RESEARCH FOR THE MECHANICAL BEHAVIOR OF SIMPLE-SUPPORTED IRREGULAR REINFORCED CONCRETE SLAB BRIDGE

Wei Chen[1], Guojing He[1]

[1]Central South University of Forestry and Technology

No. 498 Shaoshan Road, Tianxin District, Changsha, Hunan Province, China,1204422136@qq.com

ABSTRACT

Reinforced concrete slab bridges are of excellent integrity, small beam hight and flexible structure. In order to adapt to the topographic condition， road alignment and traffic function in practical engineering, the superstructure of slab bridge is usually designed as irregular shaped structure. Irregular slab bridges, as a kind of typical space structures, are always in multiaxial stress state and display complex mechanical behavior. So, precise analysis theory and practical simplified calculating method are necessary to be improved. In this paper, a simple-supported irregular bridge, Wayaoxi Bridge, located in Tuokou town, Guizhou Province, is taken as background project. The irregular slab bridge of Wayaoxi is simulated by three numerical finite element models, namely，shell model, solid model and space beam grillage model. Furthermore, test of bridge in-site is carried out. By comparing the results of numerical calculation and bridge test, mechanical behavior and dynamic characteristic of the irregular slab bridge under highway design load can be obtained. Applicable conditions have been presented through the analysis of computational accuracy of each finite element modal. Finally, the conclusions of this research can be applied to the calculation, design and construction of this type of irregular slab structures.

KEYWORDS

Irregular bridge, Reinforced concrete bridges, Finite element modal.

INTRODUCTION

Slab bridge is commonly used in small span bridges, with many advantages such as small building height, concise configuration, simple templates. With the development of transportation, especially the increasing number of highways, urban interchanges and viaducts, irregular shaped slab bridges has been more widely used. Irregular shaped slab bridge not only meets the road alignment, building clearance and driving comfort requirements, but also has good architectural aesthetic effect. However, irregular shaped slab bridge has more complex stress state than ordinary linear orthogonal bridge, the spatial analysis and supports disposing are difficult and important in such bridges, so general concern are given by lots of engineers. In 1989, the professor Xia Gan proposed grid simulation and impact surface method to calculate irregular shaped slab structure, and established the corresponding computing program. Currently, many scholars have conducted theoretical and experimental research of irregular shaped slab structures, but its theory and practical algorithm still needs further study. In this paper, Wayaoxi bridge, located in Guizhou Province, is taken as research object, and it is simulated by plate elements model, solid elements model and space grillage model. Finite element numerical calculation and bridge test in-site are conducted to analyze the irregular slab bridge. Then, by comparing numerical calculation and bridge test results, the mechanical behavior and dynamical property of irregular slab bridge under highway design loads are got. Further, application conditions of each simulation modal can be proposed by the analysis of the accuracy of three computing models, which can provide theoretical basis and practical reference for the calculation of similar irregular slab structures.

ENGINEERING BACKGROUND AND FINITE ELEMENT MODEL

Project Overview

Wayaoxi bridge is located on the left bank tributary of Qingshui river, the outlet of Wayao River of the rehabilitation road from Lantian to Wengdong, in Guizhou reservoir area of Tuokou hydropower station. Class of loading is on highway-Ⅱ level. Bridge structure is arranged as 13m situ reinforced concrete irregular slab + 3 × 20m situ reinforced concrete simple supported T girder + 13m situ reinforced concrete irregular slab, and total length of the bridge is 93.62m. Standard span of the situ reinforced concrete irregular slab span is 13m with beam length of 12.92m and beam height of 0.7m.There are side ribs of 0.65m width and 0.75m height on each side of the irregular slab, with a cantilevered slab of 1.0m length outside each side rib. The general arrangement of this bridge is shown in Figure 1, the cross section of irregular slab is shown in Figure 2 and its plane layout is shown in Figure 3,

