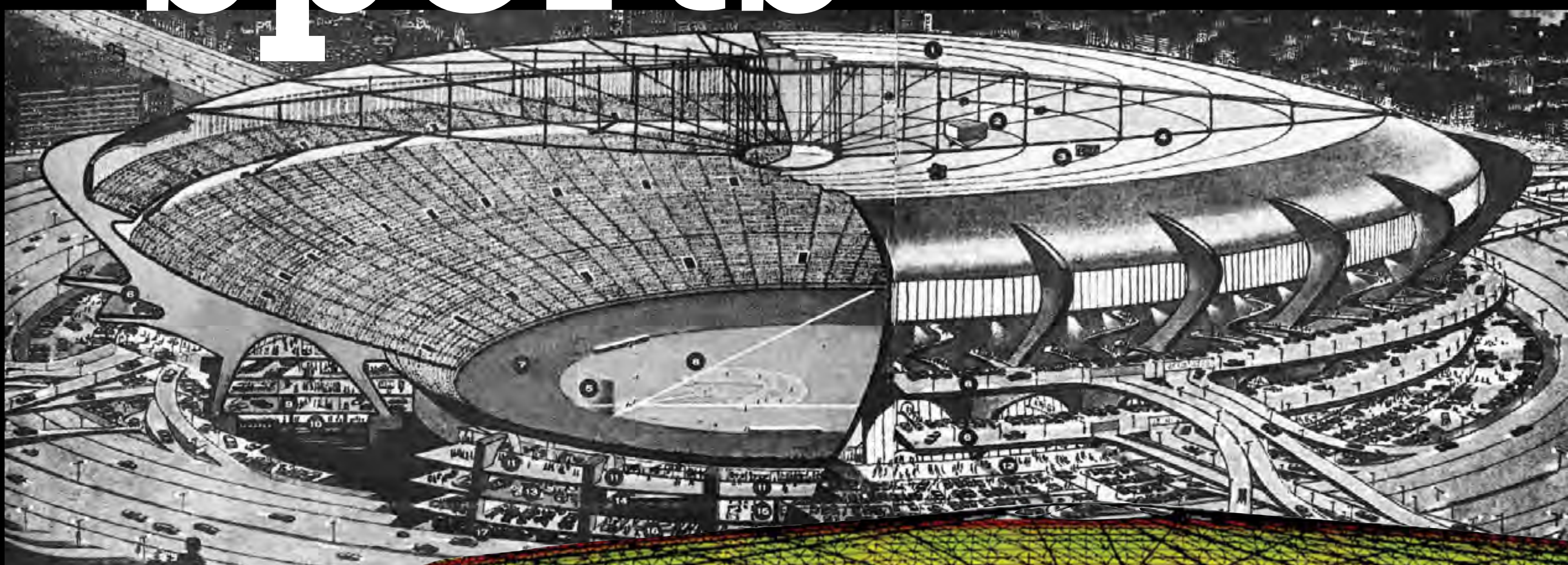
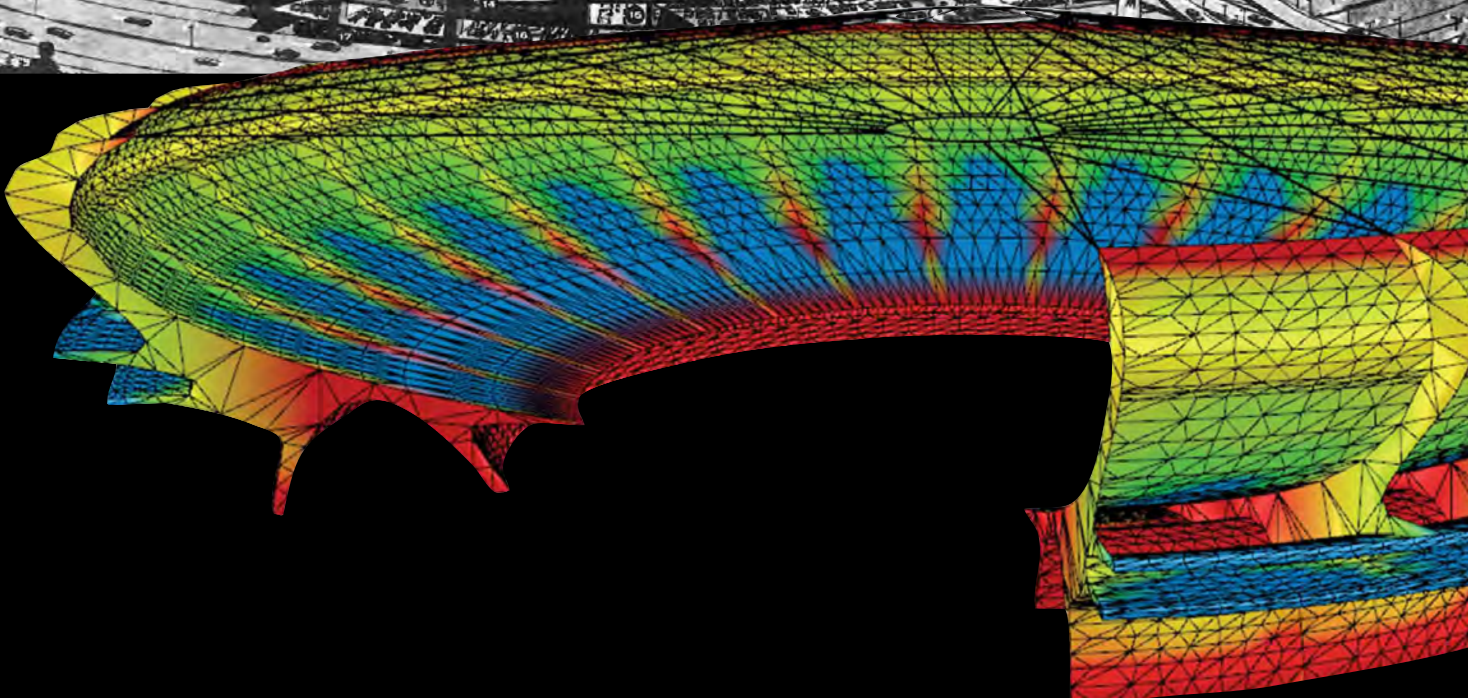
Thornton Tomasetti

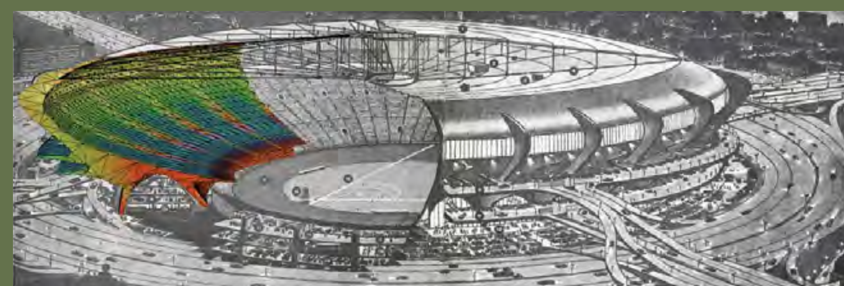
sports





"In terms of creativity … one should take an attitude not that architects and engineers sit on different mounds taking care of their respective problems, but rather that it is one complementary group working together in creating a building."

– Dr. Lev Zetlin



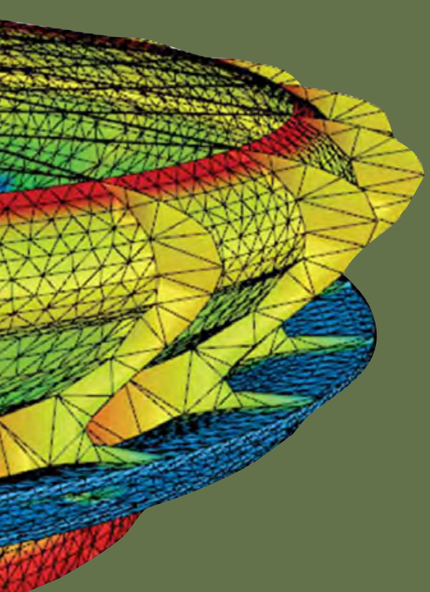
On the cover:

In 1958, Lev Zetlin – founder of the firm that became Thornton Tomasetti – developed a visionary design for "Tomorrow's Arena" that was discussed in *Engineering News Record, Time* and *This Week* magazines and in the *New York Herald Tribune*. With a capacity of 200,000, the innovative concept features a suspension-tensioned translucent roof and multi-deck parking ramps integrated into the underside of a concrete stadium bowl, close to the stands. It minimizes the use of land and material while enhancing the spectator experience.

In 2013, our computational designers used Rhino Grasshopper and Karamba to create an interactive parametric model of the design.

Today, Thornton Tomasetti continues to design sports facilities in the creative spirit of Lev Zetlin. We apply groundbreaking technological tools in innovative ways to help clients and project partners make the future of sports design a reality.

Image Credit: Drawing by Fred Freeman, based on a design by Dr. Lev Zetlin, P.E., and published by This Week magazine.



Thornton Tomasetti

sports

Contents

We Bring the Whole Team

Thornton Tomasetti provides engineering, design, investigation and analysis services to clients worldwide on projects of every size and level of complexity. Our integrated practices are able to address the full life cycle of any structure. Founded in 1956, today Thornton Tomasetti is a 750-person organization of engineers, architects and other professionals collaborating from offices across the United States and in Asia-Pacific, Europe, Latin America and the Middle East.

Mike DeLashmit, Jesse Chrismer and Haider Himairi on the Barclays Center site in 2011 (see p. 30).

Whether it's a new facility or an existing structure, Thornton Tomasetti has the technical team for your project. Our six integrated practices offer expertise and innovative techniques to meet a broad spectrum of sports facility needs.

Building Structure We collaborate with architects, owners and builders to design elegant solutions that meet the demands of challenging projects of all sizes and types – new structures, renovations and conversions. We focus on achieving the optimal balance among multiple objectives: form, function, schedule, sustainability, constructability and budget.

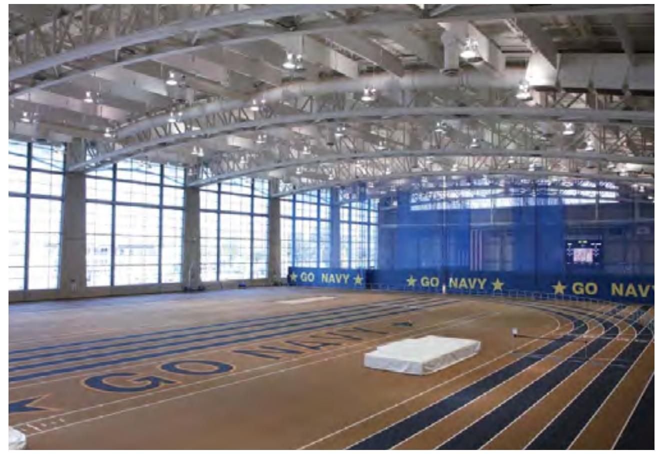
Building Skin We apply our expertise in systems and materials to integrate building skin and structural designs in new buildings, renovations and recladding projects. We provide façade consulting and engineering services to architects, building owners and developers; perform a suite of specialty analyses to meet complex design challenges, improve constructability, maximize energy efficiency and increase security; and offer a range of construction support consulting services to assist contractors during bidding, negotiation, value engineering, post-contract review and site supervision.

Building Performance We assist property owners, managers and other stakeholders with technical support for existing structures through our renewal and forensics services. Our multidisciplinary professionals – structural engineers, architects, and MEP engineers – specify maintenance regimens and assist owners with upgrades, repairs, expansions, adaptive reuses, and historic preservation. We also evaluate losses in strength, functionality and value; perform materials testing and reliability and risk analyses; develop repair solutions; and provide expert opinion and litigation support.

Property Loss Consulting We assist insurance companies, their representative attorneys and executive general adjusters in evaluating the scope and nature of losses related to natural and man-made events. We offer scope of damage determination; covered-loss assessment; cause and origin investigation; expert witness testimony; green claims consulting; and multihazard risk assessment.

Construction Support Services Integrating design and construction teams through the use of technology helps projects move smoothly from concept through to completion. We develop project delivery strategies customized to each client's priorities. Our advanced project delivery services coordinate complete structures, using a single model to create design drawings and construction deliverables, from fabrication-ready models to shop drawings and sequencing plans. We provide erection and stability engineering, lift design, fixture design and equipment and logistics planning, as well as on-site and off-site field engineering support.

Building Sustainability We collaborate in the design, construction and operation of sustainable buildings to provide innovative solutions that balance economic, social and environmental factors. Our experienced team offers sustainable design strategies, energy modeling and building physics, green building certification consulting, sustainability analysis and upgrades for existing structures, and education and training.



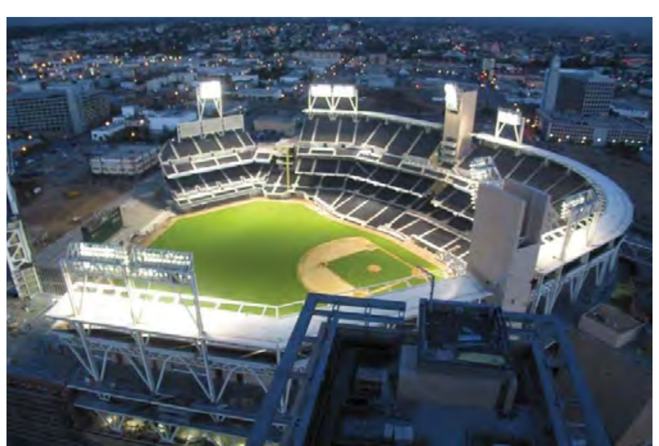


Photo credits, second row left: PSC and SmithGroup; second row right: Ed Massery; third row left: Brown + Kubican

Unmatched Experience

With hundreds of sports projects in our portfolio, our professional staff has the experience and expertise to tackle any project, anywhere in the world. Planning; new design and construction support; sustainability consulting; peer review and value engineering; assessment and investigation; repairs; renovation; expansion; and deconstruction – we've done it all. We've worked on facilities for baseball, football, basketball, hockey, soccer, softball, cricket and tennis, as well as track and field, aquatics and equestrian sports. We've worked with professional teams and clubs, colleges and universities and public-sector clients – national, regional, state and local governments and institutions. And we've collaborated with the world's premier architects and design teams, building strong relationships that enhance our ability to deliver great projects.

Through this experience, we have gained a holistic understanding of sports facilities, of the technical requirements for their design and construction, and their functional mandates – the way our design drives how they work to meet the needs of owners, operators, players, media and fans. But we also appreciate the critical role architectural aesthetics play in the success of sports projects. These projects frequently serve as anchors for urban renewal or development of new neighborhoods. They are often expected to set the style or tone for their surroundings or reflect aspects of the history or culture of their location. On many projects, the roof, canopy or building skin becomes the iconic feature. Our integrated practices and services can analyze, design and coordinate them all. We've learned that close collaboration among all disciplines is the key to successfully balancing all these elements.

This approach to design means we don't limit our focus to just our scope of work. We look beyond the obvious and explore alternatives, searching for the unique approach best suited to each project. We consider the ways each discipline's work will intersect with our own, and we look for innovative ways to integrate them all for the overall benefit of the project and its stakeholders.

Clockwise from top left:

Philips Arena, Atlanta, Georgia

Wesley Brown Fieldhouse, Annapolis, Maryland

Prudential Center, Newark, New Jersey

CONSOL Energy Center, Pittsburgh, Pennsylvania

American Airlines Arena, Miami, Florida

Petco Park, San Diego, California

Kentucky Horse Park, Lexington, Kentucky

Ford Field, Detroit, Michigan

BUILDING LIFE CYCLE

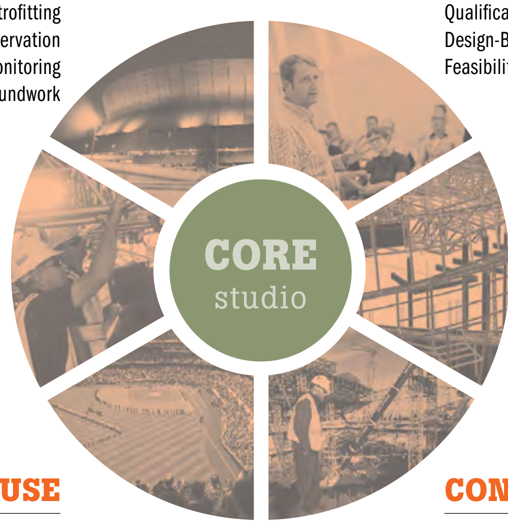
Our unique suite of practices, services and resources, combined with our experience, has given Thornton Tomasetti an unparalleled ability to help our clients plan, design, build, maintain and renew sports facilities of every kind. We work collaboratively to create and support sports projects at every stage in the building life cycle.

RENEWAL

Design & Construction for Repair, Renovation, Expansion, Adaptive Reuse, Recladding, Upgrade & Retrofitting ▪ LEED EB: O&M Administration ▪ Historic Preservation ▪ Deconstruction Engineering ▪ Field Monitoring ▪ Preparation for Groundwork

GROUNDWORK

Education & Training ▪ Business Development ▪ Qualifications & Proposal ▪ Design Competition ▪ Design-Build Pursuit ▪ Project Award ▪ Master Planning ▪ Feasibility Study ▪ Project Programming



LOSS

Emergency Response ▪ Investigation ▪ Assessment & Documentation ▪ Forensic Information Modeling (FIM) ▪ Litigation Support & Expert Witness

DESIGN

Kick-off ▪ Charrette ▪ Concept Design ▪ Specialty Analysis & Modeling ▪ LEED/BREEAM Administration ▪ Schematic Design ▪ BIM ▪ Design Development ▪ Construction Documents ▪ Connection Design ▪ Detailing ▪ Peer Review ▪ Value Engineering

USE

Energy Measurement & Verification ▪ Tenant Alteration ▪ Due Diligence ▪ Vulnerability & Risk Assessment ▪ Condition & Performance Evaluation ▪ Sustainability Audit

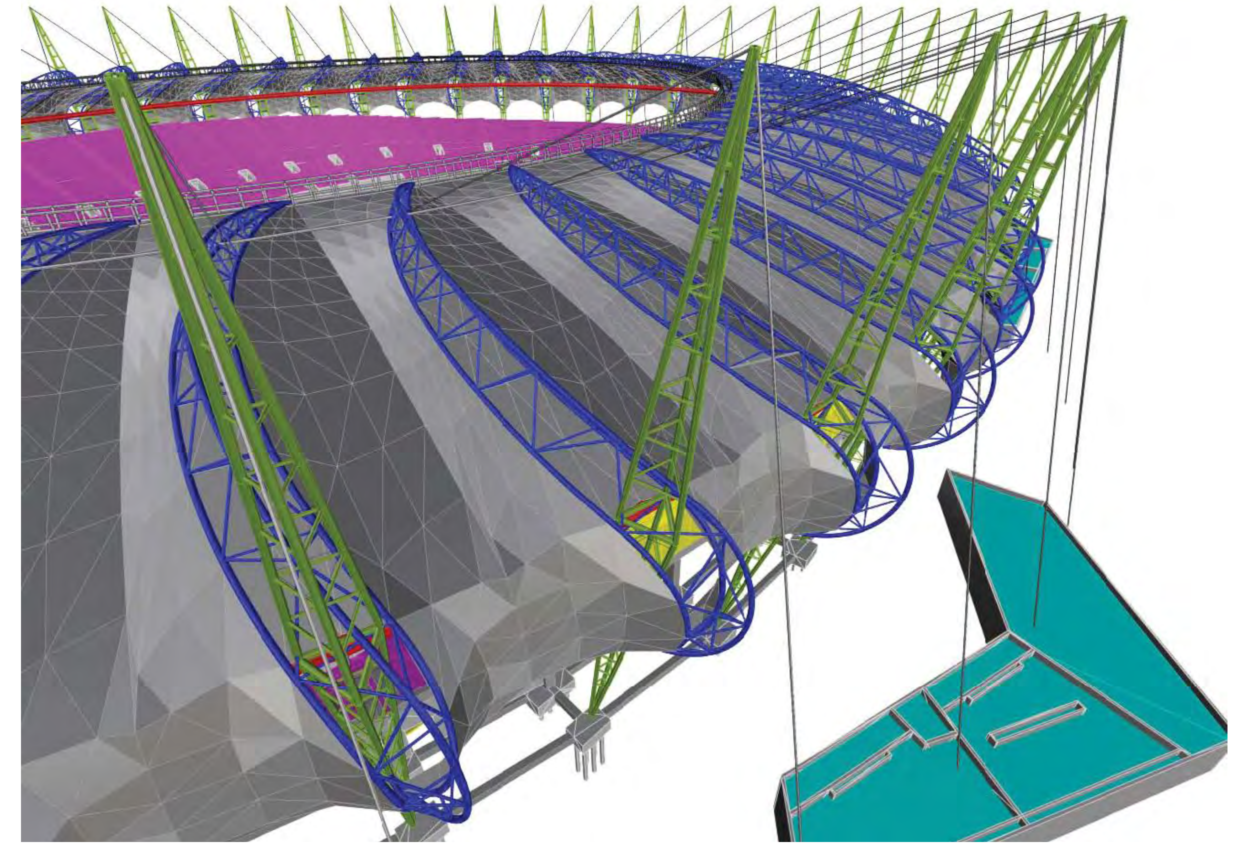
CONSTRUCTION

Bidding ▪ Contractor Sustainability Workshop ▪ Fabrication ▪ Erection & Stability Engineering ▪ Groundbreaking ▪ Construction Administration ▪ Field Inspection ▪ Topping Out ▪ Interior Fit-Out ▪ Commissioning ▪ Opening

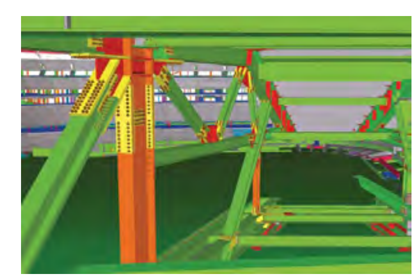
CORE studio

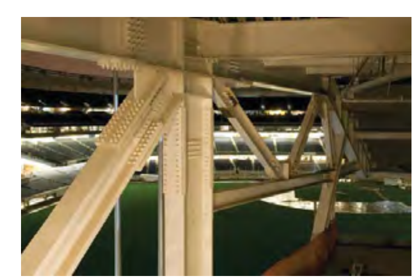
Central to all of our services is the CORE studio, our engine for innovation. A borderless team of multidisciplinary professionals, CORE provides technology-focused expertise to each of our practices and to clients and industry partners. CORE enhances collaboration and responsiveness through a range of creative initiatives, including research and development, computational modeling and design services, and software and app development.

