Structural Identification of a Long-span Concrete-filled Steel Tubular Arch Bridge

Yun Zhou[1], Junkai Zhang[1], Songbai Chen[1], Weijian Yi[1]
[1,2,3,4] *Hunan University, Changsha, China*

ABSTRACT

Structural identification (St-Id) of long-span bridges using test data provides a benchmark to characterize mechanical behaviors and predict future responses quantitatively. It is a cognitive process including conceptualization, test and decision-making whereas various uncertainties involved in experimental and identification processes impact the reliability of identification results. During the identification process, model calibration plays a critical role in uncertainty mitigation. In this paper, Laihua Bridge was chosen as an example to research possible strategies for coping with uncertainties confronted when identifying characteristics of long-span arch bridges. The application is conducted by precise modeling to establish an initially calibrated model whose geometric features corresponds well to real structure and followed by a parameter validation process including sensitivity analysis and objective function optimization. Following a description of calibration process, the result is evaluated by comparing different identification scenarios including deflections and modal frequencies. The aim is to get a calibrated model that comprehensively represents real structure and to prepare for health monitoring and reliability assessment.

INTRODUCTION

Long-span Bridge plays a critical role in connecting adjacent districts recently while many injuries and bridge failures occurred recently. In the United States, a third of total 6 million Bridges have been in service for more than 50 years and about 43% of them are identified defected [1]. Most damages are induced by environment erosion such as flood, corrosion, overloading as reported by professor Satish.B. Mohan [2]. Many commissioning bridges built in the 19th century were designed for live loads quite different from the traffic they are subjected to today. Besides, traditional visual observation methods, ultrasonic flaw detection and radar technology have failed to meet the requirements of condition assessment in modern life, which emphasizes more significance of structural identification (St-Id).

Originally, St-Id was widely applied in civil engineering since its paradigm was proposed by Yao in 1978 [3]. St-Id refers to any systematic approach for identifying structural parameters through the use of input and output data. It can also be understood as a practical process including conceptualizing, experiment design, model construction, condition assessment and decision-making [4]. The experiment design can be classified into controlled load tests and vibration tests. In contrast to traditional impact tests, ambient vibration tests may exhibit better applicability such as eliminating the impact of weight of vibrator on bridge and enough energy induced at low frequency band without blocking traffic [5]. Establishment of finite element (FE) model is usually conducted according to design information and blue prints.

Two kinds of uncertainties may exist when using FE model to predict future response. That is, aleatory uncertainty and epistemic uncertainty. The former is an inherent variation associated with the physical system or the environment, also referred to as stochastic uncertainty and random uncertainty. And the later is an uncertainty that is caused by a lack of knowledge of quantities or processes of the system and environment. The parameter compensation theory indicates that various types of uncertainties may compensate for each other such that bad model predictions match measured values [6]. Therefore, it's essential to mitigate geometric uncertainty before further calibration. The application of St-Id and model calibration is extensive. Xia et al [7], Brownjohn et al [8, 9] and Bijaya Jaishi et al [10] have conducted model calibration on many cases.

In this paper, controlled load tests and ambient vibration tests was conducted on Laihua Bridge to acquire data for condition assessment and model calibration. Sensitivity information is obtained to evaluate the dominant factors that affect response. Afterwards, calibration is conducted by optimizing an objective function based on modal parameters. The purpose of this paper is to get a calibrated model that represents real structure comprehensively and assist to further researches including condition assessment, damage detection and reliability analysis [11].

MODEL CALIBRATION METHOD

In order to mitigate uncertainties in model, geometry calibration and parameter calibration are conducted. Geometry calibration is completed by precise modeling in which many details can be fully considered. The result is a conceptualized model whose geometry characteristics are identical with real structure in detail. However, as illustrated by Lan F.C. Smith, accuracy of response that model predicts is not proportional to number of parameters in model which could only be determined by engineer's experience [12]. Parameter calibration is conducted by optimizing objective function and validating uncertain parameters [13]. Thus, the selection of objective function and optimization methods is critical. In this paper, traditional advance-retreat method based upon sensitivity analysis is used to carry out optimization. In each step, search space is narrowed down according to previous optimal solution until optimum value is found.

