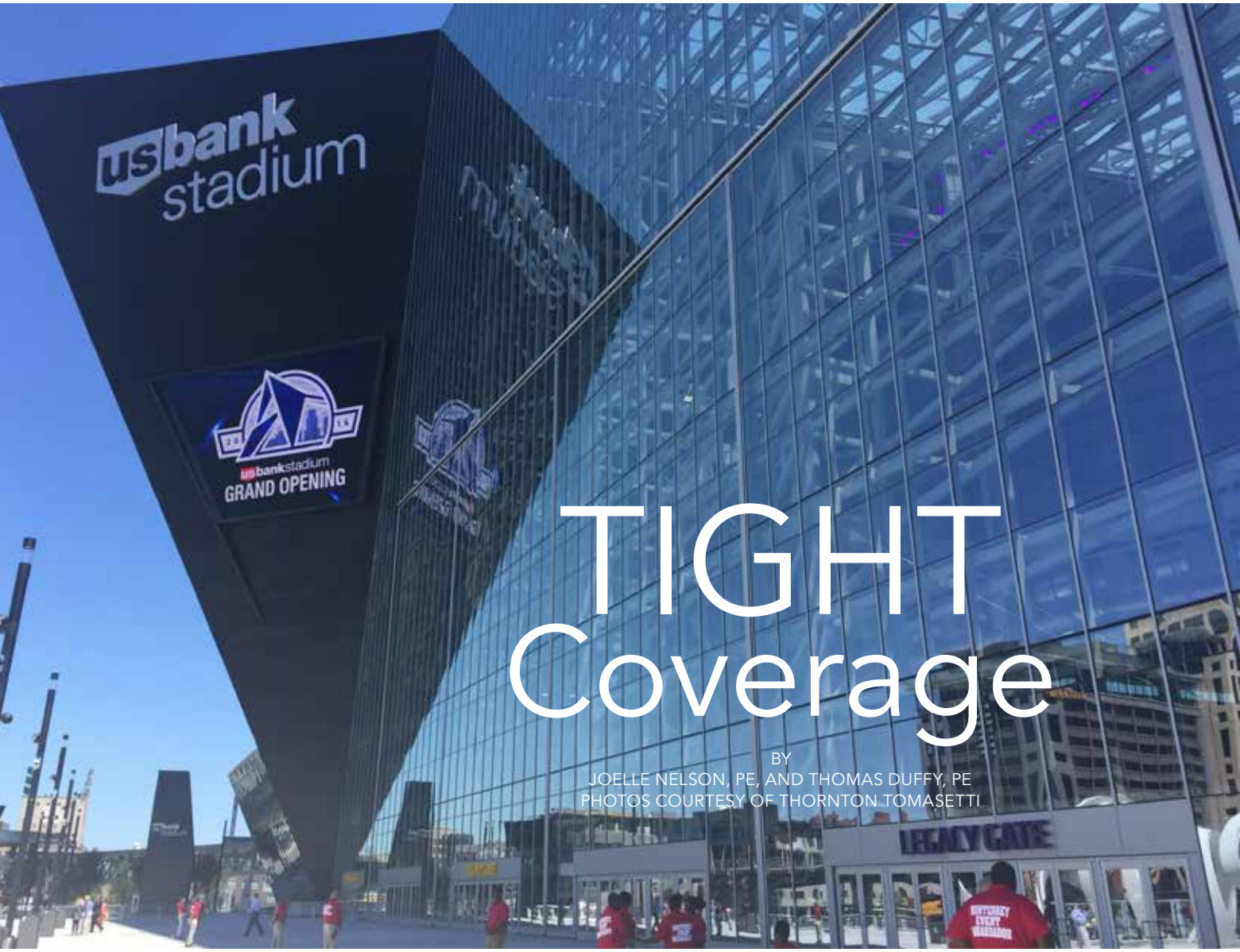
The new home of the Minnesota Vikings ushers in a new age of NFL stadiums with its steel-supported ETFE roof and giant operable wall panels.



TIGHT Coverage

BY
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PHOTOS COURTESY OF THORNTON TOMASETTI

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U.S. BANK STADIUM gives Minnesota Vikings fans the best of both worlds.

With natural sunlight pouring in through the clear roof and the glass western wall, the stadium conveys a feeling of being outdoors without subjecting fans to the sometimes harsh winter weather conditions and extreme temperature swings for which Minnesota is well known—especially late in the NFL season.

This outdoor experience is exactly what stadium officials were looking for, though not quite how they imagined it. The trend

U.S. Bank Stadium, which opened in time for the 2016 NFL season, seats more than 66,000 and is expandable to 73,000.

Each panel has a triangular truss that wraps around a 36-in.-diameter steel pipe building column.

in state-of-the-art stadiums was to incorporate a retractable roof, and that's what the Minnesota Sports and Facilities Authority initially envisioned. However, after much consideration the design team, led by architect HKS and structural engineer Thornton Tomasetti, determined that with Minneapolis' ground snow loads in the range of 50 lb per sq. ft and drift loads over three times that, a retractable roof, which would rarely be opened, would come at a hefty price tag. Instead, they presented the idea of a fixed transparent ETFE (ethylene tetrafluoroethylene) roof, the largest application of its kind in North America, paired with the world's largest pivoting wall panels—and that is what the project team delivered.

