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3D Simulation and Crash Testing of Resistance Barrier Gates

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Abstract

At the Rt. 37 Eastbound Mathis Bridge, a double leaf bascule structure, the WSP team was requested by NJDOT to design resistance barrier gates to comply with the 2015 AASHTO Manual for Assessing Safety Hardware (MASH), sustain a Test Level 2 impact, improve time of operation, and provide an infinite fatigue life in an aggressive coastal environment for design wind gust speeds of 125 mph. These challenging requirements came late in Final Design due to the release of MASH and the then current AASHTO, further amplified by the Department's need for a more robust fatigue design due to then recent gate failures after Superstorm Sandy. There was no prior history of successfully meeting these mandates applied to New Jersey's movable bridge sites along the coastline that were particularly vulnerable.

The presentation will discuss site-specific challenges in designing a gate not only robust enough to meet the infinite life fatigue design, but also be flexible enough to absorb the mandated vehicular impacts, provide sufficiently safe ride-down acceleration, and limit Occupant Impact Velocity. While this type of significant design change is typically a multi-year undertaking, the close collaboration with a gate manufacturer and a research facility to develop a prototype for a Finite Element simulation analysis helped in completing efforts within a short period to verify all aspects of performance. Simulation included sophisticated modeling of the gate, anchorages, cables, and members. Test Level 2 simulations included a small vehicle (passenger car) and a heavy vehicle (pickup truck). In addition, field crash tests were performed on the gates identical to the simulated model; the results were in excellent agreement with the simulation.

Following the successful analysis and crash testing of the resistance barrier gates on the Mathis Bridge, the Department tasked WSP with completing a similar replacement of the drop arm gates on Rt. 30 over Beach Thorofare, a single leaf bascule bridge in Atlantic City, New Jersey. This structure was also designed to the same stringent design requirements as Mathis (TL-2 ,125 mph wind speed and infinite fatigue life), however the unique geometry at Rt. 30 required the project team to overcome new challenges. Rt. 30 is a six-lane highway with full sidewalks on each bound, requiring a dual arm gate, each being much longer than the Mathis Bridge and locking together at the median in the existing condition. At the time of this writing, finite element modeling and crash test simulation is complete, and Shop plans are submitted for the manufacturer's design. The contractor has begun submitting their shop drawings for the gates, and detailed analysis is under way. Actual crash testing is to be scheduled after approval of drawings and calculations. By the time of the conference, additional progress is expected, allowing WSP to further update the industry on this unique design.

Crash-testing newly designed resistance barrier gates is an expensive mandate. The cost of developing physical tests to crash multiple gates and the sacrificial vehicle for tests exceeds several hundreds of thousands of dollars. Alternatively, it has been demonstrated that a detailed finite element simulation may achieve, at a much lower cost, demonstrating similar end results, and allowing owners flexibility in reducing the number of crash tests.

Introduction and Background

The Route 37 Eastbound Bridge over the Barnegat Bay, Thomas Mathis Bridge, was constructed in 1950. The sixty-six span (sixty-three approach spans with a double leaf bascule main span and adjacent anchor/flanking spans) bridge is 4,877-feet long. Each leaf of the bascule span is 50'-0" from toe break to centerline of trunnion. The bascule span crosses over the tidal Barnegat Bay and provides an 80-foot horizontal clearance between existing fenders. The bridge carries three (3) 10’-0” wide eastbound lanes and is posted at an advisory speed of 40 mph.

The Route 30 Bridge, built around 1941, is a 7-span, 471-foot-long bridge composed of 5 approach spans with concrete encased steel stringers, a single leaf simple trunnion bascule main span with three main girders, floorbeams and stringers and a girder-floorbeam anchor span. The bridge carries three lanes of traffic in each direction ((2) 11’-0” lanes and (1) 12’-0” lane, each direction), is divided by a concrete median barrier and also has a sidewalk ranging from 6’-3” to 7’-11” along each side. The Route 30 Bridge is a critical link to Atlantic City and is vital to its economy. Situated very near the city’s commercial corridor, the Route 30 Bridge also provides important access to the Atlantic Ocean.

Both structures are emergency evacuation routes, and also must open for recreational and commercial vessels that use the waterway which directly connects to the Intracoastal Waterway and the Atlantic Ocean.

Crash testing/construction at the Mathis Bridge is complete. Design/simulation at the Route 30 Bridge is complete, with construction having started in November 2020. Final crash test data is pending.

Pre-Rehabilitation Conditions

At the Mathis Bridge, the original movable span traffic control devices consisted of traffic signals, gongs, warning gates, and barrier gates. The original swing, tractor barrier gate was a 15-inch square steel tube, and when deployed would be about 18 inches above the deck (Photo 1). The barrier gates were not energy absorbing and did not meet current NJDOT Movable Bridge Engineering Group (MBEG) requirements nor MASH crash requirements. At the Route 30 Bridge, the gates were resistance type, vertical drop arm gates and were energy absorbing but did not meet MBEG wind resistance, fatigue nor MASH crash resistance requirements (Photo 2). The location of the traffic lights, warning gates, and barrier gates did not meet all *Manual of Uniform Traffic Control Devices (MUTCD)* requirements, at each bridge site.

Photo 1: Tractor type swing gates, Mathis Bridge

Photo 2: Resistance barrier gates, Route 30 Bridge

Summertime marine and vehicular traffic at the Mathis Bridge is three to four times the off-season demand. The time of deployment of the existing rolling gate at the Mathis Bridge was close to 20 seconds, adding to the span operation time and the traffic back-ups in the peak summertime, when the span had to open on demand.

At the Route 30 Bridge, the existing traffic devices fouled the sidewalk width and did not satisfy NEC working clearances around the equipment. Furthermore, the resistance barrier gates have previously failed in 2013 and 2016 as a result of very high wind gusts while stowed in their vertical position.

At the Route 30 Bridge, which was deemed historically significant, the outside fascia balustrade is a defining feature and must be largely retained. In order to meet geometric constraints, NEC working clearances and avoid fouling the sidewalk, the gates will be installed outside the fascia on platforms. These platforms and the access openings will require the removal of small sections of the fascia balustrade, with much concern from the New Jersey Historic Preservation Office (NJHPO). This was resolved using a layout that met all clearance requirements, limiting overall impact to the balustrade, and incorporating the reuse of the newly removed balustrade sections at previously removed locations, to assuage NJHPO concerns.

