

# Refined Load Rating through Rapid Modal Testing

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16. Abstract <p>A new rapid modal testing platform and method was demonstrated and validated via comparison to conventional experimental and analytical approaches. The Targeted Hits for Modal Parameter Estimation Rating (THMPER) system is a rapid modal impact trailer, a mobile work station, and streamlined data processing software which aims to address the current lack of cost-effective methods to perform refined load rating analysis of bridges.</p> <p>The validation effort used a typical highway bridge as a test specimen and consisted of a multi-tiered comparison with current 'best practices' approaches. The THMPER system's effectiveness as a modal testing approach was assessed through a comparison of modal parameters obtained from an ambient vibration monitoring effort. Natural frequency estimations showed good agreement between the two dynamic test methods. Comparison of THMPER to a conventional static test was performed via independent finite element model calibrations using the natural frequencies and mode shapes estimated by the THMPER system and the strains observed during a truck load test. The updated parameters of both model calibrations showed similar behavior. Comparing the calibration results to a priori values, both calibrations resulted in (1) an increase of girder and deck stiffness, (2) active diaphragms and barriers (e.g. non-trivial stiffness), (3) longitudinal stiffness at expansion bearings, (4) longitudinal release of the 'fixed' bearing above the center pier.</p> <p>In general, the discrepancies between the experimental observations and the predictions made by the a priori FE model indicate that the available design plans are not representative of the structure. The a priori model either lacks a significant amount of stiffness or has too much mass. Nevertheless, the "final" parameters from each calibration were relatively consistent in behavior indicating that both the THMPER system and truck load testing experimental approaches provide similar, useful information about the structure.</p>			
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## DESCRIPTION OF THE PROBLEM

There is currently a lack of cost-effective methods to perform refined load ratings of bridges that either do not rate under simplified procedures or for which plans and documentation are not available. This research aims to demonstrate an emerging technology (termed THMPER - Target Hits for Modal Parameter Estimation and Rating) to state DOTs through direct comparison with the results of a 'best practices' diagnostic truck load test.

## APPROACH

The Targeted Hits for Modal Parameter Estimation and Rating (THMPER) system is a rapid modal impact trailer, a mobile work station, and streamlined data processing software that is used to extract modal parameters (natural frequencies and global mode shapes) of highway bridges during brief traffic slow-downs or partial lane closures. The modal testing trailer (Figure 1) is comprised of a Falling Weight Deflectometer (FWD) that was significantly reconfigured to (1) provide a single, large (~30kip) broadband impact source, and (2) collect the resulting free-decay response of the bridge's surface both locally (at the impact location) and globally (via wireless, GPS synchronized stationary sensors installed along available sidewalks/shoulders out of the way of traffic). This test method is described graphically in Figure 2. Once collected, the data is ported to a semi-automated modal processing software which performs (1) data quality checks, (2) frequency response function development, and (3) modal parameter estimation.



Figure 1: THMPER System Overview

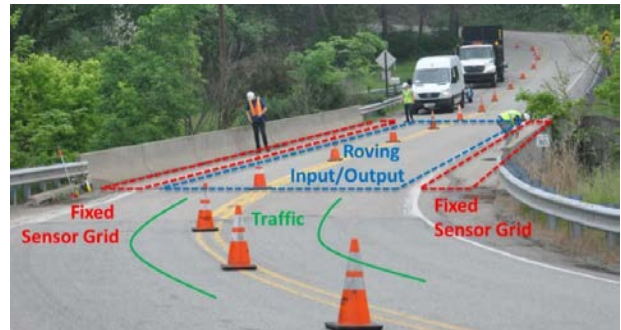


Figure 2: THMPER System Testing Approach

Validation was performed using a typical highway bridge as a test specimen through a three-tiered comparison with current 'best practices' approaches. First, the THMPER system's effectiveness as a modal testing approach is assessed through a comparison of modal parameters obtained from a conventional modal test. Second, a finite element model calibration is performed and compared using results from the THMPER system and from a conventional truck load test. Finally, comparison is made between each method as to the effect each FE model calibration result set may influence a Load and Resistance Factor Rating.



## METHODOLOGY

### Bridge Specimen

The bridge consists of 4 spans over CSX tracks carrying two lanes of I-695 north and a third onramp lane. A map overview is shown in Figure 3 and an elevation view in Figure 4. It was built in 1975 and utilizes 3000 psi concrete, 40 ksi rebar, and 36 ksi structural steel. The two outer spans (spans 1 and 4) are 26 ft. each and are reinforced concrete frames with 5 girders each. The inner spans (spans 2 and 3) are a two-span, continuous steel girder bridge with 9 kinked girders spaced at roughly 7 ft apart. The outer supports of spans 2 and 3 are expansion joints with a pinned center support resting on a 23 ft. concrete pier.



Figure 3: Overview of Selected Bridge



Figure 4: Elevation View During Underside Strain Gauge Installation

The deck on spans 2 and 3 was initially 7.5" thick. Rehabilitation drawings indicate the top 2" has been removed and replaced with a 2.5" thick concrete overlay. This overlay thickness is listed on drawings and has not been field measured. For the analysis, a 7.5" deck thickness is used with ½" wearing surface as mass only.

### Finite Element Modeling

The 3D Finite Element Model was built using plate elements representing the deck and girder webs, and beam elements representing girder flanges and crossframe members. The deck is connected to the top flange elements using rigid links to enforce composite action and master-slave type links in the non-composite negative moment region. Boundary conditions are established at their geometric locations below the bottom flanges and connected to the girders with rigid links.

