

Diaphragm Damage of Precast Concrete T-Shape Girder Bridge: Analysis and Strengthening

Yanwei Niu^{1,2,*}, Bangjun Liu³, Yu Zhao¹, Shuai Rong¹ and Pingming Huang⁴

¹School of Highway, Chang'an University, Xi'an, China

²Loess Region Key Laboratory of Transportation Ministry, Taiyuan, China

³TYLI Engineering Consulting

⁴Middle of South 2nd Ring Road, Xi'an, 710064, China

Abstract: For advantage of economical and practical construction, precast T-shape girder bridge is commonly used in China. In recent years, damage of diaphragm became a serious problem in operation and maintenance. In this study, based on finite element (FE) analysis of an actual bridge, stress distribution and failure process of diaphragm is demonstrated. The result shows that the stress of middle diaphragms started to beyond the limit firstly, under heavy load of 1.5 times equivalent Grade highway-I live load. Then, method of Double-K brace to strengthen the transversal connection of the exist bridges is proposed and applied on background bridge. Based on the field test, tensile stress of diaphragms concrete reduced 69.4% when Double-K brace were adopted, and the lateral integrity of precast T-beam bridge could be improved effectively.

Keywords: Concrete bridge, T-shape girder, diaphragm, damage, strengthening.

1. INTRODUCTION

Precast continuous bridge has the advantages of constructs conveniently and low cost, thus become one of the dominant bridge types for medium and small span bridges in China. As a main connection component along transverse direction, diaphragms connect girders as an integrity to bear horizontal forces and live load. In recent years, damage of diaphragms arise gradually, sometimes even cause collapse[1]. Many bridges need further inspection and rehabilitation [2~3]. LIANG concluded the stress of diaphragm in the midspan is the most unfavorable [4]. PENG studied the diaphragms stress after pasting steel plate based on FE analysis [5]. And lateral prestress tendon was used to ameliorate the stress of diaphragm [6]. For highway under heavy vehicle load, the process of diaphragm damage needs further study. The research background of this study is highway from Yang-quan to Zuo-quan in Shanxi Province, with heavy coal transportation. A three-span continuous precast T-Shape girder bridge is simulated by FE model to illustrate the damage process and failure of diaphragms under different grade of live load. After comparison, a strengthening method by spacial double-K shape brace is proposed and applied to enhance the transverse connection and decrease the tensile stress of existing diaphragms.

2. STRESS ANALYSIS OF DIAPHRAGM DAMAGE

2.1. Background Bridge

The span length of background bridge is 40m, composed of 5 T-Shape precast prestressed concrete girder, with 7 diaphragms along longitudinal direction: 2 end diaphragms and 5 middle diaphragms. The height of main girder is 2.5m and 1.7m width of top flange (Fig. 1) with 70cm width cast-in-place joints. The thickness of diaphragm is 20cm in mid-span diaphragms and 60cm near the bearings. Overload trucks go through the bridge is relatively common during daily operation. To void crack appearance in the diaphragms is of great caution to stakeholder.

2.2. Damage Process

Live load of Chinese Code [7] is combination of a uniform distribution load and concentrate load. In order to compared the results of FE method with truck load in daily operation, Code load is transformed to several concentrate load with equivalent internal forces: sagging moment of mid-span keeps constant before and after the conversion. The vehicle load contains 2 trucks: 12 concentrated forces in total, and the rear axle loads are 250kN, the front axle loads are 125kN. Adopting 4 load cases to observe the stress process of diaphragms with the increasing load, which is dead load (DL) plus live load to 2 times of Grade Highway-I live load (LL) of Chinese Code.

With the truck load increasing, the diaphragms of mid-span is most sensitive. Under "dead load+live load", the

*Address correspondence to this author at the School of Highway, Chang'an University, Xi'an, China; Tel: +86-(029)-82336336; E-mail: niuyanwei@chd.edu.cn

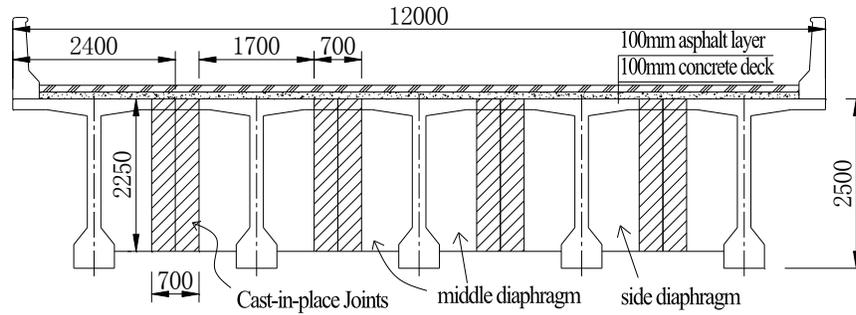


Fig. (1). Cross-section of background bridge.