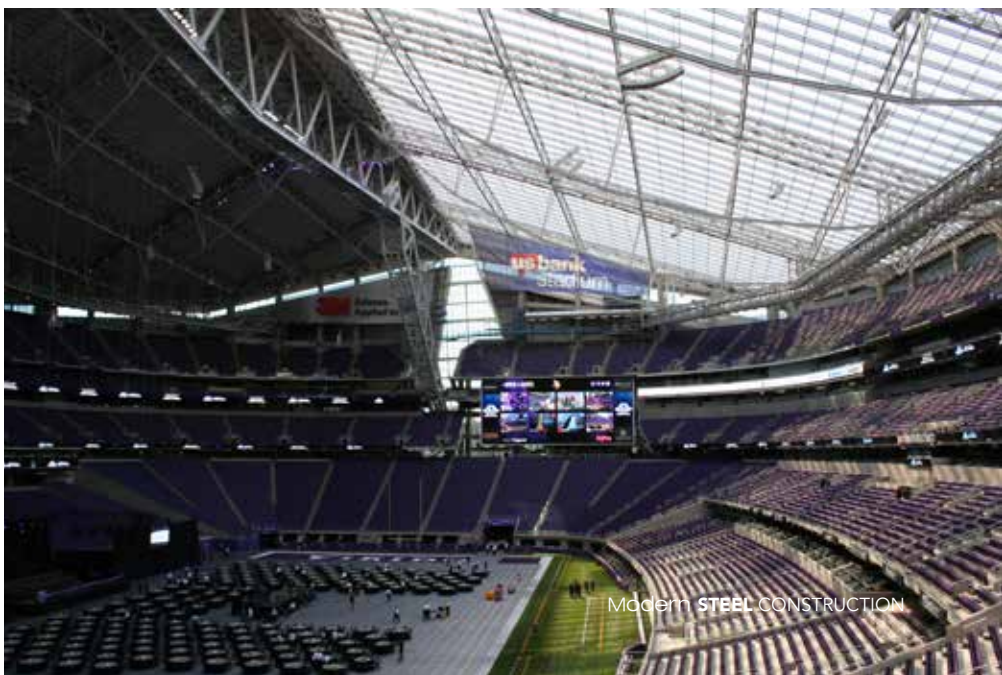
In Motion

Without the constraints of a retractable roof, the design team was free to shape the roof in a way that best accommodated the environmental and structural needs. And while the sharp peak and slope of the roof (which is supported by a 989-ft-long, 1,700-ton ridge truss located 214 ft above the field) make an architectural statement, they came as a result of snow load studies performed by RWDI in coordination with Thornton Tomasetti. The two companies worked together to optimize the roof slope for reduced snow loading, and the slope, orientation and low friction coefficient of the ETFE material allow snow to slide off the roof instead of accumulating and ponding—a problem at the old Metrodome. At U.S. Bank Stadium, the heavy, sliding snow is safely captured and contained by a sophisticated snow catchment system, where it is melted and drained away.

An operable wall, not subject to snow loading, was another suitable option for Minnesota and an appropriate complement to the roof. However, this type of wall comes with an entirely different set of design challenges, and a pivoting operable wall had never been achieved at this scale before. Located at the main entry point for the stadium along the western face, the operable wall consists of five panels that, when open, form an opening in the west wall roughly nine stories high and nearly as long as the football field itself. Each wall

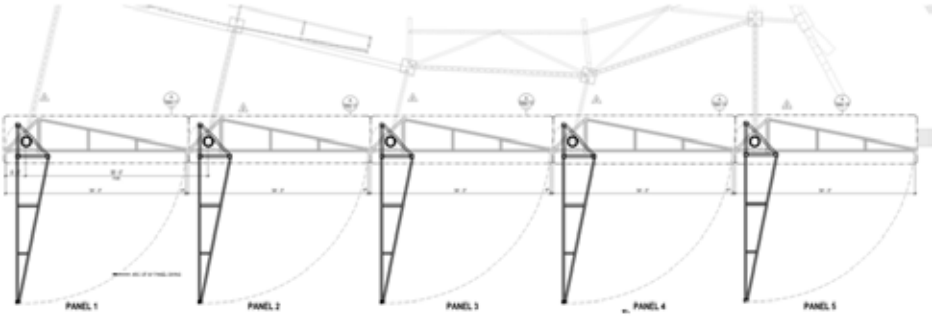
The pivoting wall panels are the world's largest.

The ETFE roof is the largest of its kind in North America.



Doors in doors: ground-level access doors in the movable wall panels.

A diagram of the panel walls, open and closed.



