The Brookfield Floating Bridge

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ABSTRACT: The Brookfield Floating Bridge was originally built in 1820 and has been rebuilt several times since. The proposed flotation system for the current structure consists of ten FRP pontoons joined to form a monolithic float. The top-side of the structure is constructed entirely of timber to match the aesthetic appearance of the original construction. The project incorporates four major structural materials (FRP, timber, concrete, and steel) and project-specific design criteria for FRP and floating bridges.

BACKGROUND

The floating bridge over Sunset Lake in Brookfield, VT is an historic structure which was originally built in 1820. During this era, residents elected to travel across the frozen Lake during the winter months to reduce commute duration as opposed to walking around the shoreline – an approximate 1 mile shortcut. One winter, after a tragic accident, logs were placed on the frozen lake to strengthen the crossing. Once the ice melted in the spring, the logs remained floating and residents continued to cross the Lake.

Since that time, 6 additional versions of the floating bridge have been built in the same location – the one discussed herein is the eighth generation.

The most recent structures at the site were comprised of timber framing and cribwork surrounding numerous individual floats – a 1936 version utilized old whiskey barrels and the most recent version from 1978 (see Figure 1) used “off the shelf” plastic floats often found in residential docking. Since both of these versions depended on a combination of flotation devices and the buoyant nature of timber, neither version had a definitive transient load capacity yet were historically posted at 3 tons.

Figure 1: Recently completed 1978 version of the floating bridge.

Aspiring to improve upon past versions, the Vermont Agency of Transportation (VTrans) defined a set of goals for the new structure and selected T.Y. Lin International (TYLI) as the prime consultant to help achieve these goals. The bridge was to be more durable, maintenance-free, modular to aid in potential major repairs, and more predictable (e.g.: the ability to load rate the structure with a degree of accuracy).

In addition to goals related to the structural behavior of the bridge, the structure was also bound by a handful of historic, American with Disabilities Act (ADA), and resource impact requirements. The proposed structure would need to look like previous versions from the top-side (timber appearance), include two, 5 ft sidewalks, limit approach ramp slopes to 8% upward and downward, and the abutments could not move from their current location at the shoreline.

STRUCTURE DEFINITION

ALTERNATIVE SELECTION – The project began with an alternative selection process that focused heavily on pontoon composition. All other primary project elements had been predetermined by historic, ADA, or resource impact requirements such as abutment location, approach ramp length, and the use of timber for the deck, sidewalk, and railing.

The goal of this phase of the project was to perform just enough investigation and analysis of concrete and fiber reinforced polymer (FRP) pontoon alternatives to qualitatively compare a variety of considerations and select an option to move forward with. Resource impacts, inspection access, maintenance, durability, cost, redundancy, and appearance, among other aspects, were considered.

Preliminary design results for the concrete alternative yielded the need for twelve, 11 foot wide, 10 foot deep, and 42 foot long hollow boxes with 8 inch walls (Figure 2). Due to their size, these would be cast on-site, have access ports to allow internal inspection, and would require temporary and permanent lake dredging to avoid bottoming-out from transient loads.

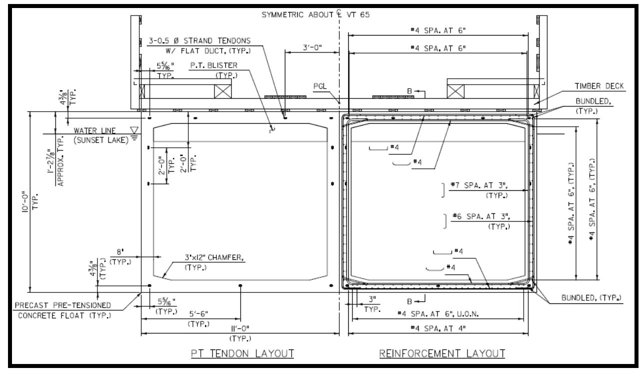

Figure 2: Concrete pontoon alternative.