Revolutionizing Design Through Technology



We worked side by side with 360 Architects during the design competition for the Al Menaa Soccer Stadium in Basrah, Iraq. The team used Rhino Grasshopper to quickly generate, analyze and document a distinctive, constructable geometry for the roof in less than a week.





Chris Linder

Tekla model and built structure at Yankee Stadium, Bronx, N.Y. (see p. 38).

Sports projects benefit enormously from the use of interoperable computational modeling. They are complex facilities, with structure and connections expressed as part of their aesthetic intent, and often include special structures, such as geometrically complex canopies or long-span tensile roofs. At Thornton Tomasetti, we develop and implement sophisticated methods to conceptualize, model and deliver our designs to benefit owners, designers and construction teams. Our CORE studio provides the technology toolkit we use to integrate the expertise of each of our practices into the delivery of all our projects.

BIM AND BEYOND

We have used building information modeling (BIM) to develop and produce our projects for more than 20 years. We have found that the use of even basic 3D BIM tools can enhance the creative process, promote effective collaboration and coordination, and improve visualization and communication during design and construction. Our advanced project delivery services employ more specialized BIM tools to accelerate the construction process by delivering models that are used by contractors to increase accuracy of material take-offs, improve the bidding process and allow early acquisition of long-lead-time materials. Our active adoption of these tools and our collaborative, holistic approach make Thornton Tomasetti ideally suited for design-build, design-assist and integrated project delivery teams. But that's just the beginning: we're also at the forefront of even more advanced methods for digital project design, delivery and fabrication.

INNOVATION AT OUR CORE

Thornton Tomasetti's CORE studio applies expertise in architecture, engineering, façade detailing, computer science, industrial design and fabrication to drive the functionality of commercially available BIM tools to the next level by developing custom tools and interoperability frameworks that streamline design processes. Our computational design specialists focus on the dynamic intersection of design, engineering and modeling techniques. They support all of our practices, allowing each to apply the flexibility and efficiency of a truly integrated BIM environment. While computational design can improve the design and construction process for every project type, its benefits are ideally suited to large facilities with innovative architectural forms that are designed and built on fast-track schedules.

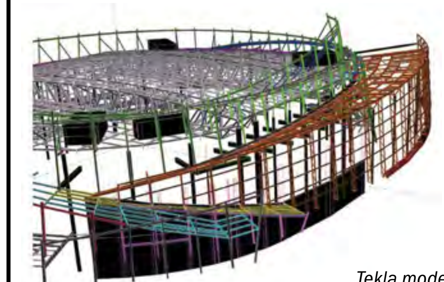
Members of our CORE studio, from left: Anne Waelkens, Elcin Ertugrul, Alfonso Oliva, Nick Mundell and Jonatan Schumacher.

PARAMETRIC AND GENERATIVE OPTIMIZATION

Parametric and generative modeling software facilitates rationalization and control of the complex geometries involved in imaginative architecture, such as twisting forms, diagrids, tensile roofs, and complex curved façades and canopies. These special structures often use unconventional materials and have load paths that require intensive analysis and optimization to design and build efficiently. Our modeling tools allow automated testing of multiple parameter combinations for specific aesthetic, performance and sustainability criteria. The ability to quickly analyze a large number of options enables the efficient identification of optimal combinations that best balance complex, and often competing, project requirements.

PARAMETRIC MODELING

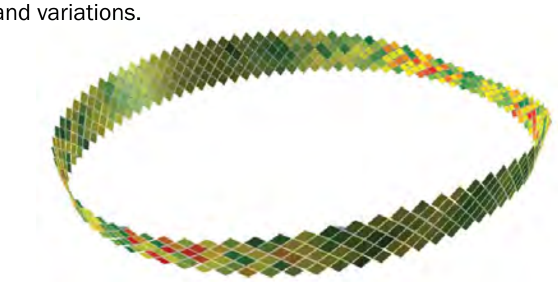
Parametric modeling applies parameters, such as materials, dimensions or performance criteria, to define elements or element categories within a model. Once entered, individual parameters can be changed, one at a time or in combination, to explore and quickly incorporate design changes. These 3D models contain intelligent information and can serve as deliverables, or they can be used to generate 2D drawings. Parametric models improve documentation speed and quality, provide excellent visualization, quickly perform geometry-based analysis tasks, and easily calculate material quantities.



Tekla model of BOK Center, Tulsa, Okla. *(see p. 42).*

GENERATIVE MODELING

Generative modeling uses scripts – instead of direct input – to generate elements, providing greater flexibility in iterating and testing numerous options. A generative model could, for example, test the structural effects of doubling the number of columns in a space by changing only one number in a script, which is much more efficient than entering the additional columns into a parametric model. These tools allow architects, engineers and other project stakeholders to work together to quickly evaluate any number of concepts and variations.

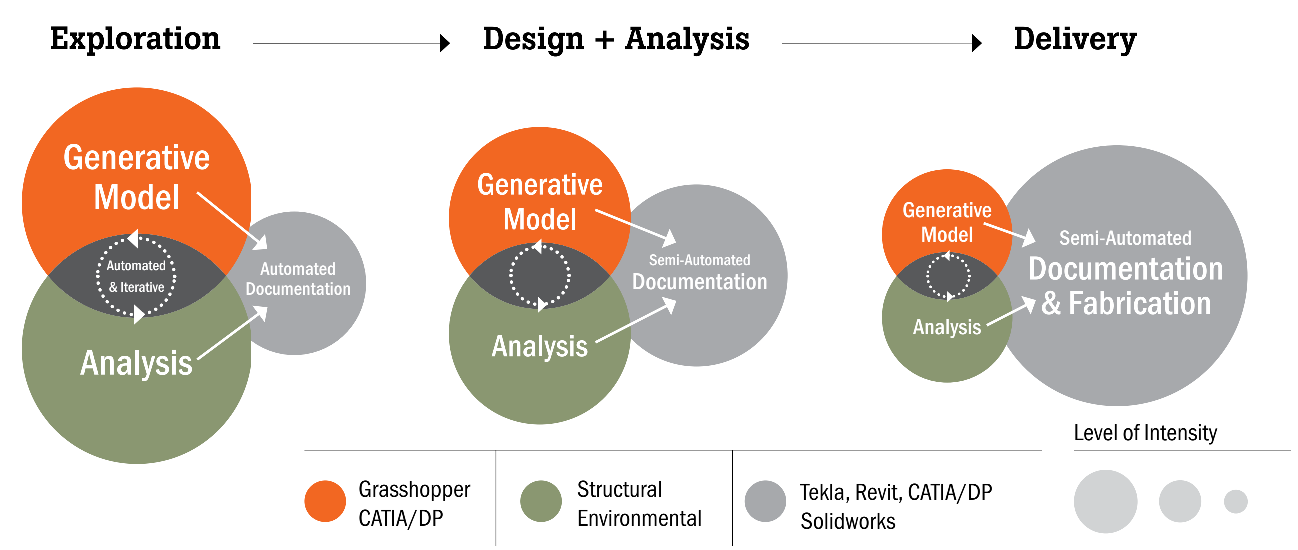


Façade panel optimization model for Hazza Bin Zayed Stadium, Al Ain, U.A.E. *(see p. 32).*

CREATING INTEROPERABILITY

Because no single platform can serve all purposes, we use a variety of software tools, as do our clients and other project team members. But the many gaps in interoperability between platforms have hindered the exchange of information between applications and disciplines. To solve these problems, we use plug-ins and translators to enable a seamless flow of project data from one application to another. When such translators don't exist, our CORE studio can develop them.

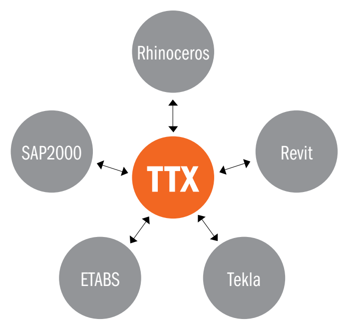
Overcoming interoperability barriers allows us to move intelligent project data back and forth between architectural surface models, generative models, analysis programs, parametric design and documentation tools, and project review programs that combine models from all disciplines for coordination and clash detection.

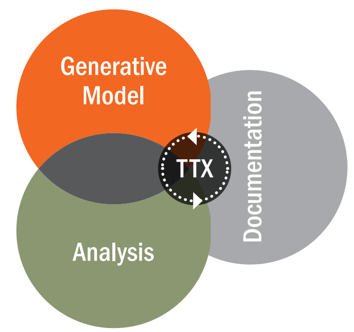


Real interoperability allows the integration of modeling, analysis and documentation platforms, which in turn offers greater freedom in exploring creative design options, increased accuracy and speed in design, and opportunities for automation in documentation and fabrication. The use of many of these tools simultaneously during analysis, design and construction is fundamental to our computational design process.

TTX INTEROPERABILITY PLATFORM

In 2013, our CORE studio launched TTX, a revolutionary interoperability platform for the translation of data across modeling and analysis applications. TTX is a central database that can “talk” directly to other programs, enabling real-time updates of information. TTX allows project team members to focus on their respective specialties in the platform of their choice – and tracks each change by date, time and user. Changes automatically update to all applications, without the need to re-translate the entire model.



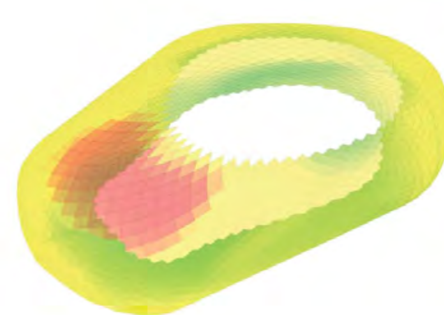


COMPUTATIONAL DESIGN IN THE REAL WORLD

Computational design does not replace the conventional design process, nor does it eliminate the need for smart, highly skilled designers. Instead, computational design gives experienced project teams powerful tools to efficiently execute complex, geometry-driven designs.

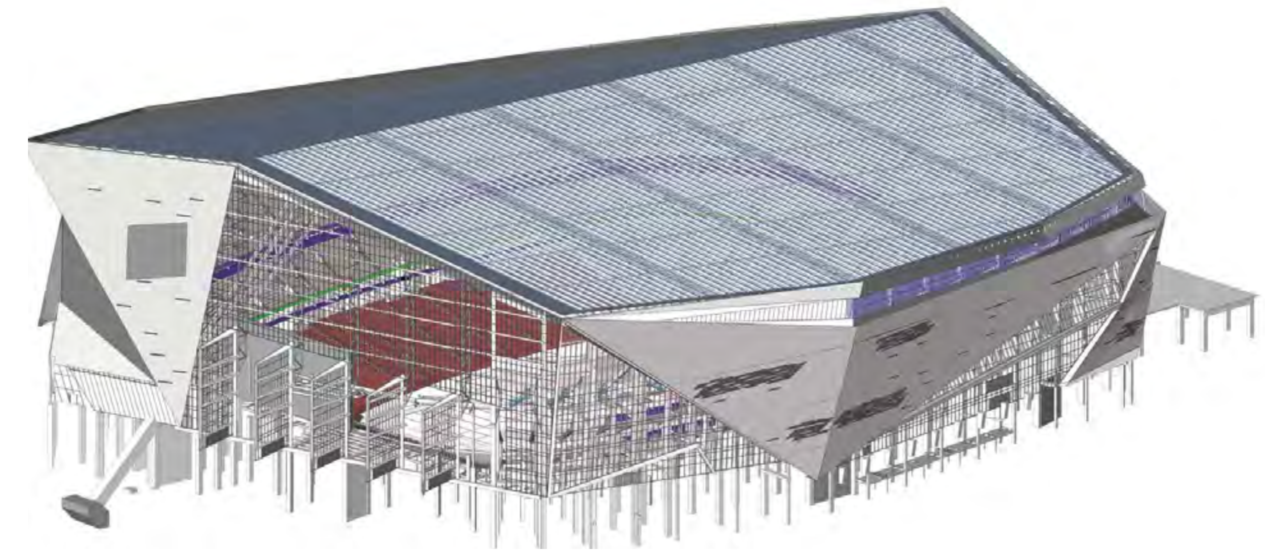
Integrated automation and optimization techniques in multidisciplinary design environments allow more rigorous early exploration, evaluation and analysis. Extracting more information from a wider range of options allows a project team to explore more innovative ideas and develop better design solutions. We use energy modeling, daylight simulations, building envelope thermal analysis and embodied carbon calculations to inform considerations of sustainability, efficiency and operational costs. When design decisions can be tested and confirmed early, more time is available for optimization, coordination, detailing and documentation. Delivering models for use in fabrication and construction offers additional opportunities for schedule and cost savings. These benefits add up to increased value for all project stakeholders.

Courtesy Manica Architecture



We used Rhino Grasshopper to rationalize the shape and size of polycarbonate panels for the Moscow VTB Arena’s curved polycarbonate façade. An architectural rendering (left) and Grasshopper visualized results (right) show panel size ranges, with red denoting the largest and green the smallest.

Thornton Tomasetti is providing structural engineering, building skin and kinetic mechanization consulting for the Minnesota Multipurpose Stadium. The 1.6 million square-foot facility will seat up to 72,000 fans on seven levels and can accommodate NFL football, MLS soccer, NCAA baseball and basketball, concerts, conventions and more.



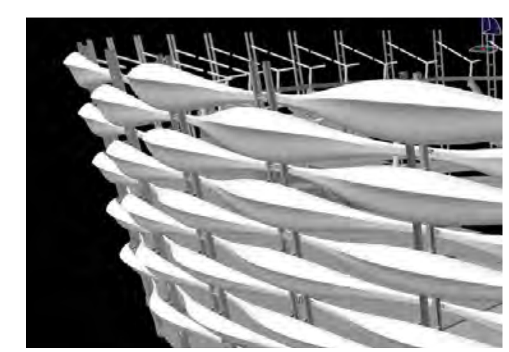
HKS, Inc. and Thornton Tomasetti

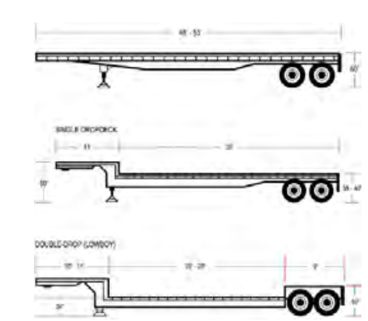
WE DELIVER THE MODEL

Thornton Tomasetti is an industry leader in the digital delivery of projects. We routinely share our models with owners, architects, contractors and fabricators during design. But we go one step further: often our model is our deliverable, provided with full right of reliance. We have delivered models to architects, contractors, fabricators and owners. Sharing and delivering models significantly improves the clarity and coordination of a given design and reduces ambiguity and questions in the field. The answer is right there in the model.

Since paper drawings are still required for code review and approval on most projects, it is critical that models and paper match – a given with our modeling approach. Our interoperability tools translate geometrical data and analysis results directly to documentation programs, such as Revit or Tekla. A change in any component is transferred to all modeling tools and to the drawings. This allows us to make use of superior geometry and analysis tools while also producing models and required drawings according to established industry standards.

Ron Garon (left) and Anjana Kadakia on-site at MetLife Stadium *(see p. 34).*





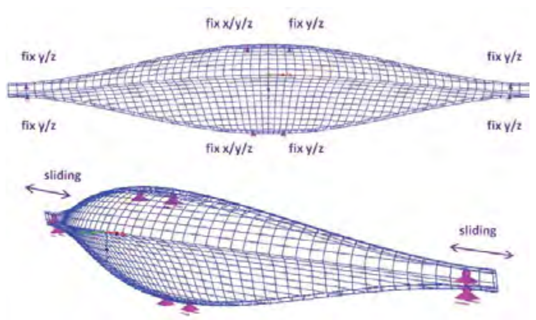
CATIA model of façade panels for the Basrah Sports City main stadium in Iraq. Design parameters included the size of trucks available to transport the panels from the fabrication facility to the site *(see p. 36).*

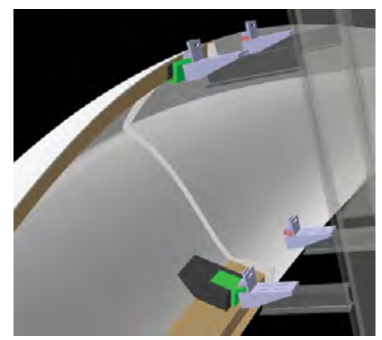
DIGITAL FABRICATION: FROM MODEL TO MATERIAL

But paper isn't always necessary. We can start with a digital sketch, proceed to analysis and design, and move directly to fabrication without a single piece of paper created or exchanged. We deliver models with embedded computer numerical control (CNC) data files that are used to directly fabricate a variety of building elements. Our analysis and design results are digitally transferred to fabricator-friendly model formats. Tekla models, for instance, digitally drive the fabrication of complex structural steel components. Our CATIA models are downloaded directly to the CNC equipment that creates complex molds for Glass Fiber Reinforced Polymer (GFRP) cladding elements.

With direct digital downloads, nothing is lost in translation. On internationally sourced projects, this can quite literally avoid losses due to language barriers that may arise in conventional document delivery processes.

We delivered models that were used to fabricate the Basrah Sports City main stadium façade panel molds and connection brackets *(see p. 36).*





Photos in bottom row courtesy 360 Architecture

A MODEL FOR THE FULL LIFE CYCLE

A coordinated master model will continue to provide benefits long after construction is complete. It can streamline commissioning and generate accurate data for LEED documentation and embodied carbon calculations. As a tool for long-term operational management and planning, the model can be used to monitor energy and water use, track maintenance, and store inspection data. Documentation of any future damage or deterioration can be incorporated into the model, as can information on remediation and repairs. Master models are also very useful in planning and executing renovation and expansion projects.