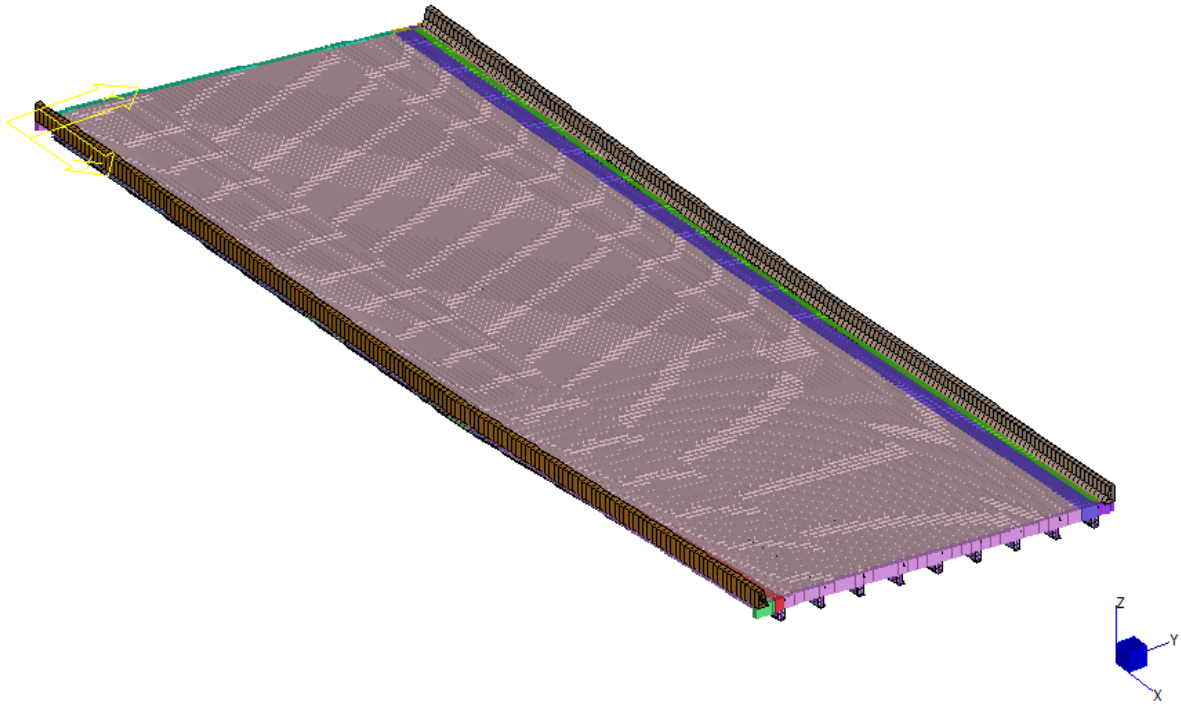


Figure 5: A Priori FE Model (Isometric View)

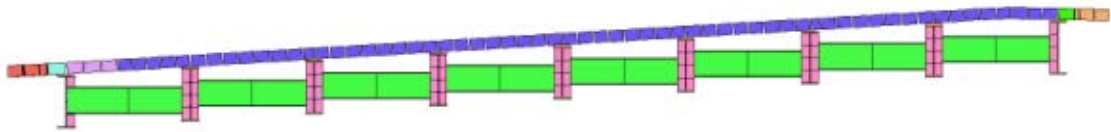


Figure 6: A Priori FE Model (Section View)

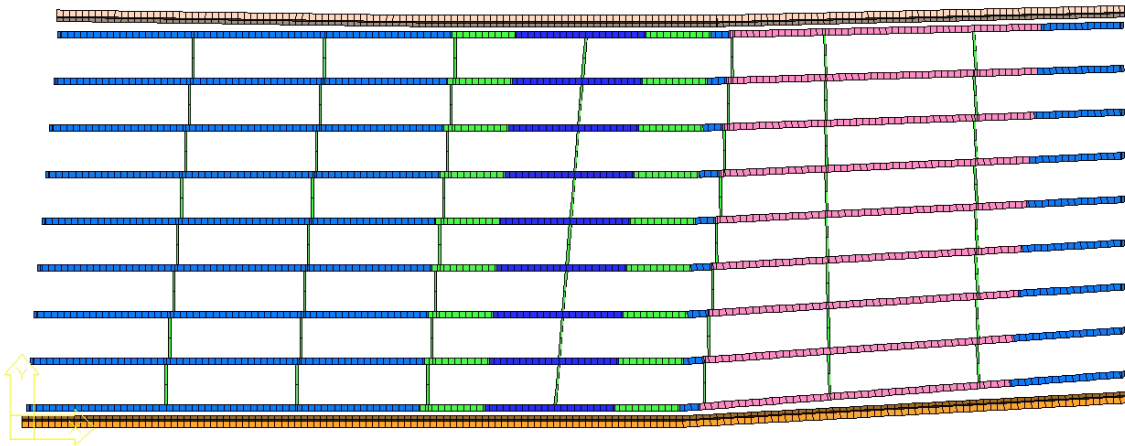


Figure 7: A Priori FE Model (Plan View)

## Field Testing Program

### Modal Testing

The modal instrumentation plan is shown in Figure 8. A total of 15 stationary accelerometers were installed along the underside of span 2 at longitudinal quarter points of every other girder. Underside access was not a test necessity but was incorporated into the modal testing plan due to the underside of the structure already requiring access to install the strain gauges used for the truck testing. This provided additional spatial resolution with minimal “cost”. The stationary accelerometers remained throughout the duration of the modal testing and continuously recorded GPS time synchronized data. Underside instrumentation of span 3 was not available due to the CSX rail below.

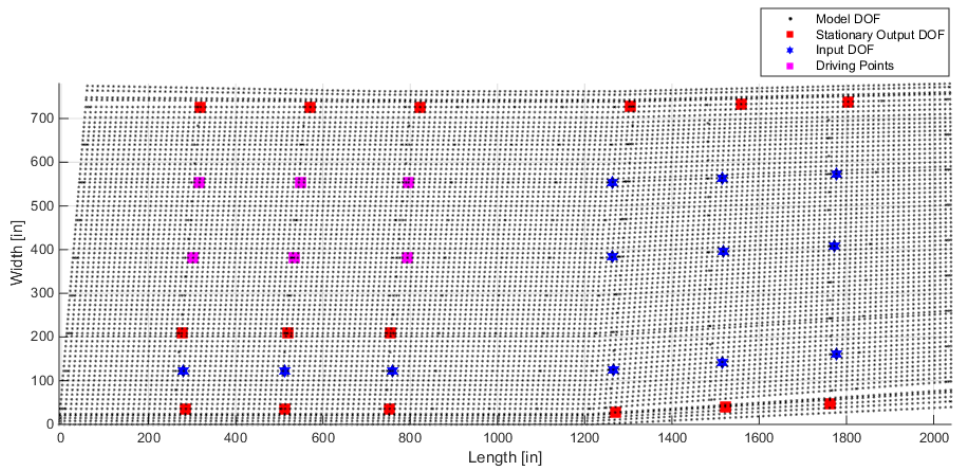


Figure 8: Modal Testing Instrumentation Plan

THMPER testing (Figure 9) utilized an additional 6 stationary accelerometers that were temporarily installed on the topside of both span’s decks via adhesive. They were installed at the outside perimeter of the deck at longitudinal quarter points along spans 2 and 3, 6 in. off each barrier. The THMPER system was used to perform roving driving point measurements via 3 lane passes, impacting at the longitudinal quarter points of each span. A total of 18 impact locations were sampled, 6 of which were stationary driving points.

