Balancing Act

Atop the completed building, the 747 awaits the installation of water slides which will exit the fuselage and drop sixty feet into the waterpark's interior pools. Courtesy of Jeffrey Diephuis.

By Jeffrey Diephuis, P.E.

The newest building on the Evergreen Aviation & Space Museum campus in McMinnville, Oregon, inspires amazement. It appears as though a massive 747 aircraft is sitting on top of the structure and, indeed, it is. This surprising sight sets a precedent in structural engineering, as never before has anyone placed a plane so large on the roof of an erected building.

On a campus known for the Howard Hughes' HK-1 flying boat (commonly known as the Spruce Goose) and a Titan II rocket, this milestone project is fitting. Visitors who come to marvel at the HK-1's vast size or the Titan II's enormous length in the adjacent buildings will soon be able to splash down from the 747 plane atop the new Wings & Waves Waterpark building as well. Stairs will lead guests into the rooftop attraction where water slides will spill from the aircraft's fuselage and into the building's wave pool 62 feet below.

Group Mackenzie of Portland, Oregon, provided the architectural and structural engineering design for the building, working in a design-build collaboration with Hoffman Construction Company.

Taking Off

Positioning the recently decommissioned 747-100 cargo plane on the constructed building required a carefully engineered solution. Despite the fact that they take to the skies daily, 747s are enormously heavy and lifting one requires exceptional effort. Completing the lift meant raising the 269,000-pound plane 55 feet into the air and transporting it 165 feet to perch atop the building frame. The construction team considered a myriad of variables including weight distribution, balance, wind speed, crane travel speed, and clearances between the crane, plane, and building.

Without access to a mobile crane that had the capacity to lift the airplane and reach over the completed building structure, the construction team had to devise a scheme for placing the 747 on the partially completed building. The resulting plan required one-third of the roof structure and the second floor mezzanine to be left unconstructed in order to provide a "slot" in the structure for crane access to the plane's final location.

Hoffman, along with their steel erection subcontractor Carr Construction of Portland, Oregon, asked Portland's KPFF Consulting Engineers to assess the plane's stability throughout the lift's phases. KPFF was also charged with bracing the incomplete structure to carry the aircraft's weight and resist added wind and seismic loads from the 747 while the structure was completed. KPFF and Hoffman collaborated with Carr Construction and Campbell Crane to identify the best solution – balancing the needs of the project schedule, construction sequence and cost. The team launched a 3-D modeling effort, which allowed them to virtually experience every step of the complex lift, move and landing, with accurately modeled building, crane and plane elements.

The first task in preparing for the lift was to determine the needed bracing for the incomplete building and accommodate construction sequencing. In addition to typical erection bracing, two temporary steel braced frames were added to resist wind and seismic loads on the building and airplane. The engineers designed the frames to resist 120kips of lateral force each. Each frame consisted of W8 wide-flange braces which connected to the building's concrete column and tubular-truss gravity framing system. After erecting the remaining building structure and completing the lateral system, the construction team removed the temporary frames from the structure.

The lifting procedure involved two cranes; however, the project marks the first time an aircraft of this size has been lifted with one principal crane. A Manitowoc 2250 with MAX-ER served as the primary crane, while a Leibherr LTM 1400 with luffing jib positioned over the nose served to control the plane's orientation and

The 747 was lifted approximately 6 feet off the ground during the test pick. Courtesy of Jeffrey Diephuis.

The plane approaches its maximum height on lift day. Courtesy of Evergreen International.

guide the nose to its rooftop support point. KPFF programmers customized a commercial crane-modeling program, and incorporated it into a 3-D computer model including the building framing and the plane. The innovative model allowed the team to track the movements of the plane and cranes throughout the lift and travel sequence. This model played an instrumental role in ensuring that the lift plan maintained adequate clearances between the plane and the cranes' booms and building structure during transport.

In planning the lift, the team established a clearance "safe zone" for the lifting/travel sequence. After initial model runs, the construction team was not comfortable with how close the body of the plane came to the boom. The team took advantage of the model's flexibility to explore various other equipment configurations for the lift. By varying the angle and length of each crane's boom and the angle of the plane to the travel path, the clearances between the plane, cranes and building were maximized. The team also removed wing flaps from the plane itself to increase the safety margin. Demonstrating this result before the actual lift would not have been possible without the 3-D model.

