The 2013 World Congress on
Advances in Structural Engineering and Mechanics (ASEM13)
Jeju, Korea, September 8-12, 2013

Investigation of the validity of the shock absorber using laminated fiber reinforced rubber for the PC girder bridge

*Tomohisa Hamamoto[1], Toshitaka Yamao [2] and Takuro Moriyama [3]

[1] *Pacific Consultants Co., Ltd., Fukuoka, Japan*
[1] *hamatomoeng@gmail.com.*
[2] *Department of Civil and Environmental Engineering, Kumamoto University, Kumamoto, Japan* [2] tyamao@kumamoto-u.ac.jp
[3] *Department of Civil Engineering, Kisarazu National College of Technology, Chiba, Japan* [3] *takuro*@c.kisarazu.ac.jp

ABSTRACT

This paper presents the results of the damage assessment by the dynamic response analysis of a PC box girder bridge with two spans. The effects of the gap size and the shock absorber with laminated fiber reinforced rubber or 50-hardness rubber on the damage of the end of PC bridge girder and the base of pier were examined. The index of damage evaluation level at the end of girder and at the base of pier was used the results of the impact analysis and of the quasi-static cyclic loading experiments on actual scale RC bridge piers. From numerical results, it is clarified that the use of the shock absorber with laminated fiber reinforced rubber in the end of the girder is effective to reduce the damage by the collision at the end of girder.

1. INTRODUCTION

In order to reduce the impact force by the ground motion, JRA (2002) has recommended the use of the rubber shock absorber as the unseating prevention system after 1995 Hyogo-ken Nanbu earthquake. As the function of the rubber shock absorber, both a smaller rigidity to reduce the impact force and a high rigidity and deformation performance to be able to absorb the energy are required. That is, the shock absorber with the laminated fiber reinforced rubber (Poly Rubber Fiber structure) was adopted to solve this problem. Poly Rubber Fiber structure in previous work by Nishimoto *et al.* (2005, 2006) (which was mixed fibers in the rubber can be expected the effectiveness of the shock absorber than the 50-hardness rubber (50Hs). On the other hand, the seismic design of the PC (Post-tensioning Concrete) girder bridge with multi-spans by Japanese Specifications of Highway Bridges is demand to take a large gap size between two adjacent girders or the girder and the abutment. Hence, the occurrence of the girder end collision or the collision between bridge girder and abutment is expected to prevent in Level 2 ground motion.

---

[1] Engineer
[2] Professor
[3] Associate Professor

If a large gap size between the girder and the abutment is adopted, relatively large expansion joints have to use, and the construction and seismic reinforcement costs will increase. Furthermore, girders falling are presumed in strong earthquake. However, if the displacement of girder bridges by allowing the girder collision at the abutment is able to restrict, it is possible to reduce the size of expansion joints and to prevent the girder falling. That is, the seismic design cost and seismic reinforcement cost will be capable to reduce. Though a lot of studies on the effect of the collision have been published, few studies have been carried out the effect of the displacement restriction of girders by allowing the girder collision at the abutment on the seismic design of girder bridges in previous work by Otsuka *et al*. (2002); Moriyama *et al.* (2005, 2009); Hamamoto *et al.* (2006, 2011). So, it is possible to shrink expansion joint or bearing in design to reduce the gap size of girder by allowing the collision of girder. Therefore, it is considered that it would be possible to reduce the costs of construction and seismic strengthening.

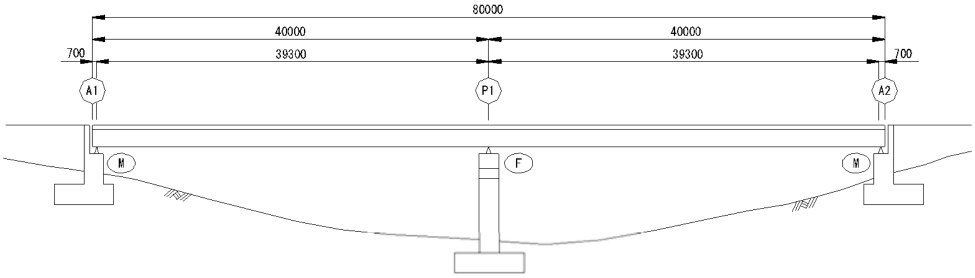
The authors (Moriyama *et al.*, 2005, 2009; Hamamoto *et al.*, 2006, 2011) have examined the effectiveness of the use of the shock absorber for between ends of a girder and an abutment in order to reduce the collision damage by the ground motion. In particular, it is expected to further effect for the use of the shock absorber with the laminated fiber reinforced rubber (Poly Rubber Fiber) in the seismic design which can be reduced the gap size of the expansion joint by allowing the collision at the end of bridge girder and the abutment.