Preliminary design results for the FRP alternative yielded the need for ten, 11 foot wide, 3 foot deep, and 51 foot long pontoons with an average wall thickness of 1.5 inches. Due to their shallow depth, internal inspection was not considered a viable option so the pontoons would be foam filled to offer a redundant flotation system. Resource impacts would be significantly lower than the concrete alternative due to off-site construction at a specialized fabrication facility and no need to dredge the lake. A partial section of the FRP pontoons with timber decking and final superstructure items is shown in Figure 3.

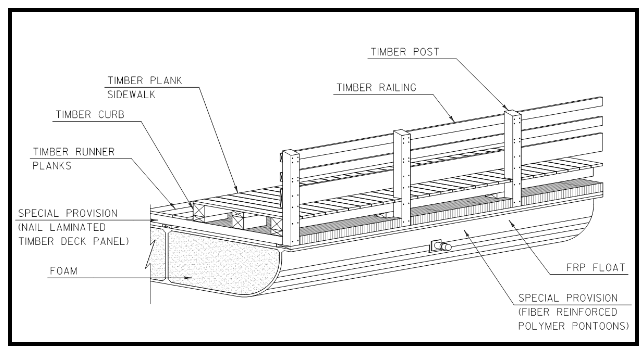

Figure 3: FRP pontoon with timber decking, sidewalk, and railing.

Final comparisons of the alternative selection phase yielded many common pros and cons between the two alternates, but the FRP alternate was selected for lesser impacts, a redundant flotation system, and was considered to be more durable than concrete for the anticipated environmental conditions.

DESIGN CRITERIA – Due to the lack of bridge design specifications for floating structures and the use of FRP as a primary structural material, a project-specific design criteria was developed. Preparation of the document began during the Alternative Selection phase of the project to aid in determination of pontoon type, but was further developed and refined immediately thereafter to progress the FRP pontoon design. In a broad sense, this document defines a number of design considerations common to traditional bridge design such as geometric needs, material selection, serviceability, design loads, and load combinations.

As the criteria developed, seemingly simple considerations often turned in to complex challenges to define. Development of the document was often faced with questions such as, what should the design temperature range be? What should the deflection limit be? Should a deflection limit independent of freeboard be considered and at what loading? Substantial research and coordination between TYLI and VTrans took place during the development of the design criteria to determine acceptable service conditions and loading parameters.

The final design criteria required that the bridge would be designed for a single travel lane and two, five foot raised sidewalks. The design live load is an H12 truck or equivalent lane loading combined with 65 psf pedestrian loading. The truck load is 4 times greater than load restrictions imposed upon past versions of the bridge and was selected to accommodate emergency vehicles. A multiple presence factor of 1.0 was used for all possible live load combinations. Dynamic load allowance (Impact) was not considered for design of the pontoons since it's assumed that the water provides substantial damping effects, similar to AASHTO's allowance for buried substructure elements.

Unique environmental loadings were also addressed in the design criteria. The bridge will remain in the Lake during winter months and not be maintained, therefore subject to static ice pressures and snow loads. A variety of sources were researched to determine appropriate ice loading on the pontoons and pressure gages were additionally installed in the Lake to better identify these loads (Figure 4). A surprising source to aid in this definition came from the local community which continues to hold ice harvesting festivals during late January. 32 years of historic records from this festival indicated ice thicknesses ranging from 8 inches to 26 inches, with an average thickness near 18 inches. Recognizing the pontoon design life of 100 years, a design ice thickness of 30 inches was used in design.

Figure 4: Ice pressure monitoring equipment.

