11 WCEE
Paper No. 118. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

SEISMIC BEHAVIOR OF DIAPHRAGMS IN RC BRIDGES

Xi ZHU, Xingchong CHEN, and Zhijian RONG

Civil Engineering Department, Northern Jiaotong University, Beijing, China

ABSTRACT

The Failure of diaphragms will weaken the transverse stiffness and stability of the main-girders and will influence the normal function of bridges. A 3-D model including piers,girders and diaphragms is adopted in this paper to calculate the seismic response of the diaphragms. On the basis of linear results, a simple local elasto-plastic analysis model is presented to predict the seismic behavior of diaphragms after yielding.The calculating results match a virtual damage in the 1975 Haicheng earthquake.

KEYWORDS

Diaphragm; concrete; bridge; seismic response; elasto-plastic; interaction; resonance.

INTRODUCTION

In virtually major earthquake damage reports, there are ample examples of damage or failure of the reinforced concrete girder bridges. In the case of the 1975 Haicheng earthquake, China, for example, 84% of the railway bridges in the western region were damaged and in the 1976 Tangshan earthquake, China, 40% of the railway bridges in the region were severely damaged [1][2]. Many of the bridge's failures took place in the foundations or in the substructures while light damage occurred in the superstructures except for girder diaphragms and bearings. In the separated twin T-girders, the cracking and failure were extensive damage phenomena. A typical cracking damage of all nine diaphragms in certain girder is shown in Fig.1.

The failure of diaphragms will weaken the transverse stiffness and stability of the main-girders and will influence the normal function of bridges. This problem has been noticed by engineers. However, this kind of diaphragm is not improved since the seismic mechanism of diaphragms is not clear yet. The object of this paper is to discuss the seismic response and seismic mechanism of the diaphragms as well as to explain the cracking phenomena so as to provide a theoretical evidence for the earthquake design of the diaphragms.

ANALYTICAL METHODS

The deformation of diaphragms is very complicated during earthquakes.The behavior of diaphragms neither as beams nor slabs,probably in triaxial stress states.Restricted for memory and velocity of micro-computers,it is difficult to build a precise model for the diaphragm.In order to study the seismic behavior of diaphragms,a 3-D model of simply supported RC girder bridges including piers and girders was selected. The piers, bearings, girders and diaphragms are simulated as 3-D beam elements. The feasibility of this model is supported by a model test[3].

