Physical and Virtual Simulation of the Experiment of Bridge Structure under Static Load

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Abstract: Simulation experiment is an important method to study the performance of bridge structure, among which the simulation experiment of the structure under static load is an effective way to evaluate bridge quality and bearing capacity. In this paper, a 1:25 reduced-scale model of vehicle and bridge is used to simulate the performance of the practical bridge under static load. The finite element analysis is used for virtual simulation, and scale model experiment is used for physical simulation. Comparing the results of physical simulation and virtual simulation for the experiment, it is found that the two are basically the same, verifying the accuracy and effectiveness of this method. Physical simulation and virtual simulation complement each other, which plays an important role in promoting the experimental research and teaching in bridge engineering.

1. Introduction

Virtual simulation refers to the technology that uses a system to imitate another real system without a specific hardware platform or without components for experiment. It can be used for the demonstration of the preliminary planning or the later effect, the visual design of bridge structure, and the analysis of the bridge construction, etc. [1]. Physical simulation is based on the similarity of physical properties and geometric shapes, while other properties remain unchanged. Among them, model experiments is an important means for bridge structural research. With the development of bridge construction, especially in the past ten years, model experiment of bridge structure is in the ascendant [2-4]. Among them, it is a very simple, economical and effective way to use plexiglass as the material for the scale model for bridge experiment [5]. Zhang conducted a bridge model experiment of plexiglass winged beams in 2001, and Vladimir conducted a molecular dynamics simulation [6-7] for the plexiglass bridge model. In 2007, Hu verified the design theory of a new type of bridge through a 1:20 reduced-scale model of the first self-anchored single-span suspension bridge with steel-concrete composite beam and single-tower in the word [8].
In this paper, a refined vehicle model and a reduced-scale plexiglass T-beam bridge are used to carry out the physical simulation of the static load experiment on the bridge structure. Finite element analysis is performed in the virtual simulation of the experiment. By comparing the results of the physical simulation with the virtual simulation for the experiment, the accuracy and effectiveness of the experimental method can be verified. It is pointed out that the simulation experiment plays an important role in promoting the research and teaching in bridge engineering.

2. Model design of physical simulation

According to the reduced scale of 1:25, the plexiglass bridge model was designed and made. Meanwhile, a 1:25 refined truck model is prepared. The experimental bridge was a simple-supported T-beam bridge with a uniform width and a total length of 80cm. The span is 76cm. The width of the bridge model is 40cm and the height is 5.5cm. The structure of the bridge model is shown in Fig.1, and the physical model of the bridge and the vehicle is shown in Fig.2.

2.1 Technical standards for bridge model design

Design load: Considering the low strength of plexiglass, in order to ensure that the plexiglass is in an elastic deformation state, the design load is taken as 9.3% of the first class load of highway; and then the reduced scale of 1:25 should be considered.

2.2 The purpose of the load test

Check whether the mechanical performance of the bridge structure meets the requirements in design specification.

2.3 Experimental content

According to the purpose of the bridge experiment, a static experiment (as shown in Fig.3) is carried out to test the structural bearing capacity and stiffness of the bridge model.
3. **physical simulation experiment of bridge**

In the bridge experiment under static load, the deformation and stress are measured to determine whether the actual structure conforms to the design expectation, and whether the structural strength and rigidity meet the requirements in design specification.

3.1 **Principles for determining static experimental load**

The static load is applied by the weight of three-axle truck about 63.7N. The wheelbase size of the tested truck is shown in Fig.4, and the parameters of the vehicle are shown in Table 1.

![Fig.4 Experimental wheelbase arrangement of the truck (unit: cm)](image)

### Table 1 Parameters of actual test truck

| Vehicle         | Axle load (N) | Total weight (N) |
|-----------------|---------------|------------------|
| (Auman Kunlun)  |               |                  |
| Front axle      | 13.6          | 26+24            |
| Bottom axle+rear axle | 26+24     | 63.7             |
| (Sinotruk Youth Specialty) |     |                  |
| Front axle      | 15.3          | 25+23            |
| Bottom axle+rear axle | 25+23     | 63.7             |

3.2 **Load conditions and experimental content**

According to the *Highway Engineering Quality Inspection and Evaluation Standards* (JTG F80/1-2004), the following two conditions are proposed as the content of the static load. In test 1, the shear force in section I of beam 1 is focused; In test 2, the positive bending moment in section II is focused. The experimental conditions are shown in Fig.5.