Ed Lederman

From left: Rob Otani, Tom Poulos and Bruce Gibbons.

CREATIVE COLLABORATION

Advanced technological tools enable dramatic improvements in sports facility design, construction and operation. But they can only deliver their full potential when all contributors actively collaborate and share information throughout the process. We have a proven track record of working closely with team members to design and deliver great projects. Now we're extending our collaborative approach to develop new ways to enhance teamwork and improve the way projects are designed and delivered.

Integrated Support Across the Building Life Cycle

Thornton Tomasetti's experienced, creative professionals collaborate with owners, operators, design teams and builders to develop iconic stadiums and arenas around the world. We constantly challenge ourselves to find new ways to design and deliver sports facilities faster, more efficiently, more sustainably and more cost-effectively than ever before.

RESPONSIVE STRUCTURAL DESIGN: FORM FOLLOWS FUNCTION

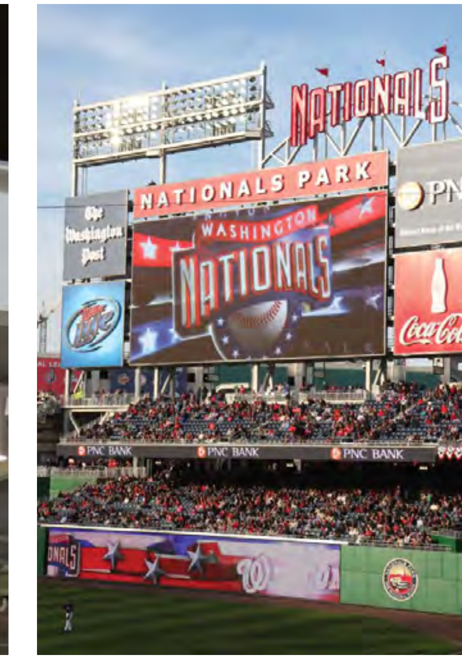
Structure plays a more visible role in the architecture of sports facilities than in almost any other building type. The structural system must support unobstructed views, spacious open concourses, and cantilevered club and suite patronage areas, while also delivering maximum efficiency and economy. The distinctive visual identity of a stadium or arena is often expressed through the exposed structure: the soaring, seemingly weightless shape of a canopy or the different configurations of a retractable roof or movable exterior wall. Our structural engineers seek out innovative and creative structural design solutions that offer an optimal balance for the seemingly incompatible goals of economics, aesthetics and function.

Built in 1960 on a tight Utica, N.Y. site with poor soil conditions, the Utica Memorial Auditorium required an extremely light roof system. The "double-bicycle wheel" cable-suspended roof – the first of its kind – was our design solution. This innovative system gave spectators a column-free interior with unobstructed views and also cost less to build than a conventional roof.

Courtesy Utica College/Jamie Callari

The city of Tulsa, Okla. wanted a distinctive, iconic arena. Tekla's analysis and visualization capabilities helped us deliver a constructable design for the geometrically-complex BOK Center *(see p. 42).*

Gayle Babcock Architectural Imageworks LLC



Nationals Park, Washington, D.C. *(see p. 40).*

SPORTS-SPECIFIC TECHNOLOGY

We bring more to the table than our knowledge of engineering principles. We understand how a variety of sports-specific features interact with structural design: rigging levels, catwalks, speaker clusters, fall protection systems, scoreboard support systems, variable-rise and retractable seating, light standards, wind screens, curtaining systems, snow fences, acoustical treatments and more. Not only have we designed all of these elements in many new facilities, we also provide operational support for such elements in existing venues: rigging reviews for large shows and design modifications that allow existing facilities to support the ever-increasing number and size of scoreboards, ribbon boards, speaker clusters and signage that generate fan excitement and increase revenues. When designing a new facility, we address these operational and revenue-critical features early, so the structure is configured to incorporate them seamlessly, efficiently and economically.

WE LOVE CHALLENGES

We Challenged Standards:
A 600-foot by 400-foot arena must have expansion joints. Why?

We asked this question and, taking an advanced analytic approach, we went on to design facility after facility without these costly joints, which are also well-documented as long-term maintenance headaches.

We Challenged Convention:
It's either steel or concrete. Not anymore!

We asked this question and went on to rigorously evaluate dozens of innovative building systems and structural combinations: concrete transitioning to steel, hollow-core plank concrete, metal deck, post-tensioning, skip-joists, waffle slabs, double-tees, tensile systems, braced and/or rigid frames, shear walls and buttresses – and more. And we have real-life data and recent cost comparisons that allow us, along with the other members of the design team, to quickly compare the functionality and costs of a variety of systems under consideration.

We Challenged the Experts:
Structure must impact architecture. We don't agree!

When our experience confirmed that the costly and intrusive down-turned stems on precast seating beams were not needed for most spans, we persuaded the Precast/Prestressed Concrete Institute to revise its recommendations and eliminate them in most designs.

We Challenged Preconceptions:
A long-span roof in a cold-weather climate will be a heavy structure. Not necessarily!

Working closely with our in-house building skin and sustainability experts, as well as the MEP and micro-climate consultant, our team developed a combination of roof shape and cladding material that essentially cut the design snow load in half, while providing significant energy consumption advantages.

Courtesy Daveynin

Courtesy 360 Architecture

Top left: Pepsi Center, Denver, Colorado

Top right: PNC Park, Pittsburgh, Pennsylvania

Bottom left: Coliseo de Puerto Rico, San Juan, Puerto Rico

Bottom right: Al Najaf Sports Complex, Al Najaf, Iraq

UNIQUE SOLUTIONS FOR EVERY PROJECT

Experience has taught us what works. We've learned that each project has a unique combination of elements and requirements that demand the development of new solutions and innovative designs. We have designed sports facilities in countries around the world, and performed assessment and design for repairs, renovations and expansions of numerous existing structures. We have built a body of knowledge that allows us to look beyond "how we did it on the last one." While we always draw upon our past successes, we deliberately set aside preconceived notions and seek out tailored solutions that best suit the specific needs of each project.

Because the most obvious response to a challenge is often not the best one, we test different ideas to find the right solution for each project. Our computational design and BIM capabilities let us evaluate many options quickly and analyze the system under consideration to maximize efficiency and address specialized needs, such as vibration control for long-span and cantilevered seating areas. We take advantage of the visualization benefits of 3D modeling to work with architects on exposed structural elements and connections. We can, for example, make real-time changes in the model during design meetings to make sure the structure aligns with aesthetic priorities, while verifying that engineering criteria are still satisfied.

DIGGING DEEPER TO OPTIMIZE FOUNDATION DESIGN

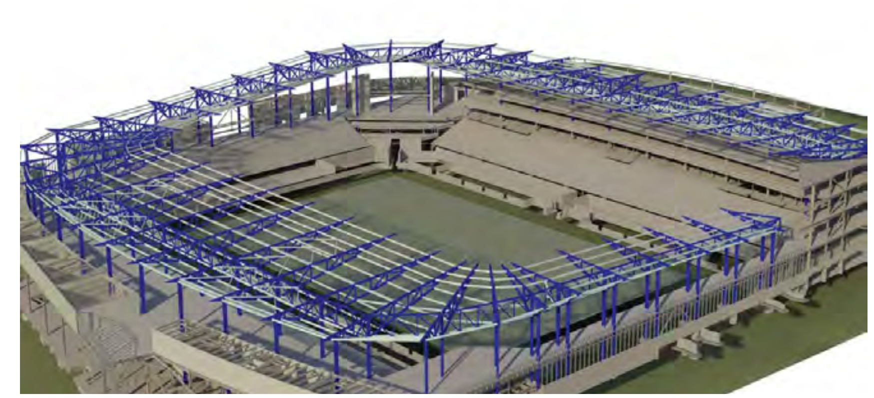
An extensive knowledge base in sports design informs our approach to foundations; we've learned that geotechnical recommendations aren't always set in stone. Thornton Tomasetti has helped avoid unnecessary costs and many months of construction time by considering alternatives to the deep foundation systems that conventional wisdom often deems necessary. We work proactively with geotechnical engineers to analyze the interaction between a site's soil conditions, foundations and structural system options. We often find we can configure the structure to accommodate and overcome potential differential settlement issues, allowing the use of more economical shallow foundations.

Sports facilities often have "donut-shaped" floor plans that don't allow for conventional methods of resisting the large lateral soil loads on an event level built 40 feet or more below grade. We routinely work with geotechnical engineers and foundation contractors to develop site-specific measures to minimize the cost and schedule impacts of complex below-grade construction. On many projects, combinations of top-down construction, one-sided-form or shotcrete walls, tiebacks, controlled low-strength backfill materials, and mechanically stabilized walls and void spaces (to economically remove much of the soil loading from the structure) are used to resolve these design challenges while saving on costs and construction schedules.

DEFINING CANOPIES AND LONG-SPAN ROOFS

The defining architectural element of many sports facilities is a long-span roof or cantilevered canopy. These large, highly articulated structures must satisfy an array of aesthetic and functional requirements. They are expected to appear weightless while supporting such heavy operational equipment as scoreboards, video and speaker clusters, rigging and catwalks. Increasingly, they also support critical components of a venue's sustainability program: solar panels, green roofs and translucent cladding that can decrease the need for artificial lighting or promote radiant heat gain to reduce energy use for heating in cooler climates. Translucent cladding – glass, polycarbonate, ETFE or other fabric – leaves the underlying structure exposed to view from both inside and outside, requiring extra care in design and detailing to align with aesthetic priorities.

To design canopy and roof structures that meet all of these aesthetic and functional requirements, our structural engineers draw upon years of design experience, construction knowledge and understanding of architectural, mechanical and other requirements. We collaborate with all project stakeholders to ensure that the vision and needs of all are addressed. We apply the analytical power of our computational design tools. And we confer with in-house building skin, sustainability and construction support specialists, who provide valuable multidisciplinary perspectives. This integrated approach maximizes our ability to produce designs that deliver elegant, economical, sustainable and constructable structures.



Sporting Park, Kansas City, Kansas (see p. 35).

CONSTRUCTABLE DESIGN

Our overall design approach – working collaboratively with all team members and using computational design and BIM for design and delivery – makes constructability a priority throughout our design process. On large, complex projects like sports facilities, experience has shown that thinking about means and methods from day one prevents problems in the field.

Our experience providing integrated services across our practices reinforces this focus. When we design a building's structure and its skin, for example, questions about how the two systems will come together during construction get discussed early and often. This habit is hard to break, so our designers routinely seek advice and input from all our practices, even when our contract doesn't include that work.

Mark Tamaro of Thornton Tomasetti (left) and Mike Davis of Bosworth Steel Erectors, Inc. on the site of Nationals Park in 2007 (see p. 40).

CLEAR COMMUNICATION LEADS TO CREATIVE SOLUTIONS

Courtesy HKS, Inc.

When the Minnesota Vikings said they wanted a retractable roof, we asked why. They wanted to provide a view corridor to the Minneapolis skyline and to have the feel of being outdoors while providing protection from the harsh extremes of the local climate.

We collaborated with the architect to develop a dual approach: a sloping 240,000-square-foot ETFE roof lets in light and sheds snow, while a series of operable panels in a glass end-wall pivot to create an opening that frames the cityscape. This combination fulfilled the client's goals with systems that cost less to construct and maintain than a conventional retractable roof.

KINETIC STRUCTURES

Kinetic structural and architectural elements are increasingly important components of the modern-day multipurpose sports facility. Retractable roofs, operable walls and doors, and convertible seating create functional, flexible spaces that are scalable, sellable and enhance the overall user experience.

Our understanding of kinetic structures is informed by lessons learned over 20 years of investigating underperforming systems, assessing system failures and designing repairs and enhancements for existing retractable roof facilities. Performance issues have resulted from poorly executed interfaces between the structure and mechanization systems. This experience has taught us what works – and what doesn't. Our understanding of the unique demands that structural and mechanical components impose upon each other, coupled with an appreciation of maintenance requirements, has made Thornton Tomasetti a recognized expert in this field.

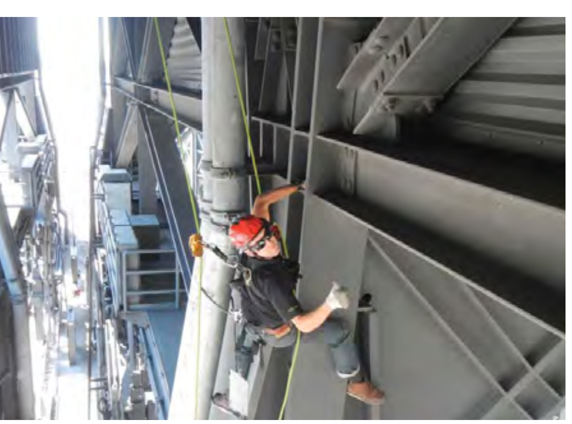
The successful integration of kinetic features into a sports facility requires structural and mechanization systems that complement each other. We work with owners, architects and facility managers to clearly articulate the underlying functional requirements and their effects on aesthetic goals. We apply the combined expertise of our structural engineers, building skin designers, sustainability experts and construction support specialists to develop a holistic approach that balances aesthetics, efficiency, sustainability, constructability and cost.

We look beyond the conventional answers – considering the full range of systems, design consultants and procurement options – to help the project team find integrated and holistic solutions. Our goal is to provide the best value for each individual project.

Left: Chuck Van Winckle gets a close-up look at the retractable roof at Seattle's Safeco Field, where we performed structural analysis for an investigation into wheel bearing failures in the roof drive system and then helped develop a repair strategy. We now provide annual inspection services at the stadium, focusing on the roof and its supporting structure.

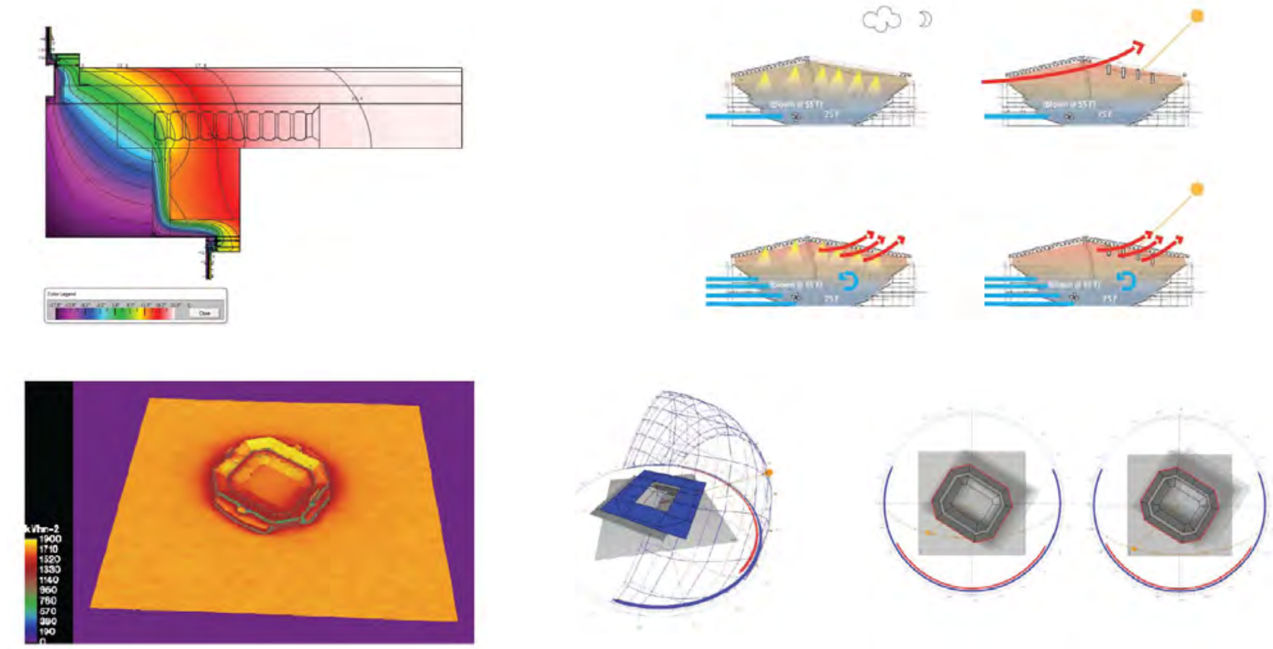
Middle: We investigated the failure of Reliant Stadium's steel and fabric retractable roof after Hurricane Ike struck Houston, Texas (see p. 50).

Right: We designed a program to replace failing pivot bearings for five movable roof panels at Miller Park in Milwaukee, Wis. (see p. 44).



Center, courtesy Matt Steiner; near left, courtesy Hardesty & Hanover

We provide sustainability analysis and modeling services using a variety of tools and software platforms. Clockwise from top left: a thermal analysis in THERM; a natural ventilation study; a sun/shade study using Grasshopper's Ladybug plug-in; a multi-platform photovoltaic analysis; and a solar radiation model in DIVA.



MULTIDISCIPLINARY DESIGN MAXIMIZES SUSTAINABILITY

The physical form of a stadium or an arena has a large effect on its environmental impact. Our combined expertise in building sustainability, building skin and building structure promotes a holistic understanding of how the many elements of a sports facility work together and affect one another.

This knowledge informs the work of each practice when working separately, and gives us a unique ability to offer comprehensive, integrated sustainable design when the three practices are selected to work on a project together.

SUSTAINABILITY: BUILT IN FROM THE BEGINNING

As large structures that accommodate big crowds, stadiums and arenas have a significant environmental impact. They are also very much in the public eye, so greening a sports facility not only reduces its environmental footprint and costs, it also boosts the public image of the team and owner. Our building sustainability team has the expertise – in sustainable strategies, energy analysis and building physics, green building certification, existing building services, and sustainability training – to significantly reduce the impact of these structures at all points along their life cycle.

Sustainability programming is an innovative service that offers owners and design teams advice on how to integrate sustainable concepts into design from the very beginning. We apply a clear understanding of the interconnectedness of multiple factors – including location, orientation, configuration and building systems – and the ways in which they affect one another to determine the most sustainable design choices. Incorporating these elements in the earliest stage of the project achieves the greatest benefit at the lowest cost, since green concepts are then intrinsic to every aspect of the design throughout the process. Data from climate analysis, energy modeling, thermal, daylight and solar radiation studies and carbon optimization tools help guide the design team's selection of architectural form, massing, mechanical equipment, structural system and materials to maximize a facility's potential for sustainability. This approach has a fundamental effect on what structure gets designed – and built.

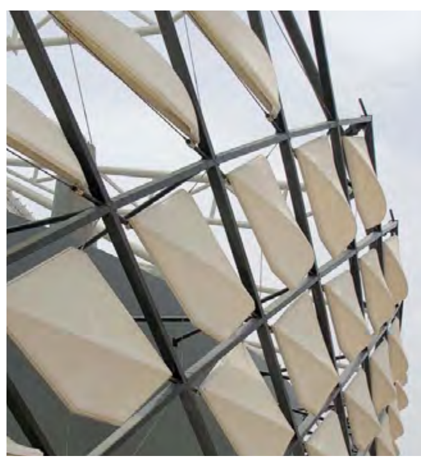
We offer a suite of sustainability services – administration for building certification; thermal, energy and daylight analysis and modeling; and green MEP consulting, which helps select and develop strategies for optimized building systems – to assist in implementing and verifying the holistic strategies developed during the early design phases. Or we can provide these services separately to fill any design team's sustainability needs. Our green teams are accustomed to applying whole-systems thinking to maximize the sustainability of large, complex projects. The benefits? Reductions in materials, runoff and pollution; reduced energy use and operating costs; and a comfortable and daylit stadium space that invites return visits.

