Project Title: Massachusetts Large Blade Test Facility

Covering Period: 8/31/2009 to 8/30/2011
Date of Report: July 29, 2011

Recipient: Massachusetts Clean Energy Center
Award Number: DE-EE0000495


Cost-Sharing Partners: Massachusetts Clean Energy Center
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Project Objective: The Massachusetts Clean Energy Center (CEC) will design, construct, and ultimately have responsibility for the operation of the Large Wind Turbine Blade Test Facility, which is an advanced blade testing facility capable of testing wind turbine blades up to at least 90 meters in length on three test stands.

Background: Wind turbine blade testing is required to meet international design standards, and is a critical factor in maintaining high levels of reliability and mitigating the technical and financial risk of deploying mass-produced wind turbine models. Testing is also needed to identify specific blade design issues that may contribute to reduced wind turbine reliability and performance. Testing is also required to optimize aerodynamics, structural performance, encourage new technologies and materials development making wind even more competitive. The objective of this project is to accelerate the design and construction of a large wind blade testing facility capable of testing blades with minimum queue times at a reasonable cost. This testing facility will encourage and provide the opportunity for the U.S wind industry to conduct more rigorous testing of blades to improve wind turbine reliability.

Design and Construction Team: The WTTC team, working with the Massachusetts Port Authority as our construction agent and utilizing the Commonwealth of Massachusetts procurement process, selected Architerra, Inc. and Turner Construction Inc. as the prime contractors for design and construction of the facility. The design team, most notably the structural engineering firm LeMessurier Consultants, were responsible for the design of the building and test stands. Turner Construction and its subcontractors, most notably the concrete firm Francis Harvey and Sons, were responsible for the construction of the facility. Turner Construction is an international firm with notable projects like Yankee Stadium and the Burj Khalifa tower in Dubai. In addition, top wind consulting firm DNV-GEC and European labs Blaest and Narec were tapped to review and assist with the facility design from an operational standpoint.

Job Creation: We estimate that approximately 50 FTE years were created for design/engineering jobs and 250 FTE years created for construction jobs.
Site as of June 30, 2011

Status:

April 1, 2011 to June 30, 2011 activities include the completion of the project.

The images below illustrate the finished facility.
Project Summary --- June 2009 to June 2011:

The laboratory features three post-tensioned concrete test stands supported by a massive reaction footing on drilled concrete shafts. Wind turbine blades can be mounted to these test stands as cantilevers for static and dynamic testing with an unprecedented range of loading regimes in vertical, horizontal and biaxial directions. Blades are mounted to the concrete test stands via 20ft diameter, 74ton, precision machined steel faceplates. The laboratory is enclosed by eleven steel trussed frames 140ft wide and 82ft high, spaced 30ft on center. The 7ft deep, three-dimensional frames are fixed at the base and self-stabilizing in all directions. The most complicated joints for these frames were developed as elegant structural steel castings in order to carry substantial joint loads, facilitate fabrication and erection, and reduce cost.

Location: access to open ocean via Boston Harbor
The caisson drill drove down 165 feet to the bedrock below. Numerous rebar cages were constructed and installed in the 165 foot bore holes and then encased in concrete to structurally support the building and prevent shifting and settling.

A partially assembled caisson drill and a rebar cage is pictured above.

On average each caisson was drilled to approximately 179 feet and filled with 110 cubic yards of concrete.
Caisson drill rig pictured here.

There are 18 caissons and 54 piles in total providing stability to the building.

Pile installation pictured here.

Concrete Test Stand Structures:

Shown above is the rebar, or reinforcing steel, and formwork for the reaction footing mud mat, or the concrete layer between the ground and the test stand structure. Concrete was poured into this structure in order to create a flat working surface from which to start the process of building the reaction footing.
Shown above is the reaction footing mud mat, which was poured over the rebar in the previous picture. The mat took 150 cubic yards of concrete to pour. The blade test stands were built up from this structure. Take note of the anchoring caissons and protruding rebar, which go to a depth of 160 feet. The caissons anchor the test stands and provide the needed stability for decades of blade testing.

The reaction footing, the structure built up from the mud mat, contains approximately 90 tons of rebar, some of which is pictured here to the left.
The reaction footing is a complex structure with thousands of individual pieces of structural reinforcing steel elements. The elements were assembled in stages. The picture below depicts the vertical stands which provide support for horizontal bars which in turn provide additional support.
Shown above is the reaction footing support structure with post tension strands (PT strands). The horizontal galvanized ducts contain the PT strands which are cables that were tensioned after the reaction footing was poured.

A total of four layers of PT strands were incorporated into the reaction footing structure.
Shown above are the two hoses from the concrete pump trucks. The hoses were lowered into the rebar cage at different locations throughout the reaction footing where the concrete was pumped and vibrated in order to bring the concrete to grade in a uniform manner. It took 165 concrete trucks and 1650 cubic yards of concrete to complete the footing.
Shown below is the reaction footing post pour. The formwork has been stripped and the concrete curing blankets reinstalled. After 28 days of curing time the PT strands were tensioned: providing the compressive strength needed to resist the forces of large blade testing.
Shown below is the tying of the strong slab rebar mats. The entire area was poured with concrete and provides additional strength.