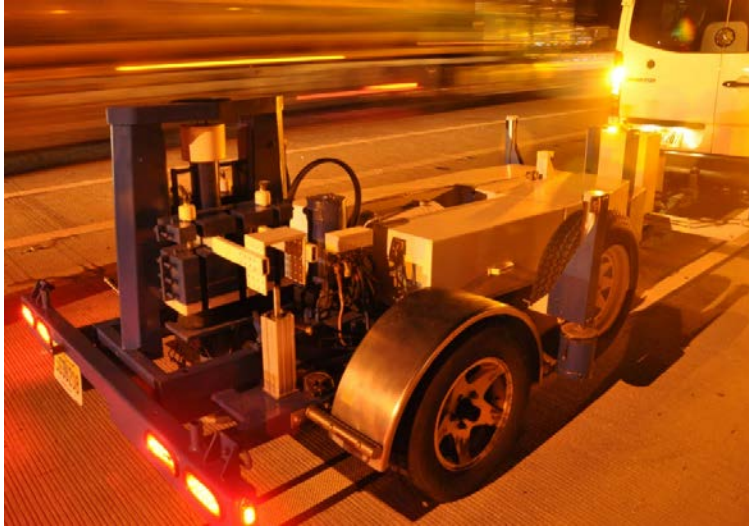


Figure 9: THMPER Modal Impact Testing During Heavy Truck Traffic

### Truck Load Testing

Truck load testing was performed by Pennoni Associates; the following is a summary of their load testing protocol used for this bridge.

A series of load tests were performed, and recorded data was used to update specific model parameters with the goal of minimizing the differences between the FE model's computed response and the actual measured responses during load tests. To accomplish this, locations of high magnitude responses were selected for instrumentation with vibrating wire strain gages (Figure 10). Three sections of the bridge were selected for instrumentation (Span 1 at midspan, Span 2 at midspan, and Span 3 at Pier 2) for a total of 59 gages. Steel sections were instrumented with three gauges: one on the bottom flange, one two on the web. Concrete girders were instrumented with a single gage on the bottom of the member.

The instrumentation plan is intended to show both the curvature (difference in bending strains over the height between measurements) as well as the bottom flange strains from primary bending. The girder sections were evaluated to determine the location of the elastic neutral axis of the composite cross section for positive bending moments. The web gages were located below this location to ensure that measurable primary bending moment strains would be captured. The load test consisted of a series of static load cases of one, two, or three trucks while empty and again fully loaded. The loading locations are shown in Figure 11 and a photo during the truck staging is shown in Figure 12.

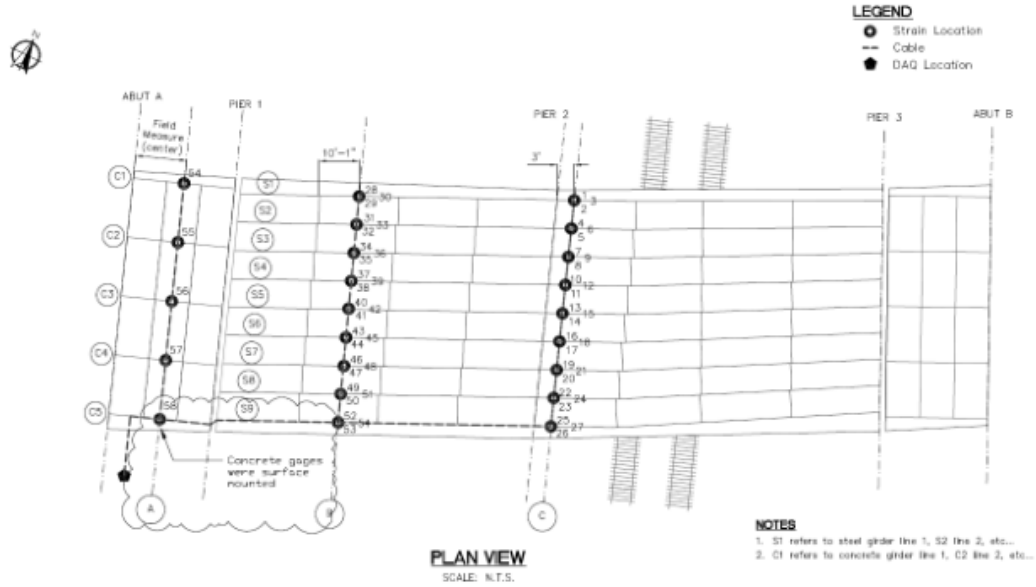


Figure 10: Truck Load Test Instrumentation Plan

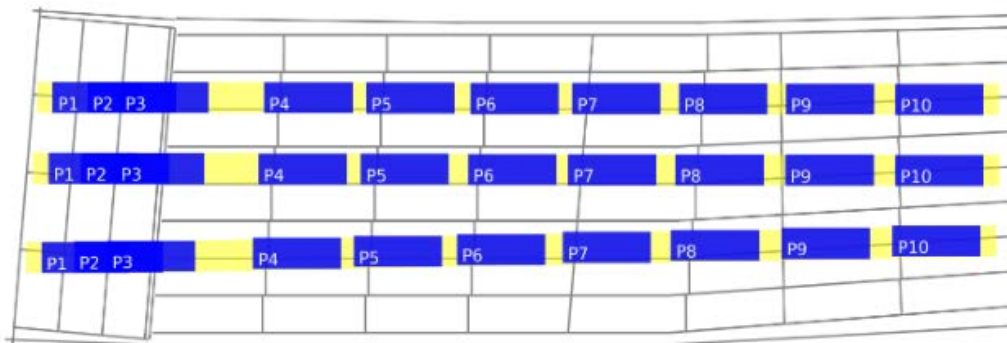


Figure 11: Truck positions of each load case



Figure 12: Truck staging during load test



## Data Analysis and Validation

### Operational Modal Analysis

Operational modal analysis was performed on the output only dynamic DOF installed on the underside and topside of the bridge. Several 5-20 minute data records were recorded during the normal operation of the bridge to ensure some non-trivial excitation. Raw data (shown below in the time domain, Figure 13, and the frequency domain, Figure 14) was recorded at 3,200 Hz to ease synchronization with THMPER data and data acquisition systems. Output only modal analysis was performed on these records to determine the structure's natural frequencies and used for comparison in the following sections.