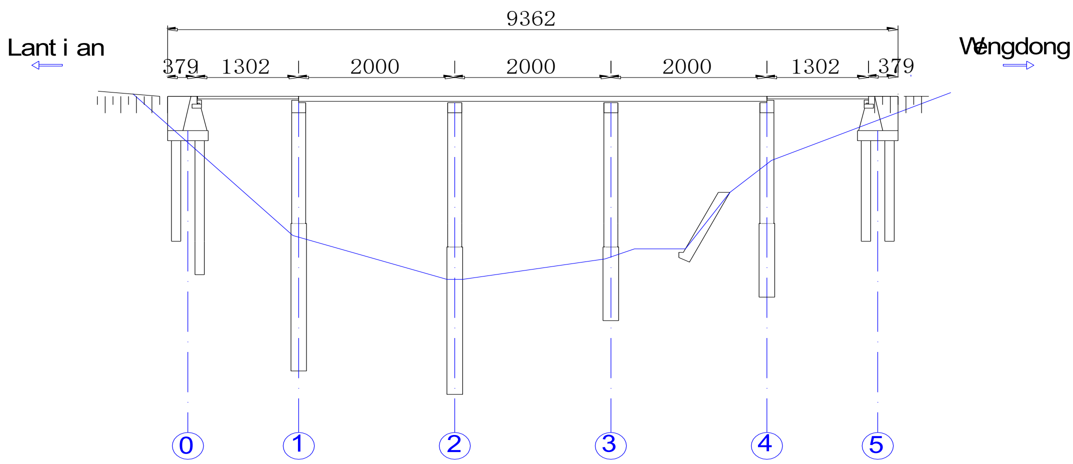


Figure 1 Bridge facade layout (dimension unit: cm)

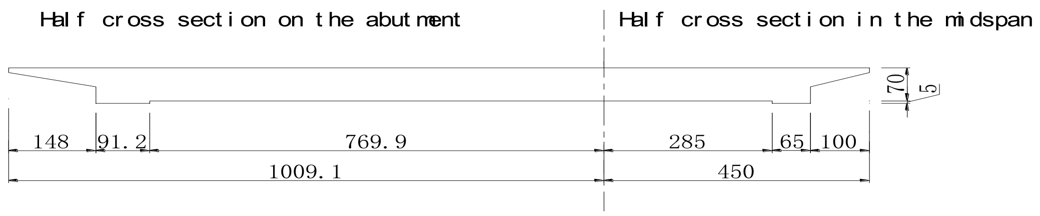


Figure 2 Cross section of irregular slab (dimension unit: cm)

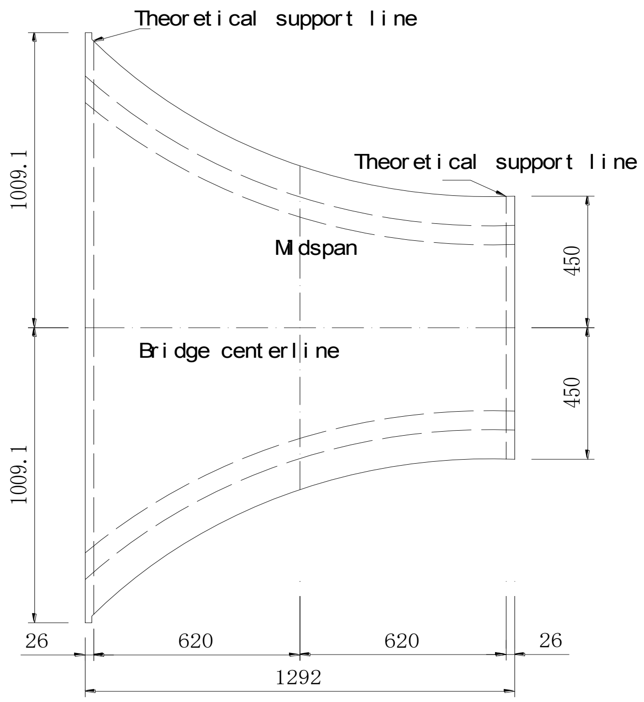


Figure 3 plane layout of irregular slab (dimension unit: cm)

Beam Grid Finite Element Model

The internal forces (axial force, shear, moment and torque) of slab superstructure are in two-dimensional distribution state, which are more complex than one-dimensional beam. Beam grid method will make bending and torsional stiffness which distributed in each segment of the slab concentrated in the adjacent equivalent beam grids, that means the longitudinal stiffness of the slab is focused on the longitudinal beam grid, the transverse stiffness of the slab is focused on the transverse beam grid, in order to achieve the equivalent slab structure. Beam grid method is to reduce the dimension of internal forces distribution and simplify the structure, it makes the concept of the force distribution clear, and the stress analysis and design of reinforcement easy for practical engineering structures.

