DYNAMIC BEHAVIOUR ANALYSIS AND EXPERIMENTAL STUDY OF STEEL TUBE ARCH BRIDGE MODEL

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SUMMARY

Combining with an actual arch bridge, this paper designed a scale steel tube arch bridge model, established a finite element model of the scale arch bridge model and finished dynamic behaviour analysis and test study of the bridge model. The numerical simulation analysis is compared with test results of experiment. The results showed that the except second frequency, the front order frequencies of model test and numerical analysis values are in good agreement, and the relative error is only 4.1%. The maximum error of test frequency and the frequency by the finite element analysis is 11.1%.

Keywords: *Steel tube arch bridge; model design; numerical simulation; test of dynamic behaviour; modal analysis.*

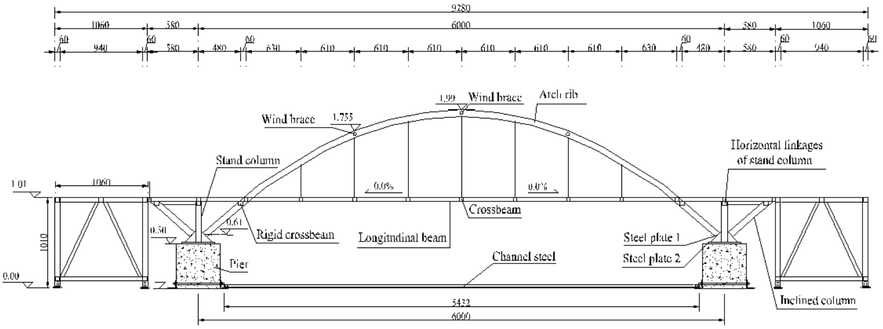
1. INTRODUCTION

The methods of bridge test can generally be divided into two kinds: the prototype bridge test [1] and laboratory model test. In general, the test model is made by appropriate materials and right proportion according to the similarity theory and actual bridge. The experimental model study can not only check bridge design theory and calculation method, but also provide some data and guidance for the actual bridge design and analysis [2-3]. According to the similarity theory, the mechanical behaviour of the prototype bridge can gained by the reduced scale model test and analysis, which is greatly convenient to solve some difficult problems in the bridge design phase. It can also help engineers update and explore more reasonable design theories and calculation methods.

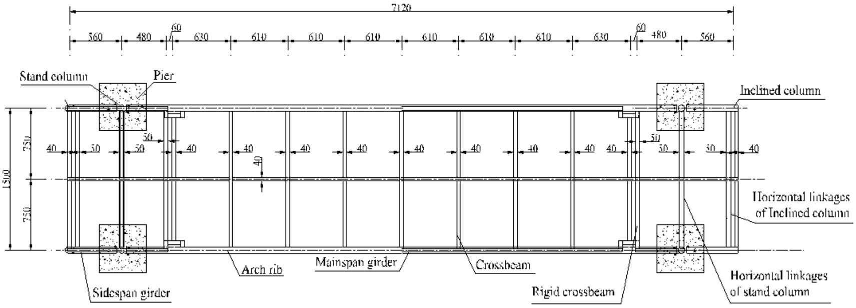
There are a lot of work about experimental study of static and dynamic behaviour of bridge models [4-7]. But the few bridge models designed for an experimental teaching demonstration platform for bridge health monitoring and modal shape experiment can be seen. For this, the author etc. especially designed and fabricated a reduced scale half-through steel-tube arch bridge model for an experimental teaching demonstration platform. and analysed its mechanical behaviour as well as did the relevant load tests [8]. This paper mainly focus on discussing the design and fabrication detail of the reduced scale half-through steel-tube arch bridge model and analyzing dynamic properties of this bridge model, describing the dynamic responses and method for measuring modal shape of this bridge model.

