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The Open Construction and Building Technology Journal, **2013**, *7*, 1-7 **1**

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Design and Application of Hydraulic-Walking Incremental Launching Equipment

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Abstract: This work designs a novel hydraulic-walking incremental launching equipment. The working principle of the equipment is proposed. Considering that the contact in incremental launching construction is a typical elastic contact problem, and changes in contact state will directly affect the stability of the incremental launching, this work proposes the equilibrium equations of computational contact mechanics and numerical analysis method for the incremental launching equipment through analyzing the working process of the equipments. The proposed model and method are applied in the analysis of typical working conditions of the incremental launching of Donghua Bridge. The structural characteristics in the construction process are analyzed and discussed. The analysis results show that the strength and stability of the steel box girder can meet the construction requirements. The incremental launching of Donghua Bridge was completed successfully. The proposed model and method can be used to predict and analyze the structural performance in incremental launching construction as well as provide theoretical reference and analysis method for similar constructions.

Keywords: Incremental launching, contact mechanics, steel box girder, numerical analysis.

1. INTRODUCTION

Incremental launching method is widely applied in bridge construction. It is common to employ incremental launching method to construct continuous bridge when there are constraints of topography and geology as well as limitations of road alignment [1]. Incremental launching method can take advantage of structural piers, and does not need large-scale over-water hoisting equipment and constructing assembling support in water or closing the river. Steel box girder is manufactured at the construction site and the quality of welding and painting is easy to guarantee [2-4]. Incrementally launched bridges grant the owners lower first cost and maintenance cost than any other segmental concrete bridge construction method [5]. Therefore, incremental launching method is widely used in bridge construction.

Incremental launching is a building technique where large amount of prestressing is needed to avoid tensile stresses [6]. In incremental launching method, the bridge superstructure is assembled on one side of the obstacle to be crossed and then launched into its final position [7]. The stability and stress concentration of steel girders are more prominent than that exhibited by concrete girders during the launching because of their slender web plates and thin flange plates [8]. Therefore, incremental launching equipments are complex and delicate. They are subjected to huge loads on long spans, often the weight of an entire span [9, 10]. The incremental launching equipments and piers are subjected to a horizontal force in launching direction due to friction, which requires an appropriate design of the equipments. De spite of the wide application of the incremental launching method, little has been reported on the design and application of the incremental launching equipments.

This work presents a new design of incremental launching equipment. The working principle of the incremental launching equipment is proposed. A calculation model for the contact between the upper structure and lower structure of the equipment and the contact between the equipment and the steel box girder is built. The equipment and analysis method are applied in the incremental launching construction of Donghua Bridge in Guangdong Province, China. The analysis results are discussed to provide necessary information for the actual construction process.

2. WORKING PRINCIPLE OF THE INCREMENTAL LAUNCHING EQUIPMENT

2.1. The Incremental Launching Equipment and its Operation

Hydraulic-walking incremental launching equipment is designed in this work. The equipment consists of sliding structure, jacking cylinders, launching cylinders, and horizontal adjustment cylinders, as shown in Fig. (**1**). The equipment has the functions of jacking, translation and horizontal adjustment, and can perform the movement or adjustment along, vertical or transverse to the bridge, which can ensure a smooth process for the incremental launching construction. The maximum launching force of the equipment is 700kN, the maximum jacking force is 7000kN, and the maximum horizontal adjustment force is 700kN.

The hydraulic-walking incremental launching has the two alternating steps of “lift” and “push”. It holds up and pushes the steel box girder until the completion of a cylinder stroke, as shown in Fig. (**2**); then the steel box girder is placed on

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the temporary piers and the cylinders implement the next cycle. Through the cycle of “lift” and “push”, the steel box girder can be sent to desired location.

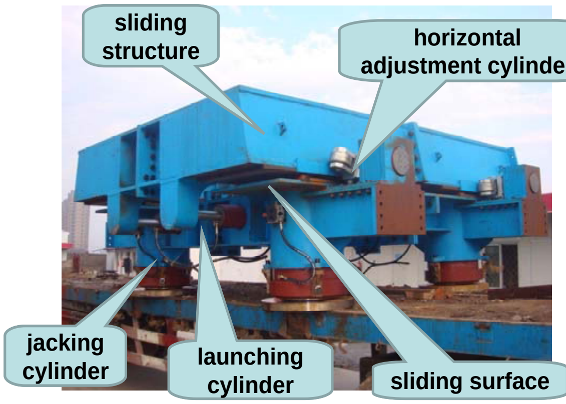


Fig. (1). The incremental launching equipment.