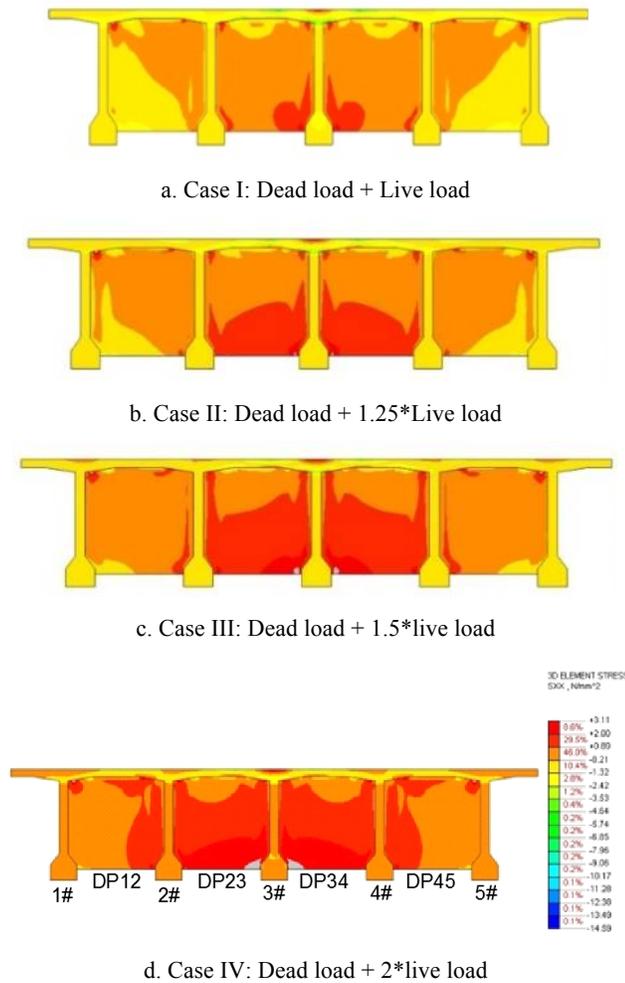


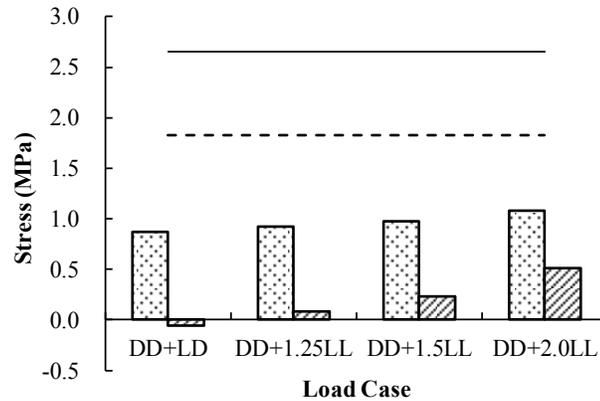
Fig. (2). Stress of concrete under different live load intensity.

upper fiber of side diaphragm (DP12 and DP45 in Fig. 2) was tensile, bottom fiber of side diaphragms was compressed; while both upper and bottom fiber of middle diaphragms (DP23 and DP34) were tensile. The maximum tension stress was 1.07MPa, near the lower part of T-Shape girder.