New Movable Span Safety Devices

During the latter part of Final Design for the Mathis Bridge, about 6 months prior to advertisement, AASHTO released the 2015 MASH standards which superseded NCHRP-350, the previous guide for roadway safety devices. NJDOT tasked WSP with updating the gate design to meet current MASH Test Level-2 (TL-2) criteria. To comply with Mash TL-2, the gates were each required to function as a non-redirective crash cushion capable of resisting the 1100C (Small Vehicle) and the 2270P (Pickup Truck) test vehicles impacting at 44mph.

NJDOT also required an AASHTO compliant strength design for wind resistance and infinite fatigue resistance. In reviewing the changes in the wind maps, the wind intensity for new designs along the New Jersey Coastline was between 120 MPH and 125 MPH, much larger than what had been used in earlier designs. Previous design speeds in New Jersey varied between 70 and 90 mph for gates. Historically, wind gusts at the Mathis Bridge have been higher than the inland areas. The NJDOT ultimately decided on the higher design gust wind speed of 125 mph for new designs. For the Mathis Bridge, the *AASHTO Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals (LTS-6)* was chosen as the governing code for gate wind design as the most appropriate code for aluminum appurtenances subject to high wind velocities, using either Chapter 3 or Appendix C. For the Route 30 Bridge, the *2015 AASHTO LRFD Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals (LRFD LTS-1)* was utilized.

Following Superstorm Sandy in October 2012, which hit the New Jersey shoreline with extremely high winds (91-mph sustained wind, recorded by NOAA), NJDOT discovered that some of their existing barrier gates, particularly on bridges along the shore, exhibited cracking at the welded connections of the members and/or braces of the tubular gates. The cracks would typically occur on connections at or near the base of the gates. During collaborative meetings and after assessing existing gate performance, NJDOT decided on additional fatigue and other performance requirements for all new gate designs. The requirements were;

1) Shall be resistance type, of tubular construction, using non-spliced tubes
2) Shall resist the 125-mph gust wind speed in any position
3) Shall meet MASH TL-2 performance requirements when deployed
4) Shall meet AASHTO Fatigue design for Infinite life
5) Shall cut time of gate operation by half or more

With less than 6 months to submission of the Mathis Bridge bid documents, and not having a successful history of meeting all these requirements, the team started contacting other state agencies along the eastern seaboard to verify the individual state mandates and history of comparable successful designs and fabrication. Not much useful data could be gathered as the combination of the requirements was fairly new to other state agencies as well. At the same time, the team also reached out to the some of the gate manufacturers that NJDOT has historically approved for their gates, and as expected, initially drew cynicism on the viability of the design and successful fabrication to meet all of these mandates within the short time available. Such an effort to analyze, custom design and qualify a gate design typically takes 12 to 15 months, as it is a highly iterative process that involves costly full-scale testing prior to acceptance. At that time, there were only two or three gate manufacturers. Further, due to Federal funding restrictions, the gate fabrication and materials was limited to the United States only (Buy America policy). All the same requirements and constraints were applicable for the Route 30 Bridge as well.

Feasibility Assessment

For the Mathis Bridge, with limited information, a tight time frame, and no previously qualified products that could be modified in a manner that could be considered insignificant, the team met with NJDOT and presented the idea of a detailed 3D simulation study of a prototype gate to quantitatively verify its behavior and response to simulated MASH vehicular impact, design fatigue resistance and mandated wind resistance. The NJDOT was willing to sponsor a simulation study as a basis of assurance that such a gate could be manufactured and bid upon accordingly. Therefore, the team reached out to some of the gate manufacturers to request assistance on supplying materials, test specimens to verify strength, preliminary prototype designs and coordination. Only one manufacturer, B & B Roadway (B & B) responded with much interest. As material strengths and properties for the simulation modelling needed to be lab tested and verified, a research facility was deemed an ideal addition to the team. Texas A & M Transportation Institute Proving Ground (TTI) has an on-site testing laboratory and was added to the team. The limited time available to complete the simulation and report was the main challenge. TTI, B & B, and the design team agreed to the aggressive schedule and to work closely together with reviews, iterations, and changes.

Due to the success of the Mathis Bridge gate design, similarly WSP reached out to different gate manufacturers but eventually the same team was chosen for the Route 30 simulation study due to the responses or lack thereof. A benefit of utilizing the same team was that the trials and lessons from the Mathis Bridge would be very helpful due to similarities in the efforts.

Therefore, for the Route 30 Bridge, the team familiarity of the needs, coupled with a similar barrier gate already designed to the same standards greatly aided the development of the prototype quickly. When the Mathis Bridge was undertaken, gate materials were supplied by B & B to TTI for testing. Gate material for the main tubes, secondary braces, base plate, receiver plates, steel cables and bolts were all tested to failure in a TTI laboratory. This step was not deemed necessary for the Route 30 Bridge as there were no changes in the materials and thus saved time. B & B and the designers worked on a preliminary gate model, and TTI built their Finite Element Model from the prototype (Figure 1). B & B has copyrighted the actual design and details and TTI owns the actual simulation models and analysis, and final results and reports are NJDOT property.

A similar schedule challenge also arose during the Route 30 Final Design. For various funding reasons, the Final Design schedule was compressed to about 9 months from the traditional 18 months, and the gate simulation schedule reduced to about 8 months. COVID-19 shutdowns further affected the schedule as of March 2020, but the team continued with very close collaboration through on-line weekly team meetings, to meet the April deadline. The availability of the Mathis gate modelling, material data and the basic prototype model, and lessons learned from Mathis Gate design, resulted in a final gate model with just one iteration and minor changes. The experience from the Mathis Bridge helped accelerate the work to ensure a quantitative verification of the longer arm gate model, just in time for advertisement.