This paper presents the results of the damage assessment by the dynamic response analysis of a PC box girder bridge with two spans. The effects of the gap size and the shock absorber with laminated fiber reinforced rubber or 50-hardness rubber on the damage of the end of PC bridge girder and the base of pier were examined. The index of damage evaluation level at the end of girder and at the base of pier was used the results of the impact analysis and of the quasi-static cyclic loading experiments on actual scale RC bridge piers. From numerical results, it is clarified that the use of the shock absorber with laminated fiber reinforced rubber in the end of the girder is effective to reduce the damage by the collision at the end of girder.

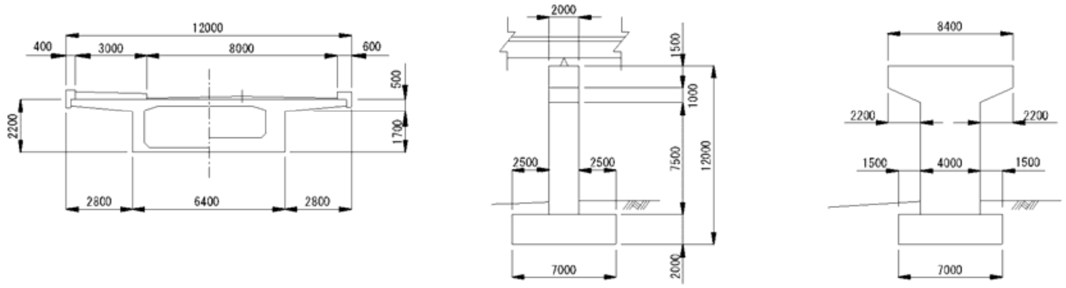
2. DAMAGE EVALUATION ANALYSIS

2.1 Analytical model

In this study, real medium size PC girder bridges with abutments at both ends were chosen as the target of the damage evaluation. Fig. 1 shows the 2 spans PC bridges with box cross-section girder designed by JRA (2002). The symbols of M and F in this figure represent the movable bearing and the fixed bearing, respectively. Fig. 1(a) is the side view and the geometrical dimension of the bridge girder and Fig. 1(b) shows the box cross-section of the superstructure. The side and front views of the P1 pier with a fixed bearing are shown in Figs. 1(c) and 1(d). This medium size bridge is expected that the girder and pier damage of the girder collision will be minimum degree in earthquake load. The non-linear hysteretic curves of the plastic hinge is used a Takeda model which can be taken into account the deterioration of the RC stiffness. The skeleton curve with the initial stiffness (K1 = 7.46×10^6 kN/m) is assumed to be a bi-linear curve. By assumption that the girder collision occurs at the abutment, the parapet



(a) Side view of the bridge Unit (mm)



(b) Cross section of superstructure (c) Side view of pier P1 (d) Front view of pier P1