Serviceability criteria focusing on in-service conditions and freeboard were discussed at length with maintenance crews and the local community. The Lake is dam controlled which provides a relatively stable water elevation. However, Q100 flood events could overtop the dam by approximately 5.1 ft and the approaches by approximately 2.3 ft. It was determined that an appropriate in-service limitation would have a lower limit of 6 inches below the dam control elevation (drought condition) and up to the point at which the approach roadway overtops at an approximate Q2 flood event. The structural and moveable components of the bridge are still required to accommodate flood events up to Q100 without damage, but the in-service range needed to maintain approach ramp grades that met ADA requirements (+/- 8%)

The targeted freeboard of the structure under live loading conditions was set to zero. This criterion was not necessarily a minimum value, but rather an overall target – the local community requested the travel surface to be as close to water level as possible. Avoiding overtopping of the deck under full live loading – considering patch loading of lane loads and pedestrian loads – limits the wet/dry cyclic exposure to the timber components under more routine loading conditions and also keeps water rout of the travel way, thereby avoiding potential hydroplaning concerns.

PONTOON DESIGN

DESIGN CONSIDERATIONS – Initial design focused on seemingly small details of the overall project that were identified as having major influences to the pontoon design. One of the first decisions to make was how to longitudinally connect the pontoons – pinned or rigid. Pinned connections are often used in residential floating dock systems, so this option was considered first. However, a quick investigation with this connection resulted in up to 8.5 inches of deflection at joint locations (Figure 5) due to concentric (transversely balanced) truck passage – deflections closer to 14 inches was found with an offset truck. It was assumed this type of motion would violate user comfort criteria for pedestrians on the sidewalks and therefore a rigid connection was advanced and mimicked a field splice connection found in traditional steel girder design.

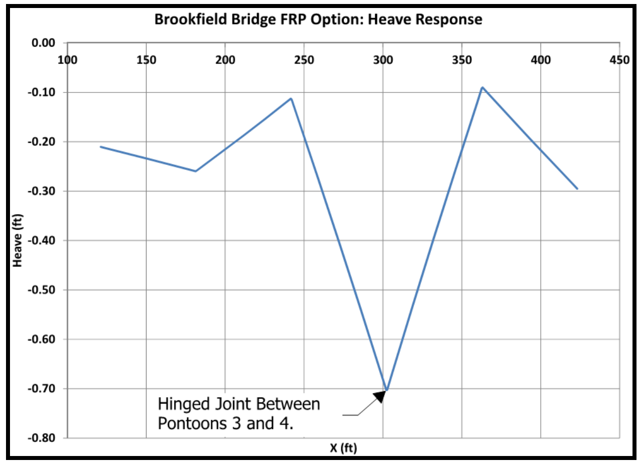

Figure 5: Heave Response for hinged pontoon connection investigation.

The other connection that received high attention early in the design phase was the connection of the timber deck to the FRP pontoons. It was agreed that inserts and bolts within the hull of the pontoons would be difficult to inspect and could become a weak point over time and be susceptible to leaking. For this reason, flanges were added along the top edges for connection locations. Flange connections are easily inspected, avoid penetrations into the flotation regions, and help meet Agency goals to have the pontoons modular for easy removal in the event of major damage.

One of the final considerations before directly advancing pontoon design was the overall geometry of individual pontoons. The length and width of pontoons was selected to be 11 ft and 50.5 ft respectively to allow trucking to the jobsite without the need for oversized truck permits. It was decided to intentionally curve the lower corners of the pontoons to aid in offsetting potentially large ice pressure loads (Figure 6). Since ice pressure acts normal to a surface, the curved corners will partially act as an arch in resisting ice loads and will also theoretically help “lift” the floating span out of the lake, thereby reducing ice pressures transverse to the bridge.

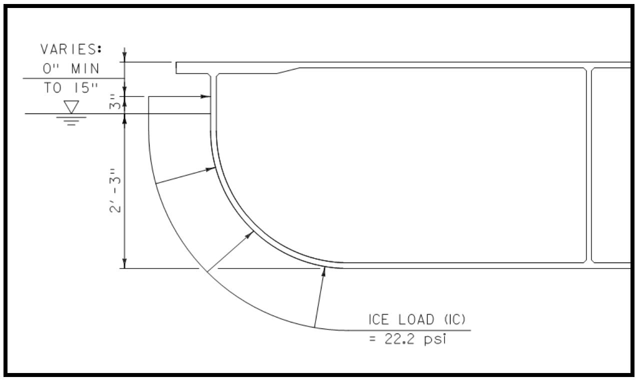

Figure 6: Curved pontoon edges with ice load application.

