Unprecedented Connections

Sound Transit's plan to operate light-rail vehicles on one of the longest floating bridges in the world has no precedent. But that did not stop an intrepid team of designers from developing and testing a novel system for ensuring the safe passage of light-rail vehicles across Lake Washington on the movable joints of the 5,700 ft long Homer M. Hadley Memorial Bridge.

By Thomas Cooper, P.E., P.Eng., M.ASCE, John Sleavin, P.E., Andy Foan, CEng, and Travis Thonstad

As part of the light-rail extension program known as the East Link Extension Project, Sound Transit, which plans, builds, and operates express bus, light-rail, and commuter train services for the urban areas of King, Pierce, and Snohomish counties, proposes to install light-rail tracks on the Homer M. Hadley Memorial Bridge, the widest and fifth-longest floating bridge in the world. Owned and operated by the Washington State Department of Transportation, the floating structure currently carries westbound and reversible lanes of Interstate 90 across Lake Washington between Seattle and Mercer Island. The approximately 5,700 ft long bridge includes concrete box girder approach spans supported by deep foundations, a floating span supported by pontoons, and transition spans connecting the approach and floating spans. Since there is no precedent in civil engineering practice, the placement of light-rail across the floating bridge presents unique challenges, including the design of a novel track bridge system to accommodate multidimensional movements at the existing expansion joints at which transition spans are connected to approach and floating spans. While all of the types of movement required have been accommodated on other structures, no structure has had to accommodate all of these movements together in the magnitudes required on this bridge.

In view of the importance of the floating bridge, the design requirements to ensure passenger comfort, and the complex design of the track bridge system, a robust program was developed to evaluate concepts, prepare detailed designs, conduct physical tests, and procure a system to carry light-rail vehicles from the fixed structures to the floating structure while meeting the necessary specifications for rider comfort and structural behavior. The work to evaluate and confirm the proposed concept designs included nonlinear finite-element analysis, detailed design, component testing, and full-scale prototype testing. These steps were required to evaluate the dynamic response of both the floating bridge and the track bridge under moving train loads and typical and extreme bridge movements.

For this turnkey research, development, and demonstration project, Sound Transit required the services of an integrated team that would include experienced structural, civil, and track engineers, as well as fabricators and constructors. This approach provides Sound Transit with the full resources of an integrated project team in which each member is ideally suited for its task on each phase of this unique, complex, and technically challenging assignment.

Seeking an innovative contracting method to develop this unique track bridge system, Sound Transit modeled its approach on the contracts used by the National Aeronautics and Space Administration. In the first phase of the

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0885-7024/14-0003-0056/$30.00 PER ARTICLE

As part of plans to install light-rail transit tracks on the Homer M. Hadley Memorial Bridge, Sound Transit hired a design team to develop a novel track bridge system to accommodate multidimensional movements at certain expansion joints on the floating structure, *opposite.* Full-scale prototype testing of the track bridge system included the use of actual Sound Transit light-rail vehicles to verify the performance of such elements as track bridge components, track fasteners, and rail expansion joints.

contract, the consultant was to develop at least one new concept, evaluate the existing concept, and run computer models to confirm the viability of each. The consultant was offered incentives in the form of increased design fees for developing a track bridge system that could accommodate a higher operating train speed and offer a shorter design and construction schedule. For the second phase, which involved testing, the design fee would start at a high level and decrease based on the amount of time and design hours required to validate the concept through prototype testing. The third phase, which involves constructing and installing the track bridge on the Hadley bridge, has not yet begun.

In November 2010 Sound Transit selected a team led by the Seattle office of Parsons Brinckerhoff and the Kent, Washington, office of Balfour Beatty to undertake the project. Although not technically advertised as a design/build contract, the procurement required the winning team to provide services pertaining to design, prototype fabrication and testing, and test track design and construction, as well as ultimately designing, furnishing, installing, testing, and, possibly, maintaining the permanent track bridge systems on the I-90 floating bridge.

A myriad of technical and commercial challenges and risks have been managed through structured risk management analysis, extensive computer modeling and analysis, component testing, and full-scale prototype testing. Furthermore, the project design has been refined based on the results of finite-element analysis modeling and physical testing. As part of this multiple-year, multiple-phase project, concept development was conducted step-by-step, enabling the design team to verify its theoretical calculations and track bridge performance parameters by means of modeling and physical testing.

The floating portions of the Hadley bridge are constantly moving because of a number of factors, particularly seasonal changes in lake level and temperature, wind and wave action, and roadway vehicle loading. Light-rail vehicle loading also will affect bridge movement. These movements vary in magnitude and frequency and are sometimes dependent on the time of year or human controls. What is more, the floating bridge could move as a result of bridge maintenance, an extreme weather event, or some other event, for example, the unlikely failure of the Hiram M. Chittenden Locks, which control the water level of Lake Washington.