The steel box girder moves when:

$$\sum T_i \geq \sum \mu N_i \quad (1)$$

where T_i is the jacking force of the *i*th cylinder; μ is the static friction coefficient between the steel box girder and the incremental launching device; N_i is the reaction force of the *i*th temporary pier.

2.2. Contact Finite Element Model of the Incremental Launching Process

Incremental launching employs a sliding device composed by stainless steel and Teflon plate, and pushes the steel box girder by a jacking force. Because of the large weight of the steel box, there will be a large pressure applying on the contact interface of the incremental launching equipment and steel box girder, which may change the contact status. In the process of incremental launching, the sliding between the sliding structure and the equipment also influences the contact status, and will directly affect the stability of the construction. The contact in incremental launching is a typical elastic contact problem. The constitutive relation of the materials is linear and there exists non-linearity on the surface [11]. Therefore, studying the contact mechanics of the contact interface in incremental launching can evaluate the stress and equipment service condition [12], which can provide a theoretical guidance and reference to the engineering application of the incremental launching.

As shown in Fig. (**1**), there are two contact interfaces in the incremental launching process of the steel box girder: the contact interface between the equipment and steel box girder; the contact interface between the upper structure and the lower structure of the equipment. The contact is an elastic contact problem with surface nonlinearity. The nonlinearity includes the nonlinearity caused by changes in contact area, nonlinearity caused by changes in contact pressure distribution, and nonlinearity caused by friction.

For the upper structure (denoted by I) of the equipment and the steel box girder (denoted by II), the equilibrium equations of the two structures are:

$$[K_I]\{u_I\} = \{P_I\} + \{R_I\} \quad (2)$$

$$[K_{II}]\{u_{II}\} = \{P_{II}\} + \{R_{II}\} \quad (3)$$

where K_I and K_{II} are the global stiffness matrixes of structures I and II, respectively; u_I and u_{II} are the displacement vectors of structures I and II, respectively; P_I and P_{II} are the load vectors of structures I and II, respectively; R_I and R_{II} are the contact force vectors of structures I and II, respectively.

Eqns. 2 and 3 can be solved when the contact states are determined. The continuity equation of normal displacement on the contact interface is:

$$u_{Ij} - u_{IIj} + \varepsilon_{nj} = 0 \quad (4)$$

where ε_{nj} is the initial normal clearance of the *j*th contact point-pair; u_{Ij} and u_{IIj} normal displacements of the *j*th contact point-pair of structures I and II, respectively.

The continuity equation of tangential displacement on the contact interface is:

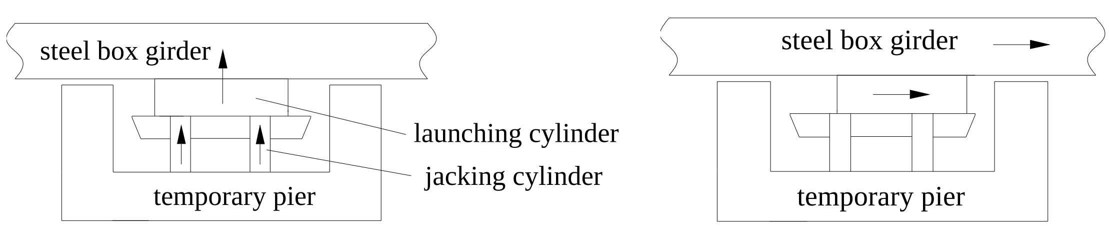
$$v_{Ij} - v_{IIj} + \varepsilon_{\tau j} = 0 \quad (5)$$

where $\varepsilon_{\tau j}$ is the initial tangential clearance of the *j*th contact point-pair; v_{Ij} and v_{Ij} are the tangential displacements of the *j*th contact point-pair of structures I and II, respectively.

The integration of surface pressure *p* is the total load *P* of the two contact objects [13]:

$$\int p(x)dx = P \quad (6)$$

The surface displacement of an arbitrary point on the contact interface is:



(a) The steel box girder is lifted (b) The steel box girder is moved

Fig. (2). Process of incremental launching.