Fig. 1 PC bridge girder

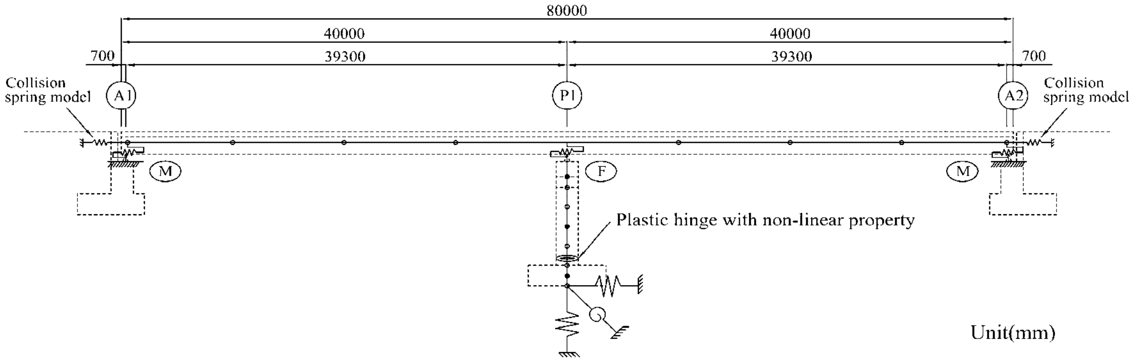


Fig. 2 Analytical model

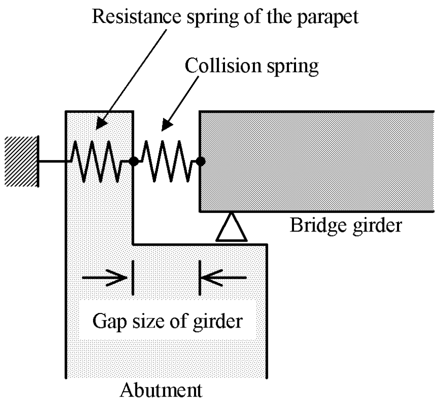


Fig. 3 Collision and resistance spring model

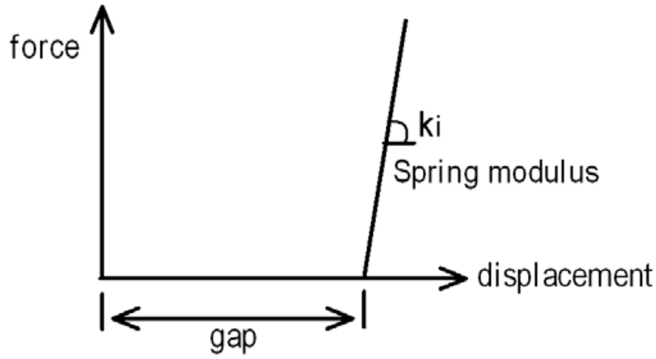


Fig. 4 Spring modulus of girder

at the abutment was rearranged by a collision spring model with non-linear properties as shown in Fig. 2.

2.2 Collision and resistance spring model at the abutment

The collision and resistance spring model at the abutment is necessary to take into account of the collision spring of girder and the resistance spring of the parapet stiffness in order to focus on the damage of the end of girder and the base of the bridge pier as shown in Fig.3. The collision spring consists of the gap and the spring modulus as shown in Fig. 4. The spring modulus was defined by the research results of Watanabe *et al.* (2002) as follows;

$$k_i = \frac{EA}{L/n} \tag{1}$$

Where E is Young's modulus of the superstructure, A and L are the cross section and the length a girder, respectively and n is number of the beam element. Material properties of the analytical model are used as $E = 2.89 \times 10^7$ kN/m^2, $A = 12.41$ m^2, $L = 40.00$ m and $n = 2$, respectively. Hence the spring modulus ki **=** 17.94 × 10^6 kN/m is obtained from Eq. (1). Fig. 5 shows the relationship between the load and the displacement of the rubber shock absorber, 50-hardness rubber and the laminated fiber reinforced rubber (Poly Rubber Fiber). The thickness of the rubber is 0.10 m.

2.3 Input wave

The input waves are used the sine acceleration wave with resonance frequency for the 2 spans model with natural period = 2.20 second. The maximum amplitude of the input acceleration waves is chosen to be 250 gal and 500 gal corresponding to the maximum amplitude of the resonance sin wave. The acceleration waves were inputted into longitudinally direction of the analytical model with a 0.01 second time step. Numerical analyses were conducted using Newmark-β (β = 0.25) where the equation of motion is integrated with respect to time taking into account the material nonlinearity. The constant time step of 5.00 × 10^{-4} was used and the total integration time was 20 seconds. The dynamic response analyses were performed using the nonlinear commercial program of (NIPPON TDAP III 1998). The parametric study was carried out changing the gap size between the end of girder and the abutment from 10 cm to 50 cm and the effect of rubber of the shock absorber.

