Parameter identification of a reinforced concrete T-beam bridge

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ABSTRACT: Parameter identification based on model updating is one of the most important links in Structural Identification. The benefits of combining finite element (FE) analysis with on-site measurement through model updating are significant and growing as more reliable experimental, modeling and model correlation approaches become available. The authors have successfully applied Structural Identification to numerous bridges over the past decade. However, manual model updating of structural parameters has significantly limited the application of model updating on large infrastructures. The methodology proposed within aims to use the Application Programming Interface (API) function in the Strand7 FE software package to automatically update selected parameters using Matlab. The proposed methodology was applied to a three span, simply supported T-beam bridge. Both the elastic modulus for the global structure and the crack height of the primary girders were utilized as updateable parameters in two separate cases. The results show that the average crack height parameter reproduced the static measurements with a high degree of accuracy and is a reasonable parameter choice for this class of structure.

1 INTRODUCTION

The objective of this paper is to present and discuss the results of the parameter identification of a reinforced concrete T-beam bridge (the Smithers Bridge) using two sets of updateable parameters. This specific application comes from a project sponsored by the West Virginia Department of Transportation aimed at assessing the capacity of a series of deteriorated RC bridges that lacked documentation.

During the fall of 2008, the authors conducted a series of load tests on the Smithers Bridge, which is located near Charleston, WV. The test was designed to assess and evaluate the condition and capacity of the bridge by synthesizing analytical results with field observations and measurements. This paper presents the deflection and strain results of the static load truck test on the densely instrumented first span, and the model updating results using two different parameters, the elastic modulus E for the global structure and the average crack height y for the six primary girders.

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2 THE SMITHERS BRIDGE LOAD TEST

2.1 *Description of the Smithers Bridge*

The Smithers Bridge (Fig.1) is a three span, simply supported concrete T-beam Bridge with a skew of approximately 18^{o}. The bridge, constructed in 1930, lies on Rt.60 in Smithers, WV, about 30 minutes to the southeast of Charleston. Each span is approximately 48ft long, with a width along the skew of 48ft as well. The bridge was posted at 37T and 38T for two and three axle trucks, respectively. This posting was hampering the transportation of coal and negatively impacting the economy of the state. As a result, the WVDOT elected to have a load test and St-Id performed to more accurately assess the capacity and perhaps justify the removal of the posting.

The bridge exhibited deterioration in critical locations including substantial spalling on the piers, pier caps and at the beam seats. The beams showed flexural cracking and some sparse shear cracking prior to the static load test. In addition, the roadway surface showed substantial cracking at the piers and abutments. The bridge appeared to have a severe drainage problem, with water seeping out from between the diaphragms and a buildup of sediment atop the pier caps. The rest of the superstructure appeared to be in excellent condition and inspections indicated no signs of scour or other foundation related problems.

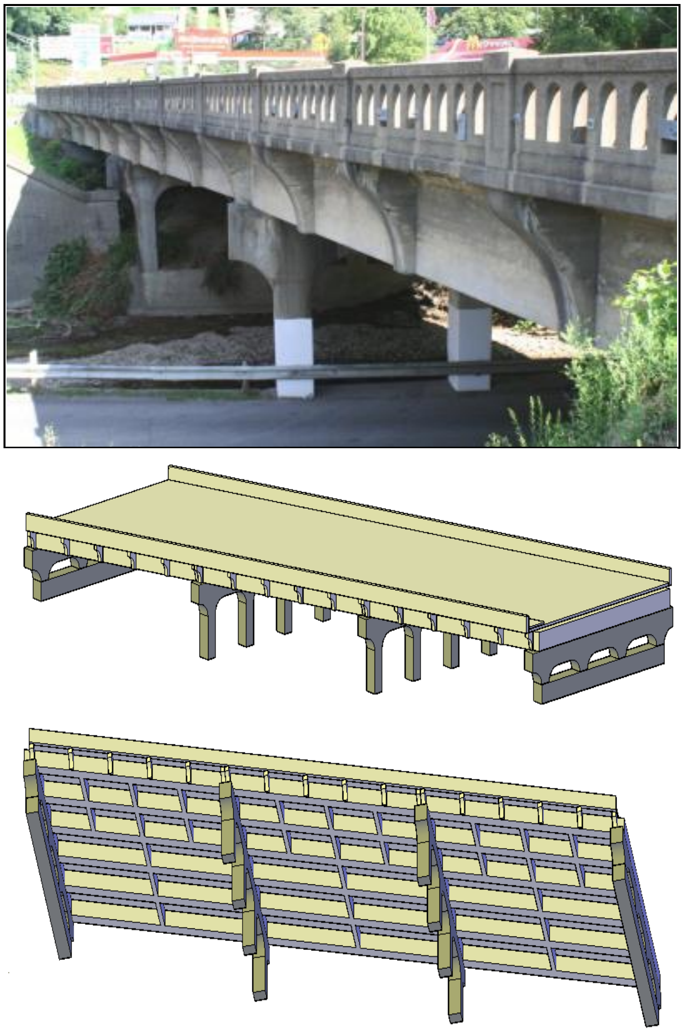


Figure 1. Smithers Bridge and 3D Autocad model .

