Complex connections in the structure's 3D, triangular trusses were simplified by the expeditious use of custom-designed cast connections.

Turning the Corner with Steel Castings

LeMessurier Consultants

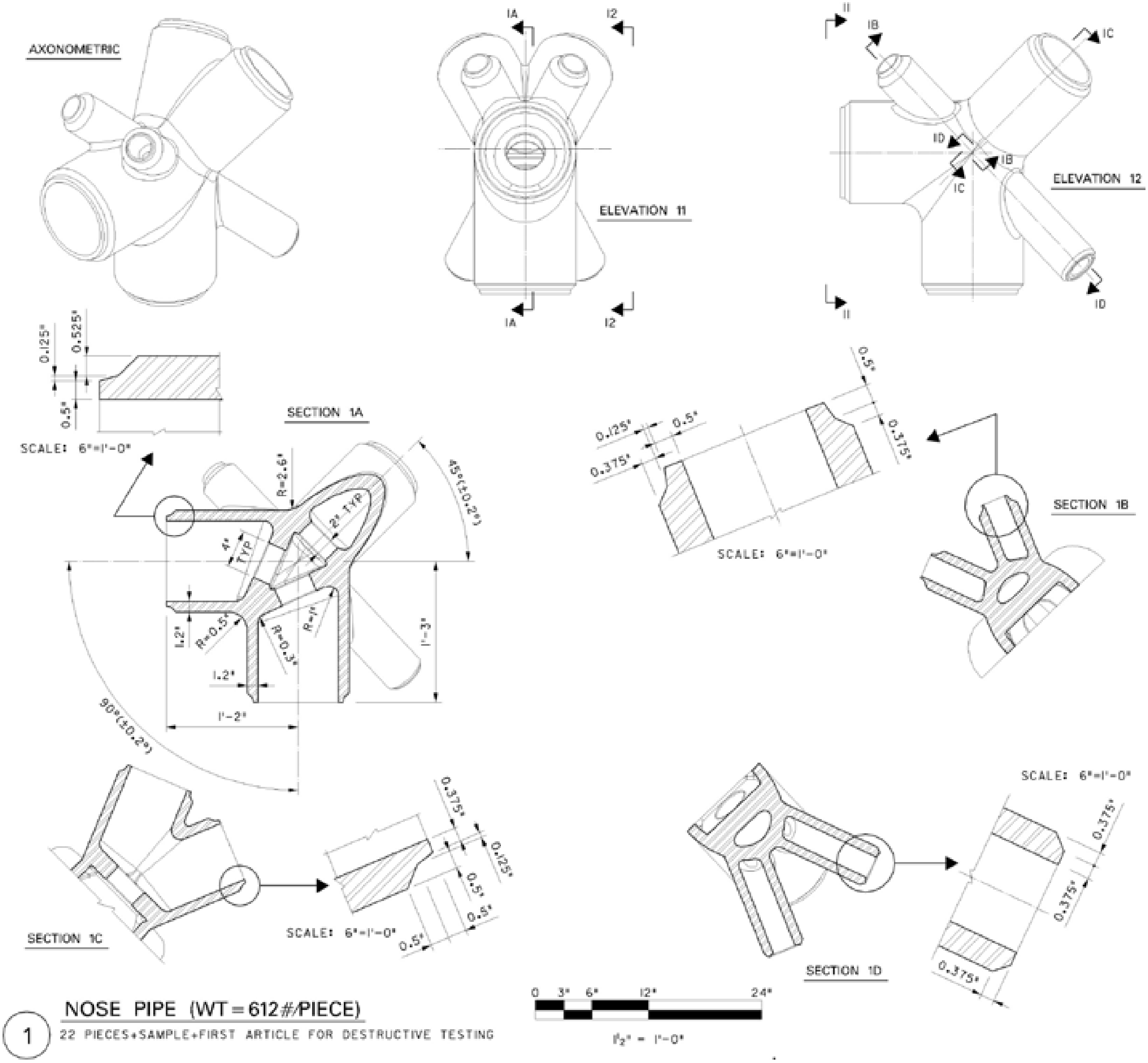
BY ERIC M. HINES, P.E., PH.D., AND WILLIAM C. GIBB