The width of irregular slab varies gradually in the plane, so gradient beam grid is used to simulate the irregular slab bridge. However, section properties along the longitudinal grillage member changes. Longitudinal beam grid members are arranged as shown in Figure 4. The flange slab and ribs are divided into longitudinal beam grid members, intermediate slab is divided into five stringers, the entire beam grid model has nine stringers, cross-sectional width of the beam gird changes gradually along the beam axis. Horizontally, the sheet bends around its own centroid, the rod member 1-2 and 8-9 approximately use the average thickness of the flange slab, rod member 2-3,3-4,4-5,5-6,6-7 and 7-8 approximately use the intermediate slab thickness. For a solid slab, the moment of inertia and torque of longitudinal and transverse beam grid are to be calculated according to the width of each slab member.

The bending moment of inertia of unit slab width: $I = \frac{d^3}{12}$ (d is the slab thickness)

The torsion constant of unit slab width: $c = \frac{d^3}{6}$ (d is the slab thickness)

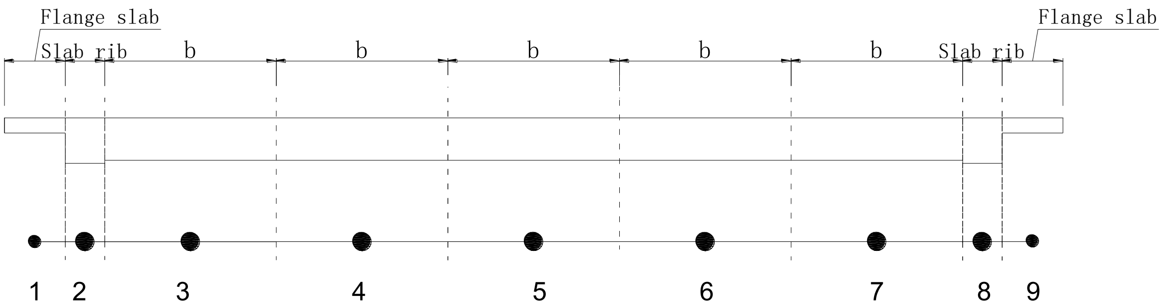


Figure 4 The division of longitudinally beam grid member

Element division and calculation modal are shown in Figure 5. Every node of each beam element has three directions of translational movement and three directions of rotational displacement, so each node has six degrees of freedom.

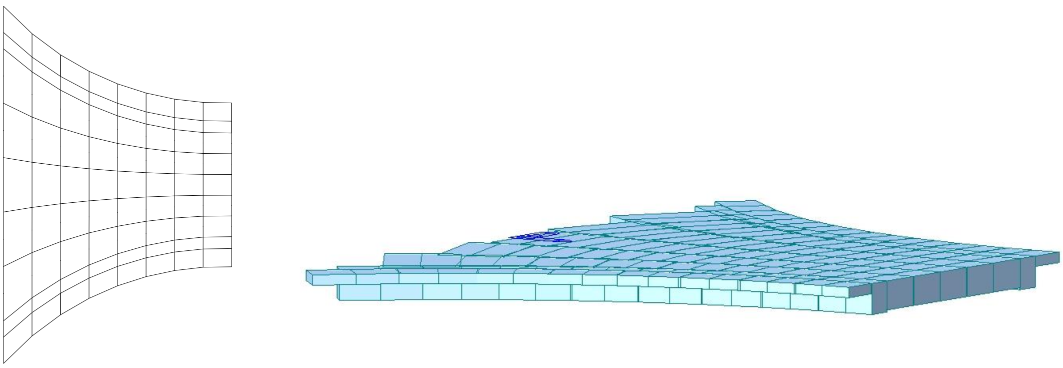


Figure 5 The division of irregular slab elements and beam grid computing model

Shell Finite Elements Model

The thickness of irregular slab is 0.7m, far less than its longitudinal length and transverse width, so this slab bridge can be simulated by shell elements. There are two types of shell elements, thin plate and thick plate, can be used in Midas civil. In this paper, quadrilateral thick plate is choosen to model the irregular slab bridge, shell finite element model and elements division are shown in Figure 6.