2.2 *Smithers Bridge load test*

In order to estimate the capacity of the bridge, a static test was conducted in November 2008 using proof load levels. Prior to the test, field measurements and material sampling was conducted to inform the development of a priori FE models. In order to acquire the concrete material properties, 3 core samples were taken from each span of the bridge in a diagonal pattern. Several samples were taken from the piers and abutments of the structure as well. The average concrete compressive strength was 7741 psi, with a standard deviation of 1697 psi. By using the ACI code elastic modulus equation, the average concrete elastic modulus was 5016 ksi.

The load for the actual test was applied using six special dump trucks capable of being loaded up to a total of 100 kips each. A dense array of instrumentation including various strain, displacement and rotational sensors was utilized to capture the response of the structure.

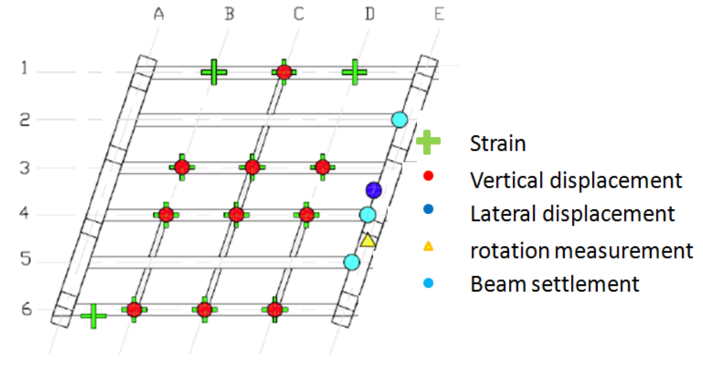


Figure 2. Static instrumentation layout for the 1st span.

More specifically, the static instrumentation of the first span of the Smithers Bridge included a total of 29 gages to capture rebar strains, vertical displacements, beam settlements and rotations. Since the first span was the most accessible span from the underside, the majority of the gages were located there and the following discussion focuses on this span only. The other two spans were more difficult to access and therefore had minimal instrumentation. The static instrumentation layout for the 1st span is shown in Figure 2.

In the first span, 13 locations for weldable steel strain gages (Micro-Measurement Group) were chosen and the cover concrete was removed, and the gages were microdot welded to the reinforcement bar. These gages provided a reliable measurement of the actual steel strain. Fourteen strain-based linear displacement transducers (Texas Measurements Inc.) were chosen to measure the displacement. Sign posts were driven into the ground and extended up to the underside of the bridge to provide a fixed reference point to mount the transducer. The gages were carefully aligned to ensure that they were measuring as close to vertical as possible. Among these displacement transducers, three were installed to monitor the vertical deformation of the beam relative to the pier and one lateral displacement gage was installed to capture the lateral deformation of the pier cap.

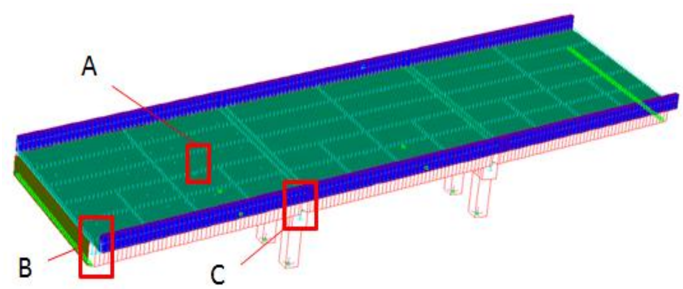
Data acquisition and signal conditioning was provided by an Optim MegaDAC system. The Optim utilizes a chassis and removable card system for data acquisition. Model AD305QB quarter bridge completion cards were used for the strain gages while model 808FB1 full bridge cards were used for all other gages. The Optim uses a 16 bit Analog to Digital converter and logged data at 20Hz.