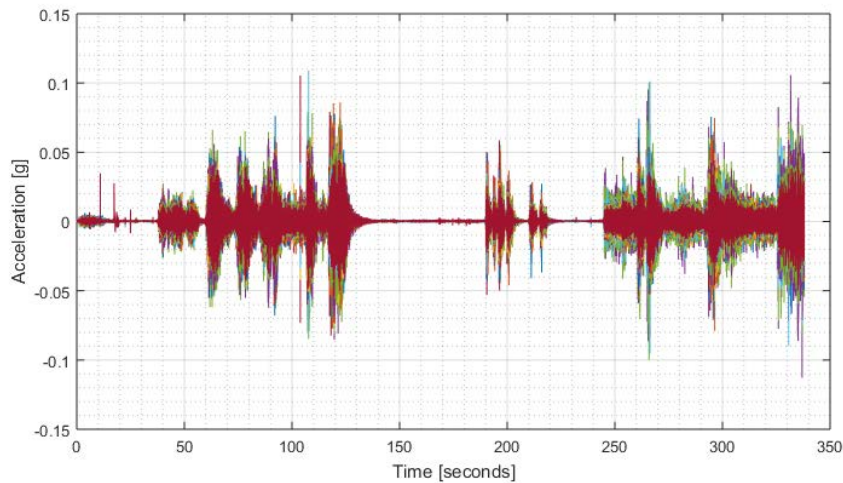


Figure 13: Typical Operating Response Record (Time Domain)

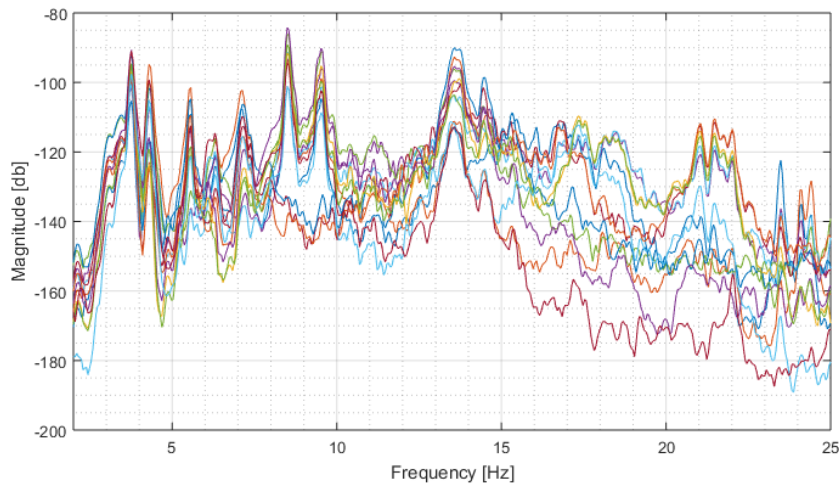


Figure 14: Typical Operating Response Record (Frequency Domain)

### THMPER Modal Analysis & Model Calibration

Raw data was recorded at a sampling rate of 3,200 Hz and a minimum of 3 records were recorded at each impact location for averaging. Typical force levels were observed up to 25,000 lbs. (Figure 15) which caused typical driving point accelerations up to 2-4g's (an order of magnitude above the

operational noise due to ambient excitation). A rectangular window was applied to the force records, and an exponential window was applied to the response records to minimize leakage effects.

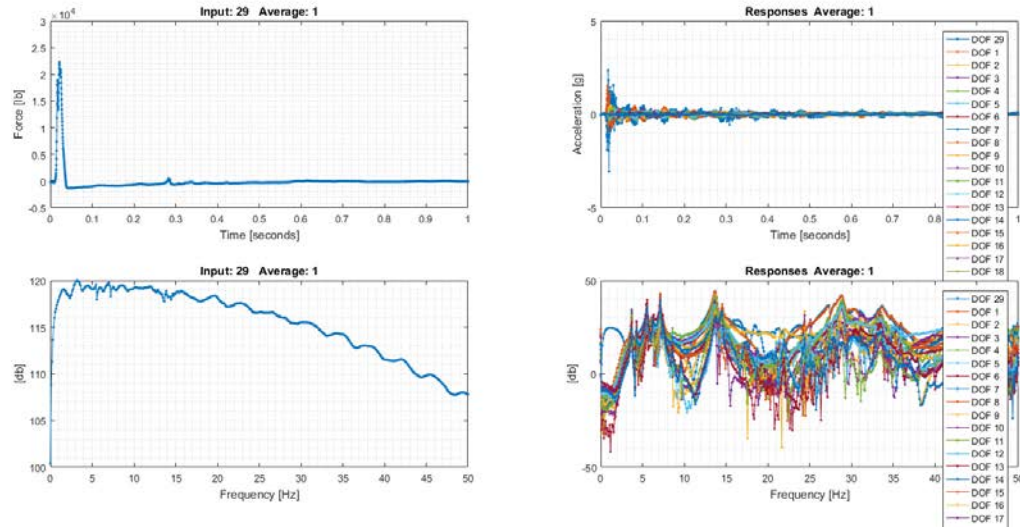


Figure 15: THMPER Force and Response Data in Time and Frequency Domains

Multi Degree of Freedom (MDOF) Modal Parameter Estimation (MPE) was performed using the Complex Mode Indicator Function (CMIF) algorithm to obtain the natural frequencies and corresponding mode shapes of the bridge. These parameters represent a dynamic structural signature that reflects the stiffness and mass properties of a structure and will be used to compare to the a priori FE model. The first nine global mode shapes of the super structure found via the THMPER system are shown in Figure 16.

Sensitivity studies were performed on selected model parameters to investigate their influence on the global load carrying mechanisms represented in the FE model as well as select reasonable bounds for FE model calibration. This was done programmatically via a Strand7/MATLAB API. Using the a priori FE model, the first 12 modes were solved for and the mode shapes used to track each subsequent sensitivity analysis via a Modal Assurance Criterion (MAC) mode pairing scheme. This ensures that modal rank is identified in each parameter step and the correct frequency comparison is made. The investigated parameters and their respective sensitive bounds are summarized in Table 1.

Model calibration was performed on 5 separate groupings of uncertain parameters (each referred to as a “trial”). For each trial, a minimum of 3 and maximum of 6 single model optimizations were performed; Latin hyper cube sampling was used to determine the initial guesses for each parameter set. Lsqnonlin, a Matlab built in gradient-based objective function minimization algorithm, was used for this calibration. An objective function is a vector describing the comparison between simulation and measured responses and is minimized by Lsqnonlin. The objective function used for this calibration effort was formed by calculating the percent difference between the natural frequencies of the first 9 global modes found experimentally by THMPER and those produced by the algorithm’s current guess.