To accommodate these movements and resolve competing design requirements, a feasible system was conceived, developed, analyzed, evaluated, and tested. The novel Curved Element SUpported RAil (CESuRa) concept is based on the interaction of curved track supports in two planes that adjust automatically to movements in the transition spans of the bridge. The innovative approach accommodates pitch, roll, and yaw, resulting in a uniform profile under all bridge movement combinations.

The purpose of the CESuRa system is to provide a smooth, load-bearing, curved track across a hinged bridge joint. The geometry is simple, and in the case of a joint that is essentially symmetrical about the bridge hinge and structural members that are thin, the smooth curve can be tangential at both ends. The CESuRa concept is based on four principles:

1) A hinge provided between two planes;

2) A curve of fixed shape on each of two secondary planes supported by the main planes and hinged with an axis along the longitudinal direction of the main planes;

3) Actuation of the secondary planes by the main planes;

4) A surface that continues from one main plane through the smooth curve and onto the second main plane.

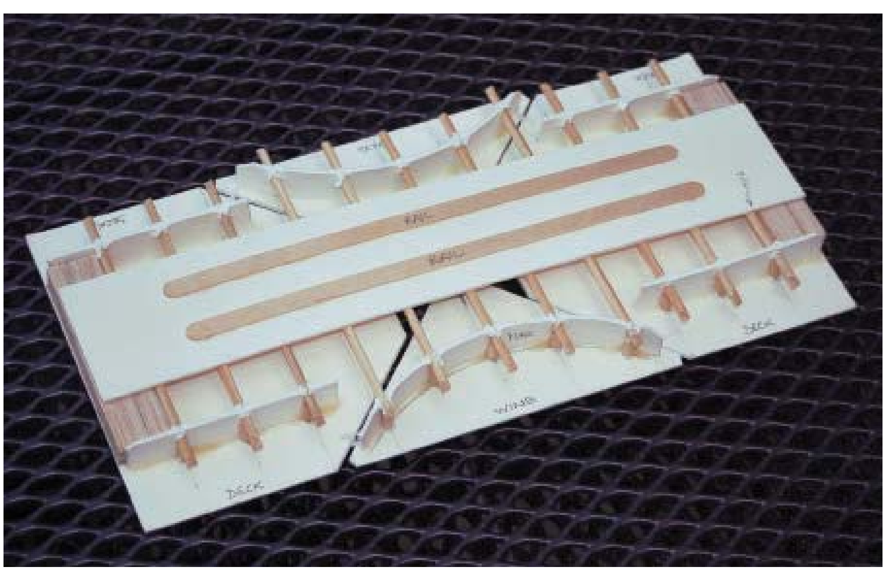
A simple model was created to convey and examine the basic kinematics of the concept (see the image below). From this model the primary geometric relationships could be understood. However, at this point in the development of the concept no structural members had been identified. After several iterations of member concepts, a larger scale (1:20) physical model was constructed to again demonstrate and examine the geometric and kinematic relationships.

These relationships were studied in more detail using a three-dimensional geometric computer program in which the sensitivity of the rail geometry to variations in structure positions was considered. Three-dimensional models were made using MicroStation software—developed by Bentley Systems, Inc., of Exton, Pennsylvania—to evaluate the physical interfaces of the track bridge elements with one another and with the bridge. Ensuring that the components of the proposed project do not interfere with the existing structure is a key concern in developing a robust long-term solution.

The refined CESuRa system (see the figure opposite) acts like a pin-ended beam that spans the hinge point between the transition and fixed span or between the transition and floating span. The main elements of the system are as follows:

• The two longitudinal box girders, or wings;

• The transverse bearer bars,



A simple model was used to convey and examine the basic kinematics of the Curved Element SUpported RAil (CESuRa) concept.