2. DESIGN AND FABRICATION OF SCALE ARCH BRIDGE MODEL

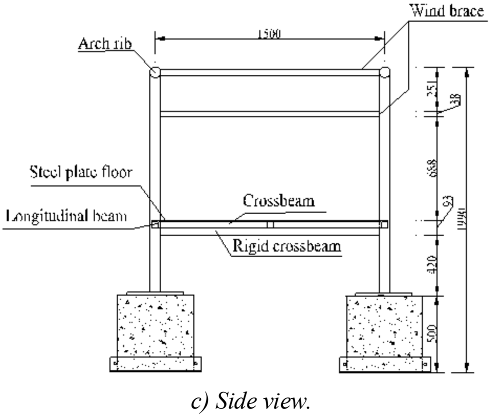
The reduced scale model is a half-through bridge of two main arch ribs with a rise-to-span ratio of 4.21, which are made of seamless round steel tubes with a diameter of 70 mm and wall thickness of 5 mm. The longitudinal beams and crossbeams of the bridge deck system are assembled by rectangular steel tubes.



a) Elevation view.



b) Plan view.



c) Side view.

Fig. 1. *Schematic of technical drawings of scale arch bridge model (unit: mm).*

There are three longitudinal beams in the bridge deck system, and two side ones are supported at the junction of the arch ribs by the rigid crossbeams, whose ends are welded on the arch ribs. The length of the crossbeam in the longitudinal direction is 610 mm, and the distance between the rigid crossbeam and the adjacent crossbeam is 692 mm. The bridge deck is overhanged by suspenders which are made of steel wire ropes with a diameter of 3 mm. 7 pairs of suspenders whose ends are anchored to the arch ribs and the side longitudinal beams are installed symmetrically with respect to the mid-span. For convenience of disassembility and installation, three transverse wind braces are installed at the vault and quarter points to ensure the lateral stability and stiffness of the scale arch bridge model, which are made of seamless round steel tubes with a diameter of 38 mm and wall thickness of 4 mm. Two stand columns and two inclined columns bracings which are connected by the rectangular steel tubes with a side length of 40 mm and wall thickness of 4 mm are installed at the arch foot as the transition between the deck system and the platform. The material of all the steel tubes is grade Q345. The schematic of technical drawings of the scale arch bridge model is illustrated in Fig. 1. Fig. 2 shows the photos of the reduced scale arch bridge model.

Fig. 2. *Photos of scale arch bridge model.*

3. FINITE ELEMENT ANALYSIS OF DYNAMIC BEHAVIOUR

The FEM is used to analyze the dynamic properties of the arch bridge model. Fig. 3 shows the spatial finite element web dividing model of the scale arch bridge model. The established finite element model in all has 1193 elements and 935 nodes. Spatial beam elements were adopted to simulate arch ribs, wind braces, longitudinal beams, crossbeams, stand columns, inclined columns and transverse connection beams. Suspenders were simulated by truss elements. Thin plate elements including transverse shear deformation were used to simulate the bridge deck. The boundary condition at the arch foot was a clamped support. The elastic connection which can only bear compressure was adopted to simulate vertical support between the bridge deck and rigid crossbeams.

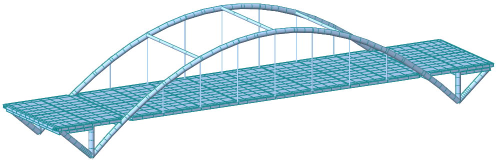
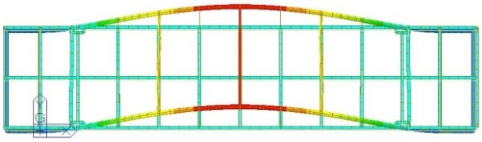
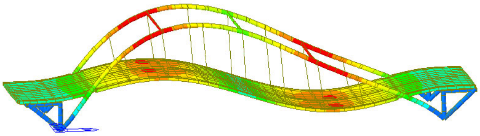


Fig. 3. *Spatial finite element model of scale arch bridge model.*

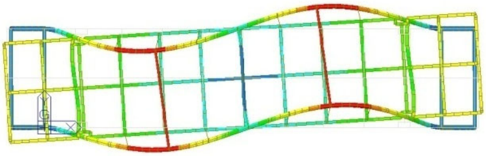
Once established dynamic finite element model of the scale arch bridge model, this paper analyzed its natural vibration characteristics. Fig. 4 shows the front six vibration modes of this model. Tab. 1 lists the front ten natural frequencies and the effective mode participation mass in all direction of the front ten vibration modes.