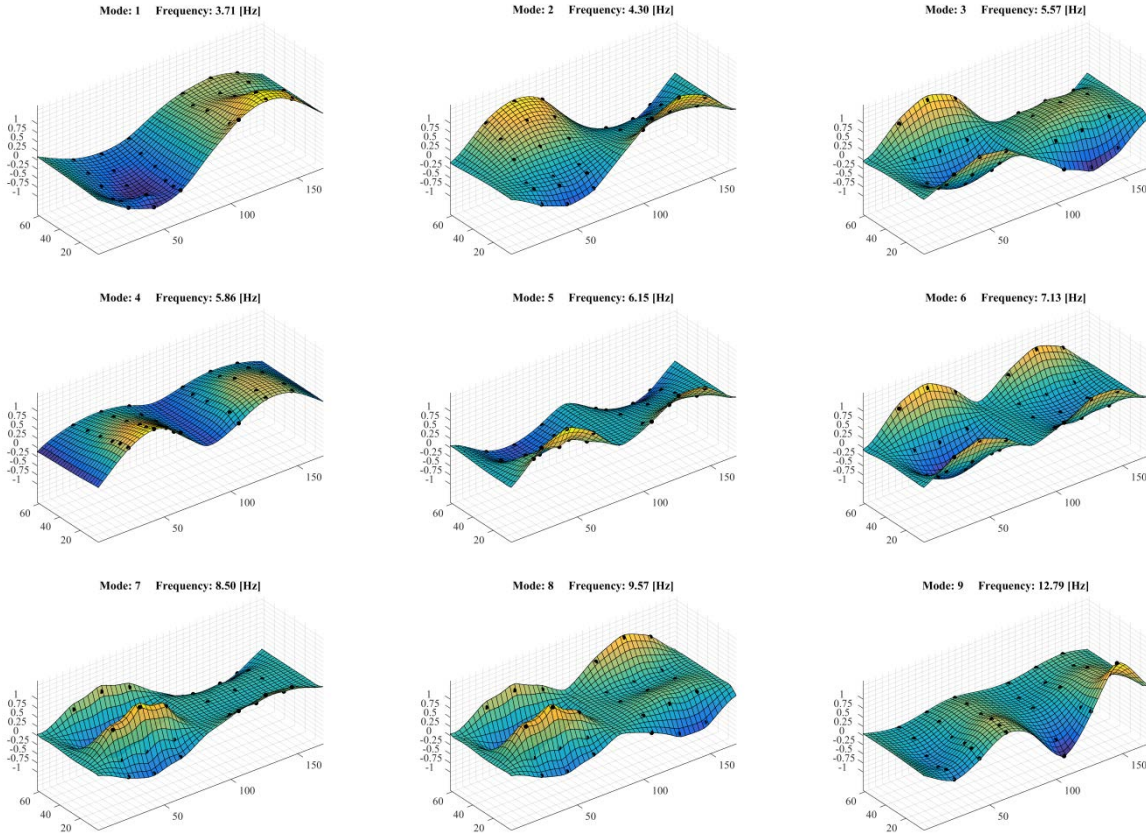


Figure 16: THMPER Experimental Frequencies & Mode Shapes

Table 1: THMPER Model Calibration Parameters

<b>Name</b>	<b>Type</b>	<b>Base</b>	<b>Scale</b>	<b>Lower Bound</b>	<b>Upper Bound</b>
Girder Stiffness	E [psi]	2.90E+07	linear	0.8	1.2
Diaphragm Stiffness	E [psi]	29000	log	1	3
Deck Stiffness	f'c [psi]	3.16E+06	linear	0.18	1.8
Barrier Stiffness	f'c [psi]	3.16E+06	linear	0.1	1.5
Longitudinal Stiffness at Expansion Joints	[lb/in]	1	log	4	8
Longitudinal Stiffness at Center Pier	[lb/in]	1	log	4	8

A summary of the modal calibration results is presented in Table 3. In this table, the percent error is compared between each trial – the extreme right column is the root mean squared (RMS) error per mode and the extreme bottom row is the root squared sum value for that trial. Trial 5 was selected as the final modal calibration result set as it was the trial that contained the lowest aggregate error of the five trials. A set of representative results from the calibration of this parameter set is shown in Figure 17. Each column subplot represents a calibration result set from trial 5. In each plot, the x-dimension is scaled to the relative parameter bounds, and the y-dimension reads bottom-to-top to show the optimization algorithms progress during its search for a minima. This is useful information as it shows the algorithm’s ability to properly sample and traverse a parameters full range.



Table 2: Summary of THMPER Model Calibration Trials

<i>Name</i>	<i>Trials</i>				
	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>
Steel Modulus of Elasticity		x			x
Diaphragm Stiffness	x	x	x	x	x
Deck Stiffness – Longitudinal Only			x		
Deck Stiffness – Transverse Only		x	x		
Deck Stiffness – Combined				x	x
Barrier Stiffness	x	x	x	x	x
Longitudinal Stiffness at Expansion Joints	x	x	x	x	x
Longitudinal Stiffness at Center Pier	x	x	x	x	x

Table 3: Summary of THMPER Model Calibration Results

		<b>Model Calibration Results [% Diff]</b>						
	<b>THMPER</b>	<i>A Priori</i>	<i>Trial 1</i>	<i>Trial 2</i>	<i>Trial 3</i>	<i>Trial 4</i>	<i>Trial 5</i>	<b>RMS</b>
	<i>Freq [Hz]</i>							
1	3.71	14.83	0.21	0.13	0.25	0.26	<b>0.48</b>	<b>0.29</b>
2	4.3	2.10	3.85	1.80	1.53	1.33	<b>0.69</b>	<b>2.13</b>
3	5.57	0.54	2.11	0.89	2.05	1.74	<b>1.52</b>	<b>1.72</b>
4	5.86	15.45	1.48	0.37	2.10	2.44	<b>2.86</b>	<b>2.04</b>
5	6.15	14.36	2.18	1.63	2.67	2.56	<b>2.47</b>	<b>2.33</b>
6	7.13	16.66	0.57	0.66	0.23	0.12	<b>0.42</b>	<b>0.45</b>
7	8.5	9.15	9.17	2.17	2.49	2.32	<b>3.09</b>	<b>4.69</b>
8	9.57	16.61	7.22	0.99	1.27	0.94	<b>1.00</b>	<b>3.36</b>
9	12.79	11.97	11.43	9.15	8.43	8.46	<b>7.28</b>	<b>9.05</b>
	<b>RSS</b>	<b>38.08</b>	17.13	9.84	9.85	9.76	<b>9.00</b>	