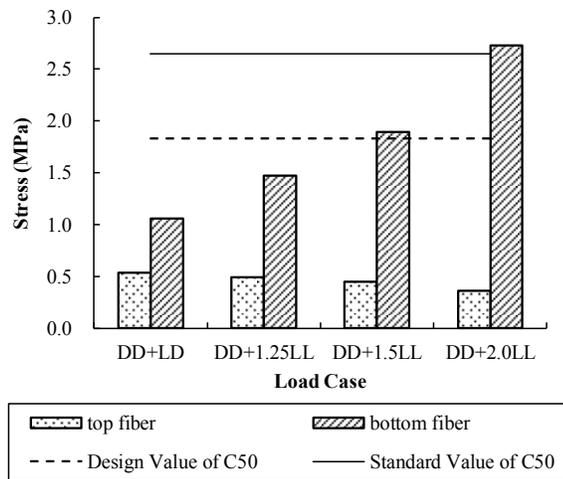
Under “1.25*live load”, the stress side diaphragms changes a little, and the bottom fiber of becomes tensile, the tension stress is 0.085MPa. While the tension stress of bot-

tom fiber of middle diaphragms increased to 1.475MPa, which is greater than design value of concrete (C50) tension strength. Concrete near the lower part of T-shape girder begin to crack.

Under “1.5*live load”, tension stress of all bottom part of middle diaphragms increased to 1.893MPa; cracks between middle diaphragms and T-Shape girder keeps extending upward.



a. side diaphragm



b. middle diaphragm

Fig. (3). Concrete stress of mid-span diaphragm under different live load.

When live load attend “2*live load”, the stress of middle diaphragms totally over tension strength of concrete, and the middle diaphragms crack and damage.

To sum up, with the increasing of truck load, damage of precast continuous T-shape girder bridge started from zones between middle diaphragms and lower part of T-shape girder, and keep extending upward. Until the upper fiber of middle diaphragms totally craked, the diaphragms was damaged (Fig. 3), and the integrity of the bridge dropped sharply.

3. TRANSVERSE STRENGTHENING OF PRECAST T-SHAPE GIRDER BRIDGE

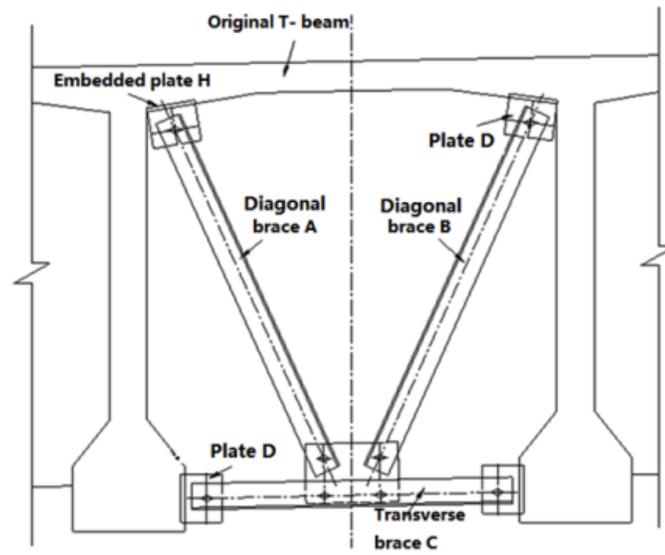
Based on the damage process of diaphragms, spacial steel braces were adopted to behave together with concrete diaphragms. There are 3 kinds of space braces considered: straight brace, cross brace and K brace. As shown in Fig. (4), in both lateral and vertical direction K-shape brace was used

to form a reliable and integrate structure, so it is named for “spacial double-K brace”. The eccentric distance of space straight brace is small, so the efficiency is smaller than cross brace and K-shape brace. Further more, the installation and welding of space double-K brace is more convenient than cross brace, so finally spacial double-K brace was adopted. For construction convenient, spacial braces were set at the 1/3L and 2/3L (Fig. 5) span of backgroud bridge.