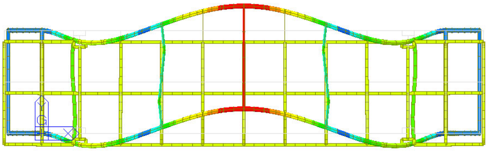
a) The 1st order mode shape (Freq. :9.18 Hz)



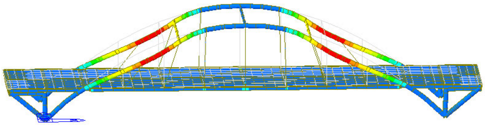
b) The 2nd order model shape (Freq.:14.75 Hz)



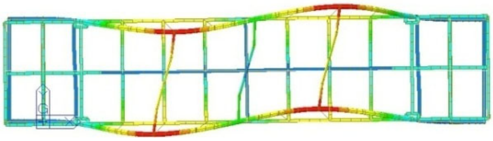
c) The 3rd order model shape (Freq.:19.16 Hz)



d) The 4th order model shape (Freq.:22.86 Hz)



e) The 5th order model shape (Freq.: 27.94 Hz)



f) The 6th order model shape (Freq.: 30.75 Hz)

Fig. 4. *The front six order vibration modes of the steel tube arch bridge model.*

Table 1. *Natural vibration period and the effective mode participation mass.*

Vibration mode orders	**Natural vibration Freq.(Hz)**	**Natural vibration period /s**	**Effective mode participation mass (%)**	**Direction**
1	9.18	0.108	42	Y: transverse direction
			11	RONT-X：torsion
2	14.75	0.068	20	X: longitudinal direction
			15	RONT-Y: torsion
3	19.16	0.052	50	RONT-Z: torsion
4	22.86	0.044	44	Y: pmtransverse direction
			6	RONT-X: torsion
5	27.94	0.036	28	Z: vertical direction
6	30.75	0.033	4	RONT-Z: torsion
7	34.84	0.029	34	X: longitudinal direction
8	35.49	0.028	14	Z: vertical direction
9	39.29	0.025	17	RONT-Z: torsion
10	45.26	0.022	3	RONT-X: torsion

From Tab. 1 and Fig. 4, we can find：

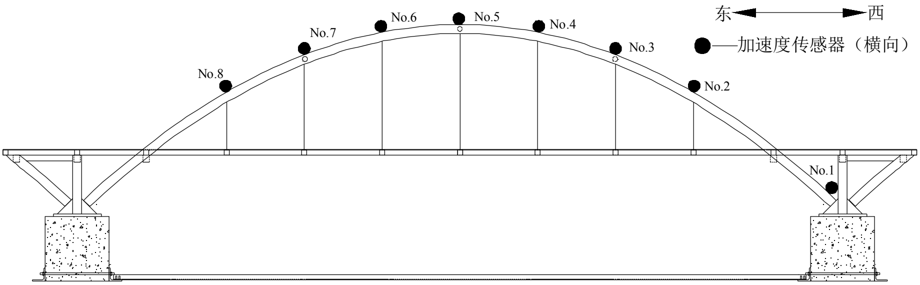
1) The arch bridge model has larger integral stiffness because its natural vibration frequency of the first order mode shape reaches 9.18Hz. However, lateral stiffness is relatively weak for the majority of transverse vibrations existing in the front ten vibration modes. The longitudinal vibrations occur in the front ten vibration modes, it shows that the longitudinal restraint stiffness of the bridge deck is relatively small.

2) Though the first mode shape is torsional vibration around the X-axis, the effective mode participation mass is not high, whose contribution rate just accounts for 19%. The wind braces and crossbeams on the arch rib play a major role in the first order mode of the torsional vibration around the X-axis (Fig. 5) and their contribution rate reaches 11%. Therefore, it is important to choose reasonable vertical stiffness of transverse connection members for half-through and through arch bridge design.