Previous research by Ren et al indicates that each kind of objective function considering modal frequency, modal flexibility, mode shape errors separately and its combination are able to lead to fine calibration but only the one considering the combination of three kinds of errors could contribute to accurate damage detection [14]. Objective function can be established according to deflection data, strain data as well as modal frequency and mode shape. As the real condition can't be determined by static test results exclusively and boundary conditions may have significant impact on deflections predicted by models, objective function in this paper is built based on modal data as shown in Eq. (1)

$$\mathrm{F(x,i)} = \sum \frac{f_{\mathrm{ai}} - f_{\mathrm{ei}}}{f_{\mathrm{ei}}} \times 100\% + (1 - \mathrm{MAC_i}) \tag{1}$$

f_a represents frequencies predicted by FE model and f_e is calculated by SSI method. x refers to the sensitive parameters chosen while i indicates the i_{th} mode considered. To evaluate the correlation of mode shapes, modal assurance criteria (MAC) is used.

The purpose of sensitivity analysis is to screen independent variables x that show significant impact on Eq. (1). Therefore, this paper completed analysis on the relationship between objective function and x in entire feasible region to cognize sensitivity of parameters comprehensively. Global calibration is conducted by seeking the optimal independent variables x meeting the requirements. (Eq. (2))

$$\Pi\,\mathrm{(x)} = \min\{\mathrm{F(x,i)}, \mathrm{x_l} < x < \mathrm{x_u}\} \tag{2}$$

x_l and x_u refers to the lower and upper bound respectively.

Bridge Description

Laihua Bridge is a concrete-filled steel tubular half-through tied arch bridge. It is located at Laibin City, China across Hongshui He River, and the main span of the bridge is 220m. The picture of the bridge is shown in Fig.1. The cross-section of two main arch ribs consists of four concrete-filled tubes. The depth of main arch rib varied from 5.50m at the footing till 3.50m at the top. The remaining connecting tubes of superstructure are K-type hollow steel tubes. There are 36 main suspenders of steel wire ropes which are vertically attached on main arch rib. The floor system is suspended through it. The floor system consists of a 250mm thick concrete slab supported directly by cross-girders. The typical rectangular cross-section of the cross-girder is $0.36m^2$. The length of each cross-girder between the suspenders is 21.6m. The main arch ribs are attached to two abutments, and connected by 4 pre-stressed strands on each side in the longitudinal direction, acting as tie bars.

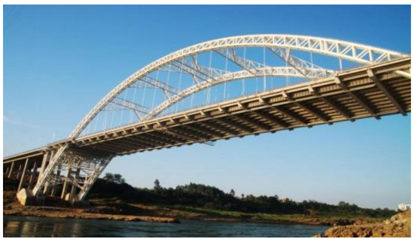

Fig.1 Picture of Laihua Bridge

Controlled Truck Load Test and Ambient Vibration Test

Controlled load tests and vibration tests can contribute to provide an accurate and reliable model calibration of the bridge. Deck and arch deflection as well as the strain on the arch were measured under truck load tests. During tests, a theodolite and a GTS are used.

In contrast to traditional forced vibration test, ambient vibration test uses the traffic and wind as natural excitation that it does not partition traffic on bridges. During vibration tests, LMS is used to collect data. Since the bridge is essentially symmetric in longitudinal and transverse direction, a total of 18 accelerometers were placed on the deck uniformly. It converts vibration responses into electrical signals while the signal conditioner is used to improve the quality of signals transmitted by cables. For each channel, the ambient acceleration time histories were recorded for 3600s. In order to achieve a seasonable time period for data collection, a sample frequency of 512 Hz was chosen to capture the transient signals. The identification employs SSI method and the result reveals 7 global modes in the investigated frequency interval of 0~3Hz. The identified modes used in following analysis are summarized in Table.3.