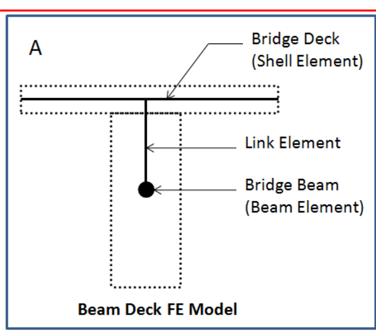
The NCHRP manual for Bridge Rating through Load Testing indicated that for this structure and the state legal truck of 40 tons, a proof load of 200kips per lane or 600 kips total was required. The bridge was loaded incrementally from three empty trucks to six full trucks for a total of 604 kips without incident. Based on the vertical displacements, it can also be said that the bridge showed very little continuity between spans as almost no uplift was seen on the spans which were not directly loaded. The response of the bridge was generally linear, though a small amount of softening was observed. No large or unexpected nonlinearities were present. The maximum displacement in the first span was -0.126 in. and the maximum recorded steel strain was 150 microstrain, which is much larger than the strains recorded throughout the rest of the span. This difference was likely a result of the proximity of the gage to a large crack in the diaphragm. The behavior of the three settlements gages remained linear and the magnitude of the response was very small.

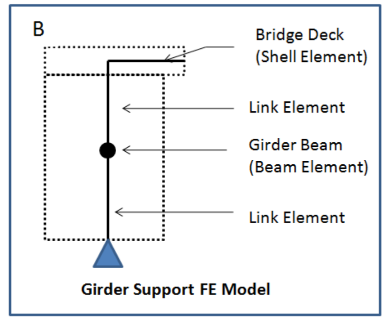
3 FINITE ELEMENT MODEL UPDATING

3.1 *Finite element mode*

Since no detailed documentation or drawings were available, the measurements taken during the preliminary field visit in August 2008 were used to develop the finite element models. The T-beam construction of the Smithers Bridge is easily modeled using a combination of frame, shell and link elements. The finite element model was built in Stand7 (www.strand7.com), which is a commercially available FE software package. As shown in Figure 3, the model used frame elements to represent the beams, diaphragms and piers of the structure, and shell elements for the deck. The beams and the deck were connected using rigid links, forcing composite action. The beams were connected to the pier caps using lateral and vertical springs, with the moment fully released at the beam boundaries. The base of the pier was fixed. In total, the model was comprised of 1946 beam elements (including spring elements), 6808 shell elements and 2080 link elements. The configurations of the critical locations of the bridge are also shown in Figure 3 in detail.







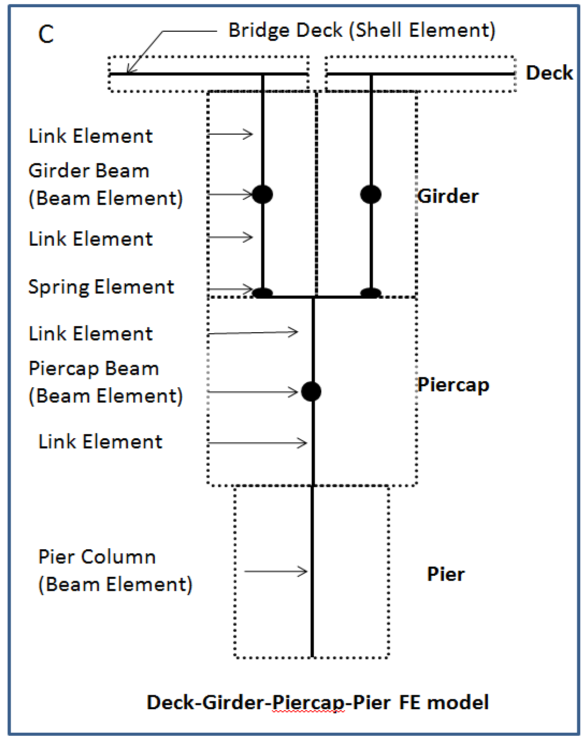


Figure 3. Finite element model and the detailed configuration.

Based on the sensitivity analysis, the stiffness of the boundary lateral and vertical spring had a large influence on the preliminary model results. These two boundary springs dominate the interactions between the pier-cap and the superstructure. By utilizing the three vertical boundary displacements and the lateral displacement of the pier cap measured during the test, the springs stiffnesses were computed directly. This resulted in a boundary lateral spring stiffness of 2.6e6 lb/in and a vertical spring stiffness is1.1e5 lb/in.

The model was loaded using measured tire weights for the six dump trucks. On average, each of the front-wheel tire loads were approximately 10 kips and the back-wheel tire loads were approximately 20 kips. The tire loads were applied as point loads on the surface of the shell element deck based on the exact spacing of the truck tires which was measured during the load tests. To accommodate this loading, the mesh of the deck was refined until it allowed for very close approximation of the actual load distribution.