3) For long-span arch bridge, the influence of high order mode can’t be ignored, especially under complex loads, because the model shows the effective mode participation mass around the X-axis has only 64% in the front 100 vibration modes.

4. DYNAMIC TEST ANALYSIS OF BRIDGE MODEL

Wood hammer striking method is adopted to excite vibration of arch bridge model. Due to the fast signal attenuation after striking and in order to get adequate data for spectrum analysis, the arch bridge model is struck again every 15s. The time-histories data is recorded for analysis when signal become stable. In general, the dynamic test analysis work of a bridge mainly includes designing or fabricating to be tested object-bridge or model and selecting sensor type according to aim and requirement of test, arranging and installing sensors on it, exciting acting on bridge or model, collecting data by the dynamic signal acquisition system and processing test data etc.



a) front view of arrangement of acceleration sensors.

b) arrangement of acceleration sensors in vertical and transverse direction for the arch ribs.

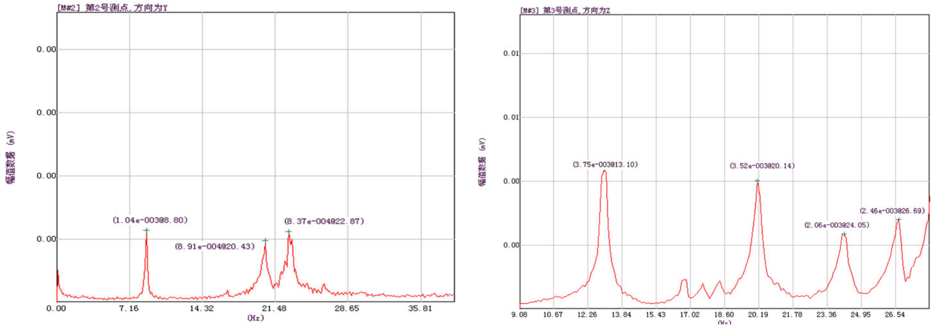
c) arrangement of acceleration sensors in vertical and transverse direction for the deck.

Fig. 6. *Arrangement of acceleration sensors.*

In order to get acceleration versus time data of the steel tube arch bridge model under dynamic loads and analyse structural vibration properties, natural vibration frequency and mode shapes, highly sensitive acceleration sensors were installed at the critical locations. DHDAS5920 data acquisition instrument was used to collect and analyse the dynamic experimental data. The frequency of acceleration collection is 200Hz and its analysis frequency is 78.13Hz. For the limited data transmitting channels of DHDAS5920, it is impossible to obtain all mode shapes just by one-time monitoring point arrangement. So the dynamic experiment was divided into six tests, including two-time vertical direction, transverse direction and torsional direction tests for the arch ribs and bridge deck. Fig. 6 presents the arrangement of acceleration sensors for the arch ribs and bridge deck in vertical and transverse direction.

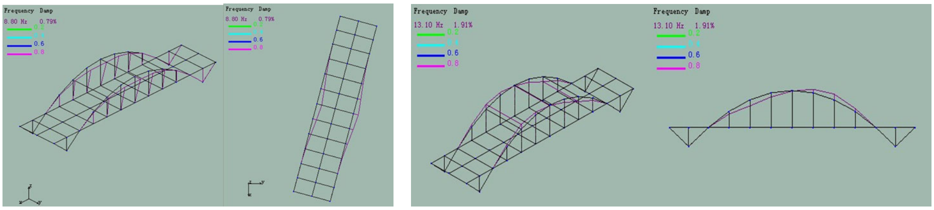
5. COMPARISON OF THEORETICAL AND EXPERIMENTAL RESULTS

With the help of modal analysis software, the measured acceleration data is analysed by FFT (Fast Fourier transform). Fig. 7 gives FFT spectrum curves of typical test points of arch bridge model. Fig. 8 and Fig. 9 further gives the measured front 1st, 2nd order test frequency and vibration modes for the arch rib and the deck respectively.