2.4 Index of damage evaluation level

In order to evaluate the collision damage of the end of girder, the abutment A1 and near the base of pier P1, the index of the damage evaluation level was introduced. The damage evaluation level of the bridge girder end was introduced from three-dimensional analytical results of Tamai *et al.* (2007) on the collision of the PC girder bridge. Fig. 6 represents the strain distribution of the abutment damage focused on the tensile strain at the maximum displacement. Table 1 shows the damage index of the end of girder obtained from the dynamic response analysis. The damage level varied such as from slight damage (A) to heavy damage (D) in proportion to the maximum response velocity at the end of girder.

On the contrary, the damage evaluation level of the base of pier was used by the experimental results by the quasi-static cyclic loading using actual scale RC bridge

Table 1 Damage evaluation at the end of girder

Maximum response collision velocity(m/sec)	Damage level	Damage degree
$0 < v \leqq 1.0$	A	↑ slight
$1.0 < v \leqq 2.0$	B	
$2.0 < v \leqq 3.0$	C	
$v > 3.0$	D	↓ heavy

Table 2 Damage evaluation at the base of pier

Maximum response rotation angle(rad)	Damage level	Damage degree
$0 < \theta \leqq 3.0\times10^{-3}$ $(0 < \theta \leqq 2\delta_y)$	a	↑ slight
$3.0\times10^{-3} < \theta \leqq 7.0\times10^{-3}$ $(2\delta_y < \theta \leqq 5\delta_y)$	b	
$7.0\times10^{-3} < \theta \leqq 10.0\times10^{-3}$ $(5\delta_y < \theta \leqq 7\delta_y)$	c	
$\theta > 10.0\times10^{-3}$ $(\theta > 7\delta_y)$	d	↓ heavy

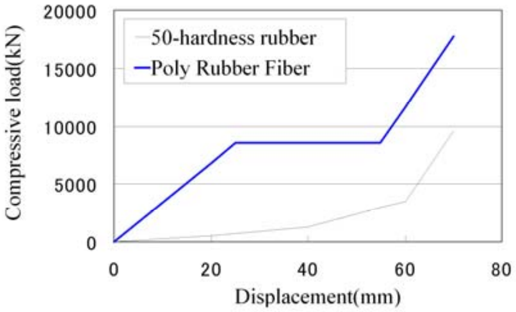


Fig. 5 Relationship between load and displacement of rubber shock absorber

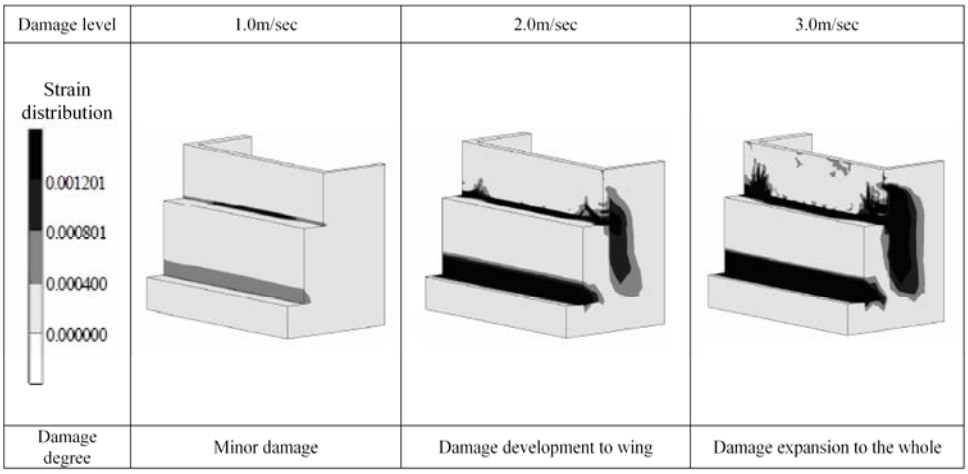


Fig. 6 Strain distribution of the abutment damage focused on the tensile strain at the maximum displacement by Tamai *et al.* (2007)