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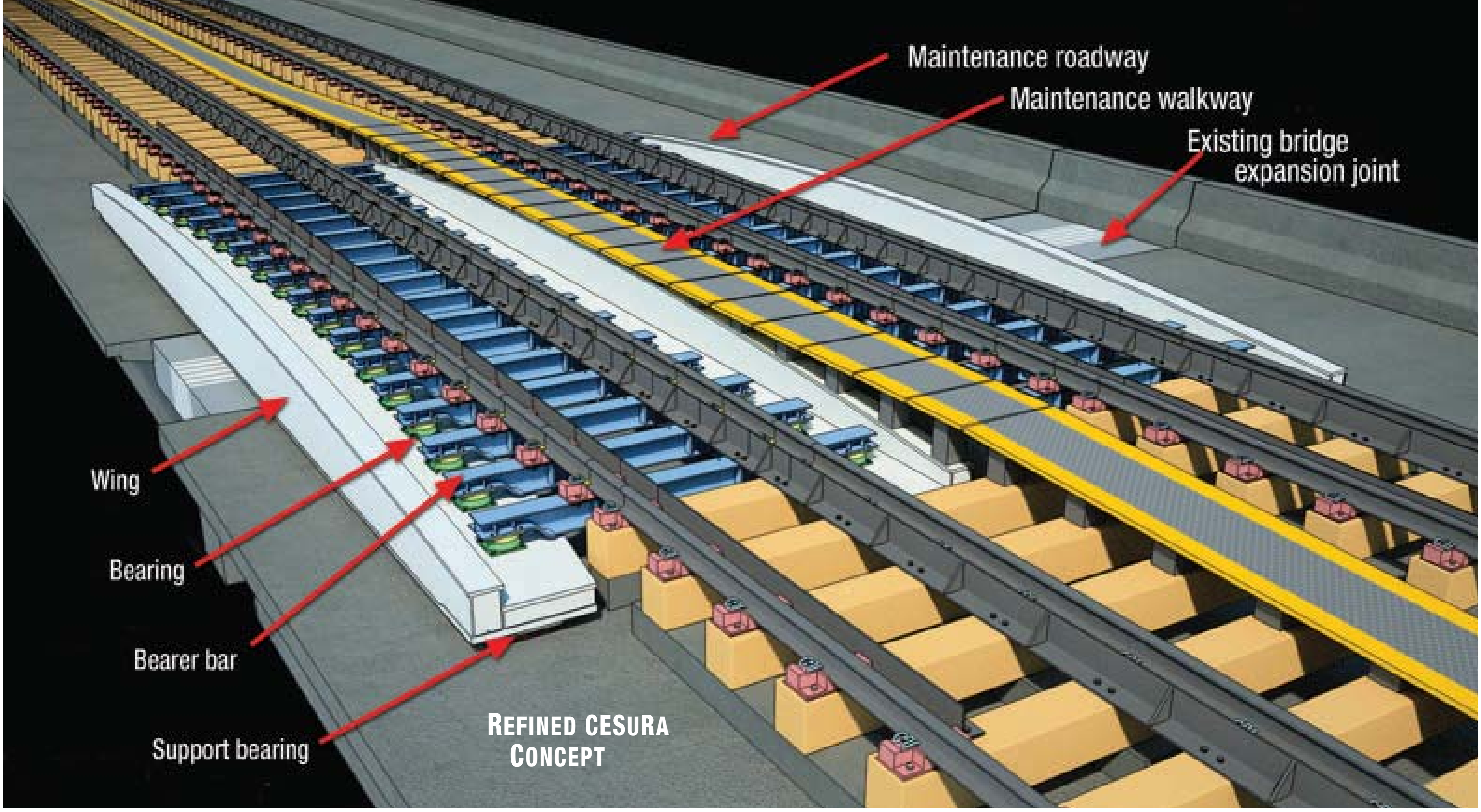

which serve a purpose similar to that of ties in a conventional track but are supported on the wings by unidirectional friction pendulum bearings that allow rotation and limited translation;

• The rails, which rest on and are secured to the bearer bars.

Because the bearings on each wing are placed in the shape of a horizontal circular curve, the bearer bars are all of different lengths, those at the ends of the wings being the longest. The wings are supported from below on the transition and the fixed or floating spans and thus move vertically with the transition span in response to lake level changes. However, the wings are supported eccentrically with respect to their longitudinal axes so that, in addition to vertical movement, they undergo rigid body rotation about their longitudinal axes. As the wings rotate, the bearer bars move vertically through different distances, and the rails bend in the vertical plane. To ensure a smooth curved transition of the rails between the transition and the fixed or floating span, the horizontal curve radius on which the bearings lie, as well as the location of the supports for the wings, had to satisfy particular geometric requirements. The length of the track bridge is designed to ensure that the rail stresses resulting from this bending are tolerable. Despite the movements of the various components, the rails are fully supported along the length of the CESuRa track bridge.

The running rail and guardrail subsystems are supported on bearer bars by means of a typical elastic fastening system for the rails and pinned connections for the guard beams. The 17 bearer bars are supported near their ends by friction pendulum bearings mounted in a curved pattern on a pair of wings approximately 42.5 ft long. Each wing sits on three elastomer bearings and is stiffened by an upturned edge beam.

Two bridge decks join at a hinge. The wings comprise two triangular secondary planes located such that they each have one long edge—shown as AB in the figure on page 60—perpendicular to the hinge and a vertex, denoted as C in the figure, on the hinge axis. On each wing the bearings are aligned along a curve, called the yoke. The track is mounted on bearer bars, which are supported by the bearings along the yoke.

With this configuration, when the hinge angle is zero and the wings are lying flat, an observer looking from the side in the direction of the hinge axis will see the yokes as straight lines. As the hinge angle increases, the wings will naturally incline inward as the long edges are forced upward. The observer will now see a developing curvature as the yokes rise on the sloping wings, and the bearer bars will now appear to the observer to lie on a smooth yet continuously variable curve that is tangential at either end to the incoming and outgoing tracks. When the hinge angle is positive upward, the road or track has a smooth, vertical curvature, or sag. When the hinge angle is negative downward, the road or track has a smooth, vertical curve, or crest.

Both the structural elements of the track bridge and the rails themselves experience substantially lower stresses with the CESuRa concept than the stress levels in previous design options. These differences in performance could improve Sound Transit operations, lower life-cycle costs, and enhance system reliability.