3.2 *Model updating based on Strand7 API function*

After the preliminary FE model was constructed, the next step was to calibrate the model and update the selected parameter to better align it with the observed responses. Model updating is an analytical technique in which one or several parameters used in a numerical model of the structure are adjusted until the computed behavior matches the observed (experimental) behavior. Generally, a sensitivity analysis is also conducted prior to updating to ensure the most relevant parameters are utilized. The most common method in large scale FE model updating consists of manually minimizing the errors between the experimental results and model output. The adjustments are based on heuristic knowledge of bridges and construction as well as the measured in-situ properties of the structure being calibrated.

Realistic finite element models, such as the one constructed of the Smithers Bridge, are difficult to code into a typical programming language such as Matlab and require the use of commercial structural analysis programs. However, these programs typically do not lend themselves to rapid, automated model updating and calibration. The Strand7 software, however, has the ability, through an Application Programming Interface (API), to interface directly with Matlab and make use of the many toolboxes available (statistical, optimization, etc.) to update realistic FE models. This code simply defines the input parameters for a Strand7 model on any given iteration, and automatically extracts and tabulates the desired responses. The data obtained can be used for further processing and analysis. The function can be used to create, read, and modify Strand7 FE model data, launch the solvers and extract results. After integration of the general coding strategy with the specific internal functions from Strand7, the model updating process can be run easily and automatically.

The flowchart of the basic interface process based on the Strand7 API is shown in Figure 4. The nonlinear least-squares algorithm was used in the updating process, and the objective functions are listed in Equations 1-2,

For displacement data,

$$obj(x) = \left\| d_E^j - d_A^j(x) \right\|_2^2 \quad (1)$$

For strain data,

$$obj(x) = \left\| s_E^j - s_A^j(x) \right\|_2^2 \quad (2)$$

In the upper equations, subscript E indicates the experimental data, subscript A indicates analytical data, and x is the parameter which was updated. In the following analysis, elastic modulus and the cracking height will be updated separately in an attempt to converge to the experimental static load test results.

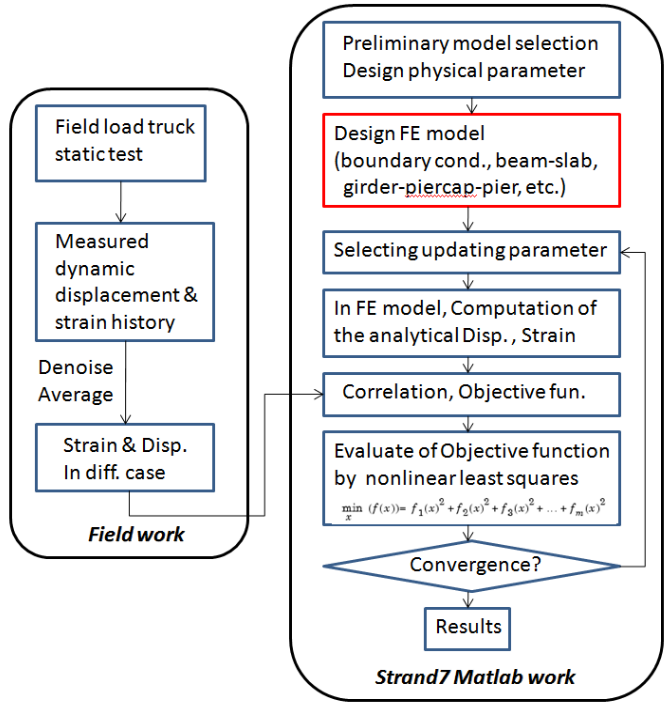


Figure 4. Flowchart of the parameter identification process based on Strand7 API function.

3.3 *Parameter identification using elastic modulus*

The elastic modulus has a direct relationship with the stiffness of the model. Since the compressive strength of the concrete has a 20% standard deviation, the elastic modulus can be regarded as an uncertain parameter. Elastic modulus, E, of the entire bridge is selected as the first unknown parameter which was updated. The initial value of E was set to 5016 ksi. The modulus' identified by matching displacement data and strain data are separately listed in Table 1. When the displacement data were used, the elastic modulus decreased 16% compared to the initial value. The experimental displacements were compared with the model before and after parameter identification in Figure 5. However, when the strain data was used in updating, a decrease of 59% compared to the initial value was observed. A comparison of measured strains and the calibrated model are presented in Figure 6. This drastic decrease was likely due to the fact that some measured strains were directly adjacent to cracks and thus were influence by very local phenomena. As a result, it is concluded that updating a global parameter, such as E, using data representative of local conditions, such as strains, is an unreliable approach. This has important implications as the vast majority of load tests conducted in the U.S. rely exclusively on strain data.

Table 1. Identified elastic modulus and objective function value of the structure.