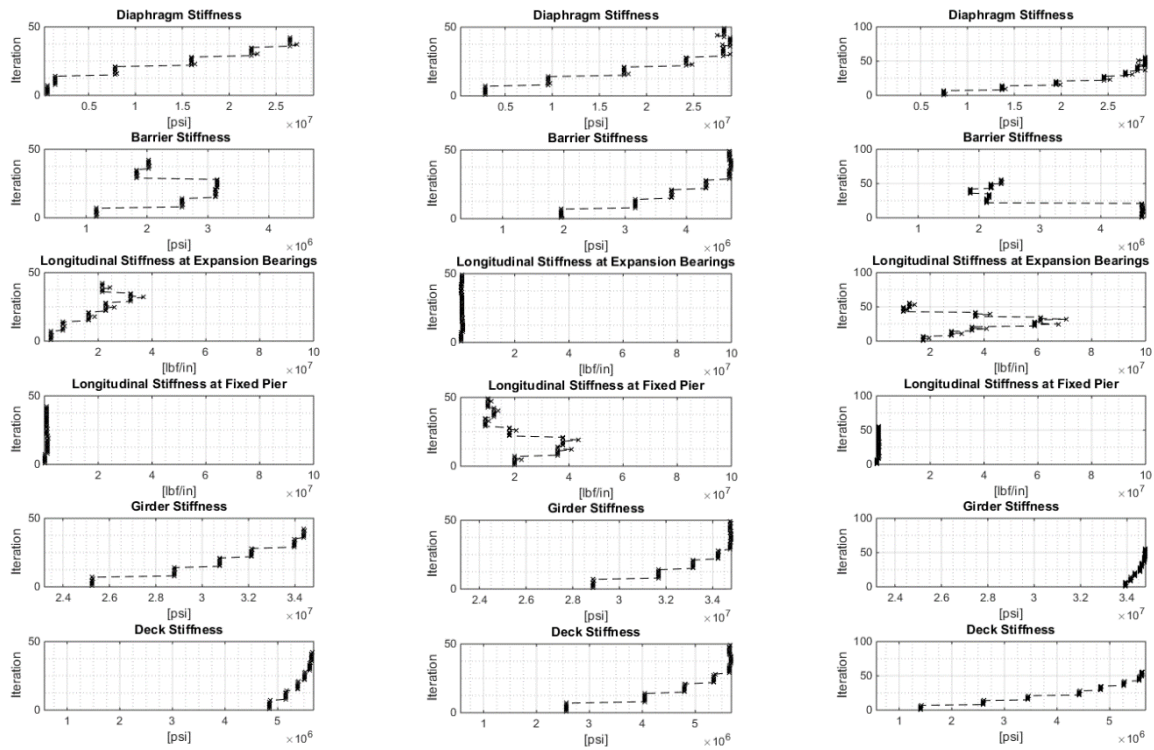


Figure 17: Representative Results of THMPER Calibration Trials

### Summary of Truck Load Test, Analysis, and Model Calibration

Static truck load testing, data analysis, and model calibration was performed by Pennoni Associates; the following is a summary of the reported results.

Results of a typical static load case is shown in Figure 18 where a schematic of the structure showing lane locations in yellow and vehicle locations in blue is included above a series of subplots. The subplot array layout mirrors the instrumentation plan, subplots in each row correspond to the same girder, and subplots in each column correspond to the same bridge section location. These subplots show the measured responses in red along with the predicted primary bending strain responses from the a priori FE model for the same load case in blue. Each line is composed of only two data points, one at the bottom flange and another where the line changes thickness. The lines are an assumed linear distribution based on these two points. A schematic of the girder cross section is shown behind each plot. If strains are considered to be the primary bending strain, as is the case for the FE model predicted strains, the location where the data lines cross the web indicates the neutral axis location. Tension strains are positive (on the right), compressive strains are negative (on the left). Web strains are computed as the average of strain on either side of the web to eliminate the potential effect of differential strain on either side of the web.

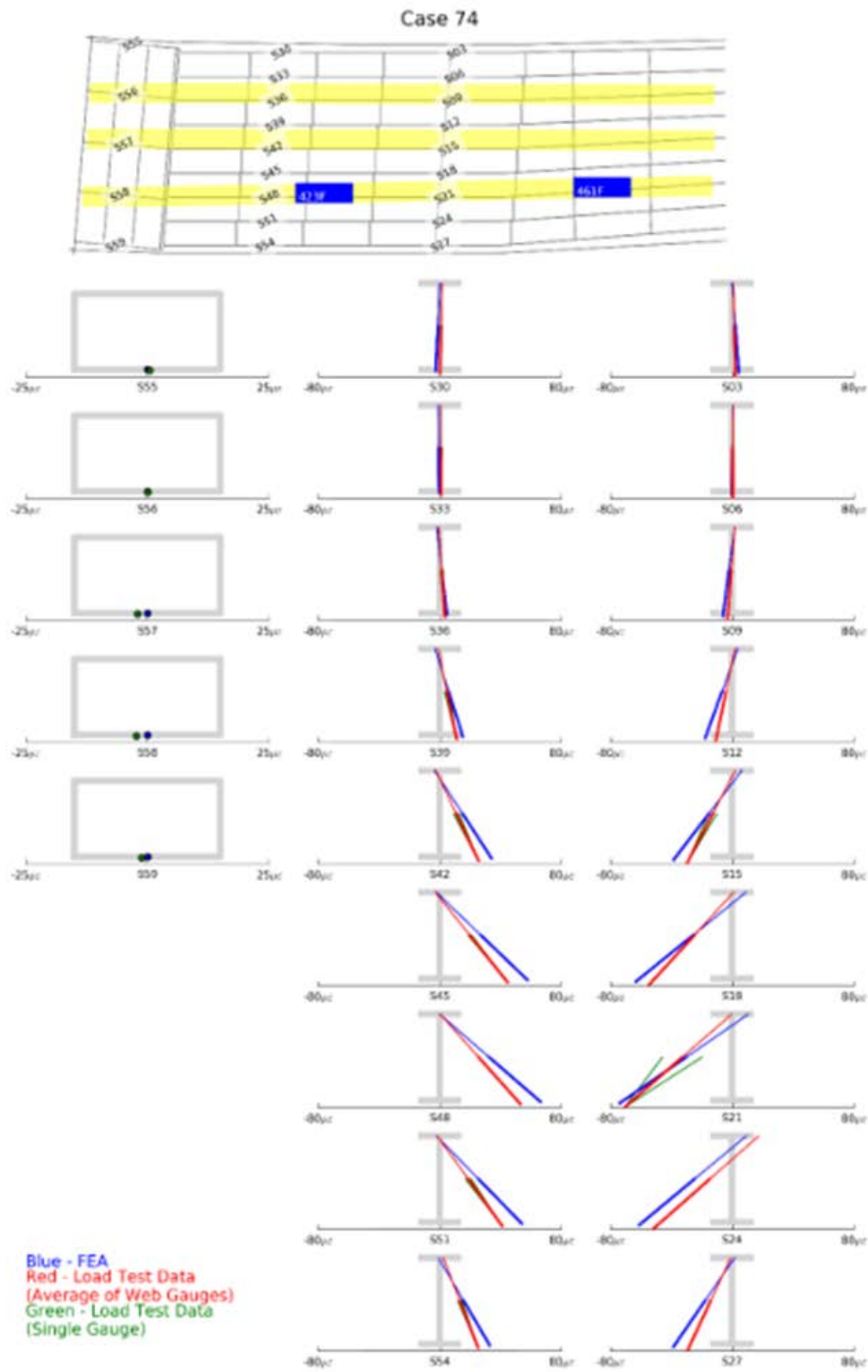


Figure 18: Example of Static Load Test Results (Load Case 74)

Sensitivity studies were performed by changing each model parameter through a range values and evaluating the response compared to the measured strain for twelve selected load cases. The cases were selected because they produced the highest magnitude response and vary loading longitudinally and transversely to generate worst case positive and negative moments. Calibration was performed using multiple random starting points during a series of repeated trials. The model identified as the calibrated model is the result of a local optimization routine that converged to a parameter set within the predetermined bounds and with a lowest total error; error is defined as the difference of predicted versus measured strain. The a priori parameter values and the final calibrated values are summarized in Table 4.