Besides traditional loads for bridges, the design loading for the track bridge included an evaluation of the system when it is subjected to movements of the floating bridge and transition spans. These conditions were defined as follows:

• Pitch caused by seasonal lake level changes of ± 1.5 ft;

• Yaw caused by sway, that is, horizontal movement, resulting from wind;

• Roll resulting from wind and "plunging" of the pontoon when light-rail vehicles are present;

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Using the ADINA software, the design team developed a detailed three-dimensional finite-element model of the entire west end of the Hadley bridge with the track bridge systems.

• Expansion and contraction of the bridge and track by as much as ±2 ft in response to changes in temperature and lake level.

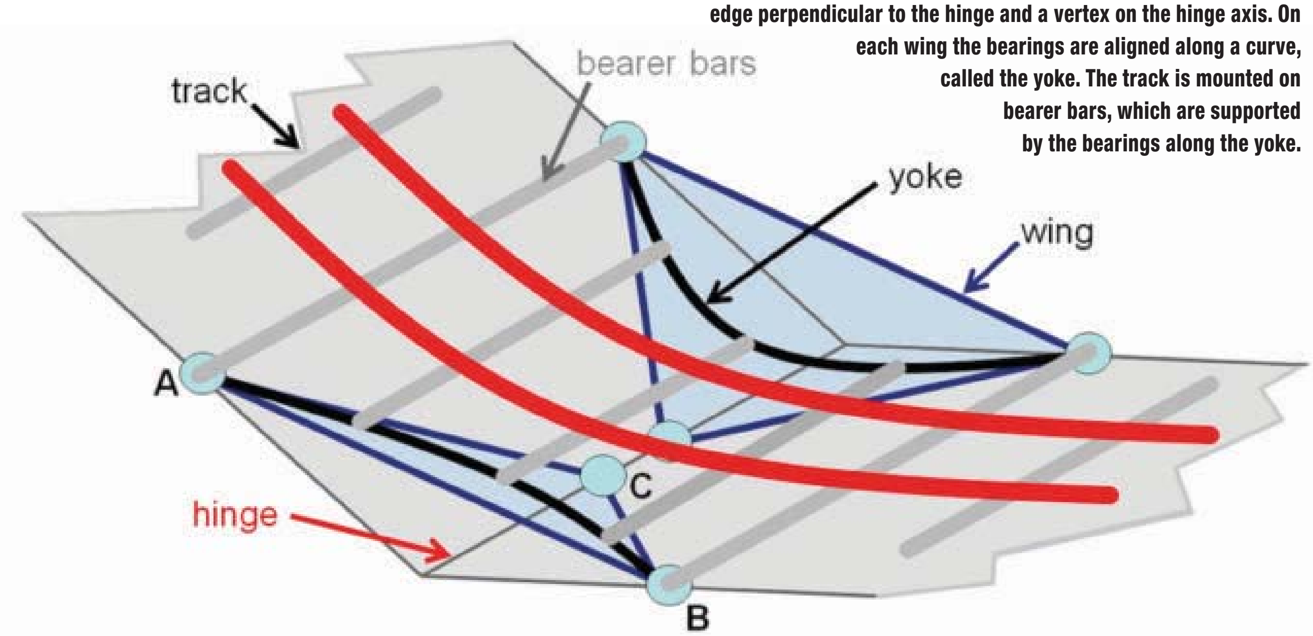
To combine these movement cases with typical load cases from the *AASHTO LRFD Bridge Design Specifications,* published by the American Association of State Highway and Transportation Officials, and Sound Transit's design manual while working through concept and preliminary designs, the design team developed four parametric cases: a neutral case, a service case, the design condition, and an extreme case. The neutral case defines conditions with the lake at midlake level in accordance with the U.S. Army Corps of Engineers' datum (zero vertical deviation), mean temperature (50°F), zero yaw, and zero roll. This case represents a condition at which bearing rotations are at zero and all the response of the track bridge comes from the light-rail vehicle. The service case represents the range of conditions and movements that can occur during light-rail transit operations at design or system speeds up to 55 mph. The design condition is intended to capture the full range of conditions and bridge movements for which the track bridges are being designed to support light-rail operations. This condition includes lake level changes outside of normal operating levels, winds up to 54 mph, and extreme temperature variations. The extreme case represents movements that the Hadley bridge could experience in an extreme event, defined by such occurrences related to the site as extreme temperatures, a cable break on the floating bridge, or the wind and wave action associated with a 100-year storm.

These conditions were used to determine if there was a limiting speed for light-rail vehicles crossing the track bridge under various service levels and extreme conditions. Based on the analytical studies conducted during design and the results of the full-scale testing, the 55 mph operating speed of the light-rail vehicles will not need to be reduced because of the behavior of the track bridge under the service or design conditions.