Items	E (ksi)	Obj.
Disp.	4217	2.9285e-4

Strain	2950	4.3894e3

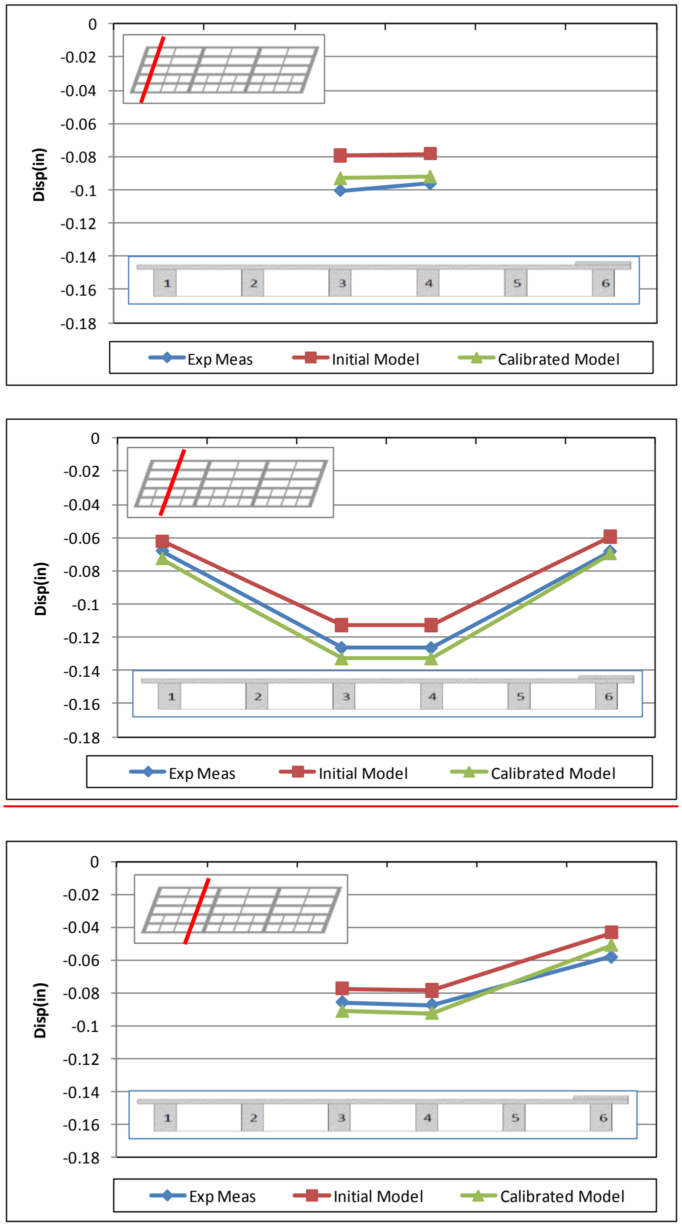
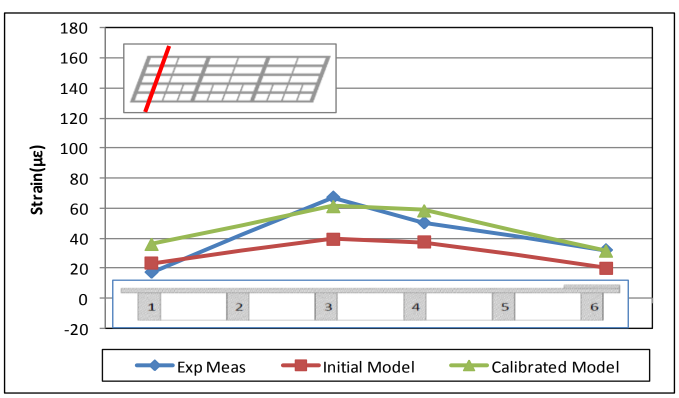


Figure 5. Comparison of the displacement before and after the elastic modulus updating for 1/4,1/2 and 3/4 line.