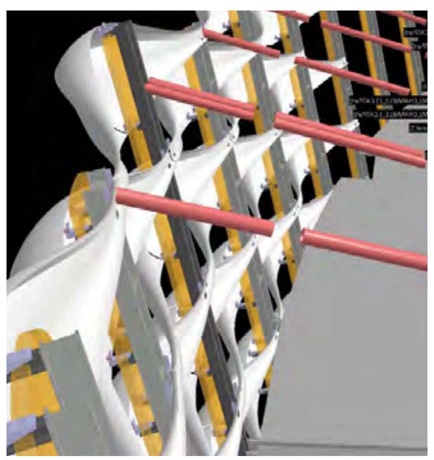
BUILDING SKIN: INNOVATIVE, INTEGRATED EXTERIORS

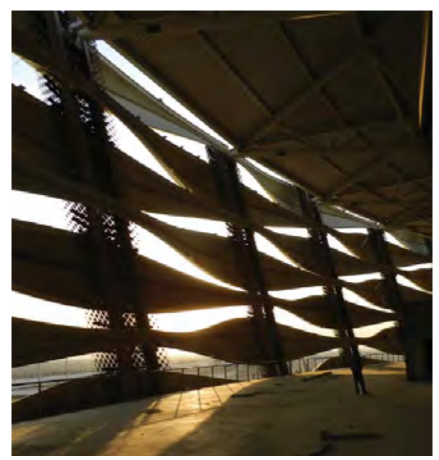
Our building skin specialists perform façade consulting, design, modeling, engineering and construction support to provide distinctive elements for sports facilities around the world. The building skin is where architectural form, structure, building physics and sustainability meet. Successful building skins are holistic systems that integrate these elements into creative design solutions.

Enclosure systems are an important factor in a building's performance. Materials, form and technical detailing are intrinsic to daylight, views, temperature, ventilation and humidity, factors that have a large impact on occupant experience and operational and maintenance costs. To evaluate the potential performance of options under consideration, we study local climate conditions, perform energy analyses, daylighting and shading studies, heat flow analyses, and computational fluid dynamics to help design teams and owners achieve energy-efficient and healthy buildings.

We use generative and parametric modeling to design façades that meet the requirements of form and function. As architectural and structural concepts evolve, our computational design capabilities allow simultaneous analysis of how changes affect the building skin system. Building enclosures can involve concentrated forces and large deflections. Our understanding of the interplay between façades and structures informs our designs to provide integrated, coordinated results.



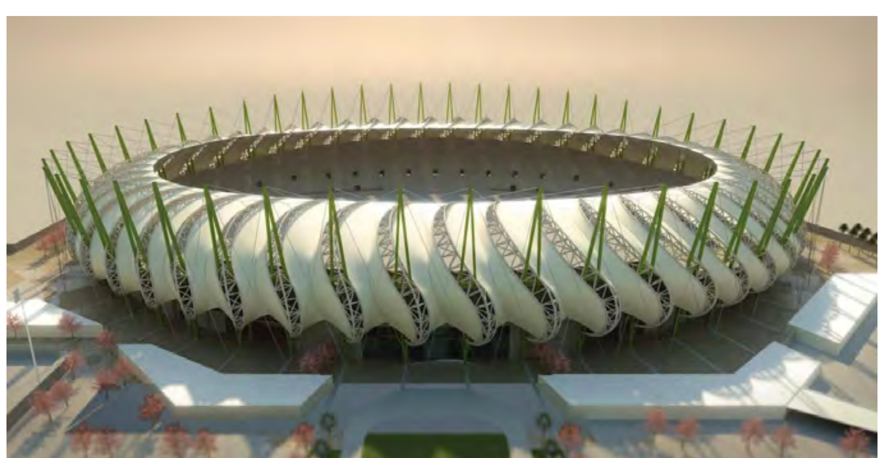




360 Architecture

Above left: The angle of Hazza Bin Zayed Stadium's façade panels adjust to meet requirements for shading, airflow and aesthetics (see p. 32).

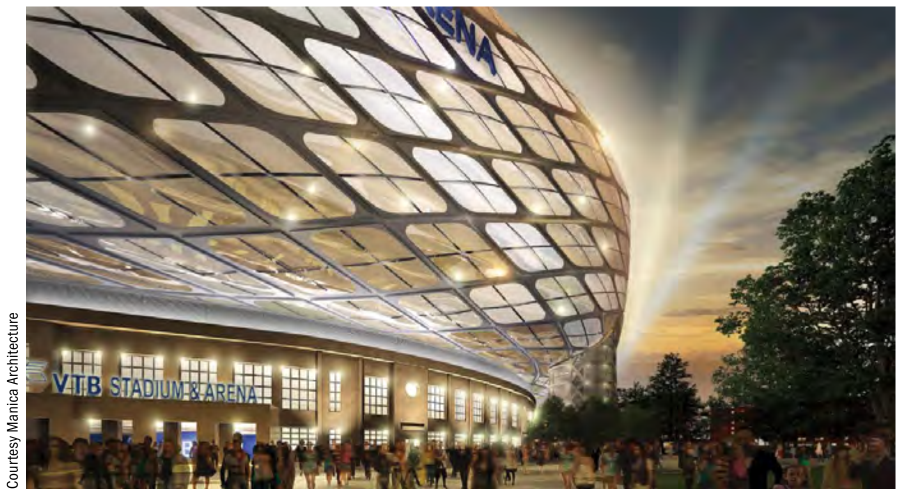
Above middle and right: Basrah Sports City, Basrah, Iraq (see p. 36).



Al Menaa Soccer Stadium, Basrah, Iraq.

360 Architecture

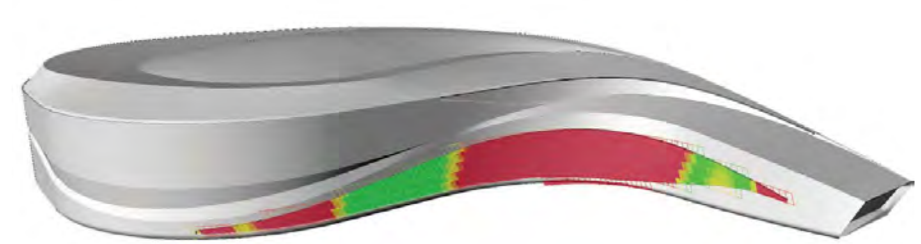
Our building skin team is experienced in the design and detailing of enclosure systems and materials that are increasingly in demand for sports facilities. We've worked with ETFE and fabric and tensioned membranes, polycarbonate, FRP and GFRP, metal, cable nets and tensegrity systems, among others. We use advanced geometry analysis to rationalize and optimize the application of these systems for projects with complex or irregular forms, and to establish efficient, constructable panelization schemes. We also supply our models directly to fabricators for use in their CNC machines.



Courtesy Manica Architecture

The Moscow VTB Arena's curving façade design uses polycarbonate panels in a variety of shapes and sizes. To increase fabrication efficiency, we designed a system in which all of the varied panel conditions require only three extrusions.

Because our building skin teams collaborate constantly with our structural engineers and sustainability staff, they have unique insight into the design and engineering of beautiful, functional, sustainable and constructable façades. When our practices work together on a single project, the result is a comprehensive, integrated design that is efficient and highly coordinated from the earliest stages.



Generative modeling tools were used for surface rationalization and warpage analysis for the design of curvilinear glass façade elements for a new arena in Edmonton, Canada.

SUSTAINABLE BUILDING SKIN SOLUTIONS

The Minnesota Sports Facilities Authority was concerned that an ETFE roof could increase energy use for heating and cooling at the Minnesota Multipurpose Stadium. Our building skin designers and sustainability experts teamed up to model and analyze the proposed system's performance under local climate conditions.

We found that an ETFE enclosure offers energy savings compared to more conventional systems. The heat gain from sunlight during the colder months of the year – which overlap with the NFL season – greatly offset the cooling required for limited summer use.

The ETFE skin not only supports aesthetic goals and allows for a super-efficient roof structure, it will also reduce on energy use – and costs – throughout the stadium's operational life.

Courtesy HKS, Inc.

CONSTRUCTION SUPPORT FOR ADVANCED PROJECT DELIVERY

Barry Staver Photography, LLC

Team members [from left: Robert Kinsella and Michael Halajian of PCL Construction; Matt Meisenbach, LPR Construction; Jesse Chrismer (seated) and Steve Hofmeister of Thornton Tomasetti] work to improve constructability during a design-assist coordination meeting for the Edmonton Arena project in June 2013.

Our Construction Support Services practice extends our firm-wide focus on constructability to new frontiers. With backgrounds in structural design, construction management, procurement and construction engineering, our construction support specialists have the expertise to fully integrate design and construction teams to effectively and efficiently move a project from concept to completion. We perform these services on Thornton Tomasetti-designed structures, and assist in the delivery of projects designed by others.

We coordinate the complete structure, using models to create design drawings and deliverables that contractors and fabricators can use in downstream production of shop drawings and building skin components. Our connection design services better define the scope of work required for structural steel contractors and erectors. Detailing, modeling and shop drawing production services – for steel and concrete – help the owner and construction manager achieve the most responsible and reliable pricing and on-schedule delivery.

Incorporating these advanced project delivery services during the design phase gives the construction team more complete and detailed information earlier than conventional approaches. The results include an improved project schedule and greater cost certainty.

We also offer construction engineering services such as erection engineering, stability engineering, lift design, fixture design, and equipment and logistics planning. We evaluate project needs and constraints to find the optimal means and sequence of construction to safely and efficiently erect a structure. And we provide both on-site and off-site field engineering support.

BENEFITS OF ADVANCED PROJECT DELIVERY

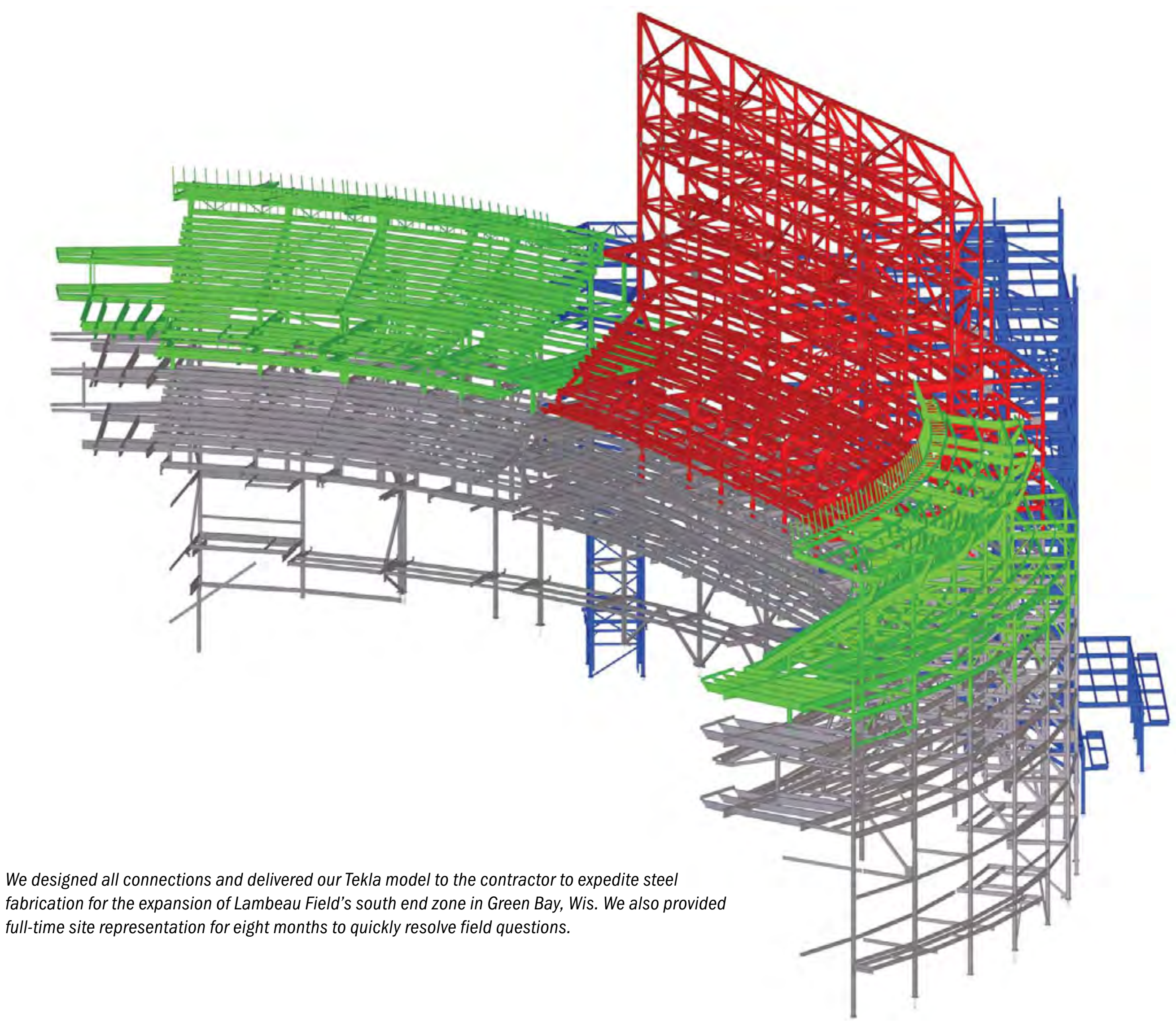
Breaking down the barriers between engineers, fabricators and erectors leads to cost-effective innovation:

Integrating the erection sequence into our design analysis can minimize, and often eliminate, the need for shoring.

Self-supporting roofs, long-span elements and cantilevers can allow their construction to overlap with superstructure construction, keeping shoring to a minimum and, in many cases, taking those elements off the critical path.

Creative methods of steel delivery – providing advanced detailing specifications within a building information model, for instance – can substantially reduce a contractor's detailing schedule.

Early involvement of the fabricator in the process allows development of the most cost-effective solution for each specific job and locale.



We designed all connections and delivered our Tekla model to the contractor to expedite steel fabrication for the expansion of Lambeau Field's south end zone in Green Bay, Wis. We also provided full-time site representation for eight months to quickly resolve field questions.

Barclays Center, Brooklyn, N.Y. (see p. 30).

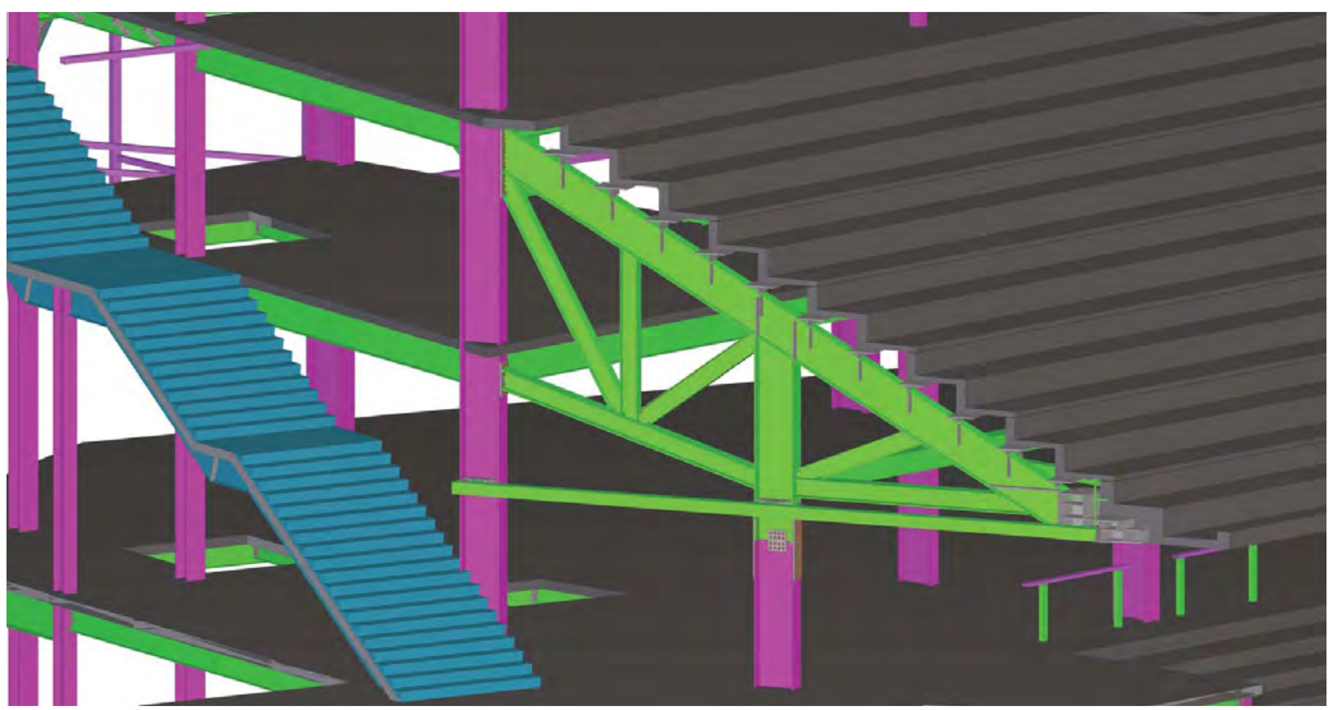
STEEL DETAILING AND CONNECTION DESIGN MODELS

We offer steel detailing and connection design services, developing 3D Tekla Structures models to three different levels of detail to meet the varied needs and resources of each project. Our Tekla models are useable deliverables that eliminate the contractor's need to create or re-create the model, a tremendous improvement over the traditional process.

Because the model is prepared during design, it can be made available just days after the design is issued. And it requires only a limited formal shop drawing review process, because it will have been thoroughly reviewed by the designers during preparation. This streamlined approach to shop drawing production and approval can significantly shorten project schedules.

CONCRETE MODELING AND DETAILING

We also create 3D models of precast and cast-in-place concrete that include all reinforcement and embeds used to connect different elements. We can deliver these models to the contractor to expedite their shop drawing preparation, or we can create and deliver shop drawings. The model can also be used for quantity take-offs, tracking, scheduling and coordination. In addition, the steel fabricator is able to use the precast model for coordination with items such as bearing plate locations and connections.



Combined structural steel and precast concrete model for Tulane University's Hertz Center in New Orleans, La., a practice facility that includes two full-size indoor basketball courts. We provided structural design and complete detailing for the project.

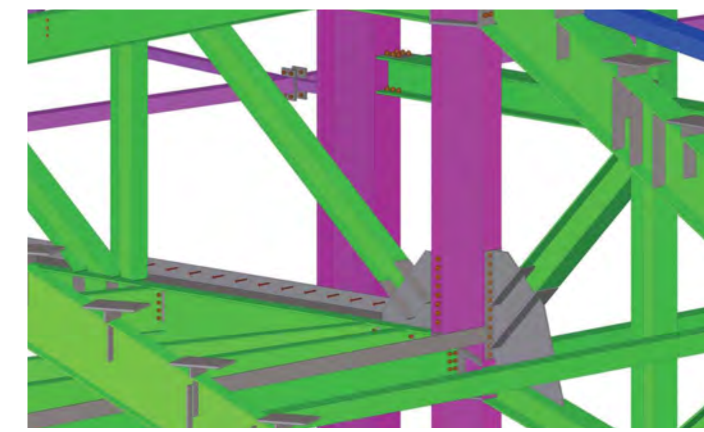
STEEL MODELING: THREE LEVELS OF DETAIL

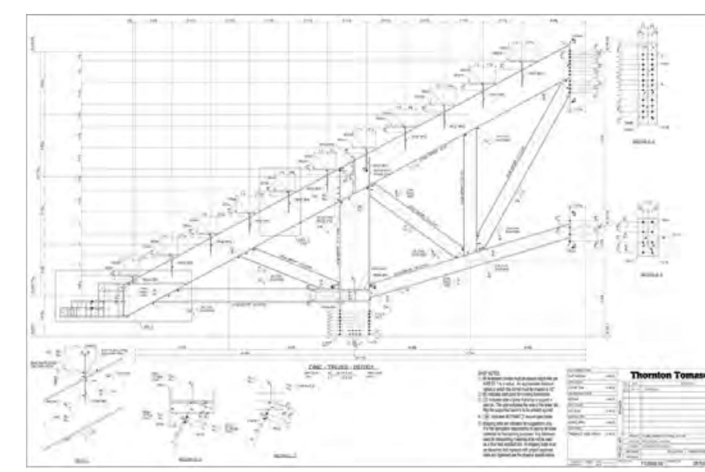
We offer steel modeling deliverables in three phases, or levels of detail, the most advanced of which goes well beyond current *BIMForum* Level of Development (LOD) specifications to provide fabrication-ready models. Our levels correspond to common construction phase terminology, which helps to clearly communicate the types of information our clients can expect in each phase.