Simulation Test Prototype

The initial design coordination with B & B resulted in the prototype for the Route 30 Bridge, seen in Figure 1, a vertical to horizontal articulating resistance barrier gate. It would be stowed in the vertical position on a platform outside the bridge fascia, supported by a frame integrated to the steel superstructure. The warning gate prototype was geometrically similar but not designed for crash loads. The barrier gate housing contains the machinery and motor for vertical articulation of the gate. At the Mathis Bridge when fully deployed, the gate tip locks into an anchor assembly comprised of steel plates, set into a High Performance Concrete (HPC) base with six 1-inch diameter high strength anchor bolts (Figure 3) and into the HPC Median Barrier with eight 1-inch diameter anchor bolts at the Route 30 Bridge. Geometric constraints at the latter bridge required the two arms of the gate to be offset from each other with independent far side receivers (Figure 2 shows plan locations of the gate arms).

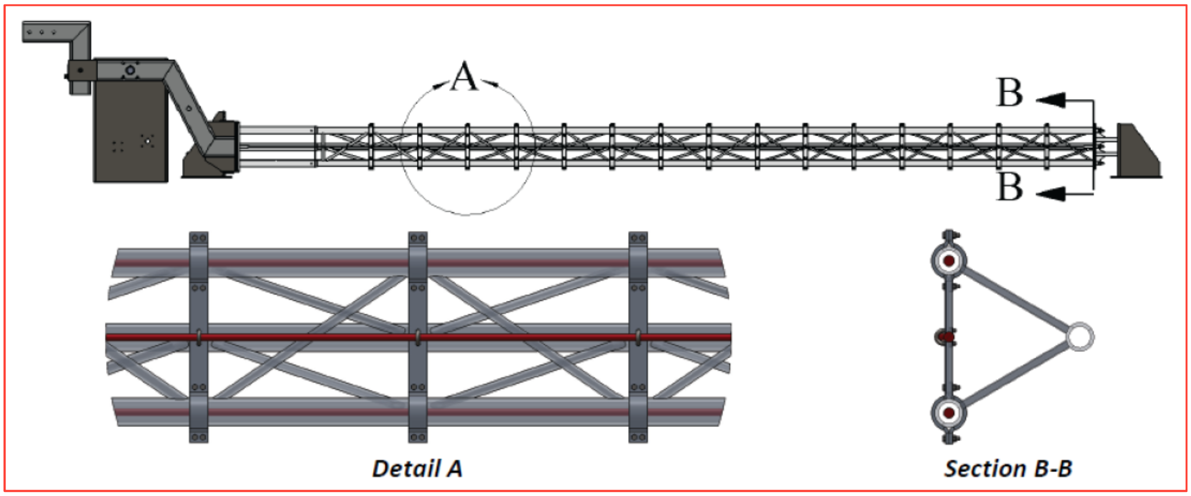


Figure 1: Route 30 Bridge resistance gate prototype

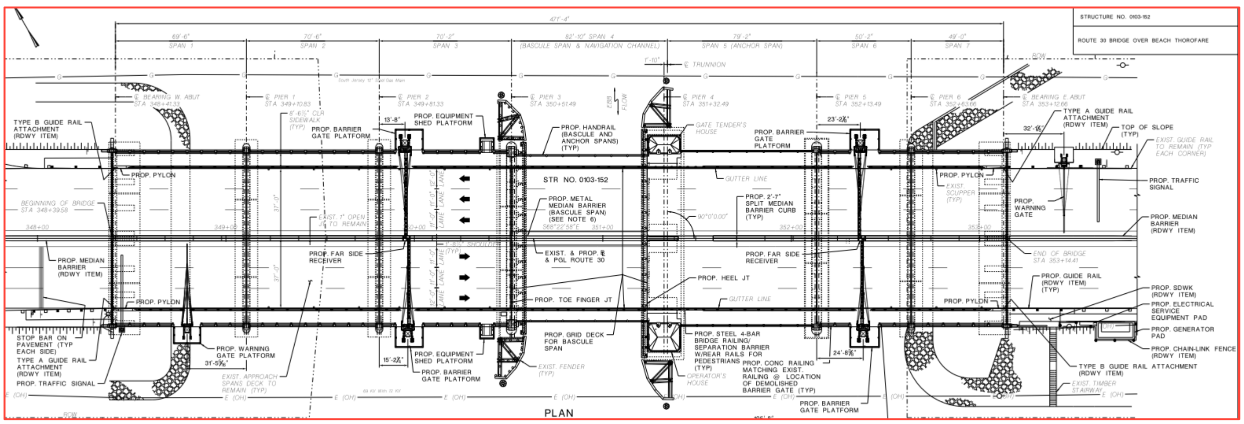


Figure 2: Route 30 Bridge plan view with movable span safety features

The gates are typically composed of three aluminum tubes (trichords), arranged such that the front two tubes are parallel, co-planar and facing traffic, with the third tube offset horizontally and set midway between the front tubes. Energy absorbing, high strength annealed steel cables are placed inside the two front tubes and one cable between the front tubes (Figure 1). The main tubes are connected by aluminum tube braces of different diameters, varying in size from the base region towards the tip region, based on demand. When deployed, the lower main tube is about 9 inches and top tube about 25 inches above the bridge deck. All aluminum used in the simulation analysis was 6061-T6. Higher stresses at the connection were addressed by upgrading the larger pipes at the base with ASTM A500 Grade B elements. The base plate and receiver components were ASTM Grade 36 steel (Figure 3 and Figure 4, shown for Mathis Bridge). The barrier arm length was custom designed for 35’-0” from base to tip at the Mathis Bridge and for 44’-4” at the Route 30 Bridge based on the deck geometry.