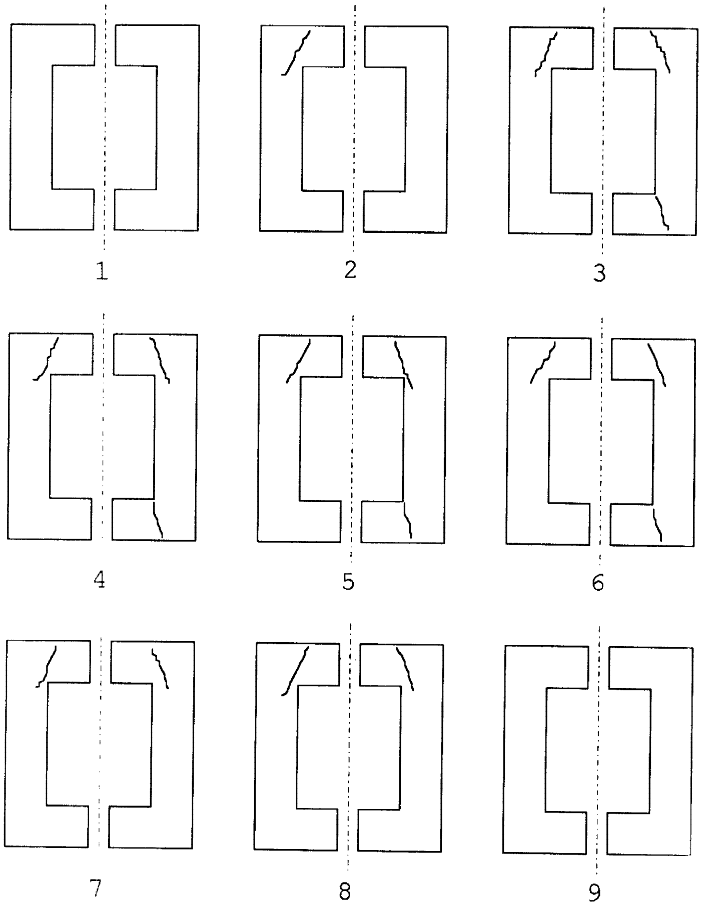

Fig.1. Typical cracking of diaphragms

The response spectrum method and the direct integration method are used to calculate the elastic seismic responses of diaphragms. The results indicate that the internal forces and deformations of diaphragms are controlled by the transverse bending vibration of the girders, and that partial diaphragms reach plasticity while the piers and girders are still in elasticity when the earthquake intensity is 7 degrees. Thus, during the further study, the diaphragms are simulated as plane elasto-plastic bending elements. The acceleration records of 1940 El Centro are adopted and are adjusted according to practical site condition and intensity. In the elasto-plastic seismic response analysis, we mainly discuss the position of plastic hinges and the yielding sequence during time history.

EXAMPLE ANALYSIS

Description of the Structure

An example bridge used herein which was located in Haicheng earthquake region was a simply supported reinforced concrete girder bridge with 16×31.7m spans. The virtual earthquake intensity was among 7 and 8 degrees. One span girder in this study (see Fig.2) is considered only. Each diaphragm in the separated twin T-girder is divided into two beam elements, which are connected to the main-girder nodes by rigid arms(shown in Fig.3). The selected heights of piers vary from 8m to 32m so as to find out the effect of piers on the seismic response of diaphragms.

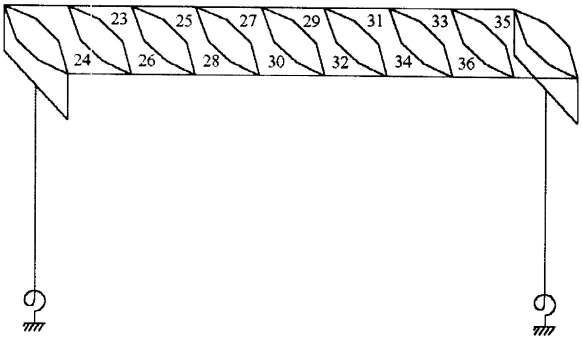

Fig.2. Discrete sketch

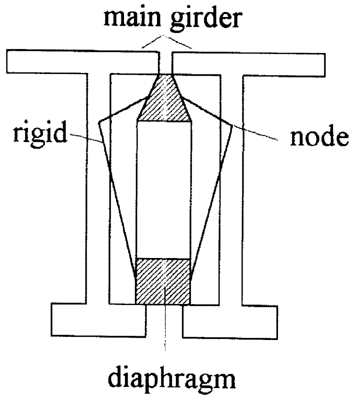

Fig.3. Beam element of a diaphragm

Linear Seismic Response

The liner analysis is performed first in order to find out the effect of piers on the seismic response of diaphragms. By using the Subspace Iteration Method to solve eigenproblems, the free vibration characteristics for two cases (the height of piers equals 8m and 32m) are calculated respectively. The shapes of first 10 modes are shown in Fig.4. In order to explain the effect of pier-girder interaction, the first natural frequencies of single-pier and single-girder are also calculated.Table 1 gives a list of the fundamental natural frequencies of the pier and the girder. The stress values at 1/4 span for different heights of piers are listed in Table 2 and the end moments of different diaphragms are listed in Table 3. The calculating results indicate as follows:

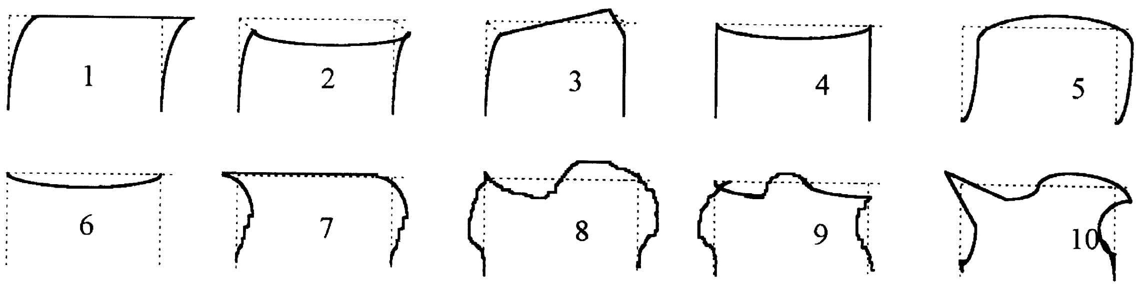

Fig. 4. First 10 mode shapes

Table 1. First frequency (rad/s)

single pier (h=32m)	single pier (h=8m)	single girder
6.4	22.4	22.1

Table 2. Elastic stresses of the diaphragm at 1/4 span (kPa)

element No.	single girder	girder-pier (h=32m)	girder-pier (h=8m)
25	18640	19840	38360
26	4980	5130	10000