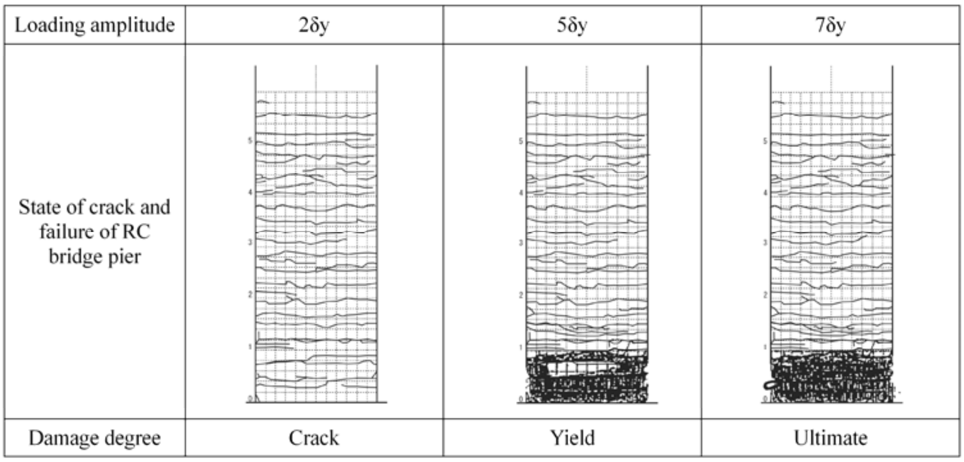


Fig. 7 State of crack and failure of actual RC bridge pier obtained from quasi-static cyclic loading experiments by Hoshikuma et al. 2001

piers with rectangular cross sections as shown in the work by Hoshikuma *et al.* (2001). Fig. 7 represents the state of crack and failure of RC bridge pier and damage degree such as crack, yield and ultimate states of test pieces corresponding to the horizontal displacement at δ = 2 δy, 5 δy and 7 δy (δy :yield displacement) obtained from the experimental results of quasi-static cyclic loading. From these results, the damage evaluation level of near the base of the bridge pier was defined as shown in Table 2. The damage level varied such as from slight damage (a) to heavy damage (d) in proportion to the maximum response rotation angle of the base of RC bridge pier.

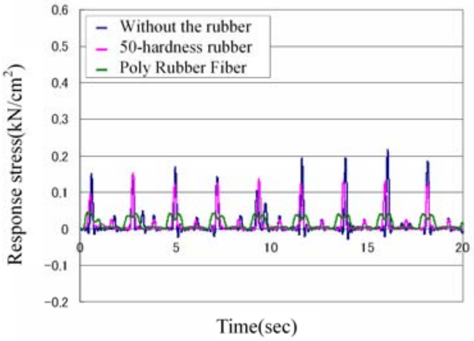
3. RESILTS AND DISCUSSION

3.1 Response stress and response velocity at end of girder

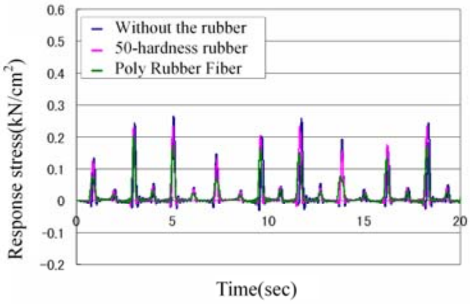
Figs. 8 and 9 show the time histories of the response stress at the end of girder with and without the rubber shock absorber input the acceleration waves of maximum amplitude 250 gal and 500 gal by changing the gap size of 10 cm, 30 cm and 50 cm, respectively. The collision at the end of girder for all girder models was occurred except a girder model with the gap size 50 cm input the acceleration wave of the maximum amplitude 250 gal. From these figures, it was found that the use of the rubber shock absorber at the end of girder can contribute to the reduction of the response stress as a whole. In particular, the effect of the use of the Poly Rubber Fiber on the response stress was greatly. The smaller gap size at girder ends is, the larger the effect of the reduction of the response stress is. The response stress of the girder model with the gap size 10 cm was varied widely from 0.217 kN/cm^2 to 0.044 kN/cm^2 by using the Poly Rubber Fiber. That is, the response stress of the girder model with the rubber shock absorber can be reduced around 80 % by comparison that of the girder model without one. This caused by highly effect of the impact energy absorption using Poly Rubber Fiber. For the input of the acceleration waves of maximum amplitude 250 gal and 500 gal, it could be recognized that the response stress of the end of girder is increased in proportion to the gap size. Fig. 10 shows the relationship between the maximum response stress and the maximum response collision velocity at the end of girder input the acceleration waves of maximum amplitude 250 gal and 500 gal. From this figure, in each case of the input 250 gal and the input 500 gal, it can be seen that the maximum response stress of the end of girder is increased in proportion to the maximum response collision velocity and the relationship of both response shows a linear.