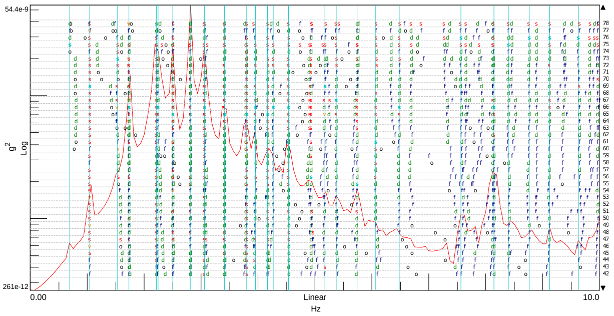

Fig.2 Stabillization figure by SSI method

FE Modeling and Geometry Calibration

A complete 3D FE model has been developed using Strand 7 software. The geometry and member details of the model are based on the design information and blue prints of Laihua Bridge. Main structural members of Laihua Bridge are girders, concrete deck, stay cables and arches, all of which are conceptualized by different kinds of elements. Modeling of the stay cables in Strand7 is possible by employing the 3-D tension-only LINK elements. Arches, girders and K-bracings are modeled by two-node BEAM elements while in-plane and out-of plane deformations of deck is simulated by 2160 rectangular shell elements with six degrees of freedom at each node. The bearings at the extremities of deck are modeled by rollers in the initial model. For fixed bearings at end of the arches, translations are restrained as consistent with design blue prints.

To mitigate modeling uncertainties in initial model, several details are taken into consideration. Safety barrier at both sides of lanes are modeled by concrete BEAM elements. Handrail by the sidewalk is simulated by steel BEAM elements with an average thickness of 3 mm. regardless of the mechanical performance of polyethylene that wraps cables, cross section of cables is simulated with a diameter of 55 mm. 12 concentrated mass elements are used to include the mass of equilibrium blocks. Ultimately, the initially calibrated model consists of 19004 nodes, 42 cables and 2256 plates. The overview of 3D model and calibration details can be found in Fig.3 as following.

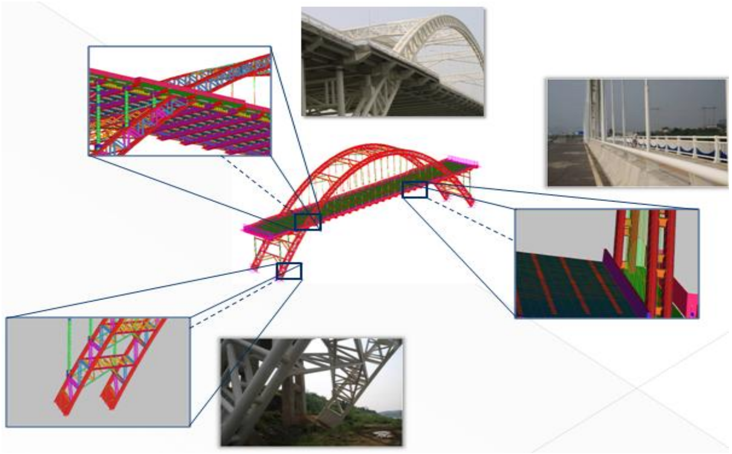

Fig.3 3D FE model and the details

Parameter Calibration

Eq. (1) is used to carry out sensitivity analysis. The chosen parameters counting for sensitivity analysis is determined by researchers' experience and uncertainty analysis. One characterization of the parameters is the inherent uncertainty due to environment conditions and limitations of measurement facility. Some parameters are summarized in Table.1, in which E_0 means the corresponding design value.

Table.1 Sensitive parameters and its bounds

Parameters	Design value	Lower bound	Upper bound	Calibrated value
Modulus of concrete in arch (MPa)	4.40×10^5	$0.6E_0$	$1.5E_0$	39601.8
Modulus of deck Element (MPa)	6.86×10^5	$0.6E_0$	$1.5E_0$	59016.7
Density of pavement (kg/m^3)	2.40×10^3	1.80×10^3	2.80×10^3	2.40×10^3
Thickness of pavement (mm)	17	17	26	19
Modulus of steel in Arch (MPa)	2.06×10^5	$0.6E_0$	$1.5E_0$	2.06×10^5
Bearings (N/mm)	Roller	10^4	10^{12}	Roller
Modulus of cables (MPa)	2.06×10^5	$0.6E_0$	$1.5E_0$	1.85×10^5

As illustrated by Eq. (2), traditional advance-retreat method is employed in optimization in which the 7 modes are attached equivalent importance. Some of the analysis results are summarized below

(Fig.4). *E* in Fig.4 (a) represents the design value of modulus.