Numerical modeling and analysis of the CESuRa system were performed using three primary software programs: ADINA version 8.8.4, a general-purpose program developed by ADINA R&D, Inc., of Watertown, Massachusetts; LARSA, from LARSA, Inc., of Melville, New York; and NUCARS, a proprietary program developed by the Transportation Technology Center, Inc. (TTCI), of Pueblo, Colorado, that is used to model vehicle and track interaction. ADINA and LARSA were used to perform structural analysis, and ADINA and NUCARS were used to analyze light-rail vehicle response and rider comfort. The results of these analyses led the design team to modify and refine the support conditions, track bridge configurations, and geometry to improve the performance of the CESuRa concept.

Using the ADINA software, the design team developed a detailed three-dimensional finite-element model of the entire west end of the Hadley bridge with the track bridge systems. This model incorporated the essential structural

The CESuRa concept is designed to enable light-rail vehicles to span the hinge at which two bridge decks join. The wings comprise two triangular secondary planes located such that they each have one long edge perpendicular to the hinge and a vertex on the hinge axis. On each wing the bearings are aligned along a curve, called the yoke. The track is mounted on bearer bars, which are supported by the bearings along the yoke.



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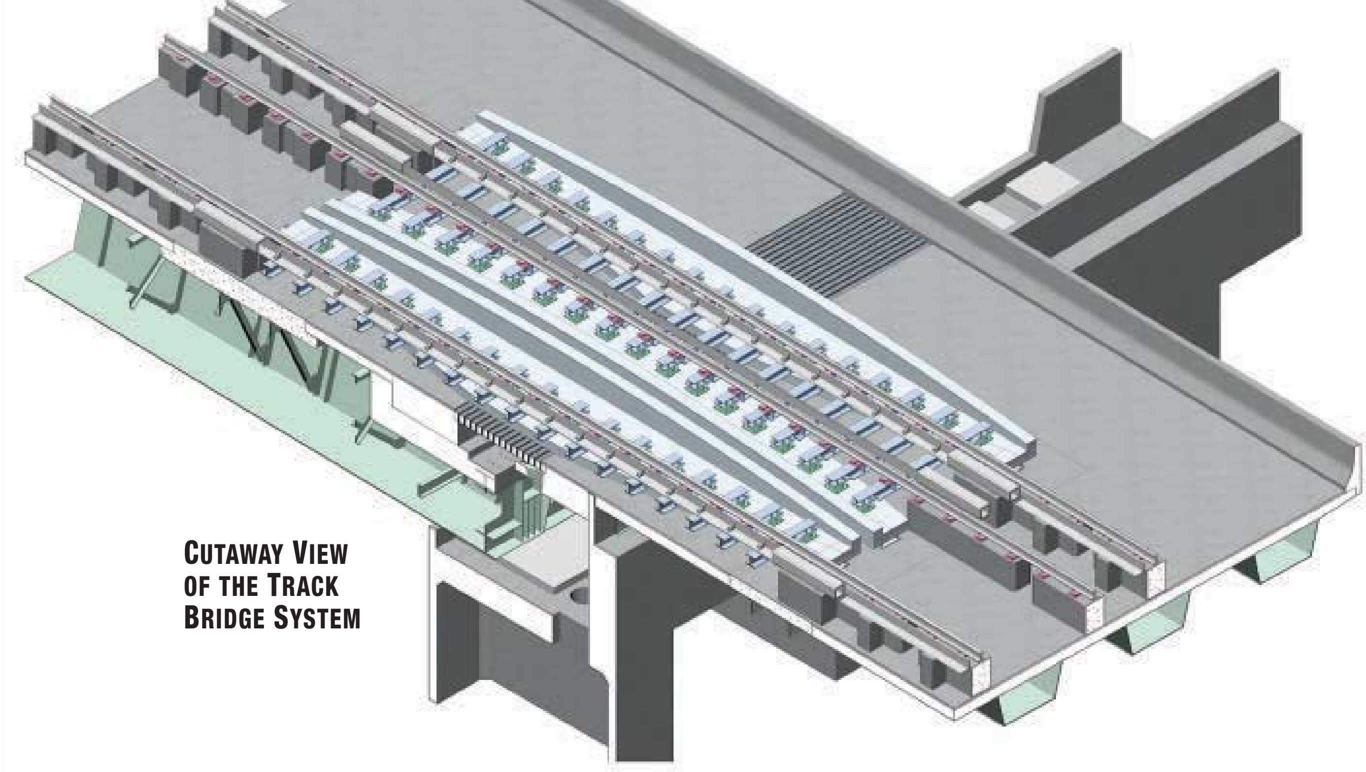

CUTAWAY VIEW OF THE TRACK BRIDGE SYSTEM

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components, including the land approach span, the transition span, and the floating span to the pontoon that represents approximately 50 percent of the total floating bridge system, which is enough to appropriately model the boundary conditions resulting from the floating bridge.

To properly design the track bridge, it was necessary to understand the movement of the transition span and pontoons and to be able to replicate these movements in the ADINA global model. To verify the response provided by the ADINA model, its predictive behavior was compared with field data collected by the Washington State Department of Transportation as part of a test program carried out in 2006 in which loaded flatbed trucks were used to simulate light-rail vehicle loads on the Hadley bridge. The ADINA model was calibrated until its results for displacement under live loads, that is, plunging, were consistent with the test data.

