Steel Construction, provides not only marketing but also support for research, technical publications, conferences, and standards development. As a result, specialty contractors and consulting engineers remain the primary means by which the technology is both advanced and disseminated.

18.4 Fabric structure resources

This section provides listings of North American-based resources that include the following:

1. Trade and professional bodies
   North American organizations dedicated entirely or in part to the design and construction of fabric structures are listed below.

   Fabric Structures Association (FSA)
   FSA is a division of the Industrial Fabrics Association International. It is a marketing-focused trade organization, rather than a technical society, with the purpose of promoting the use and growth of the fabric structures industry in the Americas. http://fabricstructuresassociation.org/.

   Structural Engineering Institute (SEI)
   The SEI is a division of the American Society of Civil Engineers. It is a broad-based technical society with limited activities and publications related to fabric architecture. Its Tensile Membrane Structures & Air-Supported Structures Standards Committee is presently updating standards for tensile membrane, air-supported, air-inflated, and frame-supported membrane structures. Prior to disbanding, SEI's Tensioned Fabric Structures Task Committee recently published the report *Tensile Fabric Structures: Design, Analysis, and Construction* (Huntington, 2013). http://www.asce.org/sei/.

2. Periodicals
   Periodicals with a complete or occasional focus on fabric architecture are listed below.

   Fabric Architecture
   Published online by the Industrial Fabrics Association International, it provides design and technical information, discussion and images of built structures, and industry news. http://fabricarchitecturemag.com/.

Specialty Fabrics Review
Published by the Industrial Fabrics Association International, this monthly magazine provides technical and marketing information on fabrics used for architectural and other applications. http://specialtyfabricsreview.com/.

3. Books and technical papers
Currently available books or technical reports authored by North Americans or published by North American publishers are listed below.

Fabric Architecture
Armijos, S. J. (2008), New York: W.W. Norton & Company
Includes a large number of color photographs displaying the range of fabric structure design.

Innovative Surface Structures
Bechthold, M. (2008), New York: Taylor & Francis
An in depth introduction to the topic of surface structures, including both membranes and rigid folded plates and shells.

Light Structures, Structures of Light
Berger, H. (2005), Bloomington, IN: AuthorHouse
A general text on fabric structure design, with detailed commentary and photographs of the author's own work.

New Tent Architecture
Drew, P. (2008), New York: Thames & Hudson
Includes a limited general introduction to fabric structure technology, with detailed information and images of built structures.

Tensile Fabric Structures: Design, Analysis, and Construction
Huntington, C.G., editor (2013), Reston, VA: ASCE
Authored by specialists associated with the Task Committee on Tensioned Fabric Structures, the volume includes chapters on history, materials, loading, form determination and analysis, connections, and construction.

Tensile Membrane Structures (ASCE/SEI Standard 55-10)
ASCE (2010), Reston, VA: American Society of Civil Engineers
An ASCE standards document that provides minimum criteria for the design and performance of membrane-covered cable and rigid member structures.

The Tensioned Fabric Roof
Huntington, C.G. (2004), Reston, VA: American Society of Civil Engineers
A general text on fabric structure design, with detailed discussion of fabric structure form, details, and construction, as well as energy use, aesthetics, and other nonstructural considerations.

4. Academic resources
Individuals with university affiliation who have a teaching or research interest in fabric are listed below. At this time, there are no multicourse programs in fabric structure design available at North American universities.

Bonnemaison, Sarah; Dalhousie University, Nova Scotia, Canada.
sarah.bonnemaison@dal.ca
http://architectureandplanning.dal.ca/architecture/visitors/faculty/bonnemaison.shtml

Teaches a tensile architecture seminar and a hands on learning course where students construct a tensile structure in the summer.

Daas, Mahesh; ACSA Distinguished Professor of Architecture, Ball State University. mahesh@mahesh.org.
www.mahesh.org
Daas is interested in the digital design, fabrication, and construction of tensile fabric structures. He has taught design-build studio courses on fabric architecture, and consulted to IFAI on the development of a fabric structure teaching curriculum.