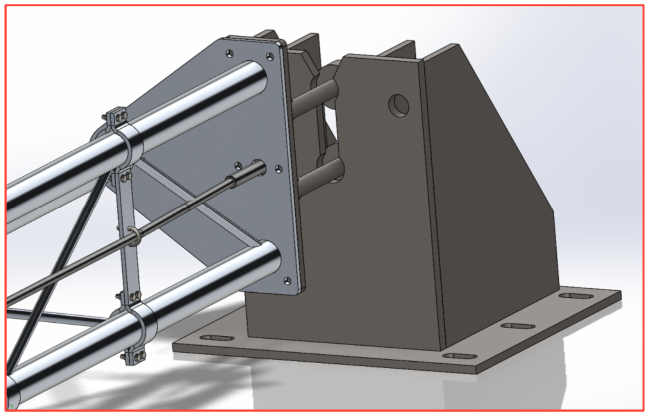


Figure 3: Far side receiver assembly

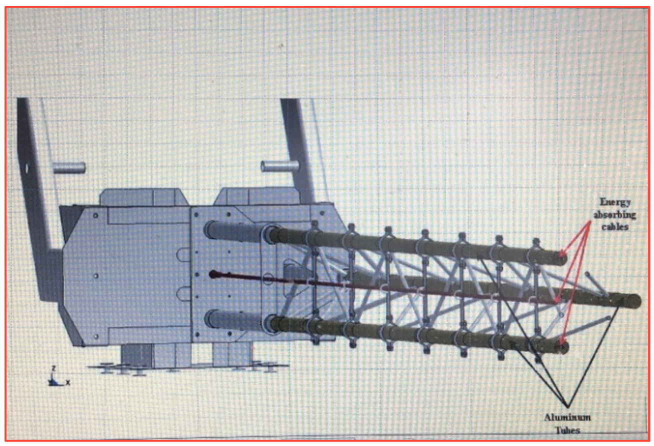


Figure 4: Near side connection to base

Wind Load Analysis

To comply with AASHTO LTS-6 specifications, the wind contours included in Section 3 along the New Jersey shoreline were utilized in addition to ice loads on the gate elements. The wind load was applied to all components and attachments including flashing lights, support brackets, exposed cable, and delineators. The base of the gate was set at about 40 feet above the Bay High Water, corresponding to the base of the platform plus another 7 feet. This is typical for both bridges as the conditions and sites were comparable. The wind pressure was applied as 3-second gusts for the 50-year Mean Recurrence Interval, for a basic wind speed of 125-mph. Load combinations as shown in Table 1 were utilized. Three critical positions within the range of gate movements were chosen for analysis; deployed (horizontal – Position 1), stowed (vertical – Position 3) and midway between extremes at 45 degrees (Position 2) to capture the range of motion. All positions were modelled as free cantilevers, considering the horizontal position just prior to locking at the tip (Figure 5). Load resistance by the cables for wind analysis was conservatively neglected. Applying wind load along the bridges' longitudinal axis (normal to the gate arm) produced the maximum stress conditions.

	AASHTO LOAD COMBINATION	% of Allowable stress
Group I	Dead Load	100
Group II	Dead Load+Wind	133
Group III	Dead Load+Ice+1/2 Wind	133

Table 1: Load combinations

For the horizontal position of the gate arm, a constant value of K, the height and exposure factor, was used. For positions 2 and 3, the gate arm was broken out into segments and different K values were utilized corresponding to the top of each segment, to produce a linearly distributed wind load along the arm. Wind pressure was computed considering different drag coefficients for the different components.

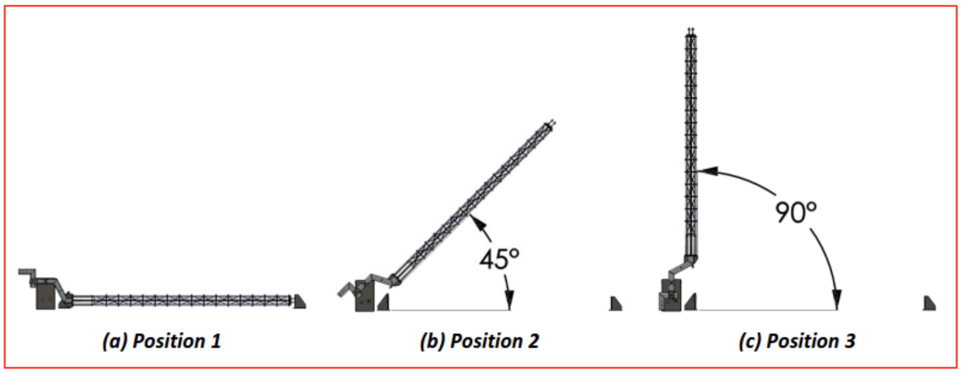


Figure 5: Range of gate motion used for wind analysis

Finite Element Modelling – Wind Design

The Finite Element Analysis Model for the Mathis Bridge gate arm was developed in ETABS 2013, a structural analysis software that can perform linear, non-linear, static, and dynamic analysis, and checks various codes as well. For the Route 30 Bridge gate arm analysis, RISA 3D software was utilized. For each, a non-linear analysis was performed. Beam elements were used for the primary elements and the support at the base was considered fixed. By modelling the base pipe composite with the aluminum main tubes, complete moment transfer was achieved at the base. For the base plate, rectangular plate elements were used, spanning between the truss chords. Stress checks for various conditions and combinations were checked in accordance with AASHTO LTS-6 or LRFD LTS-1. Stress checks included:

1) Allowable tension and compression due to bending
2) Direct tension and compression
3) Shear
4) Bearing
5) Combined bending, axial tension, and shear
6) Combined bending, axial compression, and shear

Stress ratios were verified for every element for each combination and wind direction; the maximum ratio was 0.86 for the Mathis gate and 0.68 for the Route 30 gate, validating the design for wind load. Welds connecting the braces to tubes were checked for 4043 filler wire alloy, consistent with the 6061 aluminum. At the base, the steel to steel weld was checked assuming E70 electrodes. All welds passed the stress checks.

Fatigue Analysis

For the Mathis Bridge, the then current 2013 AASHTO LTS-6 Specifications allowable stress method and Constant Amplitude Fatigue Threshold (CAFT) approach was used to verify fatigue response in the simulation. For the Route 30 Bridge, the 2015 AASHTO LRFD LTS-1 Specifications, with 2020 Interims was used. CAFT is a lower allowable stress limit, below which induced stresses must be maintained for a given welded detail. An Importance Factor was assigned per AASHTO, and equivalent static loads applied for galloping, and natural wind gusts. Truck induced wind gusts were not considered applicable due to the vertically stowed position of the gate. Conservatively, the gate arm was analyzed as a Category I Sign Structure. Galloping and natural wind gusts were applied in separate models.

