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Full scale impact tests of PC multi-girder with three-layered absorbing system

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ABSTRACT: In this paper, the dynamic behavior of a Prestressed Concrete (PC) multi-girder with a three-layered absorbing system under impact loading was experimentally studied. The PC multi-girder used here was composed of five T-shaped PC girders which were of 5 m span length and 1.2 m wide upper flange. The three-layered absorbing system was made from three layers: a 50 cm thick sand layer (top), a 20 cm thick Reinforced Concrete (RC) layer (core slab) and a 100 cm thick Expanded Poly-Styrol (EPS) layer (bottom). Impact load was generated by a 5 tf weight freely falling from a maximum 30 m height.

To have a comparative study on the performance of the three-layered absorbing system, the experiment using the single layered 90 thick sand cushion was also executed. From this study, the following results were obtained:

1. Based on the girder bending moment of impacted girder, it can be concluded that the absorbing capacity of the three-layered absorbing system for the collisional energy was almost 6.7 times that of the single layered sand cushion.
2. Since the three-layered absorbing system could effectively absorb and disperse a impact load, it is clear that this type of absorbing system could be applied to protect some kind of nuclear power plants from impact loading.

1 INTRODUCTION

In recent years, extensive studies have been reported to ensure the greater safety of nuclear power plants, fuel tanks, rock-sheds and/or other important structures which are vulnerable to impact loads such as air craft crashing, missile and rock falling, etc.. In these studies, two approaches are observed: (1) investigate anti-impact structures under impact load applying directly, (2) investigate an absorbing system to attenuate and disperse an impact load to protect the structure from the local failure. Usually, anti-impact problems of nuclear power plants have been studied by the former approach (Mikami et al. 1991, Aravindan and Kurian 1993, and Geiss and Freund 1993, etc.). If the later approach had been taken for those problems (i.e., covering nuclear power plants with a shock absorbing system), they might have been designed against the quasi-static load and might have provided greater safety than those designed as anti-impact structures.

In Japan, to absorb a impact load hammered on the rock-sheds by rock falling, a single layered sand cushion with 90 cm thickness has been adopted. However, based on the experimental results on the absorbing performance of the single layered sand cushion by the authors (Kishi and Nakano et al. 1993a), it had been made clear that the transmitted impact force to the structure becomes 1.5 times greater than the weight impact force at collision. To ensure the greater safety and to keep quasi-static behavior of the structures, it is important for an absorbing system to have a high absorbing capacity and a high dispersibility of impact force. The authors developed a three-layered absorbing system to overcome those shortcomings of a single layered sand cushion (Nakano et al. 1992, and Kishi and Nakano et al. 1993b). The three-layered absorbing system developed composed of a sand layer (top), a RC core slab and EPS blocks (bottom).

In this paper, to confirm the performance of the three-layered absorbing system, the dynamic and elastic behavior of a prototype PC multi-girder with absorbing system under impact loading was experimentally studied. In this study, a 50 cm thick sand layer, a 20 cm thick RC core slab and 100 cm thick EPS blocks were adopted as the layers (top, core and bottom layer) of the three-layered absorbing system. Impact force was generated by a 5 tf free falling weight. The performance of absorbing systems was evaluated by using the distributions of the girder and the upper flange bending moment of PC multi-girder.

2 OUTLINE OF EXPERIMENT

Impact tests were executed by using the PC multi-girder composed of five girders as shown in Fig. 1. The dimensions of each PC girder composing the multi-girder are (a) height: 90 cm, (b) span length: 5 m and (c) upper flange width: 1.19 m. The impact load was generated by a 5 tf free falling weight from predetermined heights. The falling steel weight was 1 m in diameter, and its spherical bottom was 17.5 cm high.

The measured parameters were : acceleration of the free falling weight and strains in rebars. The former was used to estimate the impact force generated by the falling weight, and the latter were used to estimate the dynamic bending moment of each girder. Based on the experimental results on the absorbing performance of absorbing systems mounted on a RC rigid foundation (Kishi and Nakano et al. 1993b), it became clear that the absorbing capacity of the three-layered absorbing system is 3 $\sim$ 4 times that of a single layered sand cushion. This means that a dynamic response of PC multi-girder using the three-layered absorbing system will be 1/4 $\sim$ 1/3 less than that using a single layered sand cushion under the same impact load input. In this experiment, to ensure the similar accuracy for the dynamic and elastic strain measurement, the falling height of a 5 tf weight was determined as 30 m and 5 m in the cases using the three-layered absorbing system and the single layered sand cushion, respectively. Conducted experimental cases are listed in Table 1.