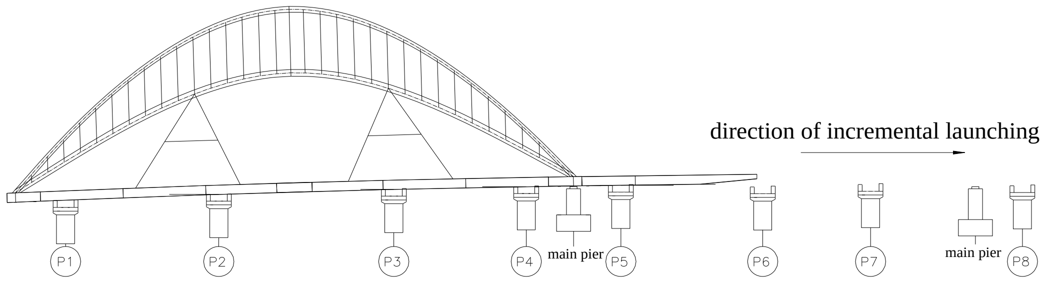


Fig. (3). Layout of the bridge and temporary piers.

$$u_k = \sum_{j=1}^{m} a_{kj} \cdot f_j \tag{7}$$

where a_{kj} is the displacement of node *k* under a unit force; f_j is the load of the node *j* on the contact interface; *m* is the nodes number.

Eqn. 7 can be re-written as:

$$\{u\} = [A]\{f\} \tag{8}$$

where $\{u\}$ is the displacement vector; $\{f\}$ is the load vector; *A* is the compliance matrix.

For the contact interface between the upper structure of the equipment and the steel box girder, the finite element equilibrium equation of I and II can be written as [14]:

$$\begin{bmatrix} K_I & 0 & K_{Ic} \\ 0 & K_{II} & K_{IIc} \\ K_{cI} & K_{cII} & K_{cc} \end{bmatrix} \begin{Bmatrix} \Delta u_I \\ \Delta u_{II} \\ \Delta R \end{Bmatrix} = \begin{Bmatrix} \Delta P_I \\ \Delta P_{II} \\ \delta_c \end{Bmatrix} \tag{9}$$

where K_I and K_{II} are the global stiffness matrixes of I and II, respectively; K_{Ic}, K_{IIc}, K_{cI}, K_{cII}, and K_{cc} are 3×3 matrixes composed by contact vectors, and the elements' values in the matrixes can be -1, 0 and 1, and are determined by the contact state; ΔR is the increments of equivalent nodal force of the contact point-pair; δ_c is the initial relative displacement; Δu_I and Δu_{II} are the displacement increments vectors of I and II, respectively; ΔP_I and ΔP_{II} are the load increments vectors of I and II, respectively.

The finite element equilibrium equation of the upper structure and lower structure is similar to Eqns. 1 to 9, and the elements' values are determined by contact state [15].

3. APPLICATION OF THE INCREMENTAL LAUNCHING EQUIPMENT

3.1. Introduction of the Construction

The incremental launching equipments are applied in the construction of Donghua Bridge in Jiangmen, Guangdong Province, China. The main bridge of the Donghua Bridge is a basket-type tied steel bridge with sub arch. The calculated span is 118m, and the bridge length is 119.3m. Each arch rib is composed by a main arch and a sub arch. The main arch is a concrete filled steel tube and the sub arch is a steel tub. A 3.9% symmetrical longitudinal slope on both sides is adopted. The top of the slope is located on the mid-span of the main bridge, and the radius of the vertical curve is 4000m. The theoretical span of the main arch and sub arch is 118m. Steel box section is used for the ties and there are two ties of the bridge.

Eight temporary piers are arranged in the incremental launching. A launching nose [16] and an A-shape support are assembled on the bridge, as shown in Fig. (**3**).

3.2. Analysis of Global Force State and Reaction Force of Temporary Piers

In the process of incremental launching, the main force of the temporary piers is a vertical reaction force which varies with the working conditions [17]. A working condition is set per 500mm sliding. The reaction forces of the temporary piers of each working condition are calculated. The vertical reaction force versus sliding distance is shown in Fig. (**4**).