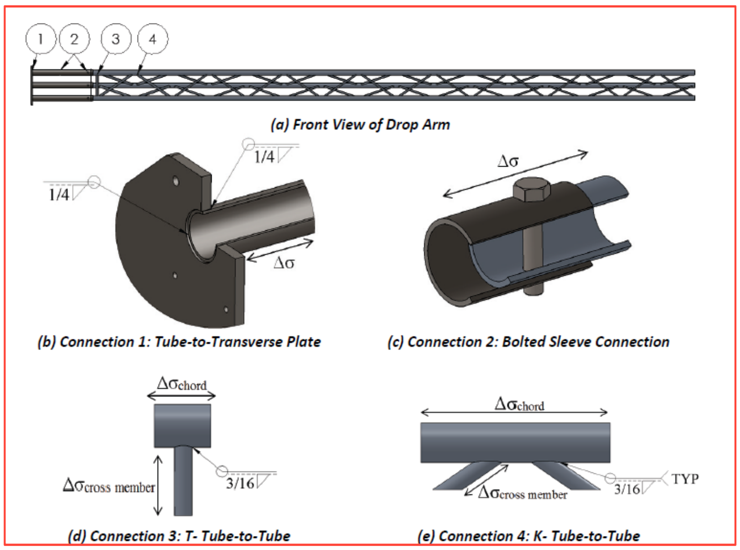


Figure 6: Typical fatigue details checked at both bridges

The critical wind load direction analyzed was the front side of the gate arm, as lights, delineators and two tubes are in the same plane. Position 1 of the arm shown in Figure 5 was used for analysis, as the fatigue effect is independent of the arm height and position. CAFT for steel was derived from AASHTO and divided by 2.6 for aluminum. Fatigue sensitive details that were analyzed and shown in Figure 6 are;

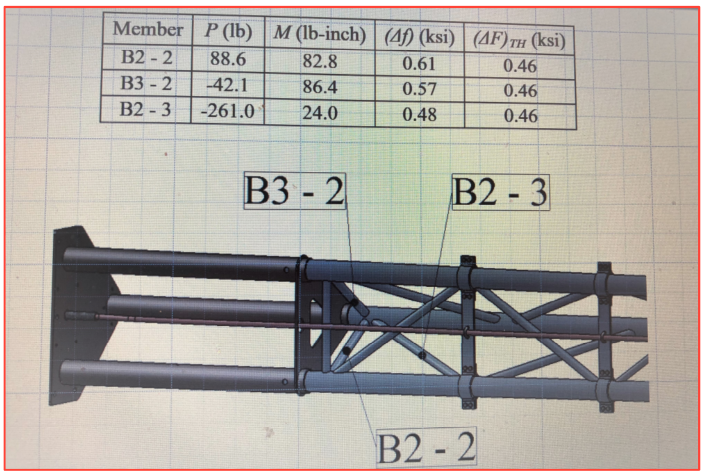
1) Four critical fatigue susceptible details exist in the gate arm
    a. Main tube to transverse plate - 1/4” fillet welded connections at top and bottom of the plate
    b. Bolted sleeve connection at the steel base tube to aluminum arm main tube
    c. Fillet welded T connection of brace to main tubes
    d. Fillet welded K connection of brace to main tube

For all locations, galloping stresses were under the CAFT, with the maximum final stress ratio of 0.66 for the Mathis Bridge gate and 0.48 for the Route 30 Bridge gate, each under 1.0, when compared to the 0.46 ksi allowable stress for welded aluminum.

Natural wind gust analysis was performed assuming a yearly mean wind velocity of 11.2-mph. National Weather Service (NWS) data was referenced to substantiate the 11.2-mph mean wind velocity for the area and confirm that average wind velocities experienced at the bridge did not actually exceed the code specified value and require additional consideration. Maximum final stress ratios were 0.94 for the Mathis Bridge gate and 0.92 for the Route 30 Bridge gate, each under 1.0, when compared to the 0.46 ksi allowable stress for welded aluminum.

Early results of the analysis indicated that three locations of welded braces did not fall under the CAFT for the Mathis Bridge (Figure 7). It was agreed by the team that minor changes in the weld size of tubes could be considered during fabrication to alleviate the concern. Ultimately the shop plans included a minor modification to address the required fatigue resistance, by including a small supplemental bracket to reduce stress which was demonstrated to be effective in the final calculation package.

At the Route 30 Bridge gate, the initial model indicated a very close allowable ratio for combined axial and bending resistance as well as higher than allowable for two diagonal truss cross members in fatigue. This was caused by a change in member size used in the first iteration which concentrated stress at this location. A more gradual reduction in chord size was used in the second iteration to reduce the stress ratio for fatigue. The base pipe was revised to a 3.5” schedule 40 pipe to reduce the ratio for the combined stress analysis.



Member	P (lb)	M (lb-inch)	(Δf) (ksi)	$(\Delta F)_{TH}$ (ksi)
B2 - 2	88.6	82.8	0.61	0.46
B3 - 2	-42.1	86.4	0.57	0.46
B2 - 3	-261.0	24.0	0.48	0.46

Figure 7: Mathis Bridge initial stress ratios and critical locations

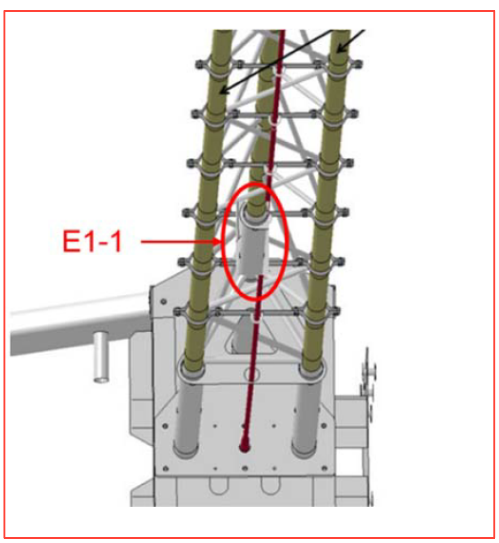


Figure 8: Route 30 Bridge critical locations

Impact Analysis

AASHTO MASH, the standard for evaluating roadside hardware does not explicitly include barriers that cross the roadway (oriented perpendicular to traffic). In discussions with NJDOT, the team agreed, MASH Test Level 2 demands would be appropriate for the design criteria of both bridges. Initial discussions with B & B indicated that TL-2 was appropriate for similar installations of previously utilized high capacity gate arms. A higher crash test level combined with the high wind load resistance required was not deemed a practical combination.