2.1 The PC girder

Each PC girder was designed based on the following conditions: (1) A single layered sand cushion (Lame's constant λ: 100 tf/m^2) with 90 cm thickness is used. (2) A three ton force free falling object falls onto the sand cushion from a 10 m height. (3) An impact force of P = 128.3 tf is estimated on the basis of the Hertz's contact theory, acts on the center of girder (Timoshenko and Goodier 1951). (4) Impact load is distributed on the upper surface of the multi-girder with an area of two times the thickness of the sand cushion. (5) Design strength, allowable tensile stress and Young's modulus of concrete are 750 kgf/cm^2, 35 kgf/cm^2 and 3.5 $\times$ 10^5 kgf/cm^2, respectively.

The PC girder was prestressed by using nine PC tendons with a post-tensioning system. After introducing the prestress in the girders, the gap between a tendon and its duct was filled with mortar grout. The material properties of tendons and rebars used here are shown in Table 2. Rebars were used for the dynamic strain measurement. Each tendon was stretched up to 28.54 tf of the effective prestress (53.76 kgf/mm^2); then the introduced effective prestress in the lower fiber became 153.1 kgf/cm^2. Lateral prestressing of the multi-girder was introduced by PC tendon arranged with an interval of 1 m. After completion of prestressing, the gap between tendon and its duct was left ungrouted. At the commencement of the experiment, the concrete had aged one year. The 28 day compressive strength and Young's modulus of concrete were 777 kgf/cm^2 and 3.8 $\times$ 10^5 kgf/cm^2, respectively.

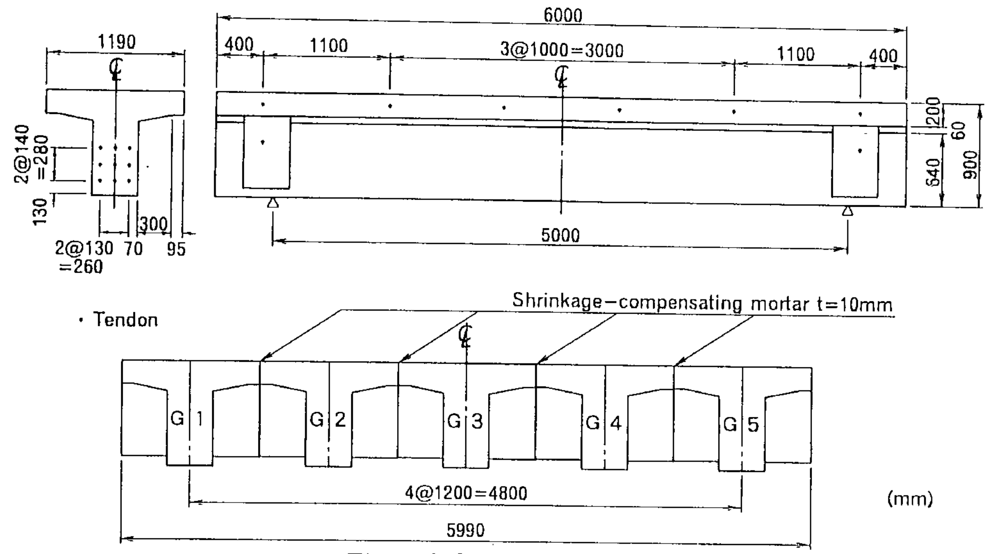

Fig. 1. PC multi-girder.

Table 1. Experimental cases

Nominal name	Absorbing system	Falling height	Impacted girder
D-30-3	3-layered abs. sys.	30 m	G3
S-5-3	Sand cushion	5 m	G3

Table 2. Material properties of tendon and rebar

	PC tendon	Rebar
Nominal name	SBPR 930/1080	SD295A
Diameter (mm)	26	-
Yield strength (kgf/cm^2)	> 9500	> 3000
Tensile strength (kgf/cm^2)	> 11000	4500-6100

Table 3. Material properties of sand

Unit weight (tf/m^3)	Specific gravity	Uniformity coefficient	Coefficient of curvature
1.64	2.55	4.85	0.87

Table 4. Material Properties of EPS

Unit weight (kgf/m^3)	Strength at 5 % strain (kgf/cm^2)	Poisson's ratio	Max. of elastic strain (%)
20	1.1	0.05	1 or less