Davis-Sikora, Diane; Associate Professor of Architecture, Kent State University. dmdavis@kent.edu.
Her work focuses on temporary membrane structures with an emphasis on inflatable, pneumatic systems. She edited and produced "Structures of Air," a short documentary on pneumatic architecture which was an official selection for the 2012 VI. Istanbul International Architecture and Urban Film Festival and the 2013 Architecture Film Festival Rotterdam.

Donofrio, Mark; Assistant Professor, University of Oregon Department of Architecture. donofrio@uoregon.edu.
Periodically teaches a full design studio course in fabric architecture.

Heshmati, Ali; Adjunct Assistant Professor, University of Minnesota College of Design. ali@leadinc.no
Focuses on fabric in teaching and student design assignments, and studies the important role that fabric plays in sustainable practice.

Mark, Earl; Associate Professor, School of Architecture, University of Virginia. ejmark@virginia.edu.
Mark has been working with computer simulation and CNC in teaching a design studio on transformable lightweight fabric design with a small ecological footprint for the Maine Coast. He is also engaged in a design-build research project using thin-film PV cells for the same setting.

Ming, Tang; Assistant Professor of Architecture, University of Cincinnati.
tangmg@ucmail.uc.edu
Fabric structures are studied in student projects. Students have competed successfully in Fabric Structures Association design competitions.

Miro, Juan; Professor of Architecture, University of Texas. juan@mirorivera.com
Student design projects sometimes focus on fabric structures. Miro has written about fabric architecture, and uses fabric in his design consultancy.

Pastore, Christopher Philadelphia School of Engineering
pastorec@philau.edu
http://www.PastoreC@philau.edu/
Conducts research in the areas of structural performance of highly extensible tensile structures and the development of sustainable materials for use as fabric structures. Periodically teaches a fabric mechanics class.

Schierle, Goetz; Professor of Architecture, University of Southern California
Schierle@usc.edu

An experienced fabric structure designer who has directed student fabric structure design projects and regularly addresses fabric structures in both studio and lecture courses.

Soto, Mauricio; Assistant Professor of Architecture, California College of the Arts
msoto@cca.edu.
www.cca.edu/academics/faculty/msoto
Teaches a seminar in tensile membrane structures covering basic design principles, form finding, materials, detailing, and manufacturing and installation. Students develop a project from conceptual design to fabrication and erection.

Speidel, Elbert; Lecturer, California Polytechnic State University
espeidel@calpoly.edu
Teaches a class on polymers in construction that includes several weeks devoted to shade, tension, and pneumatic fabric structures, and in which students design and construct a shade tension structure.

Taher, Rima; Sr. University Lecturer, New Jersey Institute of Technology
taher@adm.njit.edu
Periodically teaches an elective course on cable and fabric structures.

Tang, Ming; Assistant Professor, University of Cincinnati.
tangmg@ucmail.uc.edu
www.ming3d.com
Tang's field of specialty is parametric and computational design in architecture. He teaches the University digital skill course, and his recent book, *Parametric Building Design Using Autodesk Maya* covers fabric structure simulation using 3-D software. His students have won the Fabric in Architecture competition of the Association of Collegiate Schools of Architecture.

Wit, Andrew, Design Innovation Fellow, Ball State University.
andrewjohnwit@gmail.com
www.andrewjohnwit.com
Teaching courses related to fabric design. Research currently focuses on fabric and pneumatic envelopes which can formally adapt to both occupant and environmental conditions.

Wright, Bruce; Adjunct Assistant Professor, University of Minnesota College of Design.
wrigh050@umn.edu.
Wright is the former editor of Fabric Architecture magazine, and conducts a half semester workshop on portable construction that emphasizes lightweight and fabric structures.

5. Fabric structure contractors
A partial listing of contractors with skill and experience in the construction of tensioned fabric structures of moderate to large size is provided below.