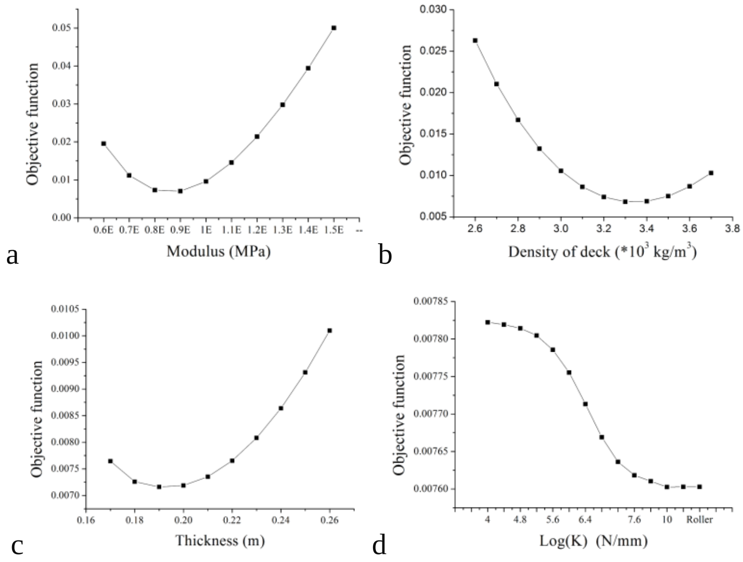

Fig.4 Relationship between parameters and objective function value
(Parameters in Fig a~d are Modulus of Concrete in arches, Modulus of deck element,
Thickness of pavement, stiffness of bearings respectively)

In sensitivity analysis, 7 parameters are analyzed. Comparatively, sensitivity of density of deck and modulus of concrete is higher, which would be essential in the parameter calibration. When the stiffness of bearings is higher than 10^{12} N/mm, modal parameters show no change anymore. Thus, setting 10^{12} N/mm as the upper bound in precious research is appropriate and it could be regarded as roller constraint. The calibrated parameters correspond to the optimum value is shown in Fig.4, which can be found in the last column in Table.1. Besides, the physical meaning of calibrated parameters must be preserved.

Results and Evaluation after Calibration

In Table.2, modal frequency errors of FE model are compared before and after calibration. Calibrated model 1 is acquired after geometry calibration and calibrated model 2 represents the one after parameter calibration.

Table.2 Comparison of modal frequency error

LMS		Initial model		Calibrated model 1		Calibrated model 2	
Modes	f_a (Hz)	f_1 (Hz)	Residue$_1$ （%）	f_2 (Hz)	Residue$_2$ （%）	f_2 (Hz)	Residue$_3$ （%）
Mode1	0.694	0.691	0.432	0.696	0.288	0.698	0.574
Mode2	1.04	1.058	1.731	1.070	2.885	1.061	2.019
Mode3	1.531	1.416	7.511	1.424	6.989	1.422	7.120
Mode4	1.730	1.749	1.099	1.768	2.197	1.719	0.636
Mode5	2.243	2.238	0.229	2.299	2.497	2.277	1.152
Mode6	2.503	2.493	0.400	2.571	2.717	2.500	0.120
Mode7	2.808	2.816	0.285	2.832	0.855	2.774	1.210

The corresponding mode shapes are summarized below (Fig.5). The left represents the analytical mode shape by FE model while the right is for the one acquired by LMS. Fig.6 and Table.4 are based on the controlled load test that 10 trucks are placed at 1/4 mid-span.