For both the sites, computer crash simulations of the prototype were performed by TTI using LS-DYNA software, a finite element (FE) program used by the automobile industry to solve non-linear, dynamic response and load-time history response of a vehicle impacting a barrier system. A 3 x 2 test Matrix based on MASH was used for testing a small passenger car and light duty truck impacting the resistance gates at quarter points and mid-span locations (Figure 9).

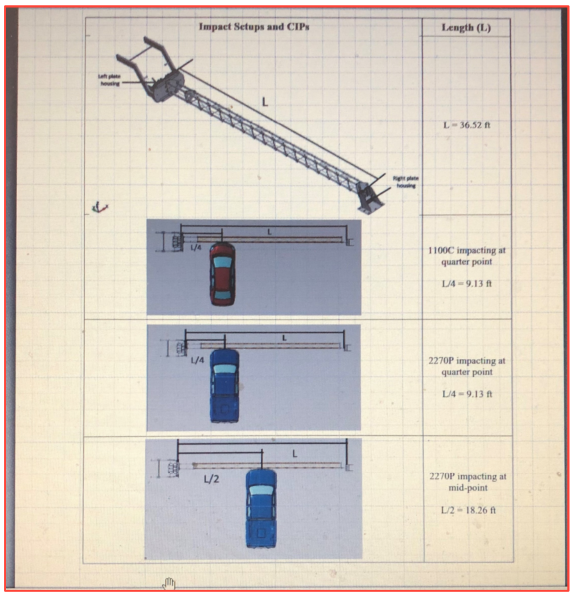


Figure 9: Simulation impact points, plan view

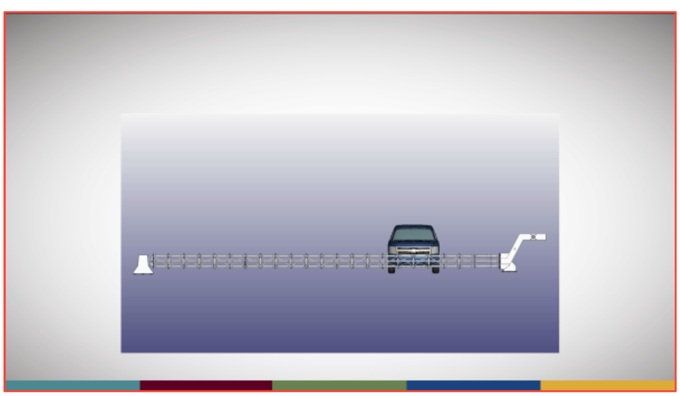


Figure 10: Simulation 1/4 span impact, elevation

A highly refined mesh was developed for the FE analysis. The cables, bolts, bracing, tubes, plates, and receivers were all explicitly modelled, and the refinement was highly iterative (Figure 11). The analysis was highly sensitive to material selection. For example, the primary resisting element of the barrier system relies on annealed cables. Initial models were based on cables similar to those used for zero penetration security barriers, which resulted in undesirable effects to vehicle occupants.

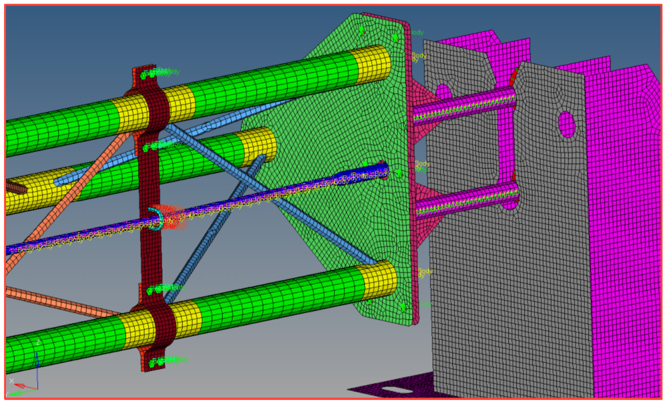


Figure 11: Typical screen shot of FEM mesh

MASH TL-2 Test Evaluation Criteria

Table 5-1 of MASH lists the various performance criteria for evaluation and the code requires consideration of Test 40 and 41 for two vehicles at the Critical Impact Point (CIP), which in this case was defined as the ¼ point along the barrier, though each site requires an evaluation of the CIP. MASH considers these types of barriers to be a subset of non-redirective crash cushions. The simulation included verification of head-on impact of the two recommended test vehicles at a speed of 44 mph, for the following criteria:

1) Structural Adequacy
    a. Acceptable performance by safe redirection, controlled penetration or stopping
2) Occupant risk
    a. Detached elements not to penetrate passenger compartment, limitations on deformation of vehicle components
    b. Vehicle to remain upright during/after collision, roll and pitch angles
    c. Occupant Impact Velocity (OIV)
    d. Occupant ride-down acceleration

In addition to the specified CIP, a midpoint impact point was also chosen/added to evaluate the barrier when considering the lane configuration, typical at each site where three lanes in each direction exist. Table 2 tabulates the values from the simulation analysis for the gates at each bridge site.

FE Simulation Results

Small vehicle (1100C, 2425 lbs.) Quarter Span Impact: The gate was impacted at the middle of the right lane and the maximum penetration distance was 5.95 feet for the Mathis gate and 7.3 feet for the Route 30 gate. This condition assessed the driver's ability to control the vehicle and maximum occupant effects, as the smaller vehicle impacting the barrier at a relatively stiff location would result in greater effects to occupants.

The kinetic energy applied to the gate at impact is dissipated by conversion into internal energy (stored in the system by deformation) and sliding energy (friction at the tires/deck interface). Almost all the initial kinetic energy is converted to internal energy by damage of the vehicle and gate components, about 10% is converted into sliding energy, with a small amount undissipated due to the remaining velocity of the vehicle.