As shown in Fig. (**4**), the reaction forces of the temporary piers P3 and P6 have a large change range, and the reaction forces other temporary piers have a small change range. The largest reaction force 6010kN appears on temporary pier P3 when the steel box girder detaches temporary pier P2. After detaching temporary pier P3, the changes of reaction forces of the temporary piers will be stabilized.

Due to the asynchrony and difference of the equipments as well as the friction effect during the incremental launching process, the temporary piers will bear horizontal force along the bridge. The maximum horizontal reaction force is 5% of the vertical reaction force in the calculation.

3.3. Contact Analysis of Incremental Launching

3.3.1. Working Conditions And Loads

From the global analysis, the maximum reaction force of the temporary piers is 6010kN. Therefore the maximum force of the incremental launching equipment is 6010kN, and the condition of maximum force is selected to analyze the stress state. Considering the cylinders' stroke, two typical working conditions are set: one is that cylinders' stroke is in the middle (case 1), and the other is that the cylinders' stroke is at one end (case 2).

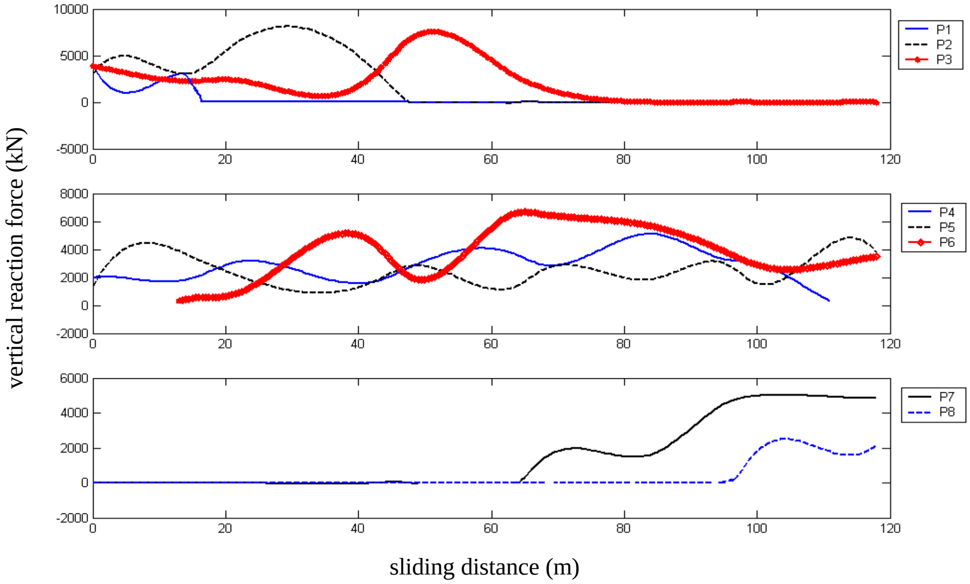
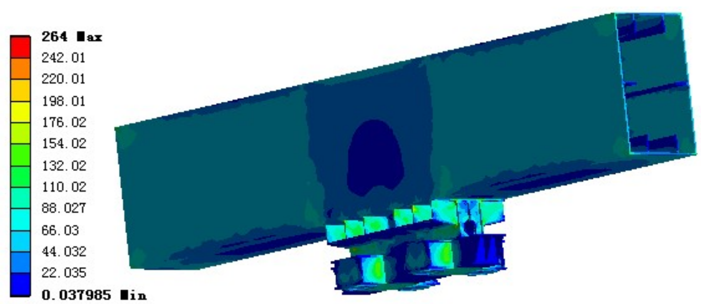
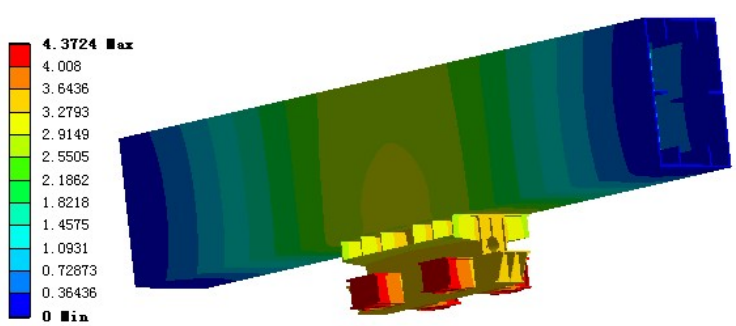


Fig. (4). Vertical reaction force in sliding process.