**Table 4: Summary of Truck Load Test Model Calibration Results**

<b>Parameter</b>	<b>A Priori</b>	<b>Calibrated</b>
Girder stiffness (psi)	2.90E+07	3.34E+07
Diaphragm stiffness (psi)	2.90E+07	1.95E+07
Deck stiffness, longitudinal (psi)	3.16E+06	4.71E+06
Deck stiffness, transverse (psi)	3.16E+06	3.78E+06
Barrier stiffness, left (psi)	3.16E+06	2.00E+06
Barrier stiffness, right (psi)	3.16E+06	2.20E+06
Longitudinal stiffness at expansion joint, pier 1 (lbf/in)	1.00E+00	1.18E+09
Longitudinal stiffness at expansion joint, pier 3 (lbf/in)	1.00E+00	2.25E+05
Longitudinal stiffness at center support, pier 2 (lbf/in)	1.00E+11	2.14E+05
Vertical boundary stiffness at pier 1 (lbf/in)	1.00E+11	2.82E+07
Vertical boundary stiffness at pier 2 (lbf/in)	1.00E+11	2.65E+11
Vertical boundary stiffness at pier 3 (lbf/in)	1.00E+11	2.43E+09

## **FINDINGS**

### **FE Model Predictions**

A comparison between the experimental natural frequencies found by the THMPER system and the a priori FE model predictions is shown in Table 5. Of the 9 total modes compared, all the predicted frequencies were low with only first torsion mode and first butterfly having errors less than 10%. Also note the inconsistent modal order between modes 3 to 5. The first butterfly mode of the a priori model has a modal rank of 5, but this mode is rank 3 in the experimental data set. In general, the discrepancies indicate that the a priori FE model is either lacking a significant amount of stiffness or contains too much mass. Several static predictions show similar disparity between the predicted and measured responses.

Table 5: Comparison of THMPER Modal Results to A Priori FE Model Predictions

	<b>THMPER</b>	<b>A Priori FE Model</b>			
	<i>Freq [Hz]</i>	<i>Freq [Hz]</i>	<i>% Diff</i>	<i>Mode #</i>	<i>MAC</i>
1	3.71	3.16	-14.83	1	0.948
2	4.3	4.21	-2.10	2	0.947
3	5.57	5.54	-0.54	<b>5</b>	0.712
4	5.86	4.95	-15.45	<b>3</b>	0.925
5	6.15	5.27	-14.36	<b>4</b>	0.713
6	7.13	5.94	-16.66	6	0.879
7	8.5	7.72	-9.15	7	0.755
8	9.57	7.98	-16.61	8	0.448
9	12.79	11.26	-11.97	9	0.835

### Modal Testing

A comparison of natural frequency estimations from both the THMPER system modal testing and the ambient vibration monitoring is shown in Table 6. Natural frequency estimations showed good agreement between the two test methods. The largest discrepancy is a **4% error** observed by the fourth mode of the structure (first bending with both spans in phase). The root mean squared error of the first 8 modes is relatively low at 1.78%. Note that the ambient testing was not able to recover the ninth mode of the structure. The discrepancies are likely due to the lack of control over the excitation in the spatial and frequency domains; the analysis makes a necessary assumption that the excitation is broadband white noise at all degrees of freedom which is rarely fully achieved in practice.

Table 6: Natural Frequency Comparison between THMPER and Ambient Analysis

	<b>THMPER</b>	<b>Ambient Analysis</b>	
	<i>Freq [Hz]</i>	<i>Freq [Hz]</i>	<i>% Diff</i>
1	3.71	3.76	1.35
2	4.3	4.30	-0.07
3	5.57	5.57	-0.07
4	5.86	6.10	4.16
5	6.15	6.30	2.42
6	7.13	7.13	-0.01
7	8.5	8.50	-0.05
8	9.57	9.52	-0.51
9	12.79	-	-

## Model Calibrations

The results from the calibration efforts are summarized in Table 7. The final value selected for each parameter is shown for both methods along with the relative change (in percent difference) from the a priori value. In general, the following behavior was exhibited:

- **Girder Stiffness:** Both sets of calibration results globally stiffened the structure. The static calibration increased the girder modulus by ~15%; the modal calibrated value was increased by ~19%.
- **Diaphragm stiffness:** Diaphragms were observed to have a non-trivial stiffness in both model calibrations. That is, both result sets indicate that the diaphragms participated in the global load path. Each calibration method reduced the a priori diaphragm modulus; the static value reduced the modulus by -32% and dynamic by -5%.
- **Deck Stiffness:** The static calibration updated deck stiffness in the longitudinal and transverse directions separately while the modal calibration treated the deck as isometric. Both calibrations resulted in a +50% relative increase in the deck's modulus.
- **Barrier Stiffness:** Barrier stiffness was treated as separate values (left and right barriers) for the static calibration and treated as a single parameter during the modal calibration. Both calibration methods saw a similar decrease in barrier stiffness by approximately -30%.
- **Stiffness at Expansion Boundaries:** Longitudinal boundary stiffness of piers 1 and 3 was treated as separate values in the static calibration and treated as a single value (representing both expansion bearings) in the modal calibration. The static calibration found the left expansion bearing (pier 1) to have an effectively fixed value at  $1.18e9$  lbf/in (effectively fixed) and the right expansion bearing (pier 3) to have an effective stiffness of  $2.14e5$  lbf/in. The modal calibration treated each longitudinal stiffness as similar and found a value of  $1.63e7$  lbf/in.
- **Stiffness at Fixed Center Pier:** Both model calibration approaches found the longitudinal stiffness at the center "fixed" pier to be effectively released, contrary to the fixed assignment in the a priori model. Though it is not a surprise to see a partial release of longitudinal fixity at support above the center 23ft. pier, both calibrations found it to be fully released.
- **Vertical Support Stiffness:** Vertical support stiffness was updated in the static calibration but was not updated in the modal calibration (the modal calibration held the vertical DOF fixed at all boundary nodes). The static calibration final values for piers 2 and 3 are at the upper bound of the sensitive range and are essentially fixed which is consistent with the assumptions made in the modal calibration. Though not fully fixed, the vertical stiffness at pier 1 was also found to have a significant amount of vertical stiffness and is at the mid to upper end of its sensitive range.