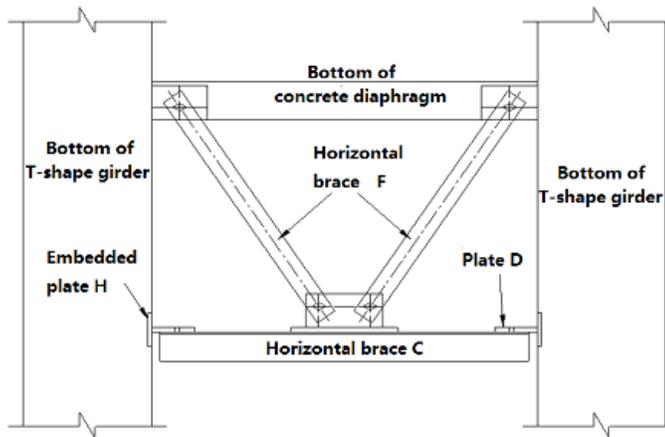
3.1. Fabrication and Installation of Double-K Brace

The embedded members were made of Q235 steel, and welded to the bars of main girder in advance, then connected with diagonal braces, tranverse braces and horizontal braces through high-strength bolts and steel plates into integrity.

Size of members was shown in Table 1, and all the angle steels and steel plates were sand-blasted and anti-rusted before installed.



a. elevation



b. plan

Fig. (4). Design of spacial Double-K shape brace.



a. Install of diagonal brace

Fig. (5). Contd...



b. Install of transverse brace



c. Final horizontal brace install

Fig. (5). Install of double-K brace.

Table 1. Member size of double-K brace.

Member	Size(mm)
diagonal brace A, B	L140×10
transverse brace C	L140×10
horizontal brace F	100×1263×10
Bolts	M20

To install the double-K brace, the diagonal brace is connect to embeded plate of flange first, then install central connection plate and transverse brace. Finally, lateral braces installed to connect original concrete diaphragm. Process of installation is shown in Fig. (5).

3.2. FE Analysis of Strengthening Method

FE solid model was adopted to analyze the stress of T-shape girder diaphragms with and without spacial braces, to

study the structural performance improvement. FE solid model contains 125067 elements. Prestressing tendon and wild reinforcement were simulated by truss elements, and the connection between bars and concrete were simulated by interface elements. Spacial double-K braces were simulated by solid elements (part of model is shown in Fig. 6).

To attain the worst condition, vehicle is load at the section 16m (about 0.4L) away from the expansion joint of side span abutment. As shown in Fig. (7), four trucks with net

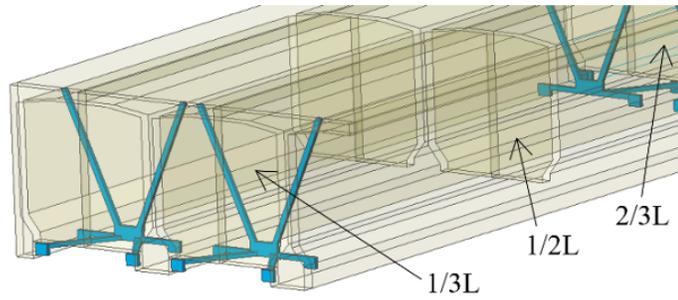
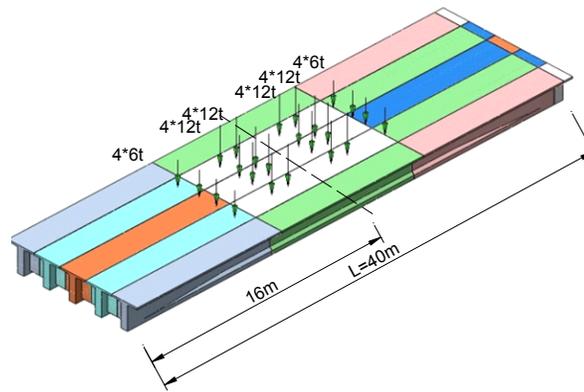
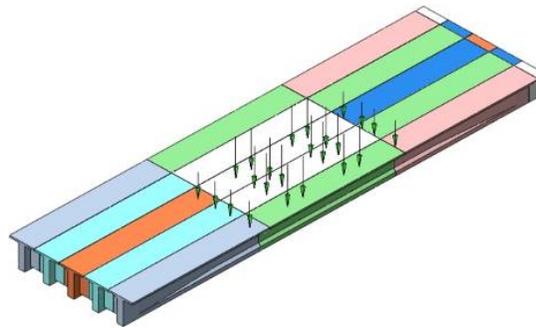


Fig. (6). FE model of bridge with double-K brace (partial view).



a. Axis load



b. Eccentric load

Fig. (7). FE model under test truck load.

weight 30t each is loading at both axis and eccentric from the bridge central line.