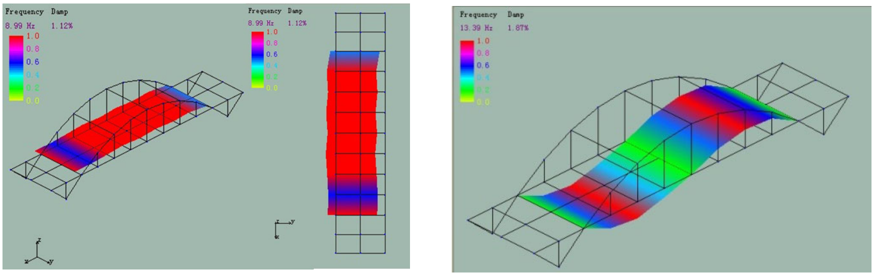
a) FFT spectrum of No.3 transverse test point *b) FFT spectrum of No.2 vertical test point*

Fig. 7. *FFT spectrum curves of typical test points of arch bridge model*



a) The 1st mode vibration freq.8.8) *b)The 2nd mode vibration (freq. 13.1)*

Fig. 8. *The measured front 1st, 2nd order modes for the arch rib.*



a) The 1st mode vibration (freq. 8.99) *b) The 2nd mode vibration (freq. 13.39)*

Fig. 9. *the measured front 1st, 2nd modes for the bridge deck.*

Table 2 listed the comparison of frequencies and their damping ratios obtained by the numerical analysis and experiment in the front 4 orders.

Table 2. *The comparison of the numerical analysis and experiment frequencies and damping ratios.*

Order number	**Modal descriptions**	**Frequency（Hz）**			**Damping ratio（%）**
		Cal. Values	**Measured Values**	**Error（%）**	
1	Transverse bending of arch ribs out of plane	9.18	8.8	4.1	0.79
	The symmetrical lateral displacement of the deck	9.18	8.99	2.1	1.12
2	Anti-symmetric deflection of arch ribs in plane	14.75	13.1	11.1	1.91
	Anti-symmetric vertical displacement of the deck	14.75	13.39	9.2	1.87
3	Anti-symmetric lateral deflection of arch ribs out of plane	19.16	20.43	6.6	0.70
	Anti-symmetric lateral displacement of the deck	19.16	19.35	1.0	2.89
4	Symmetrical transverse bending of arch ribs out of plane	22.86	22.87	0.04	1.18
	Symmetrical lateral displacement of the deck	22.86	22.78	0.3	1.18

It can be seen from Tab. 2, Fig. 8 and Fig. 9 that the model test frequency and numerical analysis value are in good agreement for 1st order modal shape, and the error is only 4.1%. The maximum error of frequency between test and analysis occurs in 2nd order modal shape, and it is 11.1%. The minimum error occurs in 4th order modal shape, it is 0.04% . The reason for resulting in these errors may be as follows:

1) The error of model parameters. Such as physical parameters (density, elastic modulus, cross-sectional area, etc.) influenced by the changing environment and manufacturing process, simplification of the boundary and connection conditions, the error of geometry size, etc.
2) The actual structure has infinite degrees of freedom, while this discrete model has limited degrees of freedom. So there must be some model order error between them.
3) The primary tension of suspenders for model bridge are ignored in the finite element model.

6. CONCLUSIONS

Based on the steel tube arch bridge test model, this paper analyzes dynamic properties of the model and draws the following conclusions:

1) When analysed dynamic response of arch bridge, the influence of high order mode can't be ignored, because the study results show the effective mode participation mass around the X-axis has only 64% in the front 100 vibration modes. It is essential to analyze nonlinear time-history properties of arch bridge.
2) The wind braces and crossbeams on the arch play a major role in the first order mode of the torsional vibration around the X-axis and their contribution rate reaches 11%. Therefore, it is important to choose reasonable vertical stiffness of transverse connection members for half-through and through arch bridge design.
3) The model test values and numerical simulation values are in good agreement for first order frequency. The error between them is only 4.1%. The maximum frequency error between test and analysis is 11.1%. In addition considering test error, it is necessary to modify finite element model and make the modified finite element model to be closer to the actual structure.

ACKNOWLEDGMENTS

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