Birdair, Inc.
Amherst, NY
(800) 622-2246
www.birdair.com
sales@birdair.com

Eide Industries, Inc.
Cerritos, CA
(800) 422-6827
www.eideindustries.com
info@eideindustries.com

FabriTec Structures
1011 Regal Row
Dallas, TX 75247
(877) 887-4233
www.fabritecstructures.com

Rainier Industries, Ltd.
Tukwila, WA
(800) 869-7162
www.rainier.com
sales@rainier.com

Span Systems, Inc.
Manchester, NH
(800) 558-3003
www.spansystemsinc.com
inquire@spansystemsinc.com

Structurflex
Kansas City, MO
(816) 889-9000
www.structurflex.com
bdreiling@structurflex.com

USA Shade & Fabric Structures
Dallas, TX
(800) 966-5005
www.fabritecstructures.com

6. Fabric structure consultants
North American consulting firms with expertise in tensioned fabric structure design are listed below.

Blackwell
Toronto, Ontario
(416) 593-5300
www.blackwell.ca
dbowick@blackwellbowick.com

Fabric Technology for Structures, PA/James Ford
St. Petersburg, FL
(727) 527-6674
fabtec@ix.netcom.com

FTL Design Engineering Studio
New York, NY
(212) 951-6361

www.ftlstudio.com
ngoldsmith@ftlstudio.com

Geiger Engineers
Suffern, NY
(845) 368-3330
www.geigerengineers.com
dmc@geigerengineers.com

Huntington Design Associates, Inc.
Oakland, CA
(510) 339-0110
www.huntingtondesign.com
craig@huntingtondesign.com

Wayne Rendely, PE
Huntington Station, NY
(631) 351-1843
www.waynerendelype.com
waynerendelype@aol.com

Schedlbauer, Joe
E. Amherst, NY
(716) 580-3593
joe@jesengpc.com

Weidlinger Associates, Inc.
New York, NY
(212) 367-3000
www.wai.com
albert.dibernardo@wai.com

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Broderick, R. (2003). *The arts of fabric, fabric architecture, March/April 2003* (pp. 46—50). Roseville, MN, USA: Industrial Fabrics Association International.

Campbell, D. M., & Lynch, K. A. (2013). The renew BC place in Vancouver, BC, Canada. In *Proceedings of the international association for shell and spatial structures symposium* (pp. 1—6). Poland: Wroclaw University of Technology.

Goldsmith, N. (2003). *Tales of light and darkness: The phoenix library and mesa arts center, fabric structures 2003 conference proceedings* (pp. 35—43). Industrial Fabrics Association International.

Huntington, C. G. (2004). *The tensioned fabric roof* (pp. 73—76). Reston, VA: American Society of Civil Engineers.

Huntington, C. G. (2008a). *Structures using uncurved or minimally curved tensioned fabric membranes, proceedings, ASCE structures congress*. Reston, VA: American Society of Civil Engineers.

Huntington, C. G. (2008b). *Bright(er) shiny day, fabric architecture, March/April 2008* (pp. 52–57, 60). Roseville, MN, USA: Industrial Fabrics Association International.

Huntington, C. G. (2009). *Design of connections for tensioned fabric structures, proceedings, ASCE structures congress*. Reston, VA: American Society of Civil Engineers.

Huntington, C. G. (2010). *Cool Water, fabric architecture September/October 2010*. pp. 24, 25.

Huntington, C. G. (2013). *Tensile fabric structures: Design, analysis, and construction* (pp. 52–53). Reston, VA: American Society of Civil Engineers.

Levy, M. (2013). *Translucent dome for Argentine Soccer stadium, structure magazine, February, 2013* (pp. 22–24). Chicago, IL, USA: National Council of Structural Engineers Associations.

Witcher, T. R. (2013). *San Diego airport expands with style, civil engineering online*. Reston, VA: American Society of Civil Engineers.