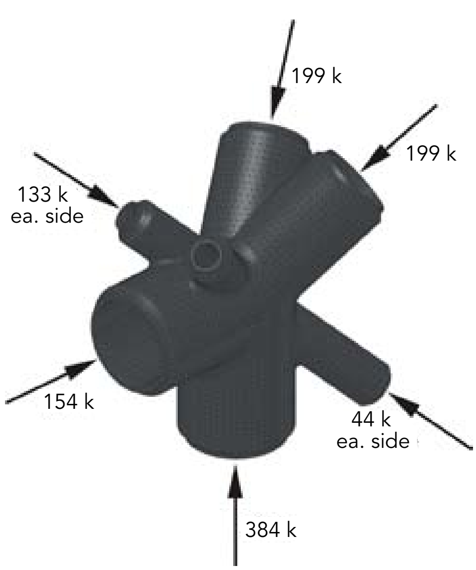
THE RECENTLY COMMISSIONED Wind Technology Testing Center (WTTC), in Charlestown, Mass., was designed to test a new generation of wind turbine blades for offshore wind farm development. Whereas the largest blades for land-based wind farms in the United States are currently on the order of 50-m (164-ft) long, and generate 2-3 MW of power per turbine, offshore wind turbines are expected to reach power outputs as high as 10 MW and require blade lengths of up to 90 m (295 ft) within the next 10 years. In order to support American research, development and manufacturing of these blades, the Department of Energy (DOE) helped fund the WTTC as the nation's first high capacity blade testing facility near a deep-water port. The WTTC is the largest facility of its kind in the world and has the capacity to test up to three 70-m-long (230 ft) wind turbine blades simultaneously or a single blade up to 90 m (295 ft) in length.

Vertical and horizontal testing protocols for the largest blades, which are expected to deform up to 40 m (131 ft), resulted in a 312-ft-long, 144-ft-wide and 82-ft-high laboratory. Within this volume are three test stands, two 50-ton cranes, hydraulic testing equipment and office spaces. In order to permit future expansion of the facility in its lengthwise direction, the laboratory enclosure is supported by 11 modular steel trussed frames, spaced 30 ft on center. The 7-ft-deep, 3D frames are supported by stiff reinforced concrete grade beams on piles that form part of the testing structure. The presence of such an extensive foundation system made it possible to fix the trussed frames at their bases and achieve a high level of lateral stiffness for a relatively light and slender structural system.

In concept, the enclosure was designed for maximum regularity, both to accommodate the facility's bridge cranes and to keep costs low. Close attention to the opportunities and constraints posed by the building's program and site enabled the owner and design team to create a structure that expresses elemental power with refinement and grace.

Fixing the trussed frames to the foundations made them self-stabilizing in all directions, and obviated the need for a conventional





This page: The nose pipe, where eight truss elements come together, was one of four castings used to make the WTTC modular steel truss frame connections.

Opposite page: Components for the Wind Technology Testing Center's triangular trussed frames were 80-ft-long pieces trucked in as standard loads.

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William Gibb

➤ Once the casting design has been finalized, a pair of very precise wooden patterns are made, one for each half of the casting. The completed nose pipe casting will look like the dark areas shown here. The smaller yellow area on the left is the runner system where the liquid metal is introduced into the mold. The small yellow squares are locations for chill placement. Chills absorb heat to control the cooling and solidification process.

➤ Sand is compressed around the wooden pattern to create an individual mold for each casting. Somewhat like a jig saw puzzle, additional pieces of sand called cores are placed into the mold to create the complex shape required. The picture shows the bottom half of the mold with cores in place. The hollow cavities are the area that will be filled with steel.

lateral system. In the transverse direction, the lateral capacity of the frames is similar every 30 ft, placing minimal shear demands on the roof diaphragm. The 3D, triangular trusses eliminated the need for out-of-plane bracing of the bottom chords and reduced the clear spans between trusses down to 22 ft. At this span, it was possible to use 7½-in., 16-gage, roof deck without purlins. The premium spent on the roof deck and frames was offset by the savings from a reduced piece count and simplified roof erection, which proceeded 82 ft clear above grade.

In order to simplify the typical 3D connections between diagonals and chords, the trusses were assembled from round HSS and steel pipes. Pipe sizes and panel points were selected to ensure that no diagonal pipes would overlap at their connections to the chords, resulting in 8-in. tail pipes and 10-in. nose pipes, with 4-in. diagonal members. The roof trusses themselves weigh 6 psf, while the frames as a whole, including roof and column trusses, weigh 12.9 psf. To facilitate drainage and increase the midspan bending capacity, the roof trusses taper linearly in depth from 7 ft at either end up to 8.5 ft at the midspan.