3.2 Damage evaluation at end of girder

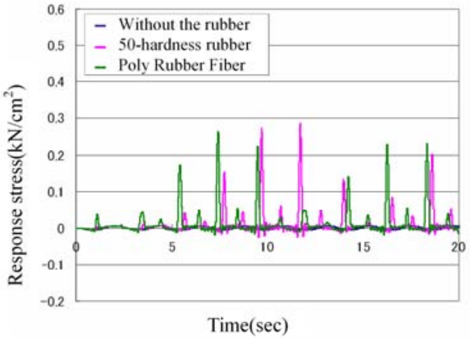
The damage evaluation at the end of girder was tried by using the damage index corresponding to the maximum response velocity. Tables 3 and 4 show the results of damage evaluation at the end of girder input the acceleration waves of the maximum amplitude of 250 gal and 500 gal, respectively. From Table 3, the damage level was (B) for the girder model with gap size 50 cm of the input 250 gal. However, the damage level is (A) for the girder with gap size 10 cm regardless of rubber shock absorber and for the girder model with gap size 20 cm only using the Poly Rubber Fiber. From these results, the effect of the use of the Poly Rubber Fiber on the reduction of the damage at the end of girder was represented. Furthermore, the damage level is (B) for the girder model whose gap size is more than 30 cm regardless of rubber shock absorber. The



(a)Gap size 10 cm

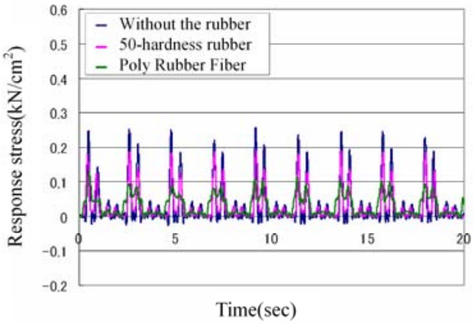


(b)Gap size 30 cm

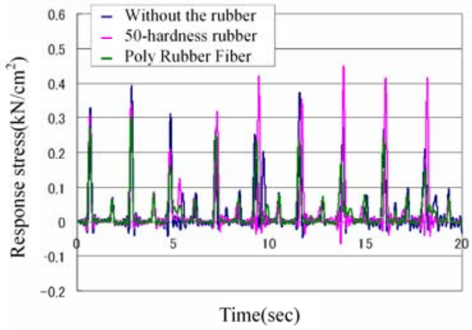


(c)Gap size 50 cm

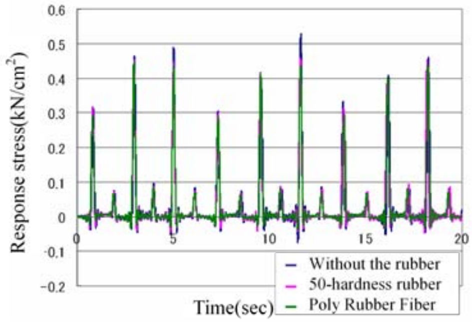
Fig. 8 Time histories of the response stress at the end of girder (Input 250 gal)



(a)Gap size 10 cm

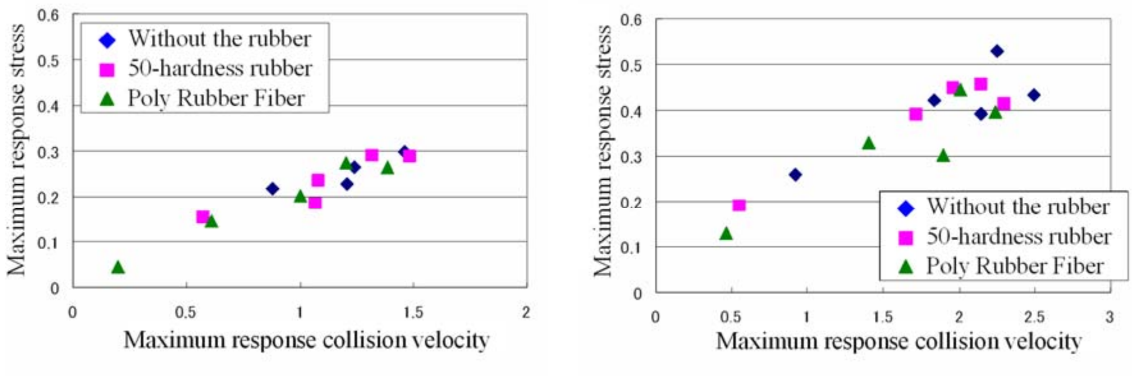


(b)Gap size 30 cm



(c)Gap size 50 cm

Fig. 9 Time histories of the response stress at the end of girder (Input 500 gal)