Shown here is the completed strong floor.
Shown below is post tensioning of the reaction footing. The PT strands are fed into the jack which pulls on the cables and tensions them to 5600 PSI. Half the strands were tensioned to their full design strength prior to the test stands being poured. After the test stands were poured the remaining PT strands were fully tensioned.
Shown below is formwork for test stands 1 and 2. Ironworkers and carpenters installed the test stand rebar, 3 inch pipe sleeves, and other pieces.
Shown here is the layout of the faceplate for test stand 2. The wooden discs are the locations of the thru rods that hold the faceplate to the test stand. 65mm ducts were installed on these discs and continue to the west side of the formwork where there is an identical layout of the faceplate to accept the duct.
Here ironworkers are installing vertical bars. These connect into the reaction footing for strength. The bottom of the picture shows the rebar and PT duct lattice work that occupy the whole of the formwork.
Shown below are test stands 1 and 2 in the final phases of preparation for concrete pouring.
Shown here is test stand three. Rebar and PT ducts were installed and forms erected on each side. Then the structure was filled with concrete. Note the 4 foot diameter steel pipe in the center. This large duct gives blade testing technicians access to the interior of the blades for affixing sensors, studying internal blade structures, etc.
Test stands 1 and 2, as shown below, have cured and the forms and blankets removed. Carpenters have added safety rails to the perimeter at the top.
Test stand 3, as shown below, is cured and the forms and blankets removed. Carpenters have added safety rails to the perimeter at the top.
Faceplates:

The faceplates are 12 in. thick, 20 ft diameter steel plates, to which blades are mounted via threaded metric bolt circles. The size and thickness of these 74 ton plates required them to be fabricated and shipped in sections to the site. Fatigue stress concentrations at the bolt holes were studied in detail via three dimensional finite element analysis with non-linear contact elements. Interaction between the threads and hole edge stress concentrations was mitigated by countersinking the threads 100 mm beneath the front surface of the face plates. Each face plate is post tensioned to its test stand with approximately 22,000 kips of force, but is also designed to be demountable and replaceable, pending future use and the actual fatigue performance of the post-tensioning bars over the life of the lab. For the safety of the laboratory personnel, special retainer systems were designed for the face plate bars to dissipate the bars' full elastic strain energy should fatigue fracture occur.
The faceplates had to be fabricated in quarter sections due to their size. The quarters of steel have a 10 foot diameter and a 12 inch thickness. They weigh approximately 50,000 pounds each. Steel mills could not produce steel of this thickness any wider than 10 feet so the faceplates had to be produced in quarters.
The sheer size of the plates make this facility unique in the world.
The post-tensioned (PT) face plates, test stands, reaction footing and drilled shafts were designed to resist high-cycle fatigue loads under \( N = 10 \) cycles—orders of magnitude higher than common criteria for components in the civil engineering industry. Special tests were conducted on 1.75 in. diameter 150 ksi cold drawn PT bar assemblies with nuts and couplers in order to establish appropriate mean stresses, half-amplitude stresses and endurance limits. Both the mean stress levels and the number of cycles for these tests were unprecedented. An image of a fractured test bar (below) shows the portion of the bar where fatigue cracks grew over the life of the loading (approximately 30% of the area) in contrast to the portion of the bar that fractured under the mean stress load after full crack growth.
Bar stresses and test stand concrete stresses were assessed with the help of three-dimensional finite element models (below). The test stands and reaction footing were designed with uniformly distributed post-tensioning stresses in all three directions in order to prevent them from experiencing tension except at the highest stress concentrations. The absence of cracking in the structure allowed for reliable models to be run with elastic elements. The final model of the test stands included loads representing each bar so that stresses could be assessed in cases where individual bars had been compromised during construction.
A principal tensile stress contour image (below) shows the rear faces of test stands 1 and 2 without PT under load case 5: biaxial fatigue loading of a 90m blade on test stand 2.
**Steel Truss Erection:**

The laboratory is enclosed by 11 steel trussed frames, each 140 ft wide, 82 ft high, and 7 ft deep. Spaced 30 ft apart and fixed at the base, the three dimensional frames are self stabilizing in all directions.