The most significant challenges posed by the trussed frames were their connections at the transitions between truss columns and roof trusses. These joints experience the highest loads in the trusses—netting as much as 440 kips in the vertical direction and 330 kips in the horizontal direction. They also are required to connect up to eight pipes converging at a single panel point. In light of these conditions and the expected difficulty in fabricating the trusses to the desired tolerance, LeMessurier designed these joints as steel castings. Keeping the 11 frames identical with respect to these joints made the castings economically competitive, and designing them in-house allowed for their bidding and fabrication to proceed within the project schedule. The concept of castings accompanied the first frame sketches and remained an integral part of the design through construction.

Months before construction documents were issued, LeMessurier began working with Steel Cast Connections, LLC, Seattle, to develop economical and constructible castings. As part of an iterative collaboration, LeMessurier developed potential casting designs in Solidworks for low weight and high strength before sending *.igs files to Steel Cast Connections, who evaluated possibilities for improving the constructibility of the castings. Steel Cast Connections provided pricing during this process, allowing LeMessurier to assess whether the castings were a viable alternative to welded steel joints. LeMessurier also worked with Steel Cast Connections to develop a separate specification on steel castings, which was included with the construction documents.

With 22 nose pipe joints, 44 tail pipe joints, 44 mid-height drag nodes, and 42 end truss X-joints, pattern costs assumed approximately 20% of the total cost for all castings, and confirmed a real economy of scale. Because many members of the design and construction teams had not worked with castings in the past, the teams placed special emphasis on assessing whether the frames or castings could be value-

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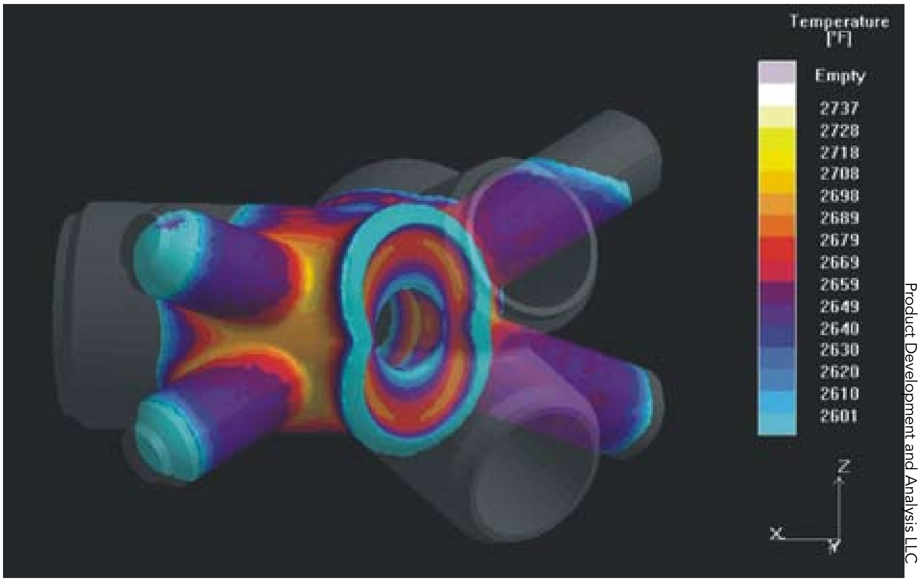
➤ A pattern like this is made for each casting design, then used repeatedly for each casting. This pattern is for the nose joint where eight members come together. The three tall yellow conical items are the risers into which additional liquid steel is supplied to the casting as it shrinks.



Product Development and Analysis LLC

This model of the nose pipe casting was made by the foundry's consultants, Product Development & Analysis LLC, to determine how to arrange the risers and the chills for the cooling process.

The nose pipe castings developed for the WTTC weigh 612 lb each. This photo taken in the fabrication facility shows one installed in a truss and two on the shop floor.

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The trussed frames were fixed to the foundation and self-stabilizing in all directions. Building end frames (left) were designed with additional bracing in between the tail pipes for additional torsional capacity.

engineered. As a result of these assessments, the fabricator ultimately adopted the castings on the construction documents as the joint design of choice, and the project was delivered on time and on budget.

Trusses were shop fabricated in four sections: north column, south column, north roof truss, and south roof truss. The roof trusses were spliced with full-penetration field welds on site before being lifted into place on the truss columns. Field connections between the roof trusses and column trusses also consisted of full-penetration field welds between the castings (connected to the roof truss) and the truss column pipes. The truss column diagonals at the highest elevation between the nose pipe castings and the column tailpipes were installed last. Once all of the trusses were erected, drag elements were installed between them and welded into place after truing. The trusses on either end were outfitted with X-bracing between the tail pipes for additional torsional capacity.