Phase I: Material Model
A phase I model includes all main structural steel framing members with their correct size, orientation and material properties. It is used by contractors to quickly progress their Advanced Bill of Materials for the purchase of structural materials, reducing the time from award to material delivery. A phase I model also reduces quantity take-off time during bidding, while enabling more accurate labor estimates through improved visualization.

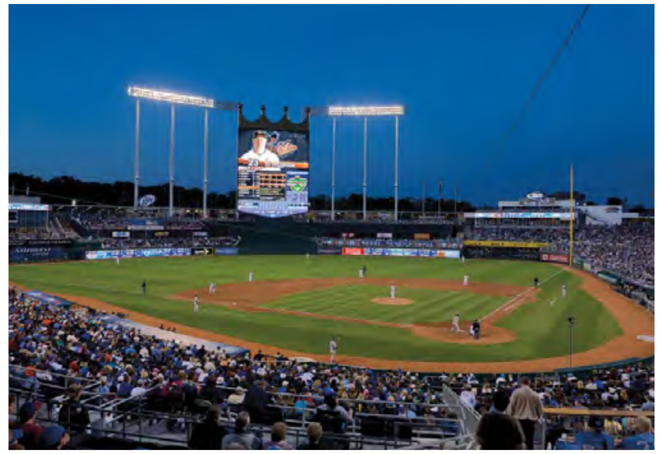
Phase II: Connected Model
A phase II model adds all structural connections: holes, bolts, shop welds, weld preparations and all connection material. It is used by contractors and steel fabricators to create shop drawings and to quickly obtain the CNC downloads that drive fabrication equipment, field bolt lists and connection material quantities. Because connections are already designed and detailed, the scope is clearly defined, virtually eliminating RFIs and change orders.

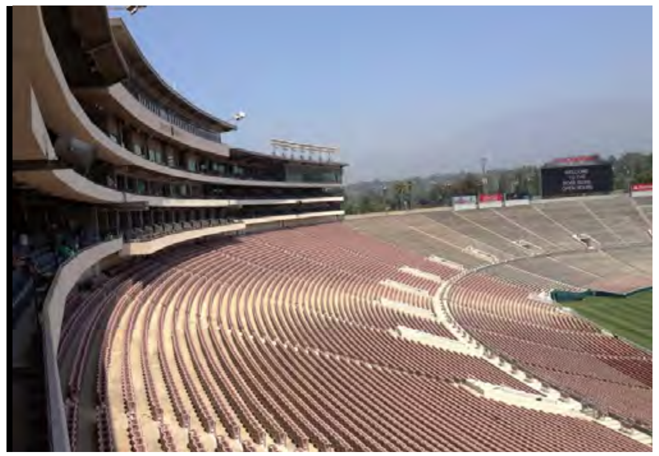
Phase III: Drawings Model
A phase III model is a fully detailed structural steel model that is used to generate final physical shop drawings, erection plans and details, field bolt lists and CNC downloads for the fabricator and erector. The model can be used directly, without additional effort, to fabricate and erect structural steel.

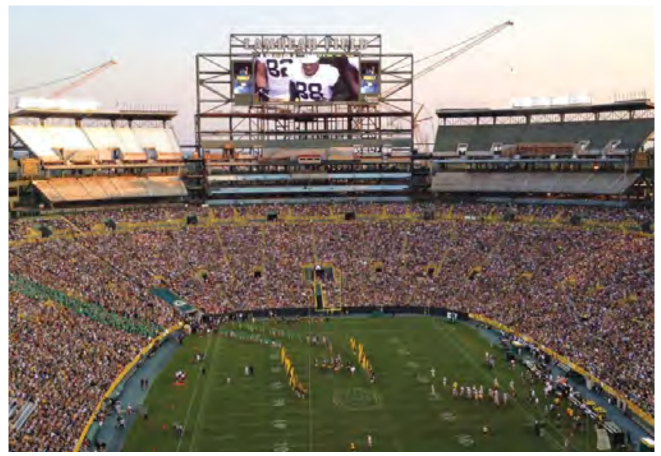


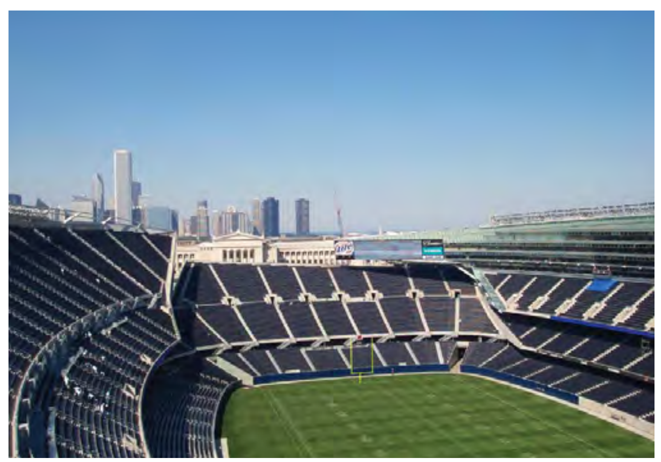


From top: a phase I material model; a phase II connected model; and a shop drawing generated from a phase III model.









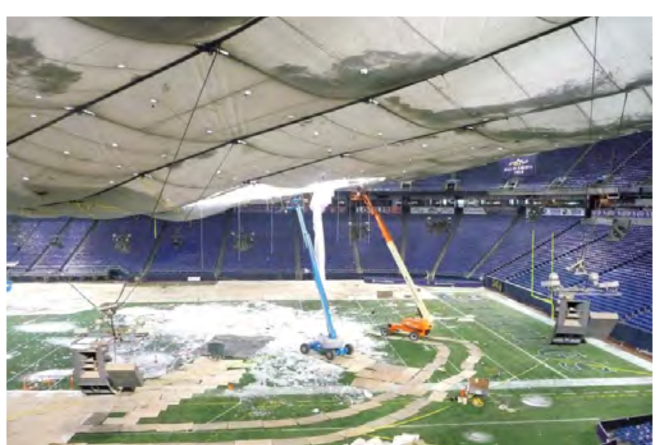


Photo credits, top left: Bill Cobb, SKYLINESCENES.COM; top right: mspillers2009

AFTER OPENING DAY

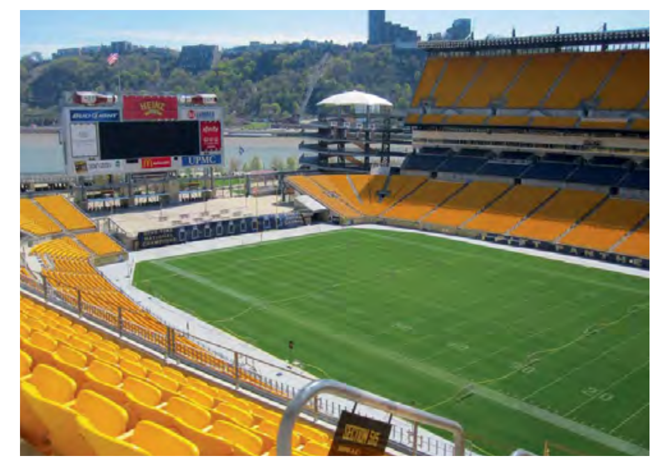
Thornton Tomasetti has decades of experience in design to modify, upgrade, renovate, re-clad and expand existing sports facilities. We apply the same capabilities, services and expertise we bring to new design to the projects that improve the performance of these structures and extend their useful life. Our technical expertise, the synergy between our practices, our technological capabilities, our collaborative approach and our focus on constructability are constants in every project.

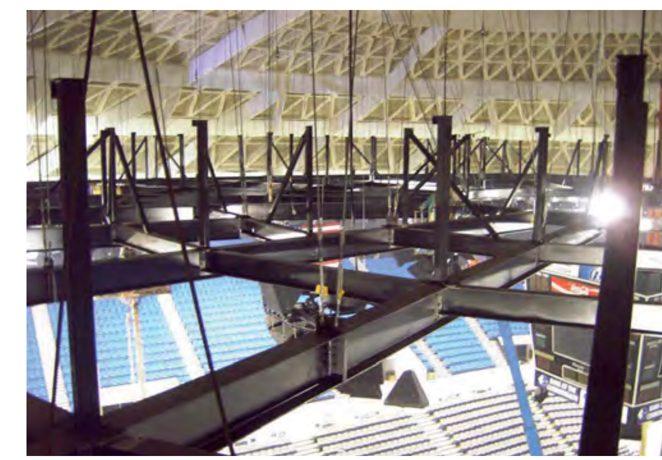
With in-house expertise in sustainability, building skin, structural and MEP engineering, forensic architecture and construction support, we also offer single-source solutions for a wide range of challenges affecting stadiums and arenas at every stage in their life cycle.

We can assess the condition and performance of a sports facility and make recommendations that will help owners weigh their options and choose the best course of action. We can detail the costs, benefits and challenges of upgrading an existing facility versus replacing it, for example.

Below left: We performed a multidisciplinary assessment and design for repairs at Heinz Field in Pittsburgh, Pa.

Below right: We designed a new rigging grid for the 40-year-old Scope Arena in Norfolk, Va. to accommodate the heavier loads associated with today's concerts and shows.





Clockwise from top left:

Sun Life Stadium Office Expansion, Miami Gardens, Florida

Kauffman Stadium Renovation and Improvements, Kansas City, Missouri

Lambeau Field Expansion, Green Bay, Wisconsin

Soldier Field Expansion, Chicago, Illinois

Rutgers University Football Stadium Renovation and Expansion, Piscataway, New Jersey

Metrodome Roof Collapse Investigation, Minneapolis, Minnesota

U.S. Cellular Field Renovation, Chicago, Illinois

Rose Bowl Stadium Renovation, Pasadena, California

Our Building Performance practice also offers multidisciplinary services in response to building failures ranging from the everyday to the cataclysmic: from gradual deterioration that erodes function and value, to sudden and catastrophic collapse. Our teams of structural and MEP engineers and forensic architects perform emergency stabilization; forensic investigation and documentation, including forensic information modeling (FIM); litigation support and expert witness testimony; design for repairs; and, when necessary, deconstruction and demolition engineering.

Our Property Loss Consulting practice provides multidisciplinary support to insurance companies and their representative attorneys and adjusters. From multihazard risk assessment to scope of damage determination, cause and origin investigation and support for property claims in the wake of losses related to natural or man-made events, our teams help mitigate risk and speed recovery.

We bring a passion for excellence and a dedication to collaborative problem-solving to our work on existing sports venues. Our experience in the design of new facilities gives our teams the expertise to effectively evaluate and modify these structures with one goal in mind: to create and support value for our clients, from opening day onward.

Game On!

Sports facilities have special design and construction considerations, so experience counts – and our portfolio of completed projects is unparalleled. But a creative, multidisciplinary approach is just as important. Our unique suite of complimentary practices and services equips us to understand our projects from a variety of perspectives. Every project we do benefits from our knowledge of sustainability principles, building skin systems, structural design, construction support services and engineering analysis and investigation. And when multiple practices work together on a project, the synergy of a "one-stop-shop" benefits the entire team.

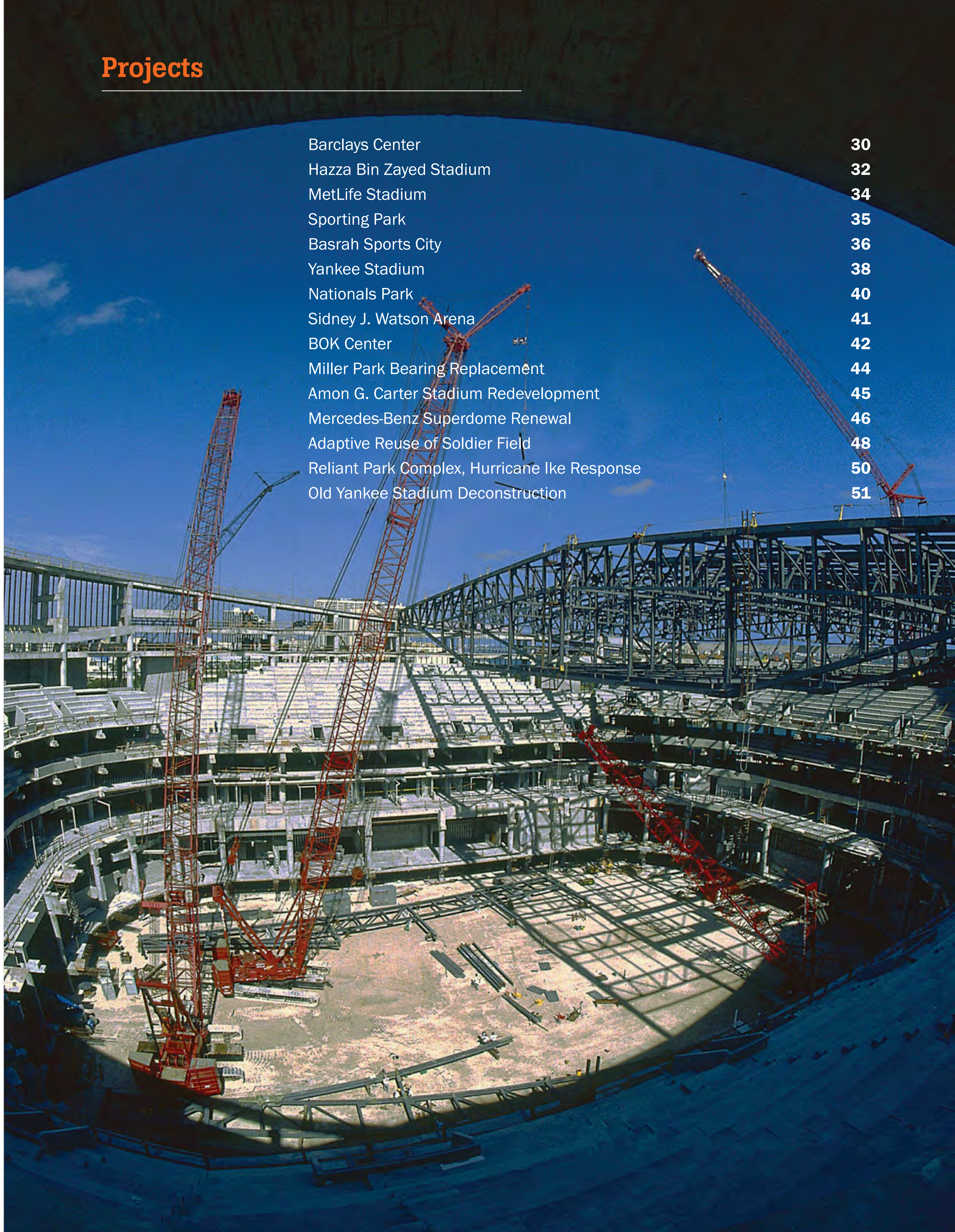
At Thornton Tomasetti, truly collaborative design is an integral part of how we deliver each and every project. We understand that our scope is just one part of a larger effort and represents only a portion of the value we bring to the project team. We are committed to the idea that our involvement should increase every other discipline's ability to enhance their contributions to the project.

We get involved early and focus on setting each project on a path to success. We work smart, providing fast, appropriate responses to questions posed within the project team or by the owner. And we volunteer ideas for saving time and money. Our emphasis on open communication among all project stakeholders is a reflection of a genuine desire to make every sports project a great project.

We've told you why we believe Thornton Tomasetti is the premier engineering firm in sports design. Now let us show you. In the following pages, you'll see examples of our work at every stage of the building life cycle.

After spending thousands of hours on the structural design of Nationals Park, Jeff D'Andrea and Luke Nisley watch the home team win on opening night.

Projects



Barclays Center

Brooklyn, New York

The design and construction of Barclays Center, home of the National Basketball Association's Brooklyn Nets, faced numerous hurdles, including challenges by neighborhood groups, changes in project team members, and complex underground construction on a tight urban site. Thornton Tomasetti provided structural design, security engineering and construction support services for the design-build project.

The steel-framed multipurpose arena's location near a subway station and train terminal presented challenges for the foundation system. The site didn't have room for a standard loading dock, so the project team added dual truck elevators and a truck turntable to service a loading dock beneath the arena. Building columns in this region were transferred using large plate girders spanning over the dock. The long-span roof structure used twin 50-foot-deep tied arches, spanning 350 feet, to support trusses that span 170 feet from the perimeter. This system was optimized and tailored to the erection preferences of the design-build team.

A design enhancement that came late to the project posed challenges that were resolved through effective team collaboration. A new weathered steel façade, with a canopy and oculus that cantilevers 85 feet over the entrance plaza, had to be quickly integrated into the base structure's design. Working closely with SHoP, we ran dozens of iterations of the canopy and façade support design, taking the architect's CATIA models and using Tekla to model the support steel and coordinate skin and structure seamlessly.

Our advanced project delivery services included connection design and erection engineering. We delivered a partially connected Tekla model that the fabricator was able to use to directly produce the mill order and expedite detailing. We also performed erection sequencing and lift engineering for the long-span roof and the entrance canopy.

Continuing support for the arena includes tenant fit-outs and review of rigging for events.

• GROUNDWORK
• DESIGN
• CONSTRUCTION
• USE

Client/Owner
Forest City Ratner Companies

Architect
AECOM Ellerbe Becket

Façade Design Consultant
SHoP Architects

General Contractor
Hunt/Bovis, Joint Venture

Steel Fabricator
Banker Steel Company

Steel Erector
James F. Stearns Co., Inc.