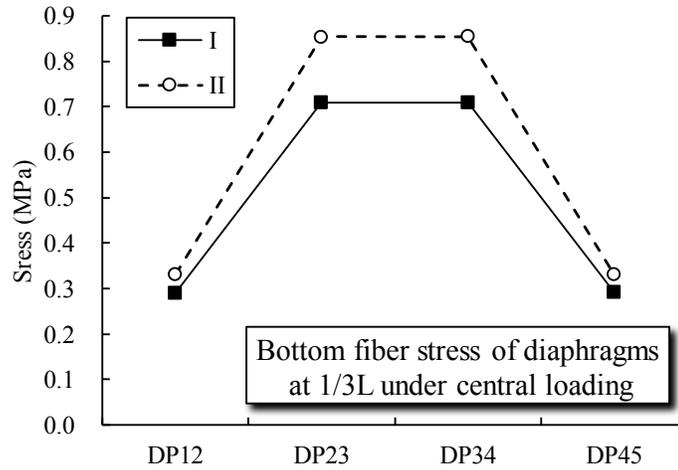
There are 4 load case considered as shown in following table:

As Fig. (8) shown, with spacial double-K braces strengthening, the tension stress of bottom fiber of diaphragms at 1/3L span reduced by 17.1% under symmetric loading and 19.6% under eccentric loading. And the maximum tension stress of bottom fiber of diaphragms at mid-span (1/2L) decreased by 8.3%, and 6.9% under eccentric loading. For stress of double-K braces, the maximum of was

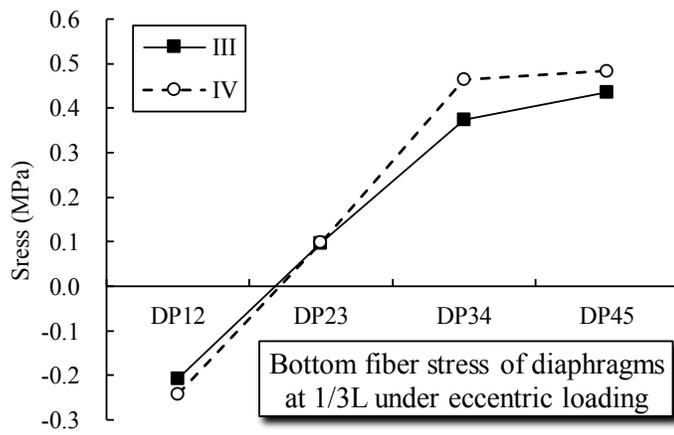
about 8.95MPa under symmetric loading and 7.66MPa under eccentric loading.

3.3. Experiment of Background Bridge

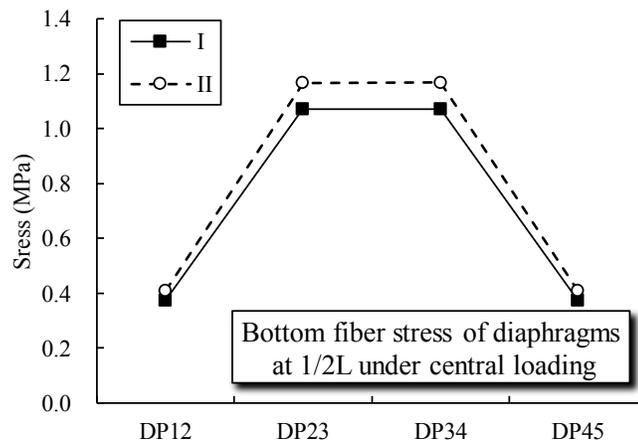
For different driving direction, background includes two separate bridges: Right-bridge from Yang Quan city to Zuo Quan county and Left-bridge along the opposite direction. To verify the strengthening effect, double-K baces were installed on the right-bridge and left-bridge keeps the original design (Fig. 9). The truck load and postion is accordance to above load case I to IV in Table 2. Strain gauges were set at