Table 7: Comparison of Model Calibration Results

Parameter	Parameter Values			% Diff from A Priori	
	A Priori	Static	THMPER	Static	THMPER
Girder stiffness (psi)	2.90E+07	3.34E+07	3.46E+07	15.17%	19.25%
Diaphragm stiffness (psi)	2.90E+07	1.95E+07	2.77E+07	-32.76%	-4.37%
Deck stiffness, longitudinal (psi)	3.16E+06	4.71E+06	5.62E+06	49.05%	77.88%
Deck stiffness, transverse (psi)	3.16E+06	3.78E+06	5.62E+06	19.62%	77.88%
Barrier stiffness, left	3.16E+06	2.00E+06	2.20E+06	-36.71%	-30.28%
Barrier stiffness, right	3.16E+06	2.20E+06	2.20E+06	-30.38%	-30.28%
Longitudinal boundary stiffness, pier 1 (lbf/in)	1.00E+00	1.18E+09	1.63E+07	fixed	active
Longitudinal boundary stiffness, pier 3 (lbf/in)	1.00E+00	2.25E+05	1.63E+07	free	active
Longitudinal boundary stiffness, pier 2 (lbf/in)	1.00E+11	2.14E+05	7.85E+05	free	free
Vertical boundary stiffness at pier 1 (lbf/in)	1.00E+11	2.82E+07	-	active	-
Vertical boundary stiffness at pier 2 (lbf/in)	1.00E+11	2.65E+11	-	fixed	-
Vertical boundary stiffness at pier 3 (lbf/in)	1.00E+11	2.43E+09	-	fixed	-

## Load Rating Analysis

A refined load rating analysis was performed by Pennoni Associates. Best practices refined load rating involves calibrating an FE model to experimental results to confirm the global load carrying mechanisms present in the a priori model match those observed from the actual bridge. Once this is established engineering judgement is used to conservatively bound uncertain parameters. The following excerpt taken from the load rating report describes the process used for this rating:

*For load rating analysis of the calibrated model, components that are not normally considered as contributing to strength limit states, such as barrier stiffness, are not included. Barrier mass is applied in the DL2 case, but the stiffness is not active in the live load cases. Additionally, longitudinal stiffness of bearings designed as expansion bearings could be beneficial to load ratings but cannot be relied on as a permanent source of resistance. Therefore, these bearings are kept as released in the rating analysis. The calibrated parameters are only applicable for the evaluation of demands. Computation of member capacities use nominal material properties.*

A summary of the controlling ratings of the a priori analysis and the static calibrated analysis is shown in Table 8. In almost each case the calibrated model produced a more conservative rating. Both calibration schemes produced extremely similar models, therefore, at this resolution of analysis a full rating comparison using the modal calibrated model would not be meaningful.

Table 8: Summary of Load Rating Analysis

Vehicle	Positive Moment		Negative Moment		Shear	
	A Priori	Calibrated	A Priori	Calibrated	A Priori	Calibrated
SHA 150k	1.22	1.23	1.01	0.99	3.47	3.44
HS20	2.01	1.97	2.28	2.22	5.35	5.34

## CONCLUSIONS

State of the art bridge evaluation utilizes the Structural-Identification (St-Id) paradigm as a means of interpreting experimental measurements into actionable metrics, such as a load rating. Experiments are designed to capture global characteristics related to load carrying mechanisms of the in-situ structure and, within the context of St-Id, are used for comparisons to predictions made by FE models. The ideal result of the process is to quantify and reduce the level of uncertainty of the predictions and decisions made with the refined model. A new rapid modal testing platform and method was demonstrated and validated via comparison to conventional experimental and analytical approaches. The Targeted Hits for Modal Parameter Estimation Rating (THMPER) system is a rapid modal impact trailer, a mobile work station, and streamlined data processing software which aims to address the current lack of cost-effective methods to perform refined load rating analysis of bridges. The validation effort used a typical highway bridge as a test specimen and consisted of a multi-tiered comparison with current 'best practices' approaches.

The THMPER system's effectiveness as a modal testing approach was assessed through a comparison of modal parameters obtained from an ambient vibration monitoring effort. Natural frequency estimations showed good agreement between the two test methods; frequency estimations differed by less than 5% error for the first 8 global modes with the root mean squared difference of 1.78%. Additionally, a comparison between the experimental natural frequencies found by both modal testing approaches and the predictions made by the a priori FE model had a root mean squared error of 12.7% with errors in the primary bending modes as high as 15%.

Independent finite element model calibrations were performed using the natural frequencies and mode shapes estimated by the THMPER system and the static results obtained by the truck load testing. The updated parameters of both model calibrations showed similar behavior. Both calibrations reduced the differences between observed and predicted structural behavior by a non-trivial amount; the total error in predicted strain was reduced by a factor of 2.64, and the total error in predicted natural frequencies was reduced by a factor of 4.23. Comparing the calibration results to a priori values, both calibrations resulted in (1) an increase of girder and deck stiffness, (2) active diaphragms and barriers (e.g. non-trivial stiffness), (3) longitudinal stiffness at expansion bearings, (4) longitudinal release of the 'fixed' bearing above the center pier. These results indicate that both experimental approaches provide similar, useful information about the structure.

In general, the discrepancies between the experimental observations and the predictions made by the a priori FE model indicate that the available design plans are not representative of the structure. The a priori model either lacks a significant amount of stiffness or has too much mass. This is reinforced by the behavior of the updated parameters in both the static and dynamic model calibrations. In each calibration the parameters contributing to global stiffness were stretched to somewhat unrealistic bounds – it is not likely that the structural steel has a modulus of elasticity 30% above the a priori value of 2.9e7 psi, for example. Adjusting the boundary and continuity conditions in the model is not enough in this case and the global stiffness parameters are brought to unreasonable upper bounds. The



distortion of these relatively known parameters to form a reasonable fit indicates that the model is missing a mechanism contributing to the global load path.

## **RECOMMENDATIONS**

The discrepancies between the experimental observations and the predictions made by the simulation models indicate that the model may be missing a mechanism contributing to the global load path. A field survey is recommended for comparison between the as-built dimensions and the design plans. Accurate measurement of the deck haunch (stiffness dominated parameter) and the deck thickness (mass dominated parameter) may provide reason as to the distortion of the global stiffness parameters during the model calibration.

Measurement of these dimensions is entirely dependent on underside access. Access under span 2 is relatively easy with equipment such as a Snooper, but the CSX rail under span 3 is significantly restrictive. As this type of field survey (and the access issues associated with it) are quite common, this provides an excellent opportunity to investigate the effectiveness of LiDAR for recovering as-built structural dimensions.