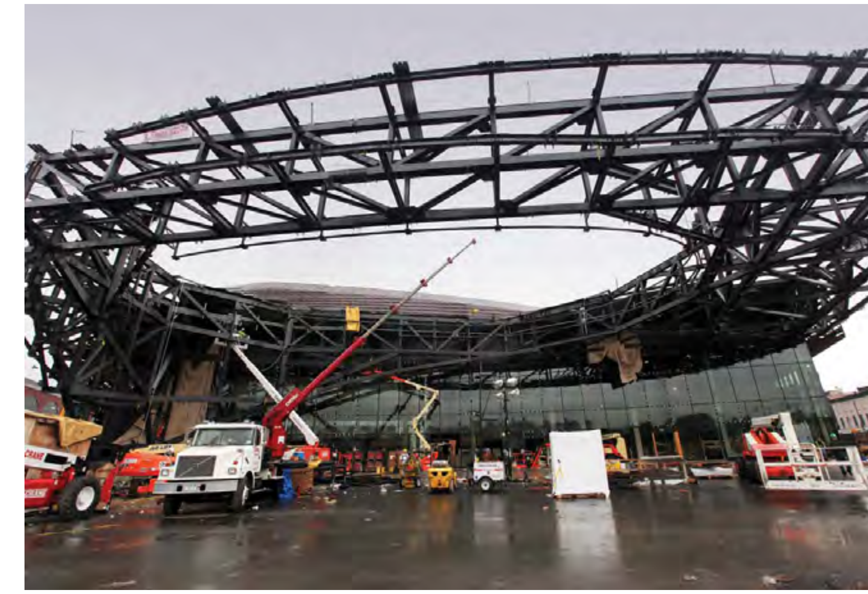
Completion Date
2012

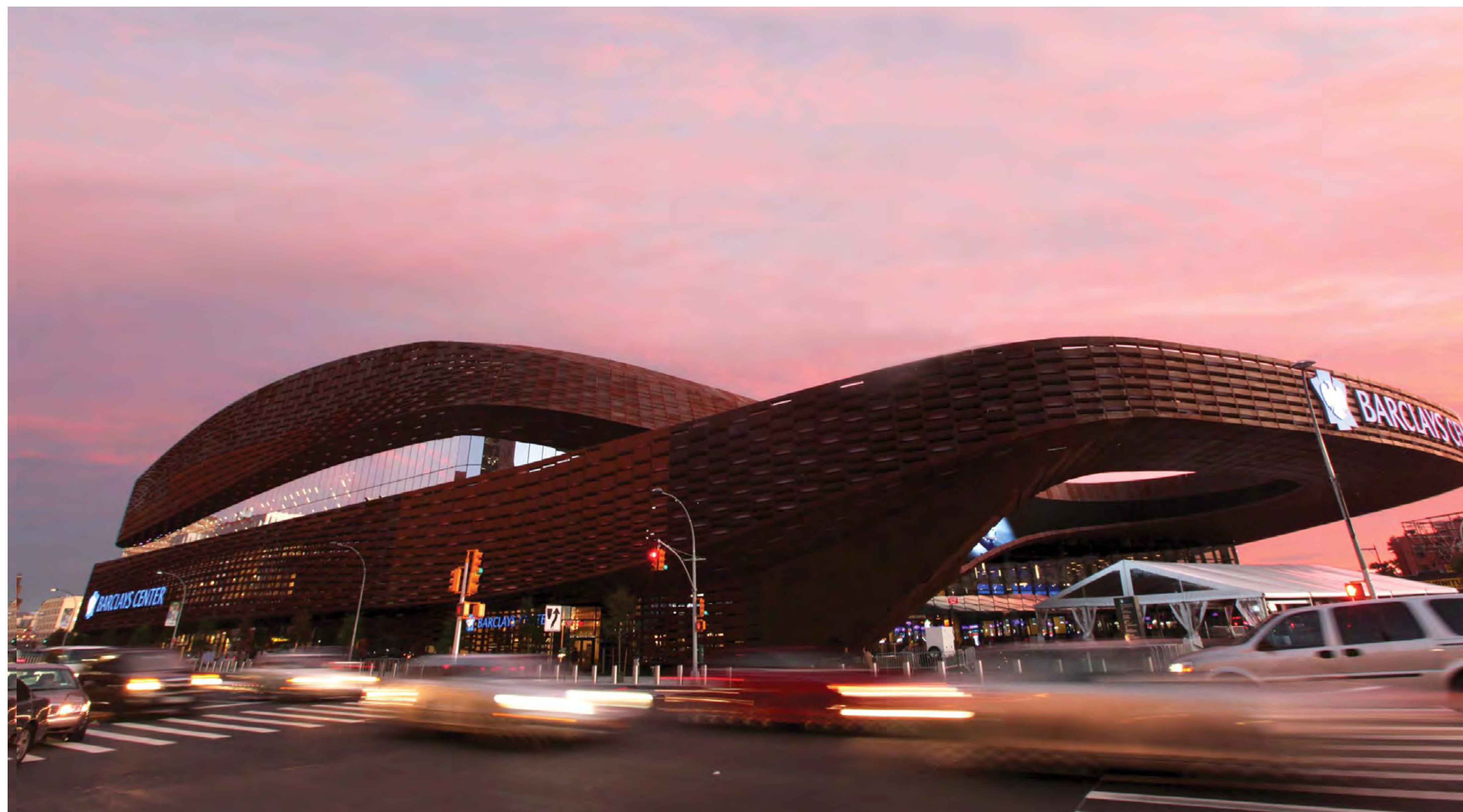
Construction Cost
$706 million

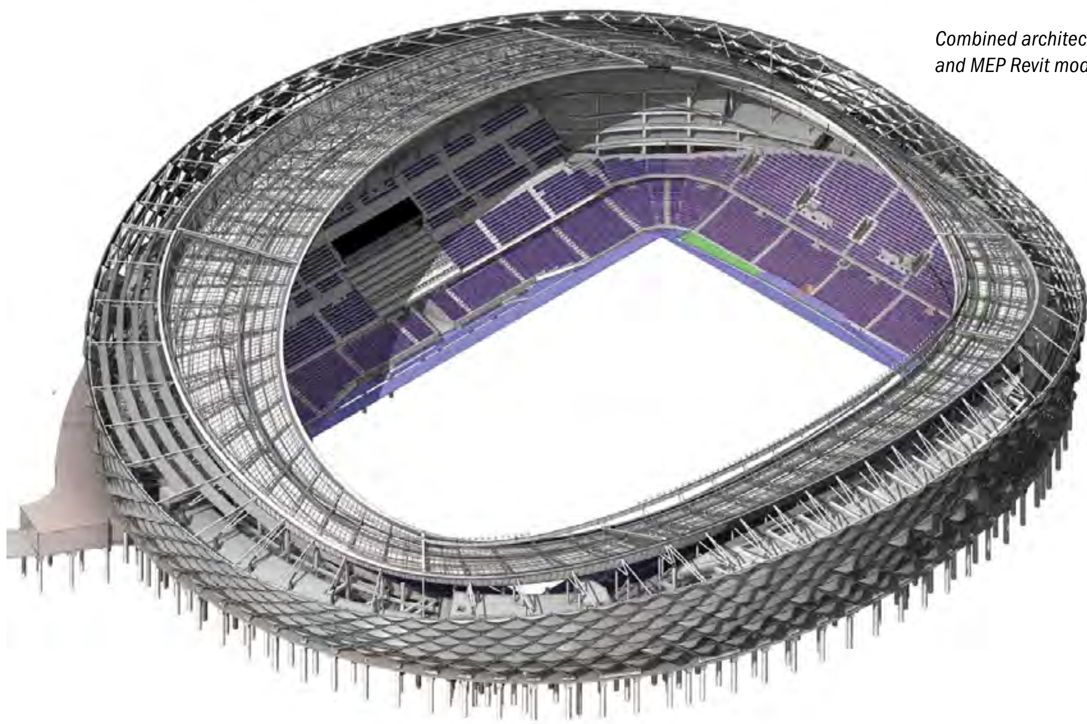
Total Area
675,000 sf / 62,710 m²

Seating Capacity
18,103

Awards
2012 American Institute of Steel Construction IDEAS² Merit Award







Combined architectural, structural and MEP Revit model.

Hazza Bin Zayed Stadium

Al Ain, Abu Dhabi, United Arab Emirates

The Al Ain Football Club's new home grounds features a floating steel cantilever roof clad with polycarbonate and tension membranes. We provided integrated structural engineering and building skin design services for the fast-track design-build project, from the concept phase through detailed design.

The entire project team used BIM throughout the process, working in parallel on one Revit model to develop the design. Integrated multidisciplinary modeling allowed for easier coordination of complex geometry and connections; faster response to owner-driven changes; and accurate monitoring of quantities for price certainty.

Our team worked closely with the architect to fine-tune the roof's sweeping form. We used Grasshopper, a generative modeling tool for Rhino 3D, to review a host of variations by manipulating multiple parameters such as framing grid configuration, panel shape and size, roof pitch, truss depth and roof extent. The model linked to SAP for structural analysis and to façade analysis software for daylight assessment and thermal/solar performance analysis. This process enabled the team to quickly identify the most structurally efficient option for meeting both functional shading needs and architectural goals.

The building façade – inspired by the pattern on the bole of a palm tree – features panels supported on a steel-framed diagrid system. We used computational design to rationalize the panel geometry, reducing the number of different steelwork connections and increasing their adaptability, so fewer panel shapes were required.

The state-of-the-art stadium is the centerpiece of a mixed-use development that includes an adjacent sports center as well as hotel and commercial facilities.

Manager/Operator
Al Ain Club Investment Company

Client/Architect
Broadway Malyan Architects (master plan and interiors)

Pattern Design, Ltd. (stadium)

Engineer of Record
Mark Habre Associates

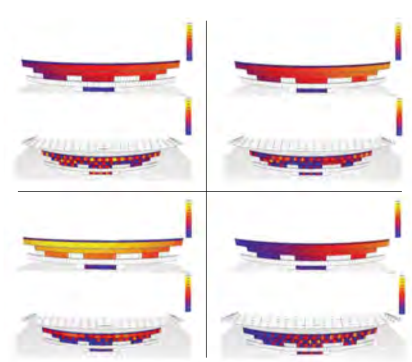
Contractor
BAM International

Completion Date
2013

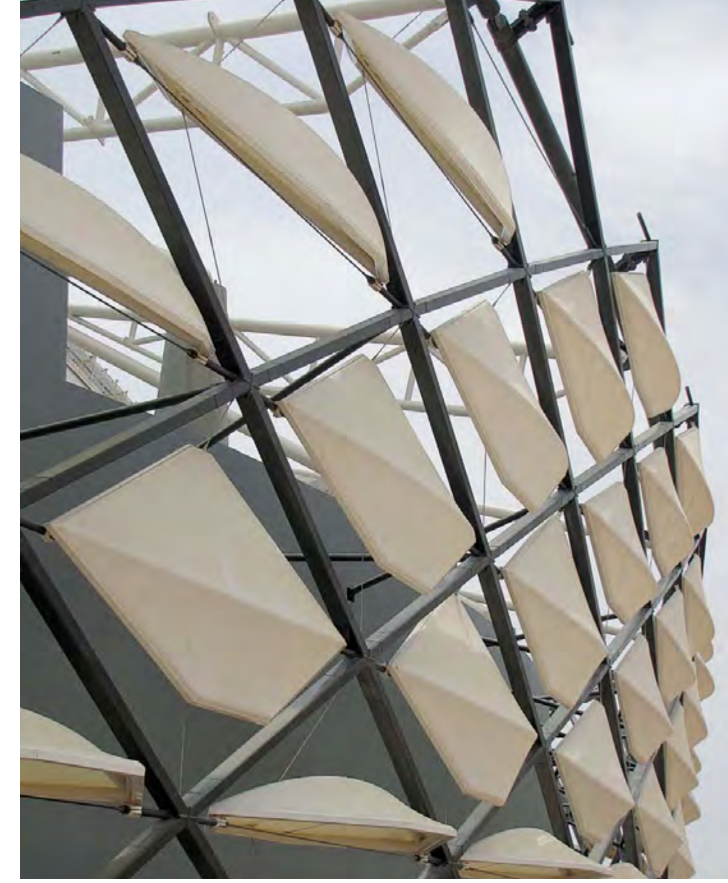
Construction Cost
Confidential

Total Area
484,380 sf / 45,000 m²

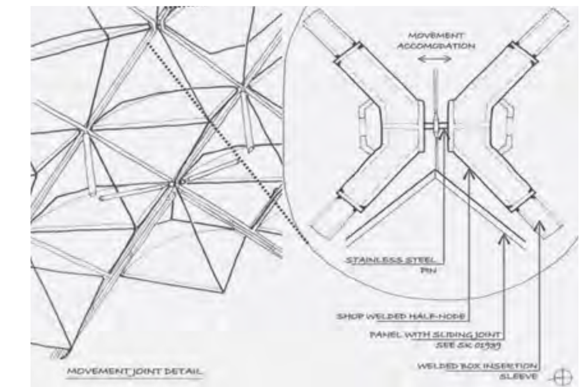
Seating Capacity
25,000



Cumulative direct solar radiation on the façade's surfaces on (clockwise from top left) the 21st day of March, September, June and December.



• DESIGN



MetLife Stadium

Rutherford, New Jersey

Owner
New York Jets and New York Giants

Client
New Meadowlands Stadium Company, LLC

Design Architect
360 Architecture

Architect of Record
EwingCole

General Contractor
Skanska

Completion Date
2010

Construction Cost
$1.15 billion

Total Area
2.2 million sf / 204,390 m²

Seating Capacity
82,500

Awards
2011 Aon Build America Award for Design-Build New, Associated General Contractors of America

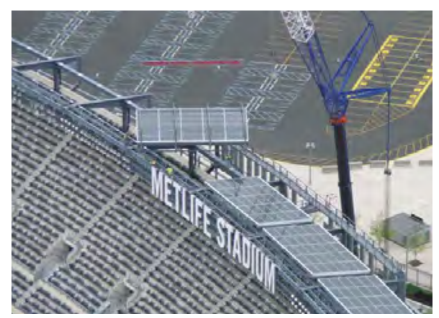
We provided structural design for the new home of the New York Giants and New York Jets, a 2.2-million-square-foot stadium, which upon completion was the second largest in the National Football League. The fast-track project opened less than 40 months after the design-build project award.

Our engineers recommended a site-specific study to review the location's seismic design category, which was just over the threshold separating categories C and D. We worked with geotechnical engineers to analyze the site's history and physical features. The results showed that it met category C criteria, which reduced the special seismic design requirements, simplifying design and construction.

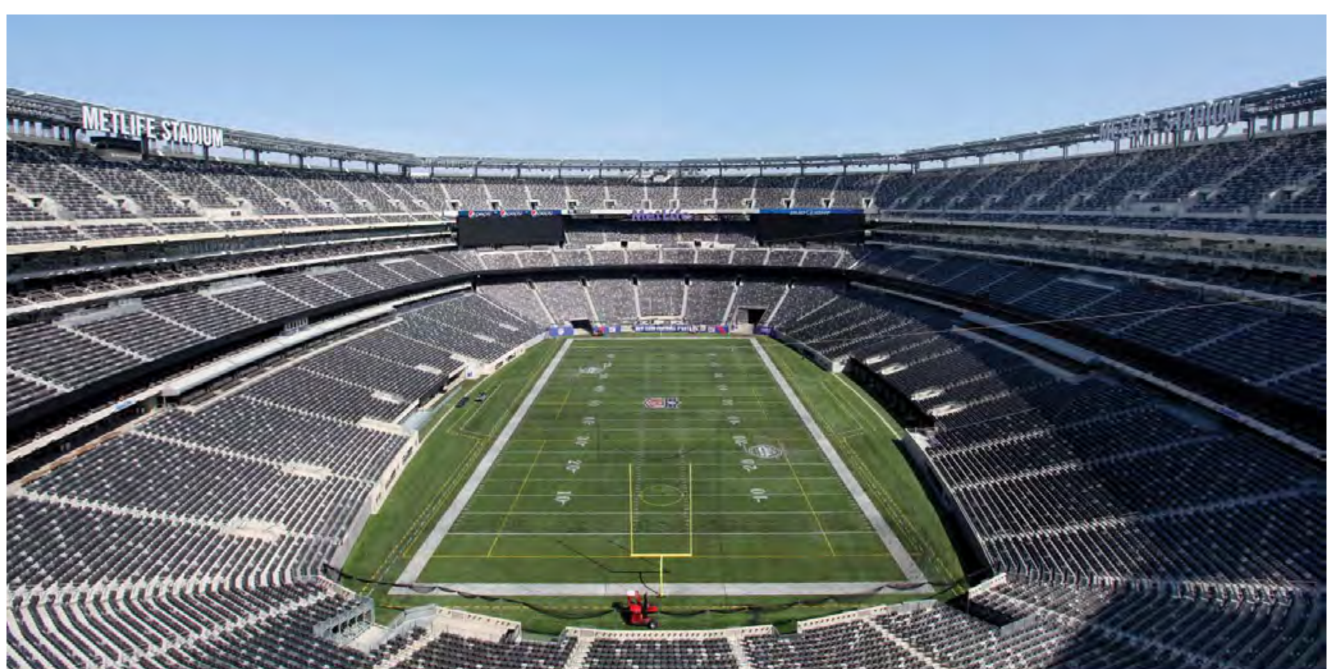
We developed a Tekla model for the all-steel superstructure and delivered it to the fabricator. This expedited steel procurement and detailing, cutting the construction schedule by several months. A composite Navisworks model was also used for coordination between architectural, precast, steel and MEP designs, eliminating most of the field issues tyically caused by clashes during construction. Electronic shop drawing review and tracking of status data in the Tekla model further increased efficiency. Color coding in the model provided a clear picture of the review and erection status of thousands of components at a glance.

We also designed steel-tube support frames for solar panels, installed in 2012, that ring the stadium's upper canopy level. Work included verification of the existing structure's capacity to support the additional weight and analysis to confirm that applicable vibration criteria were satisfied.

- **GROUNDWORK**
- **DESIGN**
- **CONSTRUCTION**
- **USE**



Courtesy Tom Kaminski/WCBS Chopper 880



Sporting Park

Kansas City, Kansas

Owner
Sporting Club of Kansas City

Architect
Populous

General Contractor
Turner Construction

Completion Date
2011

Construction Cost
$147 million

Total Area
340,000 sf / 31,590 m²

Seating Capacity
18,500

Awards
2011 New Building Award, Structural Engineers Association of Kansas and Missouri (SEAKM)

2012 Venue of the Year, TheStadiumBusiness Awards

Thornton Tomasetti provided structural design for this Major League Soccer stadium, which can also host rugby, lacrosse and outdoor concerts. An aggressive schedule – just 22 months from kick-off to opening day – demanded extraordinary performance by the design team. Collaborating closely with the architect and contractor, we produced a structural design that supported the owner's aesthetic goals and was tailored to speed construction.

The park's signature feature is a 145,000-square-foot translucent canopy. It cantilevers up to 95 feet to cover all seating sections while allowing sunlight to reach the grass playing field. Using glass would have required dense sub-framing, resulting in too much shade, so the project team turned to lightweight, high-strength polycarbonate glazing that could be supported by a slender structure.

Our engineers employed a number of strategies to accelerate construction. We hosted weekly meetings with the construction team and steel fabricator to review the 3D design and detailing model, and we split the framing design into sequenced steel packages that were coordinated with mill roll dates and the contractor's erection plan. We also provided fully designed and detailed connections for fabrication to eliminate RFIs and accelerate the submittal review process.

The project team incorporated top-down foundation construction methods to improve the sequence of construction, eliminate the need for temporary shoring and avoid the excavation of existing utilities. Our construction support experience helped our engineers design the structure with construction sequencing and excavation strategies in mind. This expertise contributed to a constructable design that helped the project team complete the stadium on time for opening day.

Thornton Tomasetti has also performed evaluations for event rigging and provided design services for minor modifications to the facility.

- **DESIGN**
- **CONSTRUCTION**
- **USE**

360 Architecture

Basrah Sports City

Basrah, Iraq

Thornton Tomasetti provided structural design and building skin services for this fast-track, design-build project, which consists of two soccer stadiums with spectator and player amenities and adjacent support facilities. The structural designs employed concrete for foundations, gravity and lateral systems, with cantilevered roof systems of steel trusses covered in metal deck. Both structures had to accommodate large thermal movements caused by extreme summer heat.

We were already designing the main stadium's structure in 2010 when the architect asked us to find a fast, cost-effective solution for the complex building skin system. The design concept called for 100-foot-long glass fiber reinforced polymer (GFRP) panels in 10 different configurations to wrap around sloping columns shrouded in perforated metal plate. But the lengthy fabrication time for the panel molds didn't fit the project's tight construction schedule.

We developed a parametric CATIA model to analyze different panel shapes – checking them against structural, logistical and economic constraints – and optimize their geometry, connection patterns and attachment brackets. Our building skin team worked closely with project architects to quickly find a combination that met the design intent using only five molds, cutting fabrication time in half.

We used the same model to design and detail highly adjustable connection brackets and beams that would accommodate varying panel sizes and positions and be easy to assemble in the field. Using a single 3D model also allowed clashes and potential constructability issues to be resolved prior to manufacturing and construction. The panel fabricator used the CATIA model to direct their CNC machines, so every piece conformed to our design specifications. We then developed an automated process to translate the steel brackets and beams into a fully detailed Tekla model, which was used to fabricate these steel components.

Owner
Iraq Ministry of Youth and Sports

Architect
360 Architecture

General Contractor
Abdullah A. Al-Jiburi Contracting Co.