Table 3. End bending moments of diaphragms (kN.m)

element No.	elastic (7 deg.)	elasto-plastic (7 deg.)	elasto-plastic (8 deg.)
23	31.4	yield	yield
24	8.0	8.6	18.8
25	33.5	yield	yield
26	8.7	9.1	21.8
27	19.1	20.6	yield
28	5.1	5.3	12.9
29	7.5	9.3	yield
30	1.4	1.9	13.8

The effects of piers on the internal force diaphragms mainly occur in the transverse vibration. By examining the modal responses, we know that the response of the bridge mainly depends on the fundamental modal vibration. For the system with high piers (h=32m), the first natural frequency of the pier is far away from that of the main-girder and the pier-girder interaction is weak. The responses of the girder and the diaphragms mainly depend on the dynamic property of piers. Whereas for the system with low piers (h=8m), the first natural frequency of the pier is close to that of the main-girder; and the forces of diaphragms reach their maximum, that is to say, the 'resonance-like' occurs. The mechanism of the amplification effect of the piers to the diaphragms can be explained as follows. The complex excitation waves inputted to the bottom of piers can be resolved into a combination of kinds of harmonic component. However, owing to the filtering action of piers, the distinguished period of acceleration responses in the pier top in transverse is nearly equal to the first natural period of the pier in transverse(see Fig.5). The vibration period of the girder is then in accordance with the vibration period of the pier. So for the system with h=32m, the girder will obtain an acceleration excitation whose period is far away from its first natural period and its amplification ratio is small. However, for the system with h=8m, the girder will obtain an excitation whose period is close to its first natural period. As a result, the amplification ratio is large obviously. This phenomenon is called 'resonance-like' in this paper and it should be avoided in design.

In brief, the seismic response of diaphragms is not only relevant to the dynamic property of girders but also to the dynamic property of substructures. So, the effect of the pier-girder interaction should be considered while calculating the seismic response of diaphragms.

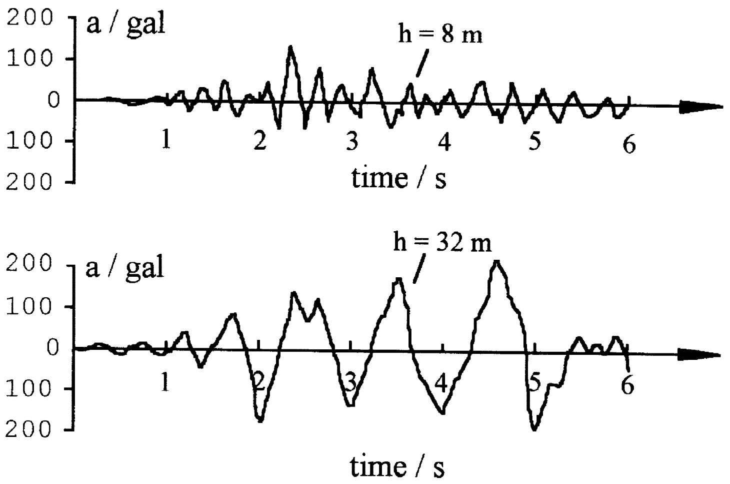

Fig. 5. Acceleration history at the pier top

From Table 3, It implies that, when the earthquake intensity is 7 degrees, those diaphragms at 1/4 and 1/8 span will yield and the dynamic property and the stress distribution of diaphragms will change after yielding. Therefore, in order to predict the behavior of diaphragms after yielding, an elasto-plastic seismic analysis must be performed.