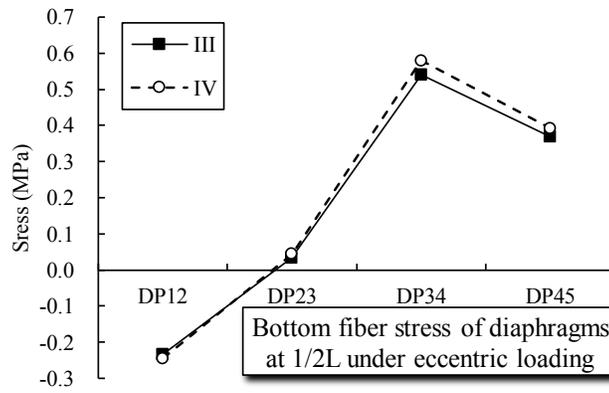
a. Diaphragms at 1/3L under central loading



b. Diaphragms at 1/3L under eccentric loading



c. Diaphragms at 1/2L under axis loading



d. Diaphragms at 1/2L under eccentric loading

Fig. (8). Stress comparison of bottom fiber of diaphragms by FE.



Fig. (9). Field test of background bridge.

Table 2. Load case of background bridge.

Case No.	Load Location	With or without double-K brace
I	axis load	with
II	axis load	without
III	eccentric load	with
IV	eccentric load	without

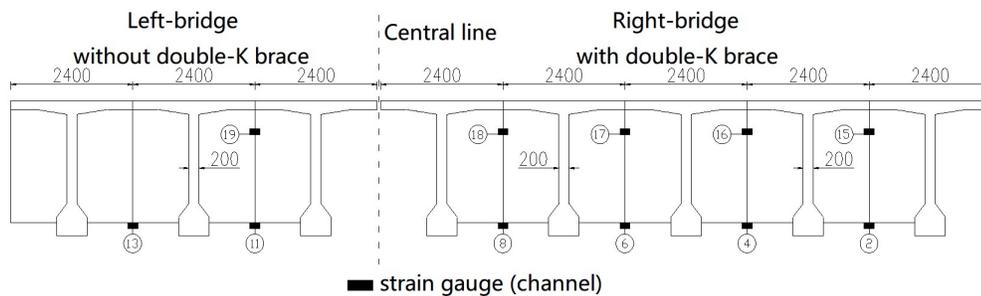
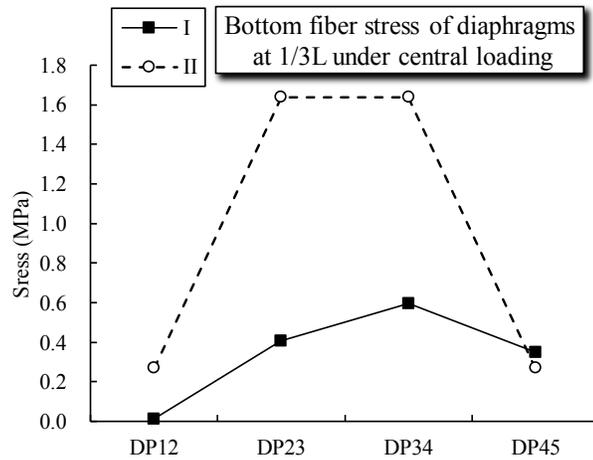
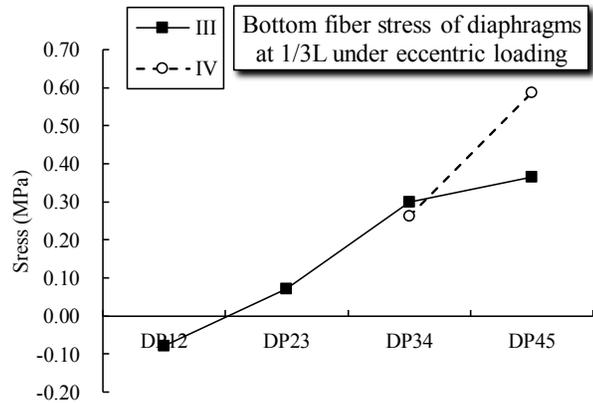


Fig. (10). Strain gauge displacement in the 1/3L diaphragms.



a. Diaphragms at 1/3L under axis loading



b. Diaphragms at 1/3L under eccentric loading

Fig. (11). Stress comparison of diaphragms by field test.

the 1/3L diaphragms to test the stress distribution along the transverse direction. For steep terrain below the left-bridge, stress gauges were only set on the two diaphragms near the central line (Fig. 10). For the data of DP12 and DP23 in Fig. (11a) is obtained by mirroring from DP34 and DP 45 where stress gauges were set.