The results indicated most components of the barrier gate including the anchor assemblies were subjected to little or no plastic strains, indicating that none of the tubes or braces would fail under small vehicle impact. Analysis predicted plastic strains exceeding 20% in the exposed cable, adjacent to the impact area, but no failure. The mounting plate at the base, however showed excessive plastic strains due to buckling but not failure (Figure 12). Blue regions represent little to no plastic strain; red regions represent plastic strain exceeding 20%. Cable forces were also predicted to be less than capacity.

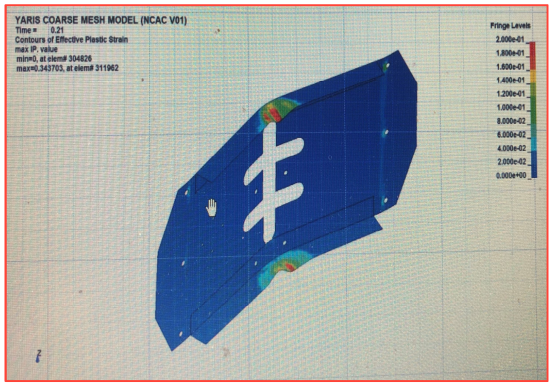


Figure 12: Mounting plate strains at small vehicle impact

Small Vehicle (1100C) Occupant Risk Assessment: The model predicted that the small vehicle remained upright during and post impact. Occupant Impact Velocity, ride-down acceleration, roll, pitch, and yaw were all under the MASH thresholds. Simulation indicated that the bolted connection at the base of the arms and the lifting plate exhibited excessive plastic strains, possibly leading to local failure but not a system failure.

Pickup Truck (2270P) Quarter Span Impact: The gate was impacted near the middle of the left lane and the maximum penetration distance was 8.31 feet for Mathis gate and 9.5 feet for the Route 30 gate. This condition assessed the ability of the gate to resist larger forces at stiffer locations, which are more prone to damage and to contain the light truck in a stable manner upon impact.

About 90% of the initial kinetic energy of the impacting vehicle is converted to internal energy by damage of the vehicle and gate components, about 7% is converted into sliding energy, less than 4% undissipated due to the remaining velocity of the vehicle. Similar results were predicted as described under the small vehicle, for the gate arm. The vehicle was maintained upright. The mounting plate at the base, showed excessive plastic strains due to buckling but not failure (Figure 13). While the bolt connecting the center cable to lifting plate was predicted to undergo plastic strains exceeding 20%, and likely to fail at this connection, the system would not fail.

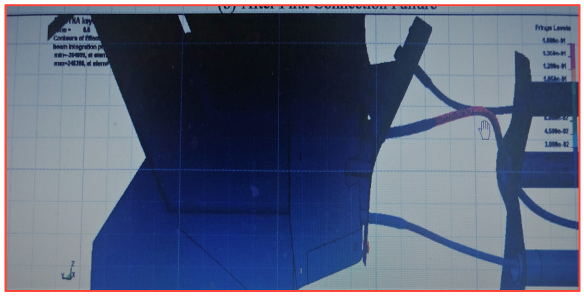


Figure 13: Mounting plate strains at pickup truck impact

Pickup Truck (2270P) Mid Span Impact: The gate was impacted approximately near the middle of the center lane and the maximum penetration distance was 9.71 feet for Mathis gate and 10.2 feet for the Route 30 gate. This condition was added to the test matrix to confirm that the gate was strong enough to prevent uncontrolled penetration (dynamic displacement) of the vehicle at the more flexible point.

About 95% of the initial kinetic energy of the impacting vehicle is converted to internal energy by damage of the vehicle and gate components, about 4% is converted into sliding energy, less than 2% undissipated due to the remaining velocity of the vehicle.

Similar results were predicted as described under the small vehicle and pickup truck at quarter span point impact, for the gate arm. The vehicle was maintained upright. The mounting plate at the base showed excessive plastic strains due to buckling but not failure. Regions that were predicted to undergo plastic strains exceeding 20% were the same as before. Strains exceeding 20% were also predicted at the connections of the gate and the lifting plate. Cable forces were predicted to be less than cable capacity.

Pickup Truck (2270P) Occupant Risk Assessment: The model predicted that the pickup truck would remain upright during and post impact. Occupant Impact Velocity, ride-down acceleration, roll, pitch, and yaw were all under the MASH thresholds. Although OIV in the transverse direction was higher than preferred, it was still under the maximum allowed.

	SMALL VEHICLE 1100C		PICKUP TRUCK 2270P		
PARAMETER EVALAUTED	FEM RESULT Mathis	FEM RESULT Route 30	FEM RESULT Mathis	FEM RESULT Route 30	MASH ALLOWABLE
Occupant Impact Velocity-Longitudinal	35.76 fps	35.43 fps	31.5 fps	32.15 fps	30 fps preferred 40 fps maximum
Occupant Impact Velocity-Transverse	3.61 fps	0.3 fps	6.23 fps	2.3 fps	30 fps preferred 40 fps maximum
Ride-down Acceleration-Longitudinal.	-14.6 G's	-17.7 G's	-12.5 G's	-14.6 G's	15G's preferred 20G's maximum
Ride-down Acceleration-Transverse	-2.6 G's	-2.9 G's	-3.1 G's	-5.5 G's	15G's preferred 20G's maximum
Roll angle	2.3 deg	3.0 deg	2.2 deg	3.1 deg	75 deg max.
Pitch angle	2.3 deg	7.8 deg	9.5 deg	13.7 deg	75 deg max.

Table 2: Comparison of FEM simulation maximum values versus MASH allowable

Simulation Results Versus Crash Tests

Upon award for the Mathis Bridge, shop plans were submitted for the barrier gate confirming that the actual gate was a replica of the simulated model (Photo 3). Physical crash tests were performed on the gates at the TTI ISO certified testing facility. There was an excellent correlation between crash test results and simulation predicted values for all parameters (Table 3 and Figure 14).

Photo 3: Mathis Bridge as constructed resistance barrier gate

Simulation showed that the gates would perform to sustain the test vehicles upright and meet MASH mandated OIV and ride-down acceleration. Gate components were deformed at impact but stopped the test vehicles and all cables remained in place. Simulation suggested in each case that the connection of arms to lifting plate at the base would be the controlling element for failure, however the system overall performed as intended, with the cables remaining in place. Simulation videos of the various test cases and actual crash test videos (seen in the presentation) validate the close correlation.