Making the Castings

Each casting was produced by filling a sand mold with molten steel and controlling the heat transfer process throughout the process of solidification, which started on the outside surface as dendritic crystals formed inward. In its liquid state the steel was highly expanded. As the casting shrank, the goal was to feed more liquid steel into the molten center until it finally solidified. Places that got cut off from this feed metal would develop small hollows called shrinks. Due to their relatively smooth boundaries, shrinks do not have the same tendency to grow as cracks do. Increased size and frequency of shrinks, however, reduces the quality of a casting and changes its structural behavior. For this reason, much of the casting design, production and testing for the WTTC revolved around minimizing shrinks.

During the design process for the joints, LeMessurier and Steel Cast Connections worked together to develop criteria for providing reasonable structural behavior, solidification and cost. Production costs for a casting are closely correlated to its weight, so one design objective was to make the castings as light as possible. For bidding purposes, the expected weight of each casting was included on the construction documents.

Proper solidification required that the casting forms be as simple as possible and that certain minimum clearances be maintained. Strength required simple load paths, adequate area and smooth transitions. Fortunately, strength and solidification requirements had much in common, so the design process for the castings became an attempt to balance these two requirements with the objective of reducing weight. The castings represented on the construction documents had been designed and modeled rigorously for strength and weight, while reflecting good practice with regard to solidification.

Steel Cast Connections teamed up with structural steel fabricator Cives Steel to win

Chuck Choi

Individual wind turbine blades up to 90 m (295 ft) in length can be tested in the new WTTC facility. The cantilevered blades are subjected to a regimen of testing that includes bending moments of as much as 84 MNm (62,000 k-ft). The expected blade deflections dictated the lab's size and clear space requirements.

the competitive bidding process. Before finalizing the pattern designs, Steel Cast Connections made some final adjustments to the interior geometry of the castings. In general these refinements consisted of adding material in selected areas to facilitate the flow of molten metal through the part as it solidified. In addition, some heavy pieces of steel, called "chills," were placed in the molding sand to serve as heat sinks. These chills force certain areas to cool faster and allow tighter control of the overall cooling order. Extra pools of metal called "risers" were added to provide reservoirs that would be needed to fill the shrinking volumes during solidification. In a process similar to the evaluation of the castings' structural behavior, 3D computational models were developed to simulate metal flow into the mold and the solidification process. Subsequent destructive and non-destructive testing confirmed the accuracy of these simulations.

Once these final adjustments had been made to the designs, the next step was to create the patterns. Attention to detail in the initial pattern rigging design is the most important step for producing a sound casting. The WTTC patterns were made from wood with a very high level of precision and skill. Between the time that the castings first became solid and the time they reached ambient temperature, each part was expected to shrink by ¼ in. per foot, requiring the patterns to be slightly oversized. The same patterns were used for the entire run of each casting, whereas individual molds were destroyed during the process of pouring.

Once each mold was complete, the steel was transported from the melting furnace and poured at around 3,000 °F. After the casting cooled, it was broken out from the mold and placed into a furnace for normalizing, which reduced residual stresses in the part. Risers were removed and the part was ground to its final shape. Each part received a final heat treatment, and the quench and temper process was applied to produce a uniform and refined grain structure.

In order to confirm the process a large number of tests were performed on the finished parts according to contract specifications. This testing consisted of magnetic particle testing (MT), radiographic testing (RT) and destructive testing along with material certifications and CVN testing. The first article of each design was physically cut into pieces to confirm the internal integrity and the results of non-destructive testing. The consistency among solidification models, the RT testing results and this dissected sample port was impressively high. This supported the idea that casting quality depended less on variations in workmanship than would complex weldments for the same joints.

Visually, the most compelling aspect of the WTTC castings is their success in making the tough transition between roof truss and column appear effortless. Up close, the castings are powerful, organic and streamlined. From the lab floor, they are hardly visible. This is their beauty. By other means, these joints would call attention to themselves and interrupt the flow of the frames. The castings make it possible for the frames to appear fully integrated, even rhythmic. Because the WTTC offices are located in the midst of the north truss columns, lab personnel and visitors experience the mid-height drag node castings up close, making this contrast between human scale and building scale a defining part of the WTTC experience. MSC

For additional information on other aspects of this project see "Testing Tomorrow's Turbines," Civil Engineering, *July 2011, pp. 64-71.*

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The new Wind Technology Testing Center laboratory enclosure is supported by 11 modular steel trussed frames fabricated using cast steel nodal connections.