MATERIAL INTERACTIONS – The bridge incorporates four major structural materials: FRP, Timber, Steel, and Concrete. The interaction of these materials and their respective corrosion resistant systems posed challenges throughout the design process.

Timber swells and shrinks with changes in temperature and moisture content. To complicate this behavior further, these movements differ in the direction of the grain and against the grain by a factor of approximately five for the southern yellow pine selected for use. However, FRP does not swell with moisture and has nearly uniform thermal deformations, regardless of direction.

Accommodating differential movements between timber and FRP as well as designing the connections between the two materials was challenging. Thermal coefficients for FRP and timber normal to grain are approximately equal ($8x10^{-6}$ and $9x10^{-6}$, respectively). However, the coefficients are approximately 5x different when comparing to movement with the grain. Since the floating span is 22.5 ft wide and 256 ft long, it was decided to place the timber with its grain parallel with the transverse direction of the bridge. This would allow the movements along the span to be of similar magnitude and the resulting differential movement transverse to the bridge is less than 1/16 inch which could easily be accommodated with oversized connection holes.

FRP CHARACTERISTICS – Material properties of a given FRP laminate are difficult to predict and often require physical testing to substantiate design values. Fabric type, orientations, fiber volume, and resin type each influence a laminate’s strength and stiffness and in different loading orientations.

In addition, even if a certain strength is targeted, difficulty in predicting the elastic modulus remains since it is not constant like steel or empirically related to strength like concrete. This makes structural analysis difficult since an understanding of a material’s stiffness is greatly important to determine deformations and force attraction through a structural system. The level of uncertainty in identifying the elastic modulus is of even greater importance for a material on an elastic foundation since the stiffness of the structure and the stiffness of the foundation interact to produce global responses. For example, the elastic modulus of a simply supported structure is linearly related to deformations yet bears no influence on moment demand. For the floating span “beam” modeled for this project, moment increases 3.5% and deformations decrease 2.5% with a 10% change in elastic modulus. These relationships generally conflict with one another in which low deformations are desired as well as low moment demand.

DESIGN APPROACH – Without being able to use a singular stiffness or known relationship between strength and stiffness, it was decided to investigate a range of values and envelope the results to account for the inherent variability. This approach considers increased force attraction due to increased stiffness as well as increased deflections from decreased stiffness. The extremes of this range are paired with conservative strengths (high stiffness, low strength and low stiffness, high strength) to ensure laminates could be fabricated to meet project needs.

Since FRP is not a common primary structural material in bridge construction or other similar practices, firm understandings of what fabricators were producing and what would be the most economical combination of material strength and plate thickness was generally unknown. To circumvent this issue it was decided to place the detailed design efforts in the hands of the fabricator as part of the construction contract.

Design phase efforts focused on global geometry definition, connections, interaction with the timber deck, and working through a sufficient number of model iterations and variations in stiffness and weight to define a set of parameters for the fabricator to work within. Four primary parameters were targeted as having a large influence on the outcome of the project and therefore enveloped values were placed in the Special Provisions:

1) Pontoon Weight – this parameter not only affects the live load capacity of the structure, but also the approach ramp grades. If the pontoons are too heavy, the deck will become submerged under live load; too light and the approach ramps will have an upward grade exceeding the 8% ADA requirements.
2) Pontoon Stiffness (E*I) – Deflections and force attraction are oppositely affected by changes in stiffness. A stiffer pontoon will deflect less, yet attract higher local forces.
3) Neutral Axis Location – Field connections between successive pontoons were developed with enveloped design loads, stiffness, and neutral axis location. Changes to this value affect load distribution at the field connections.
4) Minimum Plate Thickness – A ½" minimum plate thickness was identified.