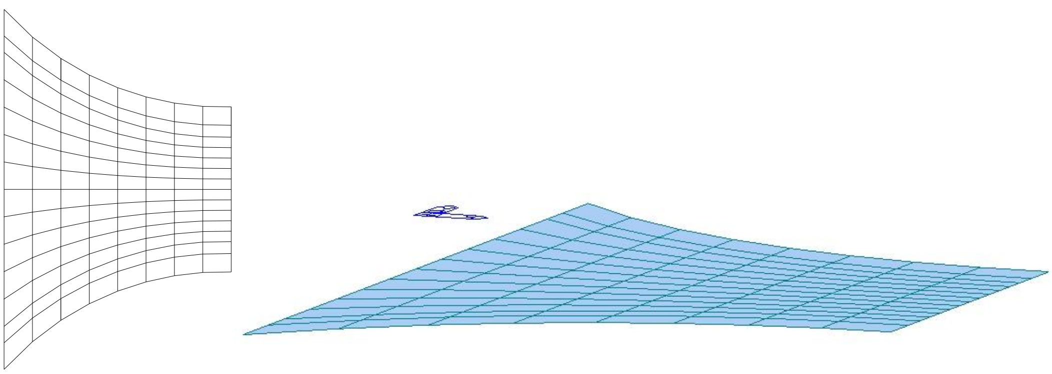


Figure 6 The division of irregular slab elements and shell computing model

Solid Finite Element Model

In this paper, hexahedral three-dimensional solid elements are used to analyze the stress state of the irregular slab. The degrees of freedom of solid elements are based on the global coordinate system, each element has eight nodes, each node has three directions of translational displacement. The three-dimensional finite element model of irregular slab and elements division are shown in Figure 7.

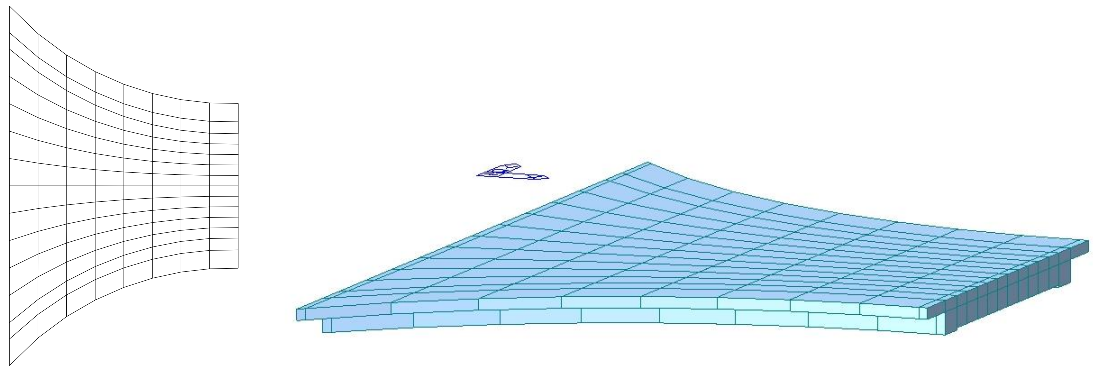


Figure 7 The division of irregular slab elements and solid computing model

ANALYSIS OF RESULTS

The beam grid model, whose concept is clear and model is simple, can better reflect the main mechanical characteristics of the irregular slab bridge structure, and is convenient to be used in the design. Shell Model and solid model can simulate the mechanic behavior of the actual structure more accurately, especially the local stress behavior. Based on the three computing model above, the static and dynamic characteristics of irregular slab bridge under design load of highway-Ⅱ level are got. Auto load consists of lane load and vehicle load, and overall calculation of bridge structure must use lane load in accordance with the specification. Lane load includes uniform load and concentrated load, and the uniformly distributed load qk and concentrated load Pk of highway-Ⅱ are 0.75 times of that of load of highway-Ⅰ level.