(a) Equivalent stress of the incremental launching equipment and steel box girder (MPa)



(b) Deformation of the incremental launching equipment and steel box girder (mm)

Fig. (5). Analysis results of case 1.

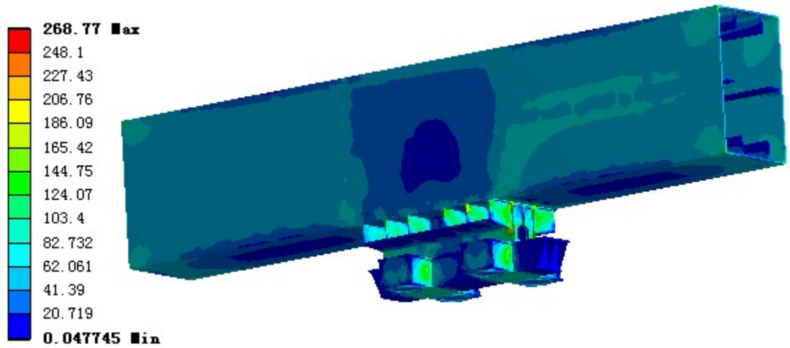
The stress state of the incremental launching equipment and steel box girder is analyzed by the contact mechanics method. The contact interfaces are the interface between the equipment and steel box girder as well as the interface between the upper structure and lower structure of the equipment. It is assumed that the contact interface is a continuous smooth surface and the surface friction effects satisfy the Coulomb law.

The models of the equipment and 1000mm long of the steel box girder are built. Four cylinders are loaded and the thrust of the cylinders is the maximum reaction force of the temporary piers, i.e., a vertical pressure 6010kN is applied to the cylinders surfaces. The dead weight of the structure and constraints of the steel box girder are also applied.

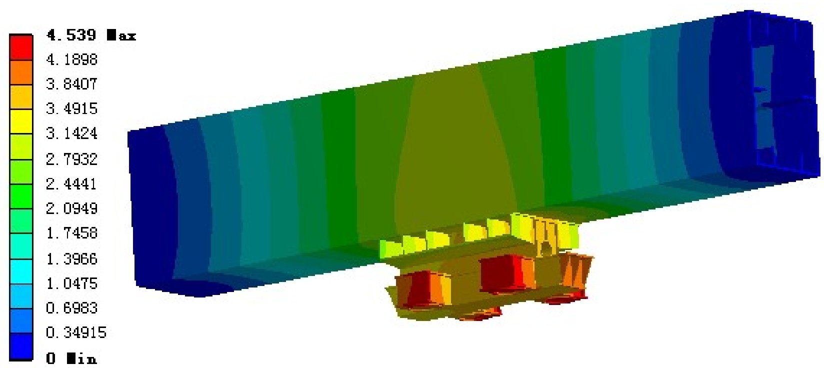
3.3.2. Results and Discussion

Through analysis to the typical working conditions, the equivalent stress and deformation of case 1 and 2 are shown in Figs. (**5** and **6**).

The equivalent stress is a physical quantity which is compared the composition of stress with the limit of yielding to measure the material's yielding state under the compli-



(a) Equivalent stress of the incremental launching equipment and steel box girder (MPa)



(b) Deformation of the incremental launching equipment and steel box girder (mm)

Fig. (6). Analysis results of case 2.

cated stress state. The materials will be in the plastics state when the equivalent stress is higher the yielding limit.

From the analysis results, some discussions are made as follows:

(1) The maximum equivalent stress of case 1 is 264MPa which centralizes in the marginal rib of the upper structure of the incremental launching equipment. The maximum deformation of case 1 is 4.4mm. The maximum equivalent stress of case 2 is 269MPa which centralizes in the marginal rib the upper structure of the incremental launching equipment. The maximum deformation of case 2 is 4.5mm.

(2) The maximum equivalent stresses of the two typical working conditions both appear on the marginal ribs of the upper structure of the equipment. The equivalent stress of the steel box girder is less than 100MPa and has a uniform distribution. The maximum deformation of the two typical working conditions both appear on lower structure of the equipment. The deformation of the steel box girder is less than 3.6mm. Therefore, the strength and stability of the structure can be assured.