TEST	VEHICLE	VALUE	ACCEPTANCE CRITERIA		TEST RESULT	PREDICTED VALUE
			Preferred	Maximum		
MASH TEST 2-40	1100C	Longitudinal OIV	30 ft/s (9.1 m/s)	40ft/s (12.2m/s)	35.8 ft/s	35.76 ft/s
		Lateral OIV	30 ft/s (9.1 m/s)	40ft/s (12.2m/s)	2.62 ft/s	3.61 ft/s
		Longitudinal Ridedown	15.0 G	20.59 G	14.2 g	14.6 g
		Lateral Ridedown	15.0 G	20.59 G	2.7 g	2.6 g
MASH TEST 2-41	2270P	Longitudinal OIV	30 ft/s (9.1 m/s)	40ft/s (12.2m/s)	32.5 ft/s	31.5ft/s
		Lateral OIV	30 ft/s (9.1 m/s)	40ft/s (12.2m/s)	5.91 ft/s	6.23 ft/s
		Longitudinal Ridedown	15.0 G	20.59 G	11.9 g	12.5 g
		Lateral Ridedown	15.0 G	20.59 G	2.1 g	3.1 g

Table 3: Comparison of FEM simulation versus full scale crash tests for Mathis Bridge gates

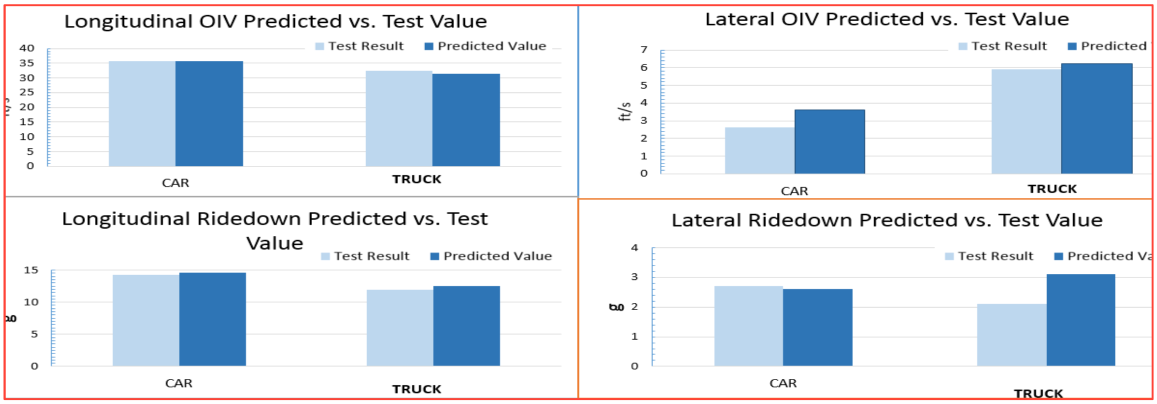


Figure 14: Comparison of FEM simulation versus full scale crash tests for Mathis Bridge gates

Photo 4: Mathis Bridge pickup truck crash test

For the Mathis Bridge, crash tests were performed on February 17, 2017, on the gates as fabricated per the approved shop plans, and identical to the simulation model. Crash tests were performed at the TTI proving grounds. The same vehicle specifications as simulated were utilized and a similar speed was recorded at impact. For the small vehicle (1100C), the impact speed at 90-degree impact was recorded at 43.9 mph for quarter span impact, and 44.9 mph for the pickup truck (2207P) for quarter span impact, (Photo 4).

In all crash tests, the riding surface was dry concrete pavement. Crash test results are presented in Table 3, attesting the excellent and close correlation between predicted and actual parameters. Crash tests also showed no deformation of the occupant compartments. At the time of this writing, the Route 30 Bridge project is in construction with the shop drawing process for the barrier gates ongoing and the final crash test results will be available at a later date.

Photo 5: Mathis Bridge far side receiver

Gate Installation

At the Mathis Bridge, the new gates were installed on precast deck panels in the winter of 2017. The installation was successful; however, some minor alignment issues became apparent after the west gate was put into service. The precast sleeves set to receive the anchorage for the gate base and the levelness of the barrier gate housing's leveling pad were slightly out of position. This was evident by some rubbing at the receiver end of the gate when it was deployed. After the fabricator visited the site, it was agreed that the anchor bolt holes in the precast panels would need to be modified with a shift in location of approximately ½". With this adjustment, and some touch-up work at the receiver end, the gates were accepted.

The deployment of the gates also required that a small opening within the crash-tested steel 4-bar railing be introduced. In order to maintain the gate arm lengths analyzed during design the tri-chord system needed to pass through the rail elements. It was considered to be a large risk to modify the gate arm and potentially jeopardize the crash testing. Therefore, the originally analyzed gate arm was approved for construction. To avoid a potential blunt end within the small railing opening, the railings were mitered and set at an angle to lessen the effect of a potential impact in the primary direction of traffic. Photo 5 shows the final condition of the railing installation at the gates. Route 30 utilized similar 4-bar railing details at the curbline to accommodate gate movement.

Conclusion

Thanks to close collaboration with a gate manufacturer and a research facility, the Mathis team developed a prototype for a Finite Element simulation analysis and completed efforts within 6 months where an analysis of this type typically takes 12 to 15 months to verify all aspects of performance. AASHTO MASH recommends an Impact Point (IP) at the ¼ span location at a minimum however additional IPs were added to the test matrix at mid-span and an additional ¼ span point, to capture potential IPs from all three lanes.

The excellent correlation between simulation and physical behavior shown for the Mathis Bridge gate indicates a high level of reliability in simulation modelling. Utilizing project specific criteria for simulation allowed WSP to assess additional IP's (in this case a total of 6, including the critical IP's). Actual crash tests are expensive with the number of gates and vehicles that are sacrificed and can easily run several hundreds of thousands of dollars. From a fabricator's perspective, an investment in comprehensive modeling/refined analysis along with a reduced investment in physical testing may yield a reasonable compromise for achievement of successful MASH testing. Site specific simulation analysis could reduce the number of physical crash tests and validate gate performance at a lower cost. Additional impact points may be investigated, to a large extent, at a lower cost within the same model analytically.