The following conditions are taken for the accuracy comparation of the results of the three computing models:

- -Case 1: self-weight load;
- -Case 2: Load of Highway-Ⅱ arranged along the midline of irregular slab + both sides of sidewalk fully covered;
- -Case 3: Load of Highway-Ⅱ arranged along the edge lane of irregular slab + both sides of sidewalk fully covered ;

Case 1 is mainly used to contrast the differences of results of three computing model under self-weight load. Ensuring the reliability of results of various computing models under self-weight, is a basic promise of proving beam grid, shell and solid models are static equivalent with the actual structure.

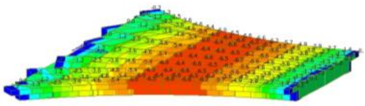
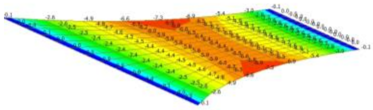
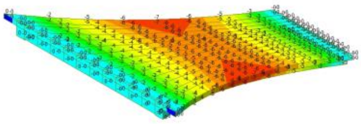
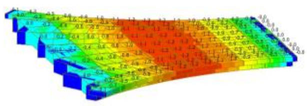
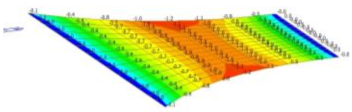
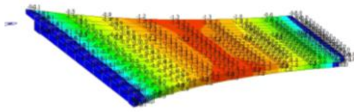
Case 2 and 3, respectively, simulate the stress states of irregular slab subjected to symmetric load and eccentric load, the difference of three models under lane load is compared. Bridge test follows the principle that the test load effect is equivalent to design load effect. The deflection and stress of bridge in each test condition are measured, finally the comparison, analysis and verification of each calculation methods are conducted.

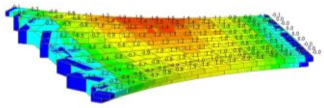
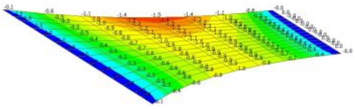
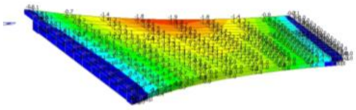
Comparative Analysis of Deflection

When structure is simulated by beam elements, shell elements and solid elements, displacement results are firstly obtained by finite element method, internal forces and stresses are obtained by further calculation based on displacement. Therefore, if the displacements of finite element model agree with the actual displacements, it indicates that the finite element model can accurately simulates the stiffness of actual structure, and can more accurately simulates the mechanical behavior of the actual structure. The calculated displacements in various conditions are shown in Table 1. Since the displacements of irregular slab under eccentric loads may reflect torsional effect of slab, the displacements of both sides under eccentric loads are listed in the table.

The results show that the displacement values under self-weight obtained by three computing methods are similar, the distribution of displacements is basically the same, but the displacement of shell model is largest among these three models.

Table 1 Displacements of finite element models under various conditions

	Finite element model	The displacement distribution	Max（mm）	The maximum position	The Maximum test value in midspan
	Bean gird model		6.7	Midspan of edge beam	
Self-weight	Shell model		7.3	Midspan of side slab	/
	Solid model		6.6	Midspan of the edge	
	Bean gird model		1.2	Midspan of Centre beam	
Symmetric load	Shell model		1.2	Midspan of side slab	1.0mm
	Solid model		1.3	midspan	

Eccentric load	Bean gird model		1.5 (1.0)	Midspan of edge beam in the loading side (Midspan of edge beam in the unloading side)	1.4mm (Midspan in the loading side)
	Shell model		1.5 (1.0)	Midspan of side slab in the loading side (Midspan of side slab in the unloading side)	
	Solid model		1.9 (1.0)	Midspan of solid in the loading side (Midspan of solid in the unloading side)	

Comparative Analysis of Stress

Concrete has low tensile strength, the bottom of simple supported slab bridge is in tension under self-weight or external loads. By making comparation of measured stress values and theoretical stress values of bottom slab, the working condition of bridge can be judged, so stress nephograms and maximum stress of bottom slab under different conditions are listed in Table 2. Further comparative analysis of stress distribution law of each finite element model can be obtained. Stress measuring point layout is shown in Figure 8.