(3) The contact stresses on the two interfaces are about 60MPa, and the contact stresses on the margins is a little larger than the ones in other area. The contact stresses have a uniform distribution.

(4) As the maximum equivalent stress appear on the marginal ribs of the upper structure of the equipment, a local reinforcement to the equipment can be made [18]. To increase the bearing capacity of the structure, it is recommended to improve construction method the decrease the reaction force of the temporary piers, and strengthen the structure to avoid stress concentration.

(5) The equivalent stress and deformation of case 1 and 2 has little difference and has the same distribution trend, which shows that the incremental launching equipment has little influence on the construction and the construction can have a continuous and stable state.

3.4. Incremental Launching of the Bridge

The steel box girder is assembled on the shore before incremental launching, as shown in Fig. (**7**). The incremental launching of Donghua bridge began on Dec. 9, 2011, and completed on Dec. 17, 2011. Ten incremental launching equipments were used. The maximum weight of the steel girder is 2600t, and the launching distance is 185m.

In the incremental launching process, the states of the launching cylinders, jacking cylinders, horizontal adjustment

Fig. (7). Assembled steel box girder.

cylinders, and steel box girder were measured by sensors. A travel sensor was used to measure the travel of the cylinders in 0-1000m, and the measurement error is 0.25mm. A pressure sensor with 5‰ measuring accuracy was used to measure the working pressure of the cylinders, and the cylinders' loads were reflected by the pressure sensor. An angle sensor with ±0.05° measuring accuracy was used to measure the girder's slope.

The steel girder and equipment in incremental launching are shown in Fig. (**8**). The completed Donghua bridge is shown in Fig. (**9**).

(a) The steel girder

(b) The incremental launching equipment

Fig. (8). Steel box girder and equipment in incremental launching.

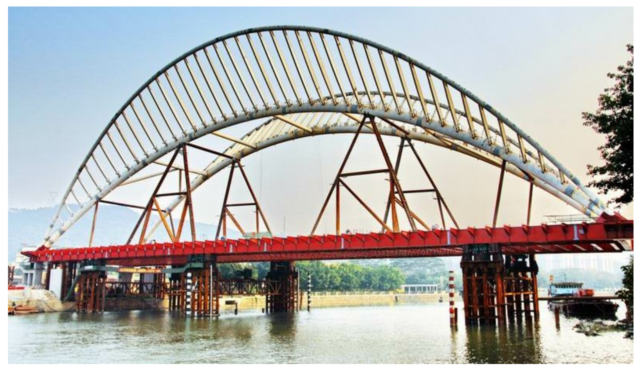


Fig. (9). Completed Donghua bridge.

4. CONCLUSIONS

This work designs a new hydraulic-walking incremental launching equipment and applies the equipment in the construction of Donghua Bridge in Jiangmen, Guangdong Prvince, China. The contact finite element model for the incremental launching is built. The equivalent stress and deformation of the incremental launching equipment and steel box girder in typical working conditions are studied, and the conclusions of this paper are as follows:

(1) The designed incremental launching equipment has the functions of lifting, translation and horizontal adjustment, and can perform the movement or adjustment along, vertical or transverse to the bridge, which ensures a smooth process for the incremental launching construction. The launching of Donghua Bridge was completed in 8 days.

(2) The computational model based on contact mechanics is built for the incremental launching construction of the steel box girder. The proposed numerical method can simulate the structural characteristics of the construction process, and can provide analysis method as well as theoretical reference for the construction.

(3) The typical working conditions of the incremental launching construction are calculated. The stress and deformation are analyzed. The results show that the incremental launching equipment and steel box girder can meet the requirements on strength and stability.

(4) Maximum stress centralizes on the marginal ribs of the upper structure of the equipment, and the deformation of the marginal ribs is larger than others ribs. Therefore, local reinforcement of the equipment can further improve the strength and load status of the equipment.

(5) Besides the incremental launching of Donghua Bridge, the incremental launching equipment and construction method are successfully applied in several bridges construction in China, and shows a good stability and convenience.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of the Fundamental Research Funds for the Central Universities, and the Scientific Research Foundation for Young Scholars of College of Mechanical Engineering at Tongji University.

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Received: September 14, 2012 Revised: October 18, 2012 Accepted: October 28, 2012