Result of the field test shows, under axis load case I and II, tension stress of diaphragms in right-bridge was obviously decreased compared to the right-bridge; tension stress of side diaphragms was relatively small, which was about 0.1MPa. And for middle diaphragms (DF23, DF34), tension stress decreased from 1.64MPa to 0.5MPa, reduced by 69.4%.

Under eccentric loading case III and IV, stress of bottom is not as significant as axis load case; for side diaphragm DP45, stress of right-bridge is smaller than left-bridge either. The result of DP34 is close, response of both bridges is relatively small.

CONCLUSION

To analyze the damage mechanism, stress under heavy load and strengthening method of diaphragms of T-shape

multi-girder bridges is discussed in this studied, main conclusion remarks are as follow:

1. With the increasing of truck load, the tension stress of the zones between middle diaphragms and lower part of T-shape girder first beyonds the design value of concrete tension strength, and the cracks appears. The stress of bottom fiber of middle diaphragms increases and the cracks between middle diaphragms and lower part of T-shape girder extends upward.

2. Based on FE analysis, the stress of bottom fiber of middle diaphragms would exceed the design value of concrete tension strength when truck load over 1.5 times of Code value. When the live load increased to 2 times Code value, middle diaphragms would totally crack and the bridge integrity drops sharply.

3. After the spacial double-K braces were set, the stress of critical part of diaphragms decreases significantly. FE analysis shows that with spacial braces, the maximum tension stress of bottom fiber of diaphragms at 1/3L span reduced by 17.1% under central load and reduced by 8.3% for diaphragms at mid-span. Under eccentric loading, the maximum tension stress of bottom fiber of diaphragms at 1/3L

span decreased by 19.6% with space braces and reduced by 6.9% for mid-span diaphragms.

4. Field load test shows tension stress of middle diaphragms at the 1/3L reduced by 69.4% in axis loading case. For side diaphragms under eccentric loading stress is smaller either. Strengthening method proposed is effective and practical, and can be referenced for similar bridges especially under heavy operation loads.

CONFLICT OF INTEREST

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

ACKNOWLEDGEMENTS

The authors would like to gratefully acknowledge the support from National Natural Science Foundation of PR China (51208056), Foundation of Loess Region Key Laboratory of Transportation Ministry (KLTLR-Y12-7) and Shanxi

Transportation Science and Technology Foundation (11-2-24).

REFERENCES

- [1] <http://news.163.com/11/0715/07/7902IAMU0001124J.html> 2011.
- [2] Y. Liu, S.F.Ma, C.X.Zhang, "Internal force effect of T-shape girder bridge transverse diaphragm damage on whole bridge," *Transportation Science & Technology*, vol. 4, pp. 38-40, 2012.
- [3] F.Li, X.L.Tang, and Y.Xu, "Research of concrete T-shape girder bridge lateral connection strengthening methods," In:*Proceeding of Evaluation and Strengthening of Existing bridges*, Nanjing, China, pp. 91-95. 2008.
- [4] Z.G.Liang, Y.Zhang, and J.L.Liu, "Damage and strengthening methods of precast T-shape diaphragms," *China Municipal Engineering*, vol. 5, pp. 92-93, 2007.
- [5] B.Peng, and J.Du, "Submodel method application in reinforcing cross beam of bridge," *Journal of Guizhou University of Technology (Natural Science Edition)*, vol. 3, pp. 67-70, 2007.
- [6] D.X.Ye, H.J.Yan, Slide bar application in precast T-shape girder diaphragms strengthening, *Engineering and Construction*, 24(6), 790-791 826 (2010).
- [7] Ministry of Communication of China; General Code for Design of Highway Bridges and Culverts (JTG D60- 2004), China Communication Press; Beijing (2004).

Received: September 16, 2014

Revised: December 23, 2014

Accepted: December 31, 2014

© Niu *et al.*; Licensee Bentham Open.

This is an open access article licensed under the terms of the Creative Commons Attribution Non-Commercial License (<http://creativecommons.org/licenses/by-nc/3.0/>) which permits unrestricted, non-commercial use, distribution and reproduction in any medium, provided the work is properly cited.