To achieve a durable product, a handful of other parameters were imposed upon the fabricator including minimum fiber content, the use of either vinyl ester resin or epoxy resin, and the inclusion of an ultraviolet light inhibitor. Overall laminate layup, composition, use of stiffeners, and individual materials were the fabricators choice.

MODELING ITERATIONS – Two primary finite element models of the floating span were developed and iterated upon. A two dimensional line girder model was used to develop global responses and internal forces. A three dimensional model comprised largely of shell elements was used to determine localized responses, primarily to ice pressure and transient loads, and aided in determination of plate thicknesses for subsequent 2D models (Figure 7). Both models were supported by a continuous elastic foundation representing the buoyant nature of the water. Multiple combinations of FRP density, elastic modulus, and plate thicknesses were considered to comfortably envelope products being produced by large-scale fabricators.

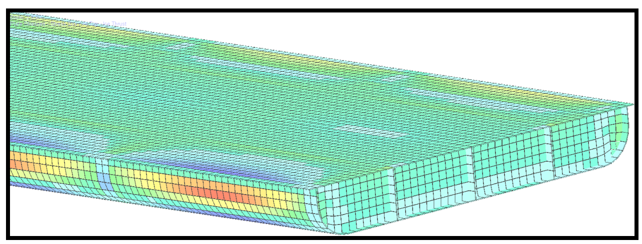

Figure 7: Finite element model showing exterior plate stresses due to ice loading.

The 2-D floating span model acts as a semi-finite length beam on an elastic foundation. Approximate methods for hand calculations are available for this type of analysis, but the process is tedious and correlations between response and changes in material properties are not direct. Since controlling load configurations weren't immediately obvious, it was decided to use influence line diagrams for unit vertical and horizontal shear, vertical and horizontal moments, heave response (displacement), lateral displacements, and roll (twist). Influence line report and step increments were 2.5 ft, or approximately 1/100th of the overall floating span. Example unit load results for heave and vertical moment can be seen in Figures 8 and 9.

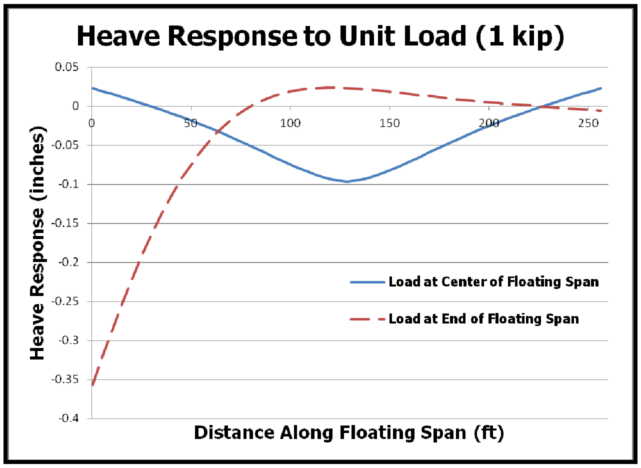

Figure 8: Heave response to unit load.

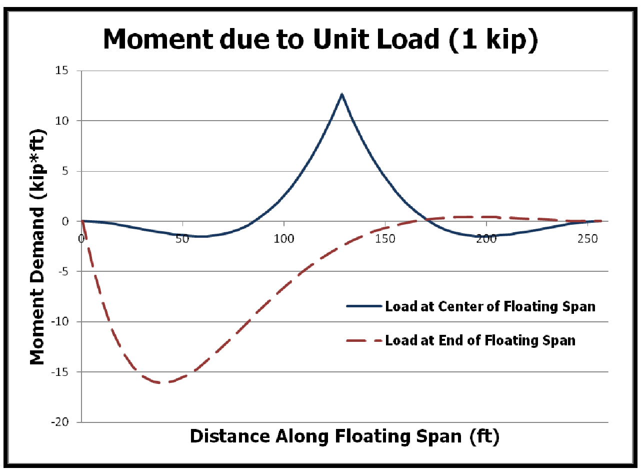

Figure 9: Moment demand due to unit load.