(a)Input 250 gal

(b)Input 500 gal

Fig. 10 Relationship between maximum response stress and maximum response collision velocity damage level is (A) for the model without a rubber shock absorber because the collision was not occurred at the end of girder.

From Table 4, in contrast, the damage level is (A) for the girder model with gap size 10 cm and is (B) for the one with gap size 20 cm input the acceleration wave of maximum amplitude 500 gal. However, for the girder model with gap size 30 cm, the damage level is (B) in using the Poly Rubber Fiber or 50-hardness rubber as the shock absorber but is (C) in no shock absorber. From these results, the effect of the use of the rubber shock absorber on the reduction of the damage at girder ends was shown. Furthermore, the damage level is (C) for the model of girder whose gap size is more than 40 cm regardless of rubber shock absorber. It is recognized that there is no effect of the damage reduction using the rubber shock absorber at the girder ends.

3.3 Damage evaluation at the base of pier

Tables 5 and 6 show the results of damage evaluation at the base of pier input the acceleration waves of the maximum amplitude of 250 gal and 500 gal, respectively. These damage evaluations were obtained from the relationship between the gap size of girder and the maximum response of rotation angle. From Table 5, the damage level was (d) for the girder model with gap size 10 cm and no rubber shock absorber input the acceleration wave of maximum amplitude 250 gal. However, the damage level is (a) for the Poly Rubber Fiber as the rubber shock absorber but is (b) for the 50-hardness rubber. From these results, it was seen that the effect of the use of the Poly Rubber Fiber or 50-hardness rubber on the reduction of the damage at girder ends was greatly. In addition, the damage level is (d) for the girder model whose gap size is more than 20 cm regardless of rubber shock absorber.

On the other hand, from Table 6, the damage level was (d) for the girder model with gap size 10 cm and no rubber shock absorber input the acceleration wave of maximum amplitude 250 gal. However, the damage level is (c) for the Poly Rubber Fiber or 50-hardness rubber as the rubber shock absorber.

Table 3 Results of damage evaluation at the end of girder (Input 250 gal)

Gap size (cm)	Without the rubber	50-hardness rubber	Poly Rubber Fiber
10	A	A	A
20	B	B	A
30	B	B	B
40	B	B	B
50	A (No Collision)	B	B

Table 4 Results of damage evaluation at the end of girder (Input 500 gal)

Gap size (cm)	Without the rubber	50-hardness rubber	Poly Rubber Fiber
10	A	A	A
20	B	B	B
30	C	B	B
40	C	C	C
50	C	C	C

Table 5 Results of damage evaluation at the base of pier (Input 250 gal)

Gap size (cm)	Without the rubber	50-hardness rubber	Poly Rubber Fiber
10	d	b	a
20	d	d	d
30	d	d	d
40	d	d	d
50	d	d	d

Table 6 Results of damage evaluation at the base of pier (Input 500 gal)

Gap size (cm)	Without the rubber	50-hardness rubber	Poly Rubber Fiber
10	d	c	c
20	d	d	d
30	d	d	d
40	d	d	d
50	d	d	d

That is, the effect of the use the rubber shock absorber on the reduction of the damage at the base of pier was indicated. The damage level is (d) for the girder model whose gap size is more than 20 cm. It is found that there is no effect of the damage reduction using the rubber shock absorber at the base of pier.

4. CONCLUSIONS

This paper presents the results of the damage assessment by the dynamic response analysis of a PC box girder bridge with two spans. The effects of the gap size and the shock absorber with laminated fiber reinforced rubber (Poly Rubber Fiber) or 50-hardness rubber on the damage of the end of girder and the base of pier were examined. In order to evaluate the damage of the girder end and the base of bridge pier, the index of the damage evaluation level was introduced. The following conclusions may be drawn from this study.