Elasto-Plastic Seismic Response

The results of the linear analysis indicate that the deformations of diaphragms are caused mainly by the transverse bending vibration of main-girders. In addition, the torsional vibration of main-girders will produce the deformation of diaphragms as well. However compared with the transverse bending vibration, the torsional deformation is too small to be considered. So in the elasto-plastic analysis, the single bending vibration in horizontal plane is only considered. The elasto-plastic hysteretic model used in this paper is shown in Fig. 6.

From Table 3, it indicates that, the yield of the diaphragms will result in increasing the internal force of other diaphragms. Studying the yield time of diaphragms, we know that the yield occurs at different time. The yielding sequences of diaphragms in succession of time are shown in Fig.7.

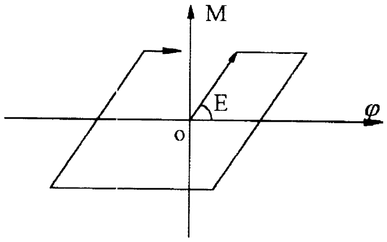

Fig.6 Elasto-plastic behavior

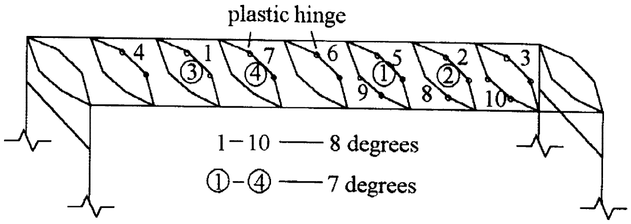

Fig.7 Yield sequence

According to the results of the linear analysis, the stress in the bottom of diaphragms at mid-span is less than the cracking bending moment (5.1 kN.m). The results of the elasto-plastic analysis show that all diaphragms except for the two end diaphragms will crack when the earthquake intensity reaches 8 degrees. So, the elasto-plastic analysis can predict more cracked diaphragms than the linear analysis.

In elasto-plastic response analysis, on the condition that height of pier H=32m, and in the following cases: case 1, the earthquake intensity is 7 degrees (According to Chinese Code for A seismic design of railway engineering), and case2, the earthquake intensity is 8 degrees. The maximum stresses at element notes are given in Table 4. In order to compare with the linear results, the linear stress are also given in this table and remarked with case 3 and case 4. The case 4 represents the condition that H=32m, no diaphragm in the main girder, it is considered as extreme condition.

Table 4. Elasto-plastic stresses (× 10 2 kPa)

No.	Elastic(7 deg.)	Elasto-plastic(8 deg.)	No diaphragm
3	24.9	47.7	35.4
7	6.2	25.3	12.5
11	19.2	54.1	30.0
25	198.4	yield	/
26	51.3	129.3	/

The maximum bending stress will occur at the ends of diaphragm elements. the cracking moment of the diaphragms is

$$Mc=W \cdot \sigma_C$$

where, W=cross-section resistance moment, σ_C = the cracking stress of the concrete
In this example, the crackings moment of the diaphragms is 5.1KN.m. The partial moments of diaphragms are given in Table 3.

Compared with a Virtual Damage

The virtual damage report shows that the cracking of diaphragms has certain randomness and that there are different cracked quantities in different girders (see Fig.1). But the statistical results show that all positions of diaphragms cracked in different girders. So, Statistically speaking, we conclude that the results of the elasto-plastic analysis are more appropriate to the virtual damage.

CONCLUSIONS

The seismic behavior of the diaphragms is exposed by a 3-D model of simply supported RC girder bridges. The relation between the responses of diaphragms and the dynamic properties of piers is obtained. And the results indicate that the 'resonance-like' will occur when the first natural frequency of piers is close to that of main-girders. The feasibility of the calculating model is supported by a model test as well as the practical earthquake damage. The cracking position of diaphragms and the yielding sequence during time history are gained by an elasto-plastic seismic analysis. The results match the damage of diaphragms in the 1975 Haicheng earthquake.

REFERENCES

Huixian liu, (1986). Damages of the Tangshan Earthquake, 3,30-66, Earthquake Publisher, China.

Institute of Engineering Mechanics, China Academy of Science,(1979). Damages of the Haicheng Earthquake, 227-232, Earthquake Publisher, China.

Xi Zhu and Xingchong Chen,(1987). Spatial Seismic Response Analysis and Test of A Simply Supported Reinforced Concrete Girder Bridge, Proceedings of National Earthquake Engineering Conference, 1,2, 387-390.