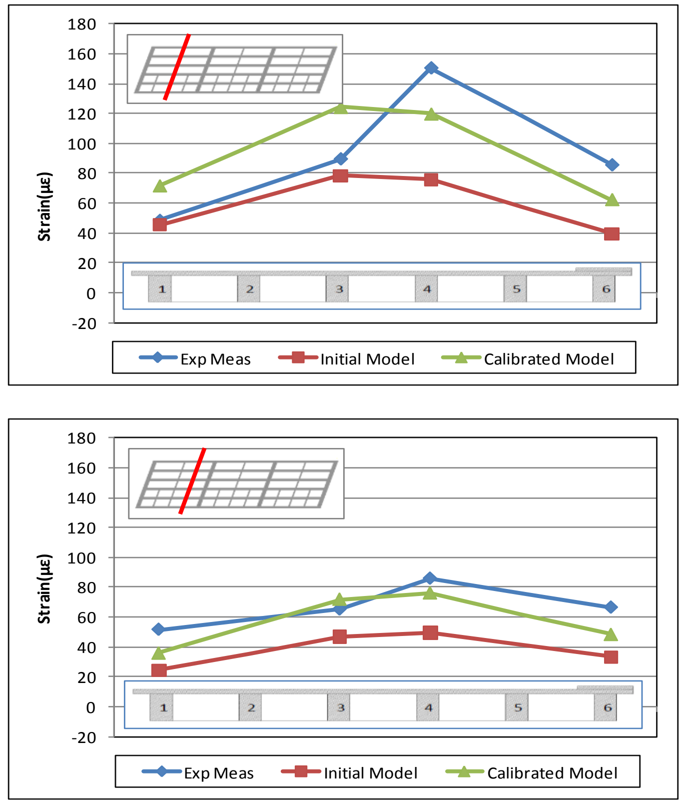


Figure 6. Comparsion of the strain before and after the elastic modulus updating for 1/4,1/2 and 3/4 line.

3.4 *Model updating using section crack height*

Under typical truck traffic, the tensile strain in the reinforced concrete beams exceeded the strain at which cracking begins. As such, the beams exhibited substantial cracking, especially in the middle portion of the bridge. As a result, the second parameter identification was carried out using the average crack height, y, for the six primary girders (the girders are shown along the axis 1-6 in Fig.2).

The rectangular girders have dimensions of 48in x 24in, and are reinforced with five No.11 bars as shown in Figure 7 (a). The transformed section properties are calculated in Figure 7 (b) with the neutral axis at 24.674in from the upper boundary of the beam. The ratio of the moment of inertia of the transformed section to the original section is about 1.0755. The crack height, y, is defined as shown in Figure 7(c). After cracking has begun, the effective compressive area is shaded in Figure 7(c). It is assumed the loading is such that the concrete compressive stress never exceeds $0.5f_c'$ and the steel does not yield. Both materials continue to behave elastically, therefore the compressive stress distribution can be approximated is a triangle. The moment of inertia and compressive area are recalculated and used here to define two parameters,

The ratio for stiffness,

$$RI = \frac{I_{Trans\_After\_Crack}}{I_{Trans\_Before\_Crack}} \tag{3}$$

The ratio for axial area,

$$RA = \frac{A_{Trans\_After\_Crack}}{A_{Trans\_Before\_Crack}} \tag{4}$$

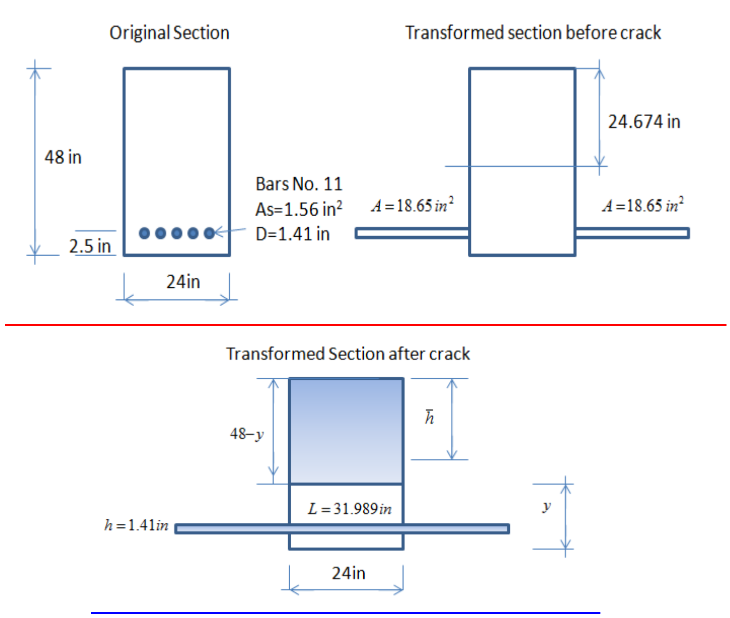


Figure 7. The girder section properties of the Smithers Bridge before and after crack appears.

In the parameter identification process, the average crack height for the 6 primary girders is set as the updateable parameter to calibrate the Smithers Bridge FE model. The elastic modulus was defined as 5016 ksi for the global structure and held constant. Both RA and RI will decrease with an increase of y, as shown in Figure 8.