The triangular trussed frames required no additional bracing besides the roof deck and their connections to the grade beams. The minimization of framing and bracing members outside of the trusses simplified erection, especially for the 82 ft high roof. These trussed frames are composed of 8 in. tail pipes and 10 in. nose pipes with 4 in. diagonal members. The frames could be very light, thanks to their continuity and the fact that their bases could be fixed to the grade beams. To facilitate drainage and increase the midspan bending capacity, the roof trusses taper linearly in depth from 7 ft at the ends to as much as 8.5 ft at the midspan. Custom steel castings were designed for the corner nose pipe and tail pipe joints, as well as for joints at the midheight splices of the truss columns. The midheight castings and the tail pipe castings were fitted with attachment points for drag elements made from 8 in. diameter pipe that runs the length of the laboratory and helps stiffen the truss columns in torsion. The drag elements enable the building to resist wind in the east–west direction as a unit. For such a light structure, however, it was important to design the system with some redundancy. Therefore, the trusses on either end were outfitted with X bracing between the tail pipes for additional torsional capacity. These end trusses are equipped to carry the entire wind load on the east or west face of the building. The X connections in these trusses also were designed as steel castings. Trusses were fabricated in the shop 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 they were lifted into place on the truss columns. Field connections between the roof trusses and the column trusses also took the form 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 tail pipes were installed last. Once all of the trusses were erected, drag elements were installed between them and welded into place after truing.
Exterior metal panel erection:

The exterior metal panels were chosen for their speed of erection and insulating properties. Each panel is manufactured with an inner and outer layer of steel with four inches of foam insulation sandwiched between. The steel provides structural rigidity and the insulation is comparable to the materials used for industrial walk in freezers. The panels help stabilize the internal temperature of the laboratory easing the strain on the heating/cooling system.
Plans for Next Quarter: None, facility complete.

The schedule (see below) presented last quarter has facility completion by the end of March-2011. Facility was completed and commissioned in May-2011.

Patents: N/A

Publications / Presentations/Travel:
Dedication Ceremony:

On May 18th, 2011 we celebrated the official opening of the WTTC. In attendance were Governor Deval Patrick of Massachusetts, Congressman Edward Markey, Congressman Michael Capuano, and Mayor Thomas Menino of Boston. The wind industry was represented by officials from Clipper Windpower, Gamesa, Blade Dynamics, etc. Chris Hart from the Department of Energy was in attendance as well as wind team members from NREL and Sandia Labs.

As a reference, in May 2009 Secretary of Energy Steven Chu and Governor Deval Patrick announced the U.S. Department of Energy’s award of $24.7 million in funding from the American Recovery and Reinvestment Act to accelerate development of the WTTC. In the picture below the WTTC site is the parking lot in the background.
Commissioning Process:

The construction management team along with the design team completed building related commissioning in accordance with relevant building codes and regulations. Included in this group are life safety systems, HVAC, etc.

The blade test equipment was installed and commissioned by representatives from NREL and MTS systems working with WTTC staff. We acquired a 47.5 meter blade with known test results and used the WTTC test equipment to test the blade to confirm our readings are within an acceptable range.

Design and Construction Challenges:

We encountered PCB’s on the site and had to find creative solutions to cost effectively manage the contaminated soil. For example, we raised the reaction footing of the test stands four feet above ground to eliminate the need for costly specialized soil erosion systems required if we were to dig six feet below ground as originally specified.

Our needs for testing modern and future blades required a clear span of over 125 feet. LeMessurier Consultants had to design a unique steel support structure utilizing custom castings.

The steel faceplates, the connection interfacing with the blades, are 12 inch thick plates of steel. They are so heavy they could not be made in one piece. Manipulating and installing these pieces to the strict tolerances presented unique challenges. Steel beam cradles were designed and constructed to support each piece during the installation. The WTTC bridge cranes were used to lift the faceplate pieces into position.
## Project Schedule and Milestones

**Award No. DE-EE0000495**

<table>
<thead>
<tr>
<th>Task Number</th>
<th>Title or Brief Task Description (EXAMPLES)</th>
<th>Task Completion Date</th>
<th>Progress Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Select Construction Manager at Risk for the facility construction</td>
<td>Sep-09</td>
<td>July-09</td>
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<tr>
<td>2</td>
<td>Final 1\textsuperscript{st} early package facility subsurface foundation design documents approved by DOE and NREL</td>
<td>Oct-09</td>
<td>Oct-09</td>
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<tr>
<td>3</td>
<td>Plan demonstrating how project will meet ARRA requirements</td>
<td>Nov-09</td>
<td>Dec-09</td>
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<tr>
<td>4</td>
<td>Final 2\textsuperscript{nd} early package including concrete for subsurface and superstructure</td>
<td>Jan-10</td>
<td>Oct-09</td>
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<tr>
<td>5</td>
<td>100% preliminary design for full facility</td>
<td>Jan-10</td>
<td>Oct-09</td>
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<tr>
<td>6</td>
<td>Final facility and shell design documents approved by DOE and NREL</td>
<td>April -10</td>
<td>March-10</td>
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<tr>
<td>7</td>
<td>Completed facility substructure construction</td>
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<td>8</td>
<td>Begin facility shell construction</td>
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<td>9</td>
<td>Completed facility shell construction</td>
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<td>10</td>
<td>Begin facility commissioning</td>
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<td>11</td>
<td>Completed operational facility</td>
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