The ADINA model was also used to simulate dynamic forces associated with light-rail vehicles passing across the fixed spans, track bridges, and transition span and then onto the floating span. Results from these analyses provided structural response, in the form of wing and rail stresses, and input for the NUCARS models, which were used to evaluate rider comfort and vehicle performance. When a train crosses a track bridge, the rails will move as a result of deflection and wing rotation. Therefore, predicted time histories of the deflected profile of each rail were developed to represent the movement under light-rail vehicle traffic considering all directions and time. This "profile time history" was the means by which the results of the dynamic analysis conducted in ADINA—in which the light-rail vehicles were modeled at varying speeds—were fed into the NUCARS model. To ensure the accuracy of the behaviors reported by these two sophisticated models, a convergence method was established. Rail deflections from ADINA were fed into the NUCARS model, and the resulting wheel–rail forces were fed back to ADINA. Results of vehicle accelerations from both models were compared, and vehicle suspension elements were evaluated and modified until an acceptable level of correlation was reached.

In parallel with ADINA, LARSA was used to model the structural system of the track bridge by a set of appropriate finite elements. The LARSA modeling of the track bridge concept was used to prepare preliminary member sizes, calculate member stresses and forces, study the structural performance of the track bridge system, and confirm the ADINA model results.

The design team used NUCARS to conduct computer model simulations of the track bridge system concepts. These models were used to calculate the vehicle performance, vertical and lateral accelerations, wheel and rail forces—and resultant lateral to vertical force ratios—ride quality, and safety performance of Sound Transit's light-rail vehicles traversing the track bridge.

Physical testing was performed on a light-rail vehicle owned by Sound Transit to confirm that the properties of its suspension system matched those provided in standard data sheets from the light-rail vehicle manufacturer. This step ensured proper interpretation of data and allowed modifications to be made to the NUCARS and ADINA models. The vehicle was actuated with dynamic and static load tests in the Seattle maintenance shop. The suspension response was measured, along with the stiffness and vehicle clearances. This was a critical step, as some of the manufacturer's data sheets did not provide the required information. In other cases, in which there were dual shock absorbers or dampers, the manufacturer's data reported either half or twice the response.

Full-scale component testing took place at the University of Washington's Structural Research Laboratory. The goal was to verify, in advance of full-scale prototype testing, that the wings, bearer bars, bearings, and rails would undergo the required movements in the manner anticipated in the design. This testing also provided an opportunity to record lessons regarding the fabrication and assembly of components, particularly with respect to tolerances, and to provide test data for validating the ADINA modeling of key components.

The complete system at full scale was too large to fit in the Structural Research Laboratory. Because of the difficulty of obtaining such components as rails and bearings at a reduced scale, the design team chose to test part of the system at full scale rather than test the complete assembly at a reduced scale. Other considerations included cost and the fact that fabrication tolerances do not scale proportionately.

THE TEST RIG WAS DESIGNED TO BE ADJUSTABLE SO THAT THE SPECIMEN COULD BE CHANGED TO MATCH A WIDE RANGE OF POSSIBLE CONFIGURATIONS, INCLUDING PITCH, ROLL, AND YAW.