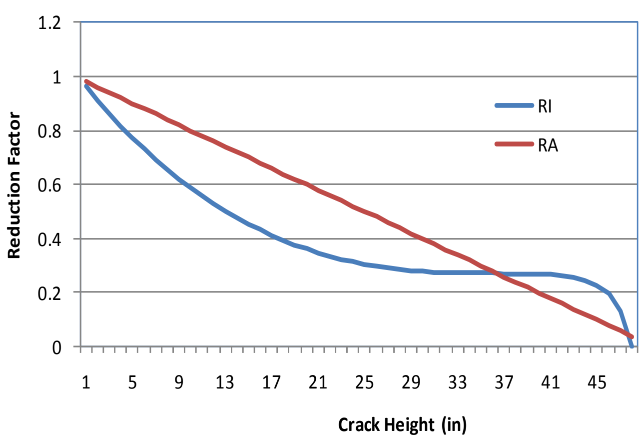


Figure 8. The relationship of RI and RA with crack height y.

Table 2. Identified crack height y and objective function value of the structure.

Item	Crack H(in)	RI	RA	Obj
Disp.	8.4658	0.6394	0.8303	2.3831e-4
Strain	5.9325	0.7346	0.8811	4.2269e3

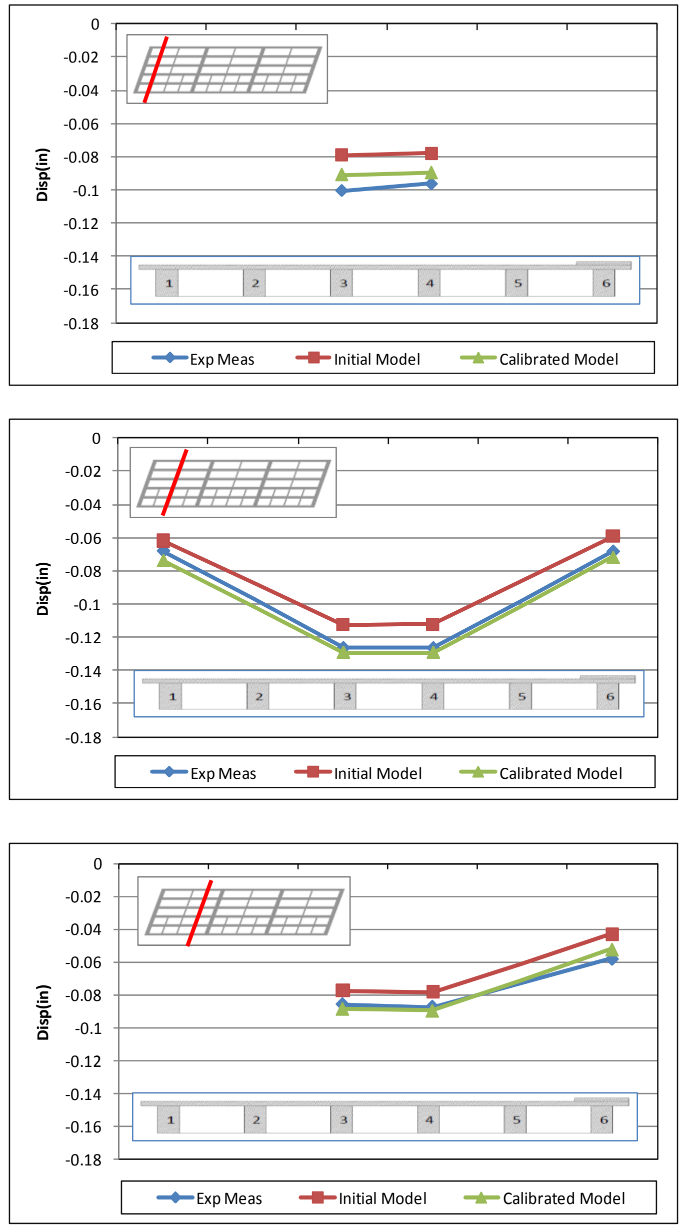


Figure 9. Comparison of displacements before and after average crack height y updating for 1/4,1/2 and 3/4 line.

It is seen that RA will decrease linearly with y while RI decreases in a nonlinear manner. After the parameter identification using the Strand7 API program was completed, the identified average crack height, y, was found. The corresponding RA and RI are listed in Table 2, as well as the crack height. The identified average crack heights using strains and displacements are close when compared to the updating of the elastic modulus. This is especially clear when comparing the two parameters RI and RA. The calculated displacement and strain results are shown in Figures 9-10. The large strain observed at C-4 (likely due to the proximity of a crack) is the reason for the difference in the identified results for strains and displacements in Table 2. Another reason may be the inaccuracy of assuming a constant elastic modulus across the entire bridge.