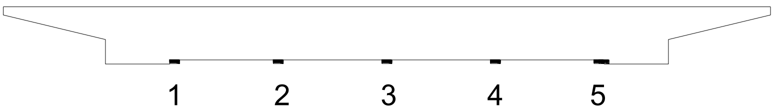
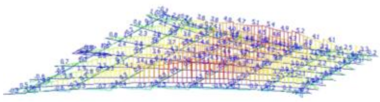
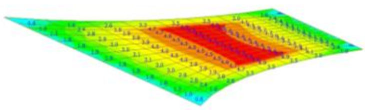
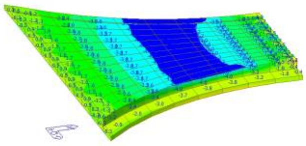
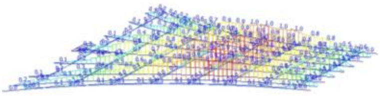
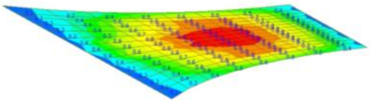
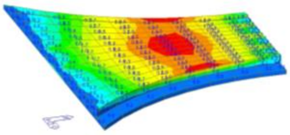
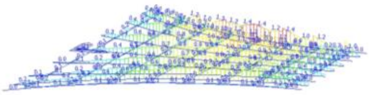
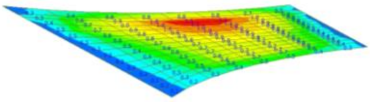
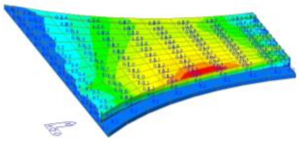


Figure 8 Measuring points layout of strain in cross section of midspan

Table 2 Stress of finite element models under various conditions

	Finite element model	stress distributing graph	Max (MPa)	The maximum position	The Maximum test value
Self-weight	Bean gird model		5.37	Midspan of edge beam	/
	Shell model		4.87	Midspan of edge rib	

	Solid model		4.81	Midspan of the edge entity	
symmetric load	Bean gird model		1.08	Midspan of center beam	1.10MPa（No3 measuring point）
	Shell model		0.90	Midspan of centerline	
	Solid model		1.07	Midspan of centerline	
eccentric load	Bean gird model		1.44	Midspan of side beam	1.42MPa（No.1 measuring point）
	Shell model		1.08	Midspan of edge rib	
	Solid model		1.47	Midspan of edge rib	

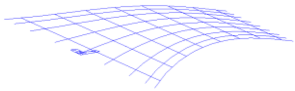
Comparison of Natural Frequencies

The mode of vibration and frequency can be calculated by three finite element models and the results of three models are shown in Table 3. Three kinds of model calculation results can show that the first mode shape are vertically symmetric and the frequency values are substantially the same, which indicates that three models can simulate stiffness of the irregular slab well.

According to the actual conditions, jumping test is adopt to conduct dynamic load test. In the case of t he bridge without any obstacles, the test vehicle crosses over a barrier of 3cm to 15cm and stop imme diately, so that the bridge produces damped free vibration, and the curve of vibration attenuation is rec orded. Test measured time-history curve and spectrum analysis diagram are shown in Figure 9.

Dynamic load test results show that: the jumping test on this irregular slab bridge is ideal, damped free vibration waveform is relatively intact and the first order of vertical bending vibration frequency can be accurately identified. Test frequency of test span is larger than its theoretical frequency, which shows that the integral rigidity of the irregular slab bridge meets the design requirements.

Table 3 The theoretical value and test value of natural vibration characteristics of irregular slab

Finite Element Model	Mode shape	Theoretical frequency value	Measured frequency value
Grillage model		6.9 Hz	
Shell Model		6.9 Hz	9.5 Hz
Solid Model		7.2 Hz	