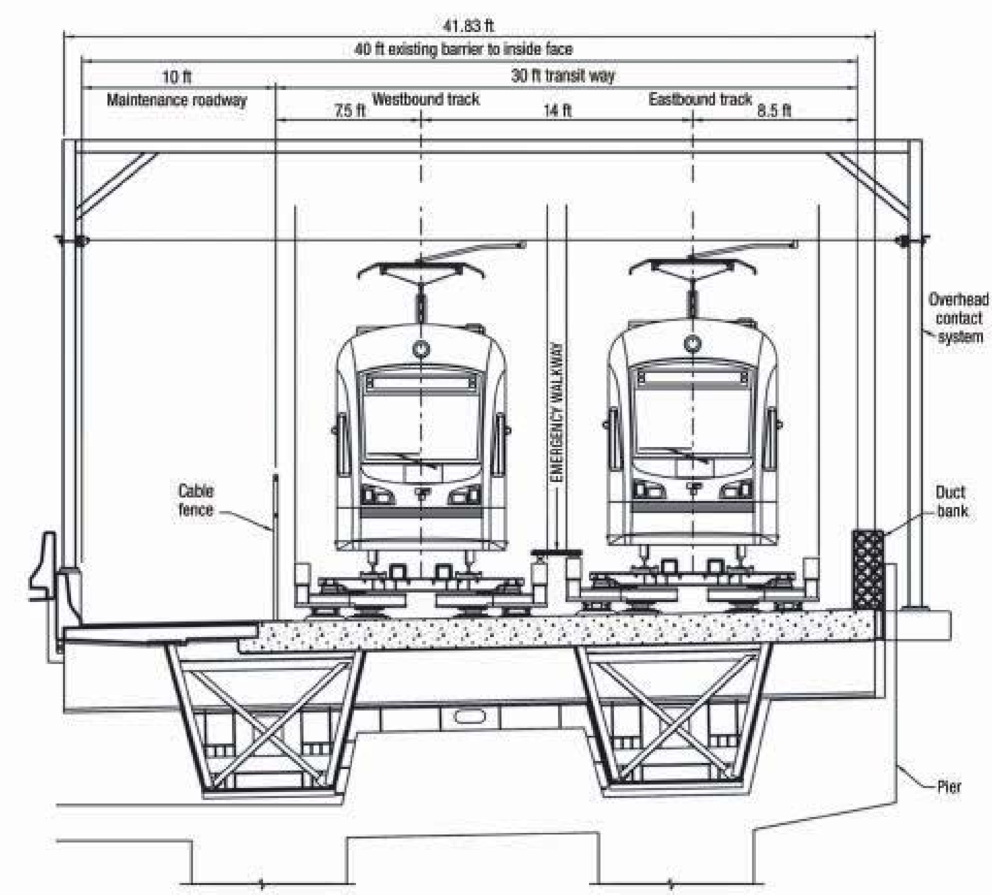
The system that was built and tested represented approximately one quarter of the track bridge and consisted of four bearer bars with the associated rails and supporting elements. The test rig was designed to be adjustable so that the specimen could be changed to match a wide range of possible configurations, including pitch, roll, and yaw. The loads were applied to the rails by means of a system that included parts of the real vehicle tires to ensure that the geometry of the contact region and, therefore, the direction of the loads were correct.

A wide range of instrumentation was applied to the testing system, including load cells, potentiometers, linearly variable differential transformers, string potentiometers, high-sensitivity two-axis inclinometers, electric resistance strain gauges, and strain rosettes. Approximately 150 channels of data were recorded, although this number varied slightly from one test to another.

Vertical load tests were initially conducted using 10 cycles of load from zero to a full axle load of 28 kips, although 20 cycles were used in later tests. Combined loading tests were conducted using a fixed vertical load of 28 kips and cyclic horizontal loads of up to 4 kips in each direction transversely to simulate wind loads. Overall, the system behaved as expected and revealed no major unanticipated shortcomings. While most of the data confirmed the model results, the testing offered two key lessons. The first was the need for a carefully planned assembly process in order to achieve the proper construction tolerances in the prototype given the many degrees of freedom of the track bridge. The second was the need to design and test the means by which the system would recenter after the lateral loads had been applied. The sliding bearings have some friction, and the design team was concerned that the elastic components of the track bridge might have insufficient stiffness to overcome the bearing friction and return the system to its original configuration. In the lab the track bridge was pinned at one end and left freestanding at the other. Although this arrangement is not the case in the full-scale prototype, it was important to confirm that the full-scale prototype bridge would recenter and not ratchet to one side. Testing conducted as part of the second phase confirmed that this ratcheting does not occur.

Full-scale in-track testing of a prototype track bridge was desired to validate the computer analysis results and confirm that the design met the performance criteria contained in the technical requirements for the track bridge system and forming the basis of the design report. What is more, the Joint Transportation Committee of Washington's legislature recommended the use of full-scale testing. To meet this requirement, the team developed a test program and worked with TTCI to conduct full-scale prototype testing of two track bridges at the Federal Railroad

TYPICAL SECTION OF THE TRACK BRIDGE SYSTEM



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Administration's 52 sq mi Transportation Technology Center, near Pueblo, Colorado (not to be confused with TTCI). Offering a wide array of laboratories and track facilities, the center provides specialized testing for all categories of freight and passenger rolling stock, vehicle and track components, and safety devices. Construction of the test track by Balfour Beatty began in February 2013; vehicle testing started in August and concluded in mid-October. Stray current testing will resume this spring when the risk of freezing weather diminishes.

Prototype testing of two track bridges was conducted at the U.S. Federal Railroad Administration's Transportation Technology Center, near Pueblo, Colorado. A separate dedicated 5,000 ft long test track was designed as a double-ended siding off the existing transit test track.

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A separate 5,000 ft long Sound Transit test track was designed as a double-ended siding off the agency's existing test track. The new test track provided sufficient length for a two-car train having the maximum crush loading—that is, all seats occupied and 6 people standing per square meter, or about 180 people per car—to accelerate to 55 mph, cross the track bridge testing area, and safely decelerate without interfering with any other testing on the adjacent test track. Two Sound Transit light-rail vehicles were provided for this testing.

The testing was intended to verify the performance of track bridge components, track fasteners, rail expansion joints, and any other component for which performance cannot be judged on the basis of common use. Although the static testing did not fully replicate the dynamic behavior of the Hadley bridge, all of the service conditions, that is, the greater limits of pitch, yaw, and roll, were tested. The use of fixed-track geometry during any one test was valid because the service condition movements experienced by the track bridge occur slowly. Although long-term movement occurs, the geometry is essentially fixed during the time required for one vehicle passage.