![Fig. 5 Static test section of bridge (unit: cm)](image)
3.3 Measurement point
The strain measuring points of each control section are shown in Fig.6. The strain gages are pasted on the bottom and web of the bridge model.

![Fig.6 Strain displacement measuring points (unit: cm)](image)

3.4 Principle of the loading
1. The maximum experimental load efficiency can be achieved by using the least number of loaded vehicles.
2. The loading conditions are simplified and merged to minimize the layout times.
3. Each loading condition is based on a certain test item, and other experimental purposes are taken into account.
4. In order to understand the variation law of bridge structure strain and displacement with the increase of the internal force and prevent accidental damage, the experimental loads are applied step by step. In principle, each working condition is divided into three steps until the maximum load.

4. Virtual simulation experiment of bridge
4.1 The internal force influence line of each control section
Through the calculation of finite element analysis software, namely MIDAS, the influence lines of internal force and displacement of each control section are obtained. The grid method model is adopted in the structural calculation, and the impact coefficient of the lane load is determined according to the first-order natural vibration frequency (64Hz) calculated by the finite element analysis. The finite element model is shown in Fig.7.

![Fig.7 Finite element model in virtual simulation](image)

The internal force of the design control sections are calculated on the basis of the influence line, and the design load corresponding to the ultimate tensile strength of the actual model is adopted. When the internal force or the displacement is calculated, the impact coefficient of the vehicle is included in accordance with the regulations, and the impact coefficient of 0.45 is considered for the simulation of the bridge. The calculation results of the control internal force and control displacement of the above control sections are summarized in Table 2.
Table 2 Design live load, hierarchical load internal force control value and load efficiency

| Experimental section | Working condition | Design load | Theoretical hierarchical loading internal force value | Theoretical hierarchical loading efficiency |
|----------------------|------------------|-------------|-----------------------------------------------------|------------------------------------------|
|                      |                  | Highway I level | First level | Level 2 | Level 3 | First level | Level 2 | Level 3 |
| Shear force of I-I section Q(N) | I | 57.2 | 32.1 | 45.2 | 55.1 | 0.56 | 0.79 | 0.96 |
| Bending moment of II-II section M(N·mm) | II | 6861 | 4758 | 5626 | 6967 | 0.68 | 0.82 | 1.02 |

4.2 Experimental loading
The experimental loading efficiency in every load step is shown in Table 3.

Table 3 Graded loading efficiency table for working conditions I and II

| Experimental section | Section I (working condition I) | Section II (Working Condition II) |
|----------------------|---------------------------------|---------------------------------|
| Load level           | First level | Level 2 | Level 3 | First level | Level 2 | Level 3 |
| Loading efficiency   | 0.56        | 0.79    | 0.96    | 0.68        | 0.82    | 1.02    |

5. Comparison of experimental results of physical simulation and virtual simulation
Table 4 shows the comparison between the measured results and the theoretical results under the load in working condition I. Table 5 and Table 6 show the comparison between the measured results and the theoretical results under the load in working condition II. According to the measured results of the structure, the following conclusions can be drawn.

1. The bottom deflection and strain effectiveness coefficient of the bridge mid-span are less than 1.0, and the theoretical deflection of the plate beam is greater than the measured deflection.

2. The residual deflection and strain of the beam are less than 20%, that is to say, the beam can be restored to the original state after unloading.

3. The test coefficient of the shear stress on the support is less than 1.0, and the theoretical strain of the beam is greater than the measured strain.

4. The relative residual shear stress on the support of the beam is less than 20%. The beam can be restored to its original shape immediately after unloading, and the plastic deformation is small. The shear resistance of the beam meets the requirements in design codes and has a large safety reserve.