The results from the influence models were used to extrapolate controlling load patterns and load combinations for displacement, connection design, and internal bending moment. Once these controlling parameters were determined for a given model, adjustments to density and stiffness (and inherently strength to an extent) were made to determine upper and lower bound material properties that met project requirements.

The first iteration of the models utilized low-grade material properties that were assumed to be achievable by nearly any fabricator. This iteration resulted in preliminary plate thicknesses of approximately 2", corresponding to a maximum practical plate thickness for the production process specified. This model produced rather a rather heavy and rather flexible pontoon system – not overly conducive to deflection based design.

Iterations thereafter targeted more realistic material properties based on the use of vinyl ester resin and a 45% minimum fiber volume by weight. These iterations produced plate thicknesses between ½" and 1" and ultimately met deflection based needs to avoid overtopping from live load and to maintain ramp grades between +/- 8%.

In all, 12 models were created during the design phase to comfortably envelope internal forces, connection designs, limiting physical parameters for fabricator use identified earlier, and span end displacement ranges for use in joint and bearing design.

SPECIFICATIONS – As previously noted, the contract documents required the fabricator to complete the design – LRFD based – of the pontoons in support of the project, also known as a detailed design. This requirement allows the fabricator the flexibility needed to tailor a design to meet their specific operations.

The contract documents (Plans and Specifications) provided connection designs, global geometric constraints, localized designed loads, global design loads, sectional requirements noted earlier, load and resistance factors, and environmental reduction factors, among other minor design parameters. AASHTO Bridge Design Specifications load factors and combinations were paired with resistance and environmental reduction factors from the ASCE "Pre-Standard for Load & Resistance Factor Design (LRFD) of Pultruded Fiber Reinforced Polymer (FRP) Structures."

A three phase submittal process was required in support of the FRP pontoons: 1) a design calculations submittal, 2) physical testing, and 3) fabrication drawings. The design calculations submittal required the fabricator to acknowledge all project requirements, assume physical material properties of the to-be-fabricated FRP, and provide a sufficient level of detail within design calculations to prove an acceptable solution. This submittal was also to be sealed by a professional engineer.

Once the design calculation submittal was accepted by the Agency, physical testing of FRP laminates used in the design calculations commenced. 10 samples of 16 different ASTM tests were required to identify strength, stiffness, weight, hardness, absorption, and fiber content of the proposed FRP. The project Special Provisions set minimal material properties regardless of design, but also noted that material properties required of the fabricators design in excess of those noted in the special provisions became the new base values. Any substandard test results would require revisions to the design calculations to prove satisfactory design.

The final submittal required detailed fabrication drawings identifying fabric dimensions, fabric lap location, VARTM process, draw time, gel time, and peak exotherm among other procedural aspects. This submittal is used by the Agency and their inspector throughout production to verify the product being fabricated meets project requirements and the fabricator's intended means and methods.

Random testing was required during production – similar to concrete test cylinders – to ensure FRP produced in a large-scale environment was consistent with tests performed during the submittal phase, in support of design calculations. A 24 inch x24 inch witness panel was created with each pontoon for five coupon tests of six different ASTM tests. Three witness panels were randomly selected for testing and the remainder delivered to the Agency for potential future use.

CONCLUSION

Pontoon fabrication occurred from July through October 2014. Onsite assembly took place from September through November (Figure 10) allowing for continued timber construction throughout the fall and winter. The project completed in mid-May and a ribbon cutting for the local landmark was held on May 23.

Figure 10: Onsite construction; diver onsite for field connections.

The project involved the creation of project specific design criteria for the design of FRP, a floating span, and all geometrics, load combinations, and attachments needed to successfully complete the design. The bridge design was a once in a lifetime opportunity, but the structure will serve as a local landmark for generations to come.