The new roof was designed to easily handle Minneapolis' high snow loads.

panel, ranging between 75 ft and 95 ft in height and 57 tons to 68 tons in weight, pivots open 90°; 6 ft of the 55-ft width of each panel swings inward into the main concourse space behind the facade, and the remaining 49 ft cantilevers out into a large public plaza. Doors of similar size would typically slide like a hangar door, and a pivoting panel of this size was unprecedented and uniquely challenging to design.

Triple Option

Each panel has a 10-ft-deep vertical steel truss, triangular in plan, that wraps around a 36-in.-diameter steel pipe building column, which also supports the upper concourses and roof. The truss geometry incorporates Vierendeel panels to provide clearance for rotating through the W33 and W36 girders that extend out of the pivot columns to support the upper stadium floors. This tri-chord truss, comprised of standard box HSS, forms the spine of the panel, with a series of cantilevered wings (also made from box HSS) extending off the truss to support the glass curtain wall. Steel rods run diagonally, serving a triple purpose: providing gravity support for the cantilevered wings, stiffening the panel and plumbing the panel during erection. The eccentricity of the facade load to the panel structure would pull the panel open at the top tip, so the engineers carefully calculated the pretension in each rod to resist this effect and keep each panel plumb.

Each panel's mechanical components, designed by Hardesty & Hanover in close coordination with Thornton Tomasetti, consist of an upper bearing, a lower bearing, three pairs of hydraulic cylinders and three to four actuating lock pins. The entire weight of each panel is supported by a spherical thrust bearing at the bottom, which, along with an HDPE (high-density polyethylene) sleeve bearing at the top, provides the lateral support for the panel, with allowance for differential movement between the panels and the stadium structure. Three pairs of hydraulic cylinders within the tri-chord truss serve as the driving force behind each panel, rotating the panels open and closed in five minutes and providing torsional resistance to the wind load.

Force to be Reckoned with

The eccentric gravity load from the panel's 49-ft cantilever imparts a significant horizontal force to the upper bearing at the top of the door and the lower bearing at the bottom of the door. The direction of this horizontal force changes as the door swings open, and the building structure

Since the wall panels serve as the main entry point for the stadium even when they are closed, they include a series of standard entry doors at the base. These door banks must be ADA-compliant, so only a minimal threshold was allowed.

had to be designed to resist this force in any direction with limited deflection.

The panels are not to be operated when wind loads exceed 40 mph, but they are designed to be held open in a 67.5-mph wind, which equates to a one-year recurrence interval. For the full-design wind event, a 90-mph wind, the panels are closed and pinned together by a total of 19 actuating pins. (An anemometer has been placed in the stadium's parking lot to alert officials when the wind speeds get too high and the panels should be closed.) While NFL regulations require that the panels be either open or shut prior to kickoff and remain in that position throughout the entire game, they allow for them to be closed should wind speeds become suddenly elevated.

The final design of the wall panel structure was completed in SAP2000, with the hydraulic cylinders treated differently under various stages. For the stationary conditions, the hydraulic cylinders are locked-off such that they behave as rigid supports—but lateral load due to overturning is to be resisted entirely by the upper and lower bearings. Therefore, using non-linear construction sequencing, each pair of cylinders was initially modeled as a torsional support and replaced by a pair of lateral supports only after the panel self-weight was added to the model.

When the panels are operating and the wind is blowing, the hydraulic cylinders do not respond as rigid supports. Instead, the control system delivers equal pressure (and load) at each pair of cylinders. For each load case, the reaction in the cylinders had to be calculated by hand and applied in the model as loads.

Sealing the Perimeter

While all of the above may sound challenging, many on the design team would say the most difficult aspect of the operable wall design was the perimeter seals. Because Minnesota has such a wide temperature range, high winds and heavy snowfall, weather-tight seals were absolutely necessary. However, this large temperature swing also causes significant thermal movement. The vertical seals are formed as the tip of one panel presses against the butt of the adjacent panel. Given the multiple swinging parts, thermal movement, curtain wall depth and minimum clearances when any single panel operates, achieving weather-tight and architecturally pleasing seals that function optimally under Minnesota's extreme temperature conditions required extensive collaboration between design team members and mock-up testing.

On top of this, because the wall panels serve as the main entry point for the stadium even when the panels are closed, they include a series of standard entry doors at the base. These door banks must be ADA-compliant, so only a minimal threshold was allowed. Thus, the personnel doors themselves form a tight seal at the base when the panels are shut but also clear the ground so as not to drag while the panels swing open. Therefore, each wall panel has an operable door bank. Before the wall panel swings open, the entire door bank, consisting of five sets of standard double doors, raises up 4 in. while the remaining length of the panel has operable sills—small panels at the base that lift a few inches before the wall panel moves.

Using 17,250 tons of structural steel, the stadium is ready for whatever the weather can throw at it, and the 66,655 Vikings fans that fill it on football Sundays (seating capacity is expandable to 73,000 for the Super Bowl) will experience the game in a first-of-its kind venue that adds a whole new dimension to the game-day experience. ■

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