5. The maximum deflection of the bridge model is less than 1/600 of the bridge span.

The shear stress in Table 4 is obtained from the maximum shear stress formula based on three strains from measurements.

\[
B = \frac{\varepsilon_{0} - \varepsilon_{90}}{2}
\]

\[
C = \frac{2\varepsilon_{45} - \varepsilon_{0} - \varepsilon_{90}}{2}
\]

\[
\tau_{\text{max}} = \frac{E}{1 + \nu}\sqrt{B^2 + C^2}
\]

where \(\nu=0.2\), \(E=2.04\text{GPa}\).
Table 4 Measured strain, residual strain and theoretical strain at the support of beam 1 (strain measuring point)

| Experimental conditions | Measuring point number | First level $\varepsilon_1$ (µε) | Level 2 $\varepsilon_2$ (µε) | Level 3 $\varepsilon_3$ (µε) | Remnant Strain $\varepsilon_p$ (µε) | Maximum shear stress $\tau_s$ (MPa) | Maximum theoretical value of shear stress $\tau_s$ (MPa) | Check coefficient of shear stress $\frac{\tau_s}{\tau_s}$ | Relatively Residual strain $\frac{S_p}{S_s} \times 100\%$ |
|-------------------------|------------------------|---------------------------------|-----------------------------|-----------------------------|---------------------------------|-----------------------------|------------------------------------------------|---------------------------------|-------------------------------|
| Working condition I     | 6                      | 0                               | 65                          | 62                          | 1                               | 61                          | 0.311                                           | 0.646                                           | 0.48                                           | 1.6                                   |
|                         | 7                      | 124                             | 233                         | 268                         | 5                               | 263                         |                                                   |                                                |                                               | 1.9                                   |
|                         | 8                      | 23                              | 102                         | 111                         | 2                               | 109                         |                                                   |                                                |                                               | 1.8                                   |

Table 5 Measured deflection, residual deflection and theoretical deflection in the mid-span of beam 1 (deflection measuring point)

| Experimental conditions | Measuring point number | The first stage load $S_1$(mm) | Second load $S_2$(mm) | The third level load $S_3$(mm) | Uninstall Sp(mm) | Elastic deflection $S_e$(mm) | Relative residual deflection $S_p/S_s$(%) | Theoretical deflection $S_s$(mm) | Calibration factor $S_e/S_s$ |
|-------------------------|------------------------|---------------------------------|------------------------|---------------------------|-------------------|-----------------------------|--------------------------------------|--------------------------------|-----------------------------|
| Working condition II    | 6                      | 0.56                            | 0.68                   | 0.84                      | 0.01              | 0.83                        | 1.2                                  | 1.36                           | 0.61                        |

Table 6 Measured strain, residual strain and theoretical strain in the mid-span of beam 1 (strain measuring point)

| Experimental conditions | Measuring point number | First level $\varepsilon_1$ (µε) | Level 2 $\varepsilon_2$ (µε) | Level 3 $\varepsilon_3$ (µε) | Remnants strain $\varepsilon_p$ (µε) | Elasticity strain $\varepsilon_e$ (µε) | Relative residual strain $\varepsilon_p/\varepsilon_e$ (%) | Theoretical strain $\varepsilon_s$ (µε) | Calibration factor $\varepsilon_e/\varepsilon_s$ |
|-------------------------|------------------------|---------------------------------|-----------------------------|-----------------------------|---------------------------------|-----------------------------|--------------------------------|--------------------------------|-----------------------------|
| Working condition II    | 1                      | 471                             | 568                         | 706                         | 10                              | 696                         | 1.4                            | 931                            | 0.75                        |

6. Conclusion
The precise finite element model of vehicle is used to carry out physical simulation of the plexiglass T-shape bridge model under static load, and the finite element software, Midas, is adopted to perform the virtual simulation analysis for the experiment. The results of physical simulation experiment are compared with the results of virtual simulation experiment, and the following conclusions are drawn.

1. Before the physical simulation experiment, the bridge model was inspected, and the structure of the support, beam and slab were in good condition. In the experiment, the loading efficiency of the shear force at the support and the positive bending moment in the mid-span is from 0.96 to 1.05, which meet the requirements in the bridge testing specification. The experimental data show that the strength and rigidity of the plexiglass bridge model also meet the requirements in the design specification.

2. The results of virtual simulation experiments are basically consistent with the data of physical simulation, that indicates both physical simulation and virtual simulation can accurately simulate the force and deformation of the practical bridge. The simulation experiment has high accuracy and effectiveness. The simulation experiment can meet the requirements of experimental research and teaching in bridge engineering, and it also improve the level of experimental research and teaching effectively. Physical simulation and virtual simulation are complementary to each other, and the close combination of the two methods promotes the development of bridge engineering.
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