(1) For the input of the acceleration waves of maximum amplitude 250 gal and 500 gal, it could be recognized that the response stress of the end of girder is increased in proportion to the gap size and the maximum response collision velocity and the relationship of both response shows a linear.

(2) The effect of the use of the Poly Rubber Fiber on the reduction of the damage at the end of girder was represented. Furthermore, the damage level is (B) for the girder model whose gap size is more than 30 cm regardless of rubber shock absorber. It is also recognized that there is no effect of the damage reduction using the rubber shock absorber at the girder ends.

(3) It was seen that the effect of the use of the Poly Rubber Fiber or 50-hardness rubber on the reduction of the damage at girder ends was greatly. In addition, the damage level is (d) for the girder model whose gap size is more than 20 cm regardless of rubber shock absorber.

REFERENCES

Gakuho Watanabe, Kazuhiko Kawashima (2002). “Analysis of pounding of two elastic rods using impact spring element”, *Journal of Structural mechanics and earthquake engineering*, No.675 / I-55, pp.125-139. (in Japanese)

Japan Road Association (2002). “Specification for Highway Bridges, Part V Seismic Design”, Tokyo, Japan. (in Japanese)

Junichi Hoshikuma, Shigeki Unjoh, Kazuhiro Nagaya (2001). “Spacing effect on inelastic behavior of reinforced concrete columns subjected to cyclic loading”, *Journal of Structural mechanics and earthquake engineering*, No.669 / V-50, pp.215-232. (in Japanese)

Hiroki Tamai, Yoshimi Sonoda, Keiichi Goto, Yukihide Kajita, Tomohisa Hamamoto (2007). “A fundamental study on the damage evaluation of bridge abutment and the characteristics of impact spring element by pounding effect”, *Journal of Structural Engineering* Vol.53A, pp.1219-1226. (in Japanese)

Hisanori Otsuka, Tomoyuki Tanaka, Daisuke Takemura, Tatsuo Soma (2002). “Pounding response analysis of steel box girder bridges using FEM”, *Bridge and foundation engineering* Vol.36 No.12, pp.39-45. (in Japanese)

NIPPON TDAP III (1998). Ver. 2.00, *User's Manual*

Masafumi Shimozono, Yoshimi Sonoda, Hiroki Tamai, Yasushi Nishimoto (2006). "Analytical study on impact fracture characteristics of laminated fiber reinforced rubber as a shock absorber", *Journal of Structural Engineering* Vol.52A, pp.1201-1208. (in Japanese)

Takuro Moriyama, Tomohisa Hamamoto, Yasushi Nishimoto, Nobutaka Ishikawa (2005). "Study on gap reduction considered the pounding of PC bridge girders", *Proceedings of the 4th International Conference on NEW DIMENSIONS IN BRIDGES*, Flyovers, Overpasses & Elevated Structures, pp.201-208.

Takuro Moriyama, Tomohisa Hamamoto (2009). "Analytical study on PC bridge considering the pounding of bridge girders", *Proceedings of Second International Workshop on Performance, Protection, and Strengthening of Structures under Extreme Loading* (CD-ROM).

Tomohisa Hamamoto, Kenji Kosa, Hironori Abe, Yasuo Inokuma, Yoshifumi Nariyuki (2006). "A study on damage mechanism of a bridge that suffered disaster with the Niigata-ken Chuetsu earthquake", *Journal of Structural Engineering* Vol.52A, pp.349-356. (in Japanese)

Tomohisa Hamamoto, Takuro Moriyama, Yasushi Nishimoto, Nobutaka Ishikawa (2011). "Fundamental considerations on the effects of shock absorber of laminated fiber reinforced rubber on pounding", *Concrete Research and Technology*, Vol.22, No. 2, May. 2011, pp.35-44. (in Japanese)

Yasushi Nishimoto, Hiroki Tamai, Yoshimi Sonoda, Masuhiro Beppu, Hiroshi Hikosaka (2005). "Analytical study on impact behavior of laminated fiber reinforced rubber as a shock absorber", *Journal of Structural Engineering* Vol.51A, pp.1625-1634. (in Japanese)