Such concerns as noise, electrical isolation of the running rails, and other issues that arose during development of the prototype design were addressed in the testing program. The goals of the prototype testing program included verifying that safety and rider comfort requirements were met, analyzing the reliability of components and the system as a whole, understanding wearing sequences and vulnerabilities, and improving fabrication, assembly, and installation techniques. Finally, the testing program verified that all design requirements were met and highlighted areas for design refinement.

The prototype testing program involved the measurement of forces and movements resulting from operating a two-car train using Sound Transit light-rail vehicles at speeds from walking speed to 55 mph over two full-scale prototype track bridges: an "exterior joint" system connecting a fixed span to a transition span and an "interior joint" system connecting a transition span to a floating span. Both prototype track bridges were installed in a test track that replicated the track profile present on the transition spans at the west end of the Hadley bridge at low lake level, including an additional 8 in. of vertical displacement resulting from the "plunge" effect. Instrumentation mounted on the track bridge structural elements and supports, adjacent track, *(Continued on Page 76)*

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(Continued from Page 63) and the test vehicles was used to measure and record track bridge member movements and stresses, vehicle ride quality, and wayside noise generated from light-rail vehicles that were operated on the track bridge. Considerable effort was made to replicate the track geometry and displacements of the transition and floating spans and reflect the limits of the defined service conditions. At extreme rotations a minor structural conflict was detected. By adding shims at the factory, this conflict was corrected before the prototype was shipped to Colorado.

Assembly of the full-scale prototype track bridge was completed in the factory of the Jesse Engineering Co., of Tacoma, Washington, where the major structural components were manufactured. Assembling the entire prototype before shipping the prototype units to TTCI ensured that all of the pieces fit together properly. Meanwhile, the assembled prototype was used to carry out limited static tests of the full-scale track bridges and demonstrate the kinematics of the CESuRa wings, friction pendulum bearings, and bearer bar by jacking the assembled joints into a range of deformed shapes and replicating the movements of the underlying Hadley bridge roadway decks under various loading and displacement conditions.

The factory testing programs used the same pitch, yaw, and roll configurations proposed for the in-track testing program. To better understand the behaviors associated with the design, the yaw and roll movements were increased over the required design values by a factor of approximately 3. The positioning of the wings and bearer bars was marked in each case for future field reference.

The final phase of the rail crossing will include fabrication of the track bridges and their installation on the Hadley bridge. As part of this phase of the program, the Parsons Brinckerhoff team will have six new track bridges fabricated, and the two that were used for testing will be refurbished and painted for installation on the Hadley bridge. The eight track bridges will be installed by the Parsons Brinckerhoff team as part of the overall East Link Extension Project.

The design for the installation of the track bridges on the existing structure is part of the prototype design and is integral to the concept. A key concern during development of the concept design involved limiting the additional weight added to the floating bridge as a result of plinths and other track works. This concern was addressed by keeping the track bridge profile close to the existing deck.

Avoiding the removal of existing transition span expansion joints, ensuring the long-term durability of the existing structure, and avoiding future maintenance problems also were critical design issues and were incorporated into the prototype and detailed designs. Such steps limit any demolition and reconstruction while maintaining the integrity of the water seals on the box girder bridges.

The final phase of the project will include the following activities:

• Monitoring the performance of the track bridge systems to determine requirements pertaining to maintenance and replacement of any of the track bridge system components for a period of time after initiation of service;

• Maintaining the track bridge systems, including making adjustments, replacing components, and other work as necessary to meet operating requirements for a period of time yet to be determined.

Design of the overall $2.8-billion East Link Extension Project is in progress. The track bridges will provide an essential link within an otherwise technically challenging project, which is set to begin construction in 2016. Construction and system testing are expected to take approximately six years, and the East Link is expected to start revenue service in 2023. **CE**


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PROJECT CREDITS Owner: Sound Transit **Project management, design management, construction management, and structural design:** Parsons Brinkerhoff, Seattle office **Cost estimating and constructability review, test track construction, and planned installation of track bridges on Interstate 90:** Balfour Beatty, Kent, Washington, and Denver offices **Special track work design:** Andy Foan Limited, Nottingham, United Kingdom **Vehicle performance modeling and full-scale testing:** Transportation Technology Center, Inc., Pueblo, Colorado **Structural and track structure interaction analysis:** SC Solutions, Inc., Mountain View, California **Civil and track design:** Jacobs Engineering, Seattle office **Steel fabrication:** Jesse Engineering Co., Tacoma, Washington **Component testing:** University of Washington, Seattle **Friction pendulum bearings:** Earthquake Protection Systems, Vallejo, California **Elastomeric bearings:** mageba USA LLC, San José, California **Sound testing and analysis:** Wilson Ihrig & Associates, Emeryville, California **Monitoring systems:** Direct Measurements, Inc., Columbia, South Carolina **Instrumentation integration:** Ergosynch LLC, Seattle