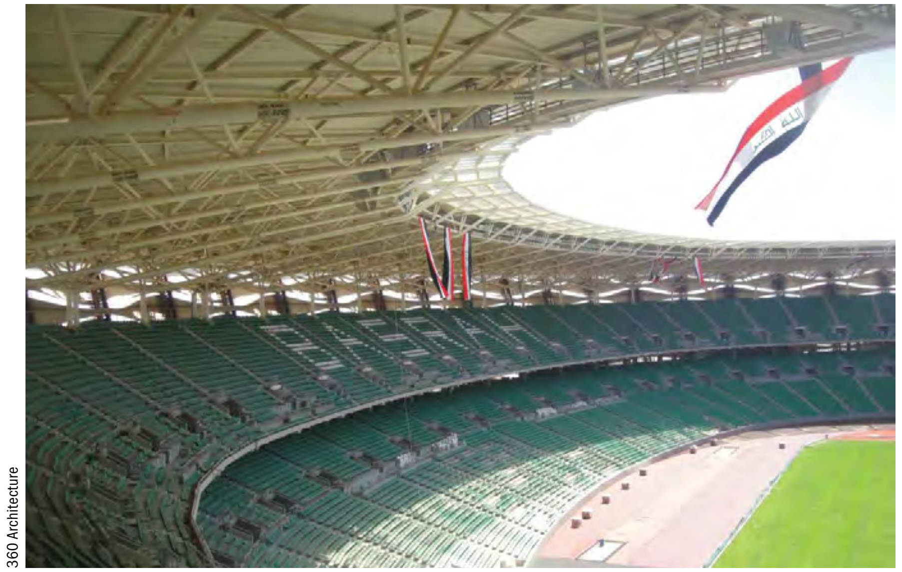
Panel Fabricator
Bahrain Fiber Glass (BFG)

Completion Date
2013

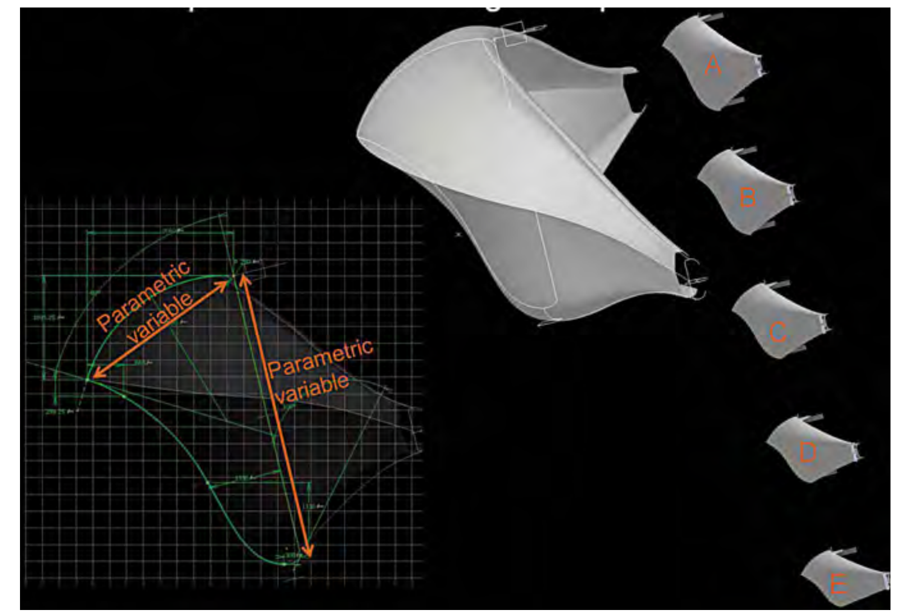
Construction Cost
$500 million

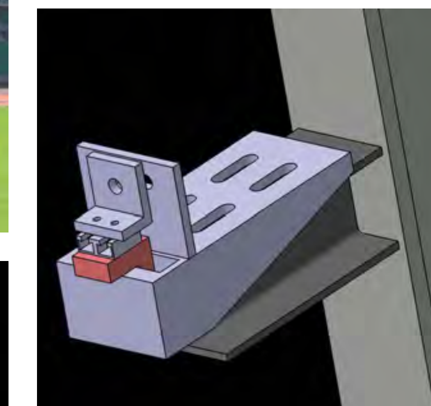
Total Area
2,500,000 sf – main stadium
270,000 sf – secondary stadium

Seating Capacity
65,000 – main stadium
10,000 – secondary stadium



360 Architecture





We used CATIA to model and optimize the panels (left) and connection brackets (above) for the main stadium's façade.

360 Architecture

• GROUNDWORK
• DESIGN
• CONSTRUCTION

Yankee Stadium

Bronx, New York

• DESIGN
• CONSTRUCTION
• USE

Owner
New York Yankees

Architect
Populous

Development Manager
Tishman Speyer Properties

Preconstruction Services
Turner Construction

Completion Date
2009

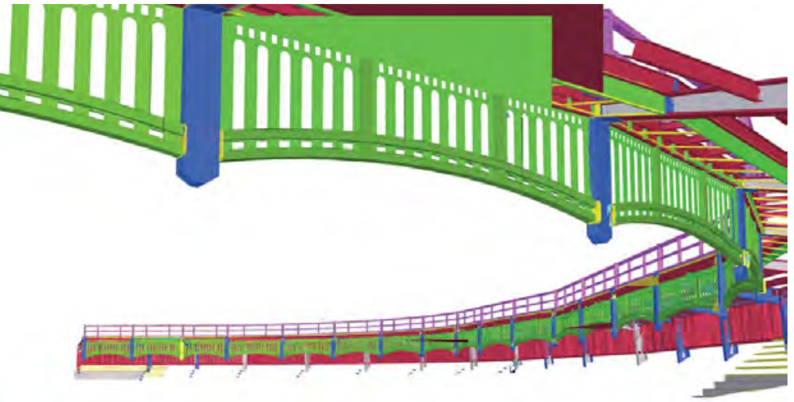
Construction Cost
$800 million

Total Area
1.25 million sf / 116,130 m²

Seating Capacity
51,000

Awards
2009 North American Model Competition Winner, TEKLA Structures

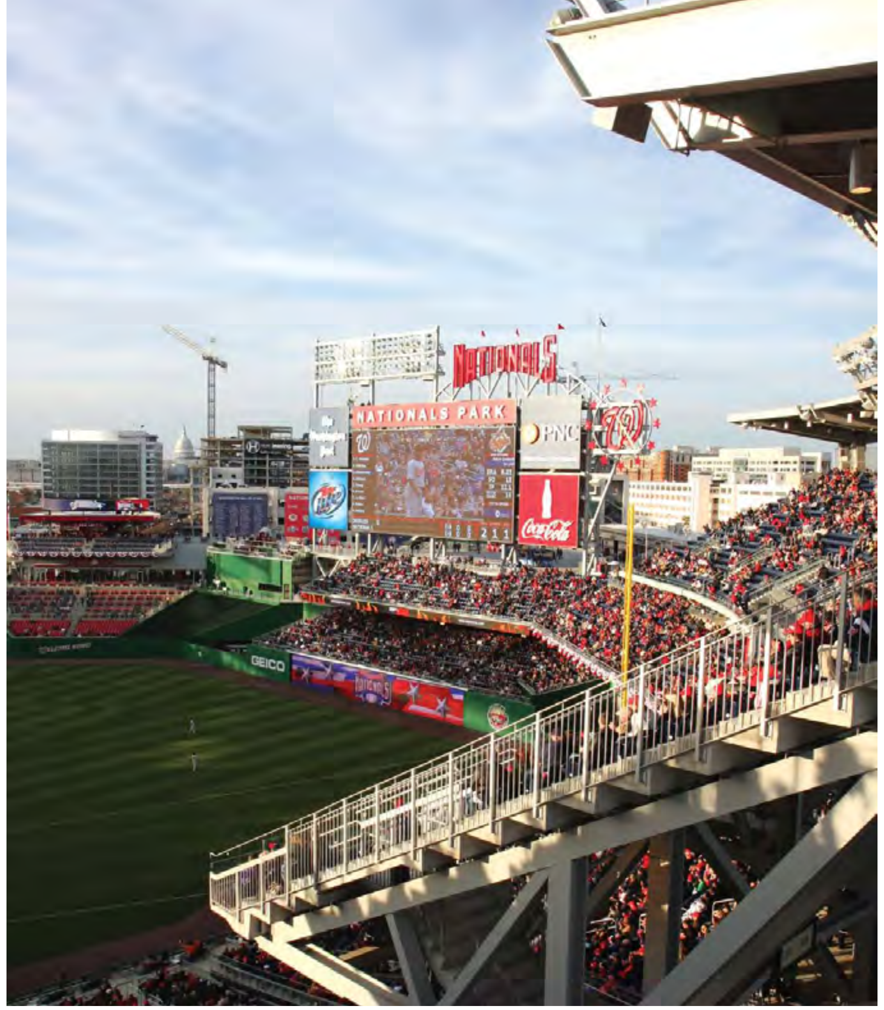
2009 Project of the Year, New York Construction



After playing in the same stadium for 85 years, Major League Baseball's New York Yankees moved across the street in 2009. Their new ballpark was modeled after the original 1923 stadium, but with the addition of modern features such as the Great Hall entry, a 500-foot-wide scoreboard/video board with cantilevered end bays, wider concourses and expanded concession and amenity space. The design also includes a suite level and upper seating decks that cantilever 50 feet beyond the main-level concourse, creating unobstructed views for fans.

The project required highly detailed aesthetic connections, including the design of the trademark frieze, which also plays a structural role as the front girder of the canopy. We developed a Tekla model that enhanced the design and review of these and other important exposed structural elements. From the beginning, our team designed the structure with the highest level of aesthetics in mind, resulting in a structure that is both technically and visually elegant.

Thornton Tomasetti has performed additional work at the stadium, including a feasibility study for adding a wind turbine and design for a suite canopy.



Nationals Park

Washington, D.C.

The 41,418-seat home of Major League Baseball's Washington Nationals was delivered through a design-build contract with an ultra-fast-track 23-month construction schedule. Thornton Tomasetti, along with a joint venture partner, performed structural design for the project.

Our team used Tekla to develop a 3D model of the structure's steel, which was transferred to the steel subcontractor. Connection detailing and design changes were made in the model and downloaded directly to the fabricator's shop. This innovative approach significantly shortened the design and fabrication schedule for the stadium's 7,800 tons of steel and allowed the structural design to be completed well in advance of the final ballpark design.

The stadium includes luxury suites and club-level seating, a 4,500-square-foot scoreboard, team offices, a conference center, a restaurant and sports bar, a picnic area and family plaza, and parking facilities. This project was the first professional sports stadium in the United States to achieve LEED Silver certification. Green features include a 6,300-square-foot green roof above the concession stands beyond left field, as well as the use of regionally produced and recycled building materials.

Since the ballpark's opening in 2008, our engineers have assisted the owner with several modifications to club and concession areas. We look forward to continuing to support Nationals Park across the stadium's life cycle.

Owner
Events DC

Architect
HOK/Devrouax & Purnell, PLLC

Contractor
Clark/Hunt/Smoot Joint Venture

Completion Date
2008

Construction Cost
$611 million

Total Area
1 million sf / 92,900 m²

Seating Capacity
41,418

Awards
2008 Design-Build Award for Public Sector Building Over $15 Million, Design-Build Institute of America

National Capital Region's 2008 Project of the Year, U.S. Green Building Council

2008 Excellence in Structural Engineering Outstanding Project Award, Structural Engineers Association of Metropolitan Washington (SEA-MW)

Project of the Year, Sports & Entertainment, Mid-Atlantic Construction Magazine Best of 2008

- GROUNDWORK
- DESIGN
- CONSTRUCTION
- USE

Sidney J. Watson Arena at Bowdoin College

Brunswick, Maine

Our sustainability practice performed LEED consulting and energy modeling services for this 1,900-seat facility, the first LEED-certified new ice arena in the United States.

The facility uses 17 percent less energy than a traditional arena, taking advantage of innovations such as energy-efficient refrigeration and dehumidification systems. Its absorption chiller, which uses ammonia instead of HCFC or HFC refrigerants, has no direct ozone depletion or global warming potential.

Other green features include waste management during construction to divert materials from the landfill, indoor air quality management during construction, recycled and regional materials use and an extensive green education component. A stormwater-management system redirects rainfall, low-flow fixtures use 38 percent less water than conventional fixtures and its landscaping does not require irrigation. Building materials are 30 percent recycled content, while 40 percent of the total materials used were sourced from within 500 miles of the campus. More than 80 percent of construction waste was recycled.

Owner
Bowdoin College

Architect
Bear Mountain Design AC, Ltd.

Completion Date
2009

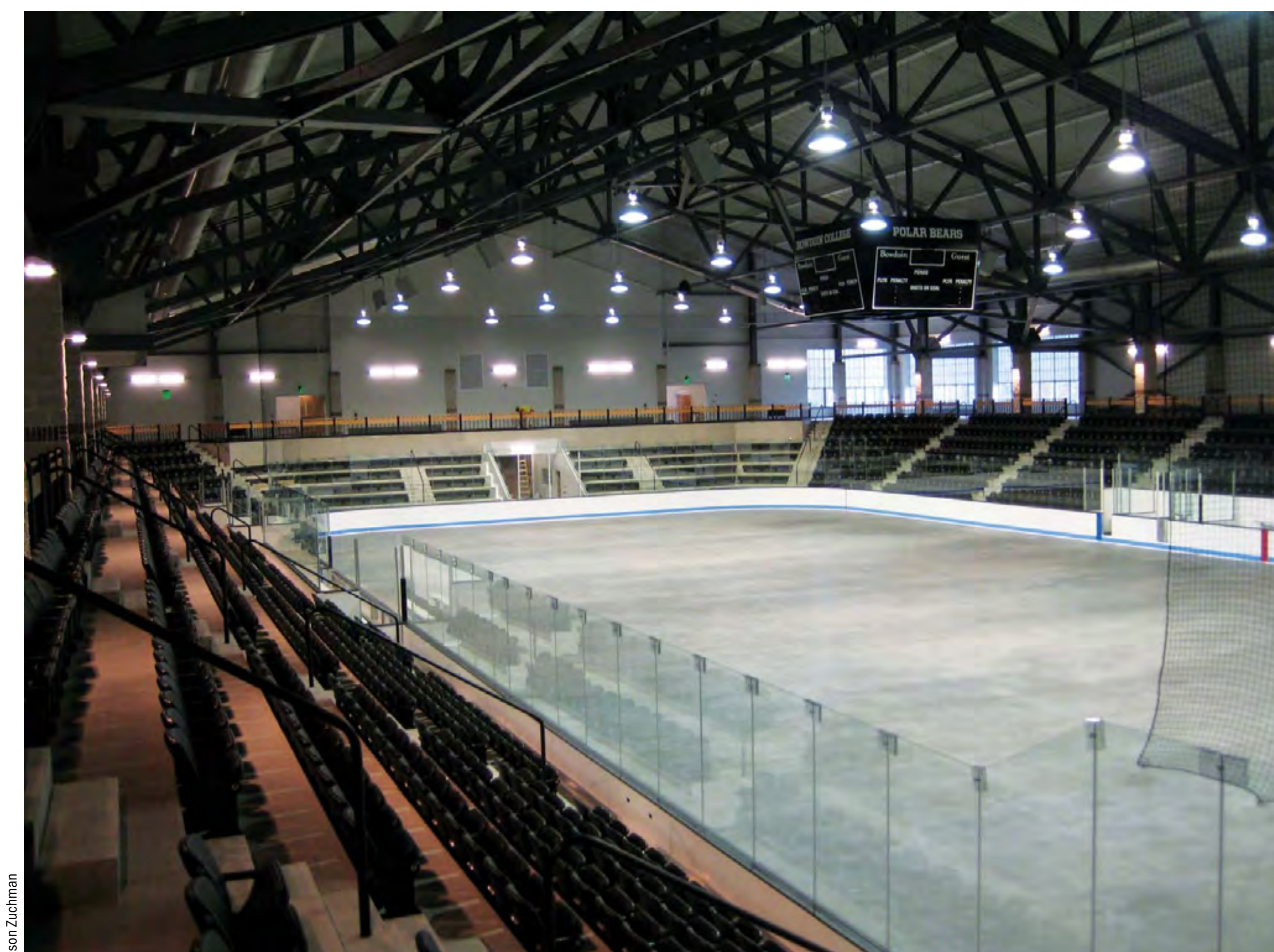
Construction Cost
$20 million

Total Area
68,000 sf / 6,320 m²

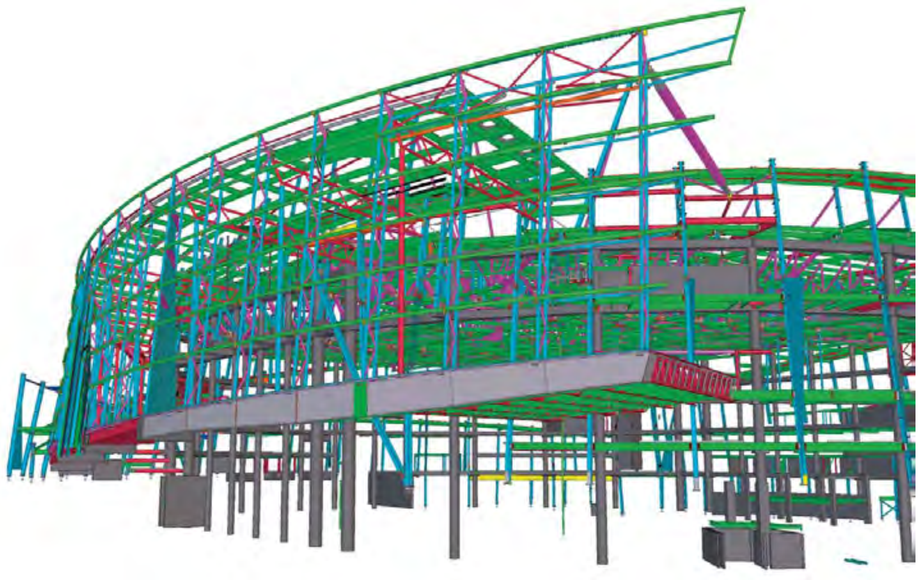
Seating Capacity
1,900

Certification Level
LEED NC

- DESIGN



Allison Zuchman



BOK Center

Tulsa, Oklahoma

BOK Center, the anchor of Tulsa's comprehensive downtown revitalization effort, provides a venue for concerts, hockey, arena football, basketball and community events. The multipurpose facility also makes a distinctive architectural statement, with a form based on a series of cone sections that intersect at irregular angles. Thornton Tomasetti provided structural design for the geometrically complex arena.

To meet the unique challenges of the structure's irregular form, we used Tekla to model the structural steel. The 3D model offered clear visualization of the arena's structure and expedited the design of complicated detailing areas and transitions.

The structural team focused on constructability from the start. The arena's roof is framed by a pair of 330-foot box trusses resting on perimeter beams, which support a system of shop-assembled trusses and purlins. This system allowed for maximum pre-assembly, which shortened the erection schedule and improved site logistics.

We also performed a construction sequencing analysis to optimize the design of the BOK Center's signature feature, a 450-foot "Icon Wall" that wraps around the arena and ends in an 80-foot glass and steel projection supported by a large box-beam cantilever. We designed a system of tie-downs to preload steel support elements to prevent cracking from dead load deflection during glass installation. This reduced the need for glazing joints – advancing aesthetic goals while making construction easier.

Owner
City of Tulsa

Construction Architect
Matrix*Odell (Joint venture of Matrix Architects, Engineers, Planners and Odell Associates)

Associate Architect
Pelli Clarke Pelli Architects

General Contractor
Tulsa Vision Builders (Joint venture of Manhattan Construction and Flintco)

Completion Date
2008

Construction Cost
$178 million

Total Area
565,000 sf / 52,490 m²

Seating Capacity
19,199

Awards
2009 National Award Winner, AISC IDEAS2 Structural Steel Building Awards Program

2009 New Building Award, Structural Engineers Association of Kansas and Missouri (SEAKM)

• DESIGN
• CONSTRUCTION

As the 2002 season was winding down for Major League Baseball's Milwaukee Brewers, the stadium owner initiated a major off-season repair. After only two years of service, the pivot bearings of all five of the roof's movable panels needed replacement. Tight quarters, severe time constraints and winter weather conditions were among the challenges Thornton Tomasetti, working with strategic partner Hardesty & Hanover, addressed and resolved.

Provisions for replacing the bearings, which support 1,200 tons of steel and roofing, were never included in the original design. Our task was to find a permanent system to replace the pivot bearings, develop a procedure for performing the work, devise a way to safely lift the 600-foot-long roof panels, and design work platforms that would fit within the cramped structure.

We developed a series of finite element assemblages to plan the replacement program. Analyses included a thorough review of the global behavior of each of the five roof panels under wind and snow loads, while on an operational pivot bearing and while jacked up; a review of the roof support structure for additional jacking loads; and detailed FEM assemblage models of the panel end and support structure in the immediate vicinity of the pivot bearings with the added jacking brackets. We also created 3D graphical simulation models to verify that the work platforms and equipment would fit within the pivot frames.