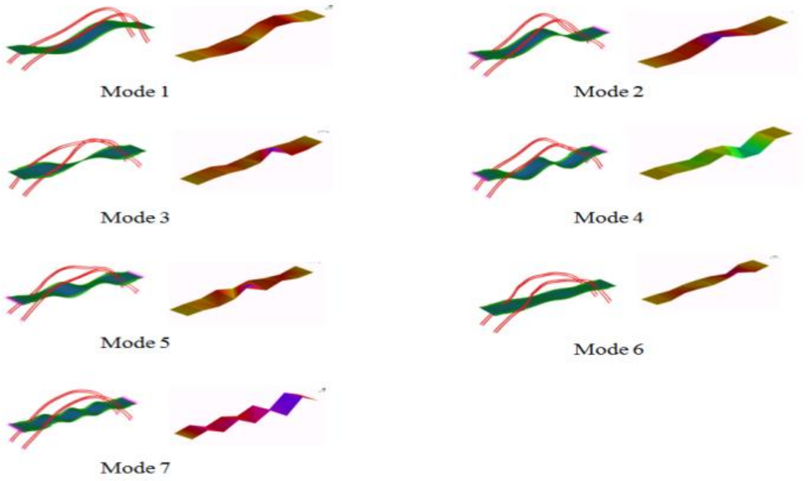

Fig.5 Mode shapes of analytical mode

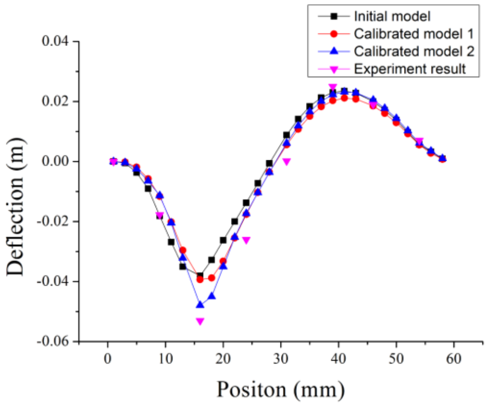

Fig.6 Deflections predicted by models before and after calibration

As is shown in Table.3, modal frequency errors appear to increase after geometry calibration, which is consistent with parameter compensation theory that different kinds of errors may lead to a bad model predicting good results because geometry uncertainties can cover parameter uncertainties up. Generally, geometry calibration is prerequisite during mitigating modeling errors. After parameter calibration, the average modal frequency residue is less than 2% and deflections predicted by the model is much close to test data, which indicates good correlation between calibrated model and real structure. At the end, Table.4 shows the verification coefficients (η) comparing the maximum value of deflection by field tests and FE model responses. S_e and S_a represent the measured value and analytical value under controlled load respectively (Eq. (3)) [15]. η_1 and η_2 in Table.4 corresponds to Point 1 and Point 2 respectively.

$$\eta = S_e/S_\mathrm{a} \tag{3}$$

Table.4 Verification coefficients of models before and after calibration

	Point 1 （1/4 Mid Span）(m)	η_1	Point 2 （3/4Mid Span）(m)	η_2
Measurements	-0.05304	/	0.01900	/
Initial model	-0.03595	0.67	0.01860	0.98
Calibrated model 1	-0.03987	0.75	0.01733	0.91
Calibrated model 2	-0.04793	0.90	0.01921	1.01

CONCLUSION

Many bridges built in the 20th century are working under damage conditions. Besides, traditional visual observation methods have failed to meet the requirements of condition assessment in modern life, which emphasizes more significance of St-Id. Field tests, data interpretation, and FE calibration of a long-span arch bridge is presented in this paper. By conducting precise modeling and objective function optimization, two kinds of uncertainties are mitigated. Based on the investigation so far, the following conclusions are drawn:

1. Controlled load tests and ambient vibration tests are employed during St-Id, which is essential to condition assessment. Data gained from both kinds of tests can be used to validate each other to improve the reliability of model calibration.
2. Precise modeling of complex structural components aids in the uncertainty mitigation from the analytical point of view. As is shown in Table.2, modal frequency errors increased after geometry calibration. It indicates that geometric uncertainties can cover parameter uncertainties up so that bad model predictions match measured values well, as is consistent with parameter compensation theory. Thus, geometry calibration of long-span bridges is essential before further calibration.
3. Parameter calibration is conducted by optimizing objective function established by modal parameters while a sensitivity analysis is conducted to evaluate the dominant factors previously. The result of calibration was validated by ambient vibration tests and controlled load tests respectively. As is implied by verification coefficients and modal frequency error, model after calibration shows good agreement with field test results.

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