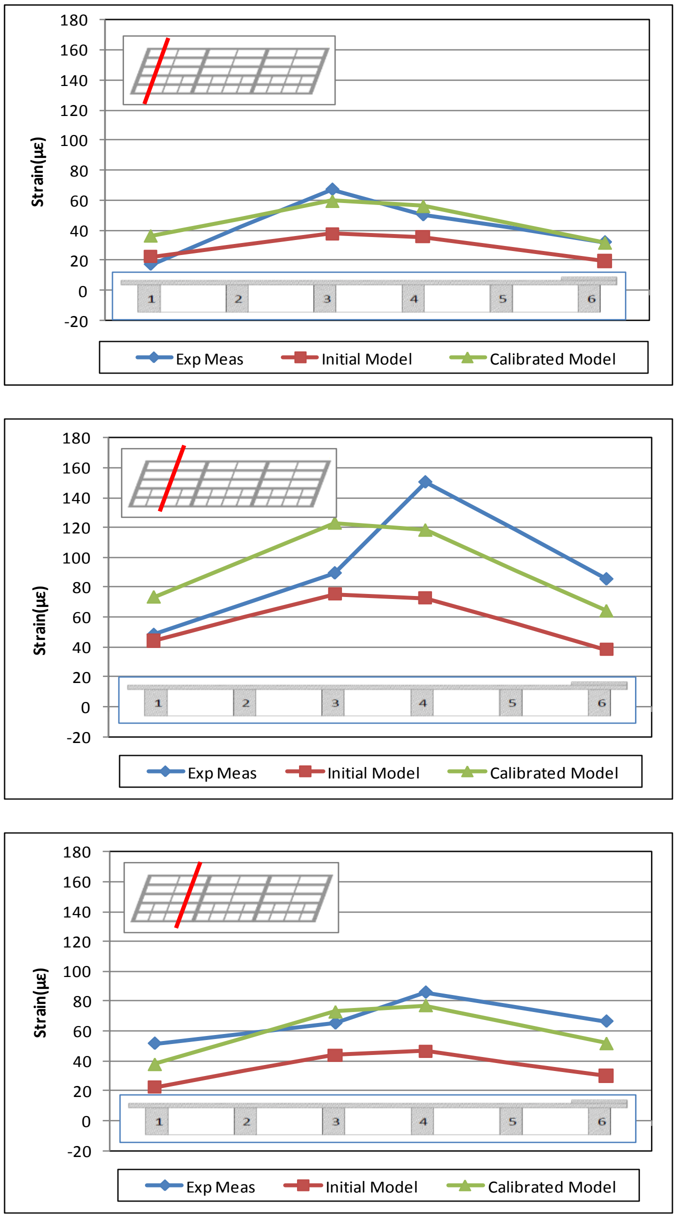


Figure 10. Comparison of strains before and after the average crack height y updating for 1/4,1/2 and 3/4 line.

3.5 *Difference and rationality of the two methods*

By comparing the results of the two different updateable parameters, the average crack height appears a more reasonable choice. This can be seen by comparing the objective function value in Tables 1 and 2, especially for the calibration using the strain data. Using elastic modulus as a surrogate for the local stiffness reduction due to cracking is not reliable as it smears a local phenomenon into the global structural model properties. In cases where only a few measurements are available, this may result in large errors. In addition, simply reducing the elastic modulus does not properly account for the influence of cracking. This can be seen by investigating the interdependency of elastic modulus and moment of inertia in flexural stiffness, EI. A 20% decrease in stiffness due to a reduction in E does not have the same physical interpretation as a 20% decrease in stiffness due to a reduction in I, which would also have a corresponding reduction in area, A. As shown in Figure 8, the interaction between I and A is not linear, as is implicitly assumed when updates elastic modulus.

4 CONCLUSIONS AND DISCUSSION

This paper describes two parameter identifications using static deflection and strain data from a load test conducted on the Smithers Bridge in West Virginia. Two updateable parameters, elastic modulus for the global structure and the crack height for the primary girders, were chosen. A comparison of the calibrated models with the experimental results show that crack height as the updateable parameter provides more reasonable results than does elastic modulus.

This project also illustrated that on-site observation is essential to reliable St-Id, as it guided the selection of updateable parameters. In this case, observation of cracking along the girders in conjunction with material sampling of the concrete used to construct the bridge indicated that crack height was relevant parameter for updating.

Successful application of the model updating for large infrastructures is problematic because of the necessity of manual iteration using commercial structural analysis software packages. The API function in Strand7 software separates the FE modeling and iterative coding into two parts, using Matlab to conduct iterations, and allowing the many refined tool boxes available in Matlab to be leveraged.

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