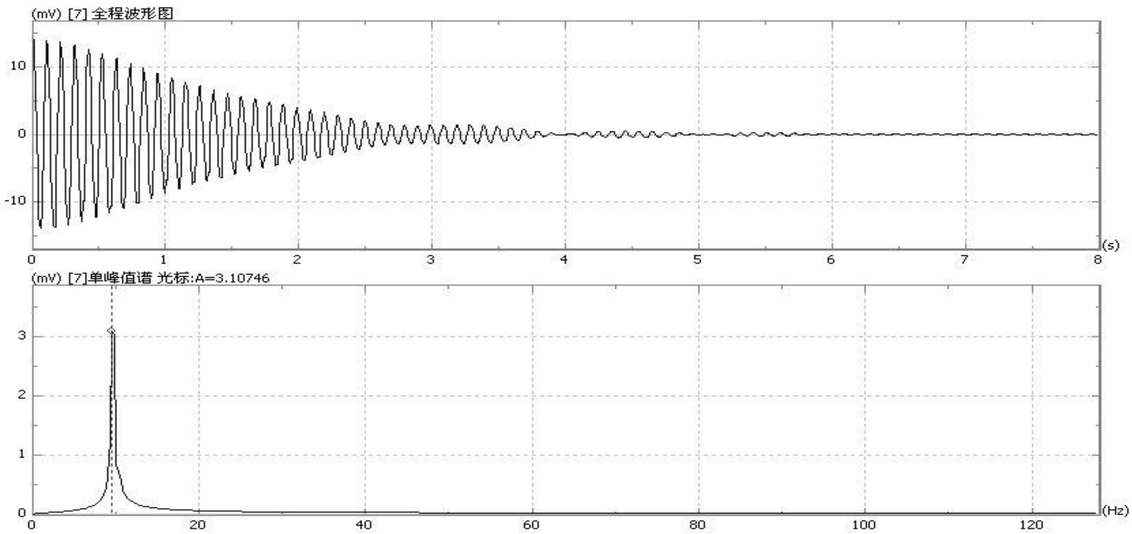
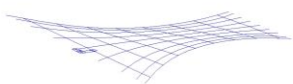
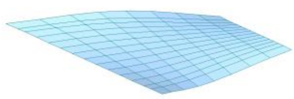
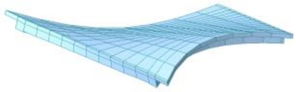
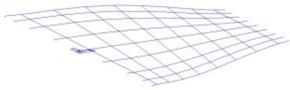
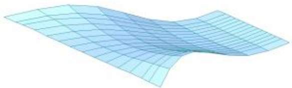
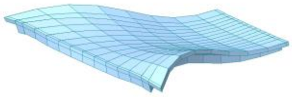


Figure 9 The schedule signal and spectrum analysis of irregular slab bridge in bump test

Table 4 The dynamic characteristics of irregular slab

	Finite Element Model	Mode shape	Theoretical frequency value
The second Order vibration	Grillage model		12.0Hz
	Shell Model		13.2Hz

	Solid Model		12.9Hz
The third Order vibration	Grillage model		16.2Hz
	Shell Model		25.7Hz
	Solid Model		26.6Hz

CONCLUSION

All the three calculation models can simulate mechanical characteristics and deformation conditions of irregular slab bridge under each working conditions well, and can also reflect the dynamic behaviors of the structure exact ly.

Under its self-weight, the irregular slab bridge is in biaxial stress state, the transverse bending moment, less than the longitudinal bending moment, but can't be neglected. An arrangement of longitudinal reinforcement is neces sary, and the arrangement of transverse reinforcement is also required.

Under lane load, whether symmetric load or eccentric load, the irregular slab is in biaxial stress state, so the reinf orcement should coincide with the mechanical characteristics. By calculation, longitudinal main steel bar is not o nly need to arrange, transverse reinforcement is also need to be arranged to bear the transverse bending moment generated by vehicle load.

The first order shape of the irregular slab is vertically symmetric and the shape obtained by three models are the same. The second order shape and the third order shape obtained from three different models are also the same, it can be found that all the models can reflect the dynamic characteristics well.

Under various working conditions, stress calculated by beam grid method is larger than the other models, it mean s that the reinforcement arranged as the results of beam grid model can be safer than the other computing models , and beam gird method is the most convenient method in fact.

REFERENCES

HAMBLYEC. (1982) "Performance of bridge superstructure", Beijing: People's Publishing House, 47—70.

Tong Yuesheng et al.,(1993) "Test research of reinforced concrete irregular slab", *Civil Engineering Journal*, (26):61—68.

Xia Gan et al., (1989) "The research for practical calculation method of irregular slab or class structure", *Journal of Southeast University*, (19): 61-68.