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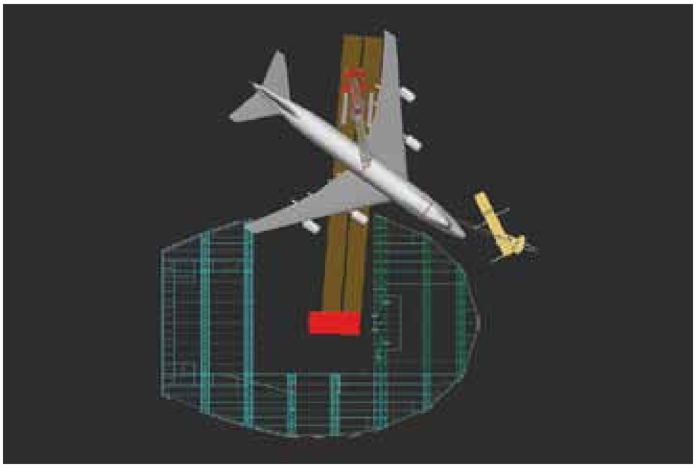
The plane in its final position on the roof of the partially completed structure. Courtesy of Jeffrey Diephuis.

The sophisticated 3-D model was intended for planning purposes, but the team also used the results in presentations to the owner, insuring agencies and stakeholders to show that the lift and placement could be completed effectively.

Dave Garske, project manager at Hoffman, says the model was also a resource for addressing issues in the contractor's detailed pre-engineering erection plan. "We wanted the team's responses to dozens of questions including design questions regarding what we'd do if the crane did not perform as expected, physical questions like 'what if a crane operator became ill', or environmental questions like 'what if the wind speed was higher than design limitations?' These types of 'what if' questions were critical on this project in particular, as this type of lift had never been done. By using the model, there was no second guessing on the day of the event."

Achieving Cruising Altitude

When the plane reached the site, the team removed its four 12,500-pound engines and replaced them with a light skeletal structure to support the engine cowlings, bringing the plane's weight to 269,370 pounds. Determining the center of gravity and subsequent loads for each crane required an extensive engineering effort. Calculations revealed that engineers needed to add ballast in the nose to provide the two-crane lift with an adequate factor of safety against tipping on its tail when raised. The team loaded eight water tanks providing 23,260 pounds of ballast, which increased the total weight to 292,630 pounds. The lift required 31,135 pounds of rigging resulting in a total "hook" load of 323,765 pounds. During the hoist, the Manitowoc 2250 bore 294,390 pounds while the secondary crane carried the remaining 29,375 pounds.



Plan view of the lift model showing the partially completed structure, the plane and each crane part way down the travel path. Courtesy of KPFF Consulting Engineers.

Positioned on the port side of the aircraft, the Manitowoc lifted the plane using a custom-designed and fabricated 38-foot long, 18,000-pound spreader. This bar was positioned over the wing and attached through the wing to the wing landing gear structure on each side. The secondary Liebherr crane used a standard spreader bar that attached to a Boeing recovery sling, which cradled the fuselage of the aircraft. These planes are so rarely lifted from above that only seven sets of 747 recovery equipment exist, and these are positioned around the world for rapid deployment in emergency and salvage operations.

One variable remained: even aviation experts and engineers could not fully predict how a static plane would react when suspended, so the team executed a test pick. They lifted the aircraft approximately 6 feet off the ground on a day with 10- to 15-mph winds. The test helped validate the center of gravity determined by calculation and reconfirm the actual crane loads. It also showed that the wind resulted in an unacceptable amount of sway.

"The plane did what it was designed to do; it reacted to the air currents and wanted to fly," explains Garske. "The team multiplied surface area by wind pressure to approximate the force required to resist the influence of the wind on the plane's position. The result was an estimated 1,100 pounds of force. What remained unknown was whether two men on a tag line could resist this influence and adequately control the position of the plane from the ground." Garske continued, "We did another test pick the following day and were able to absolutely confirm that two men on a tag line could control the plane's movement. That gave us a level of confidence."

Touching Down

In May 2010, the team raised the plane, transported the massive shell 165 feet and lowered the aircraft into the nose gear cradle first. Then they eased the rest of the plane into wing and fuselage gear cradles, designed by Group Mackenzie in consultation with Boeing engineers. After the team successfully "landed" the 747-100 on top of the waterpark building, crews bolted it into place and performed the welds to permanently secure the aircraft at its five landing gear positions. Only then did the huge Campbell Cranes release it completely. Over the following weeks, the contractor erected the remaining roof and mezzanine structure around the aircraft. Evergreen officials plan to open the $25 million waterpark in mid-2011.▪

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