We provided on-site assistance during the entire construction phase, enabling a swift turnaround for all information and shop drawings requested by the contractor. The project was completed on time for the opening of the 2003 baseball season. Since then, we've continued to provide engineering support for various stadium modifications, as well as condition evaluations and inspections.

Miller Park Bearing Replacement

Milwaukee, Wisconsin

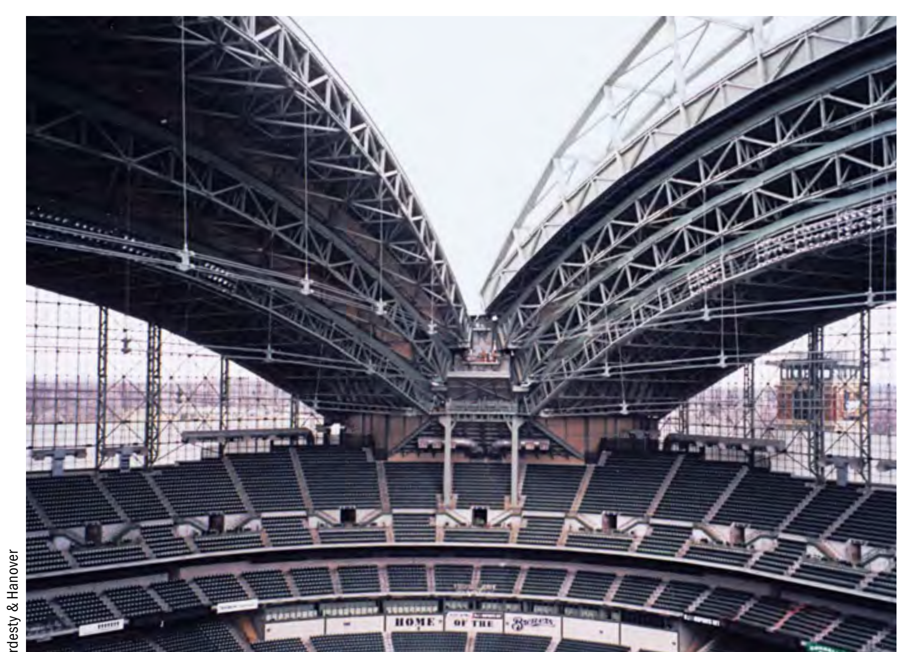
Owner
Southeast Wisconsin Professional Baseball District (SEWPBPD)

Completion Date
2003

General Contractor
Hunt Construction

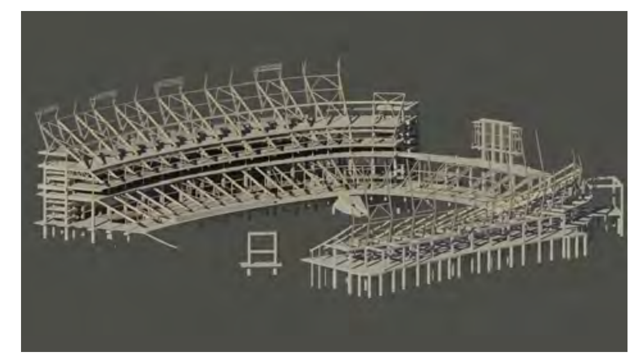
Hardesty & Hanover

Tom Duffy documents progress at the site.



Hardesty & Hanover

- **USE**
- **LOSS**
- **RENEWAL**



Amon G. Carter Stadium Redevelopment at Texas Christian University

Fort Worth, Texas

Owner
Texas Christian University

Client/Architect
HKS, Inc.

Contractor
Austin Commercial

Steel Fabricator
Irwin Steel

Steel Erector
Derr Steel Erection Company

Completion Date
2012

Construction Cost
$164 million

Total Area
711,000 sf / 66,050 m²

Seating Capacity
46,330

Our engineers provided structural design for the redevelopment of an open-air football stadium dating from 1930, the home of the TCU Horned Frogs. The two-phase project – the first major upgrade to the facility since 1956 – retained only the first 20 rows of the original on-grade seating bowl and built an entirely new elevated structure to create a modern stadium.

During design development, we worked closely with the steel fabricator and erector, in addition to the contractor and architect, to plan and design the structural steel. This early coordination resulted in steel designs and details that satisfied engineering priorities, such as vibration control, and aligned with the architect's aesthetic goals, while also being fabricator and erector friendly. The efficient steel erection that followed was key to meeting an aggressive construction schedule.

Construction for the redevelopment had to be performed during two off-seasons, so the stadium could remain in use. The phase one (west and north side) work was completed in 2011 and the phase two work on the east side was finished in 2012, in time for the Horned Frogs' season opener.

- **RENEWAL**

Mercedes-Benz Superdome Renewal

New Orleans, Louisiana

Thornton Tomasetti has provided a range of investigation, analysis and engineering design services for a variety of projects at the iconic Superdome, home to the National Football League's New Orleans Saints since 1975.

After it was damaged by Hurricane Katrina in 2005, we assessed and documented damage to the stadium's domed roof and provided litigation support and expert witness services on behalf of the owner.

Next we began work on structural analysis and design for repairs to make the stadium "football ready" in time for the 2006 season. The project included a full roof deck replacement and recladding of the arena's exterior, as well as internal repairs, new scoreboards, new camera platforms and club improvements.

We then performed structural engineering and steel connection design for additional enhancements that transformed the Superdome into a modern venue with up-to-date amenities. Interior renovations included a new 3,100-seat lower-level seating bowl, expanded concourses, new luxury suites, a new end zone party deck, relocation of the press box, installation of three full-height elevator shafts, extension of two existing elevator shafts and the addition of a mezzanine level.

Exterior work included the conversion of adjacent Champions Square into a pedestrian mall with a grand staircase leading up to the stadium.

We have continued to provide engineering support for events at the Superdome. Before 2013's Super Bowl XLVII, we conducted a structural analysis of the stadium's dome to identify appropriate points from which to hang lights and equipment could be suspended for the halftime show.

Owner
Louisiana Stadium and Exposition District (LSED)

Stadium Manager
SMG

Architect: Repair
Trahan, Billes, Sizeler, Ellerbe Becket (now AECOM) Joint Venture

Architect: Enhancements and Champions Square
Eskew+Dumez+Ripple/Ellerbe Becket (now AECOM)

Contractor: Repair
Broadmoor, LLC

General Contractor: Enhancements
Citadel/Anderson Joint Venture

Steel Fabricator: Enhancements
Postel Industries, Inc.

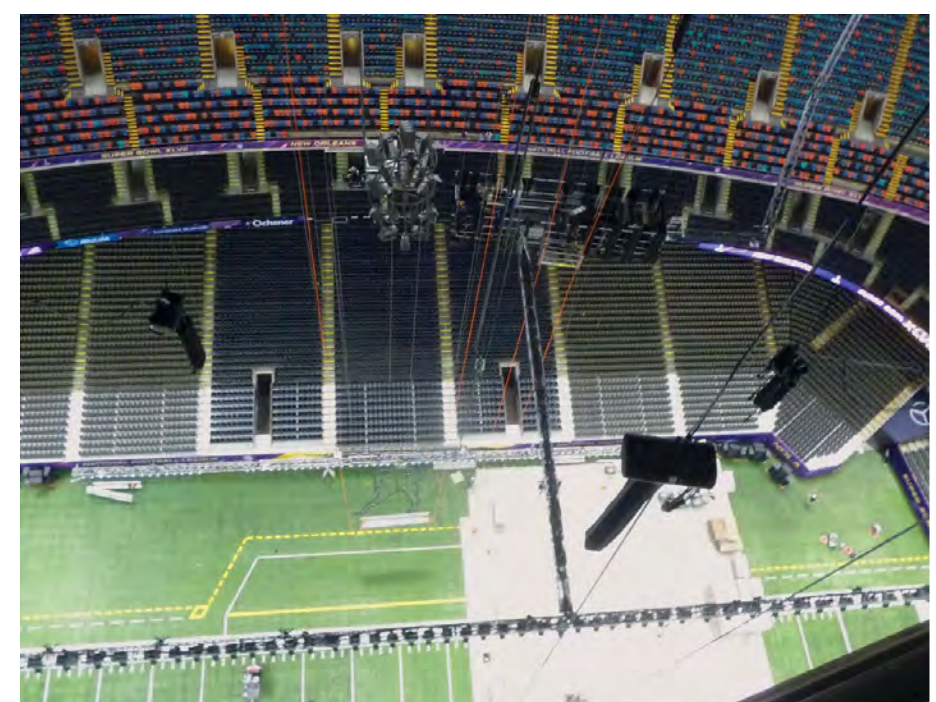
General Contractor: Champions Square
Gibbs Construction

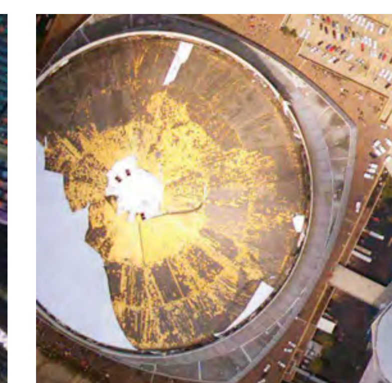
Completion Date
Investigation – 2006
Repair – 2006
Enhancements – 2010
Champions Square – 2011

Total Construction Cost
$336 million

Courtesy Bill Cobb, SKYLINESCENES.COM

• USE
• LOSS
• RENEWAL





Courtesy NOAA

Opposite page: the fully restored exterior.

Clockwise from top: Danny Vincens of LSED and H.B. Warner (right) and Wolfgang Werner (back) of Thornton Tomasetti inspect damage to the roof and perimeter gutter; the roof after Hurricane Katrina struck; enhanced interior and rigging for the Super Bowl halftime show.

David B. Seide Defined Space Chicago

Adaptive Reuse of Soldier Field

Chicago, Illinois

• **RENEWAL**

An extensive renovation of Chicago's historic Soldier Field tackled complex geometry and steel construction innovations. Thornton Tomasetti provided structural design services for the renovation, which fitted a new 61,500-seat stadium bowl into the 1920s shell and added parking for 2,500 cars.

To support the expanded stadium, 2,000 new piles were driven more than 90 feet down to bedrock. The added seats rest on precast concrete risers supported by structural steel rakers, with the rakers that support the upper grandstand extending 60 feet over the stadium's historic colonnades. The structure for new luxury suites wraps around the corners of the field, cantilevering 100 feet over the end-zone seating and providing support for massive video screens. Twenty-one tuned-mass dampers, located at the tips of the grandstand cantilever, dissipate vibrations to maintain spectator comfort.

To meet the fast-track 20-month schedule, our team modeled the steel frame in XSteel 3D (now Tekla) software. We used the model to automatically generate documentation for the steel, then provided the model to the fabricator for connection detailing to shorten the design review process. We also shared our model with the cladding fabricator. The availability of precise 3D geometry for the steel work also expedited the design and assembly of the stadium's non-rectilinear, panelized façade system. This early use of 3D modeling prevented costly miscues from design to fabrication and installation, benefiting all project stakeholders.

Client
The Chicago Bears Football Club

Architects
LW+Z, a Joint Venture of Lohan Caprile Goettsch Architects and Wood + Zapata

General Contractor
TBMK, a Joint Venture of Turner Construction Co., Barton Malow Co. and Kenny Construction

Completion Date
2003

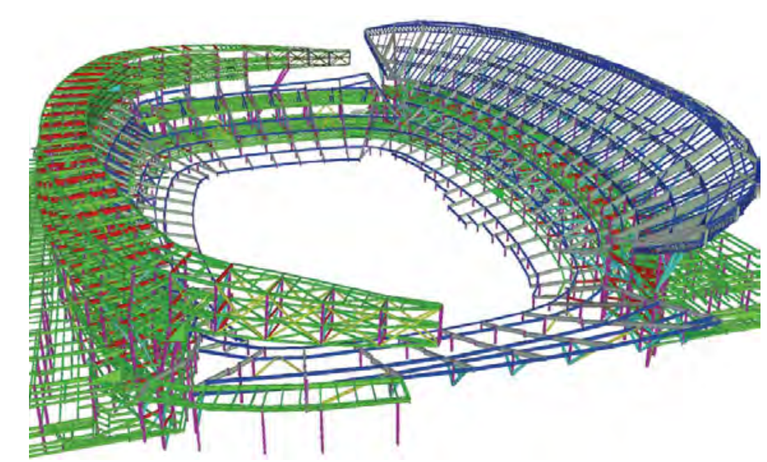
Construction Cost
$500 million

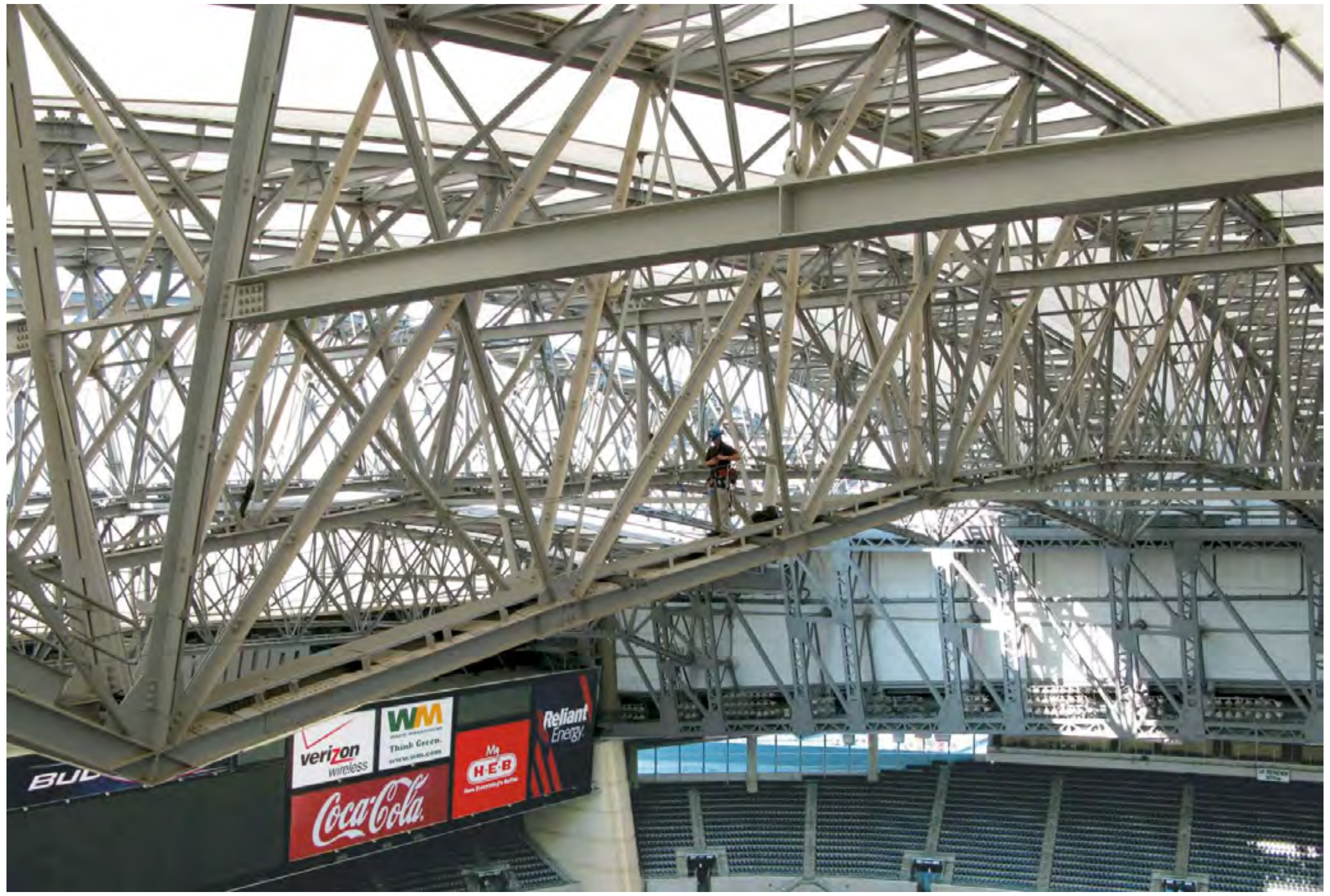
Total Area
1.5 million sf / 139,400 m²

Seating Capacity
61,500

Awards
2003 Overall Project of the Year, Midwest Construction magazine

2004 Best Structure Award, Structural Engineers Association of Illinois (SEAOI)





Reliant Park Complex, Hurricane Ike Response

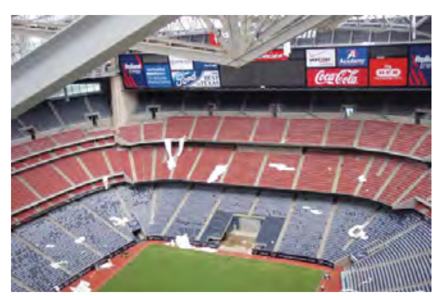
Houston, Texas

Owner
Harris County Sports & Convention Corporation

Client
Confidential

Total Area
4.2 million sf / 390,200 m²

In the immediate aftermath of Hurricane Ike in September 2008, 25 Thornton Tomasetti professionals from nine offices converged on Houston, Texas to provide emergency response services. Led by our property loss consulting experts, teams of engineers and architects experienced in building skin, structure and performance worked together to assess and document damage at Reliant Park. The 36-acre sports and entertainment complex consists of four main structures: the 71,500-seat Reliant Stadium, home of the National Football League's Houston Texans; the Reliant Center exhibition and conference facility; the multipurpose Reliant Arena; and the 65,000-seat Reliant Astrodome.


Dave Harvey

Work included an investigation to determine the cause and origin of the unanticipated failure of the retractable steel and fabric roof structure. The investigation involved a detailed review of the roof's original structural design and connection details and an analysis of the effects upon it of hurricane-force wind and rain. We developed an initial material testing program, determined wind loading parameters, and performed an independent analysis to determine the tensile strength of the fabric, cable stress levels and maximum/minimum deflections of the system. We also used 3D modeling of the structure to check the behavior and interaction of the steel and fabric.

• LOSS
• RENEWAL

Old Yankee Stadium Deconstruction

Bronx, New York

Client
Stantec Consulting

Owner
New York City Department of Parks & Recreation

Owner's Agent
New York City Economic Development Corporation (NYCEDC)

Construction Manager
Turner Construction Co.

Subcontractor
Demco, Inc.

Completion Date
2010

Construction Cost
$25 million

We drew upon an array of services and resources to devise a safe and environmentally responsible plan to dismantle the original 759,000-square-foot Yankee Stadium after completion of the team's new Thornton Tomasetti-engineered stadium across the street.

We prepared performance and planning documents for the engineered deconstruction and helped the team navigate a complicated New York City agency review and permitting process. We also provided construction support services, assisting in the development of feasible approaches and submitting a general sequence plan for the work. We built a comprehensive 3D Revit model of the stadium, which was used to analyze multiple options and plan and monitor the demolition sequence.

Our on-site responsibilities included field observation, as-needed engineering consulting, analysis of the deconstruction process, and assessment of the work's quality and timeliness for NYCEDC.

The plans for deconstruction also considered the specifications and elevation requirements for the site's next use: a public park with baseball fields, comfort stations, a play area and rain garden. The park also includes commemorative features – plaques, benches and an outline of the original Yankee Stadium field – that connect the site's rich history with its present and future.

• RENEWAL

Courtesy Chris Linder

We love to work on sports projects. But when the work is done, it's the experience of the fans in the stands that matters most.

Kelly Koscielney of Thornton Tomasetti and LeeAnn Trevino of Clark Construction at the newly renovated Rose Bowl in Pasadena, Calif.

Game day at Yankee Stadium. Tom Scarangello (left) and Mike Squarzini of Thornton Tomasetti with Bradd Crowley (center) of Populous.

Thornton Tomasetti's Young Nam (right) and Gary Moon of tBP Architecture take in a game at Angel Stadium in Anaheim, Calif.

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