2.2 Sand cushion, RC core slab and EPS

The sand cushion used for these experiments was fine aggregate for concrete. The material properties of the sand are listed in Table 3. The sand was compacted with stamping at each 20 cm layer up to its 90 cm height. At the commencement of the experiment, the moisture content and the relative density of the sand were 6.0 % and 46.6 %, respectively. The dimensions of the RC core slab were 6 m × 6 m × 20 cm. The RC slab was doubly reinforced with a 1% rebar ratio . The design strength of

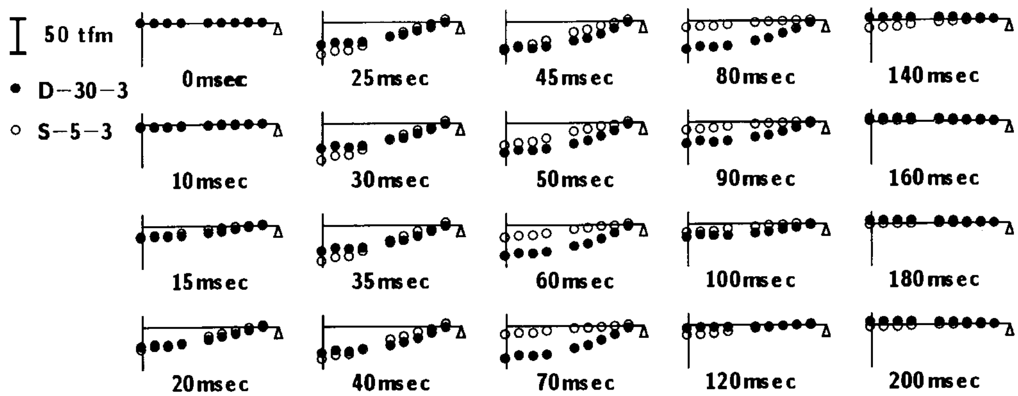

Fig. 2. Axial distribution of girder bending moment of G3.

concrete was 210 kgf/cm^2. At the commencement of the experiment, the compressive strength was 219 kgf/cm^2.

The material properties of the EPS used as the 100 cm thick bottom layer are listed in Table 4. EPS blocks (2 m × 1 m × 0.5 m) were used to form a layer.

3 EXPERIMENTAL RESULTS AND CONSIDERATIONS

3.1 Bending moment of girder

The maximum dynamic strain in the lower rebars in all cases was 353 μ. Considering the prestress introduced by PC tendons, it was concluded that no cracks occurred in the concrete; therefore, the girders behaved elastically. Thus, the bending moment of girders could be calculated using the measured strain and assuming the linear stress distribution and the full effective sectional area.

Figure 2 shows the axial distributions of girder bending moment of G3 in both cases of D-30-3 and S-5-3. The distribution of bending moment for D-30-3 was somewhat parabolic, but that for S-5-3 was almost linear. From this result, it was inferred that the impact force acted like a distributed load when using the three-layered absorbing system (D-30-3) and acted like a concentrated load when using the single layered sand cushion (S-5-3). This inference coincides with the experimental results made by the authors (Kishi and Nakano et al. 1993b) mentioned above; a transmitted impact stress was spread over the absorbing system with a similar and small stress intensity when using a three-layered absorbing system, and was concentrated near the weight dropping area with a high stress intensity when using a single layered sand cushion. In both cases, the bending moments were damped to a negligibly small value at 160 msec passed after loading, and a negative loading state (rebound) did not occur. The maximum response values occurred at the mid span in both cases were 47.9 tfm at 67.6 msec and 53.7 tfm at 32 msec in the cases of D-30-3 and S-5-3, respectively. This means that an absorbing capacity of the three-layered absorbing system used here was 6.7 times superior to that of the single layered sand cushion based on the impact energy input.

Figure 3 shows the sectional distributions of the girder bending moment at the center of the span length. In the case of D-30-3, the bending moments were distributed with a small gradient; the bending moment of G3 was the largest one among the 5 girders, and those of G1 and G5 were comparatively large. On the other hand, in the case of S-5-3, the bending moment of G3 was about 5 times greater than those of G1 and G5, and the distribution was almost linear taking G3 at the reference point. Total bending moments occurred at the mid span were 182.8 tfm and 125.2 tfm in the cases of D-30-3 and S-5-3, respectively. Based on these values, the load share ratio of the G3 were calculated as 26.2 % and 42.9 % for the cases of D-30-3 and S-5-3 ,

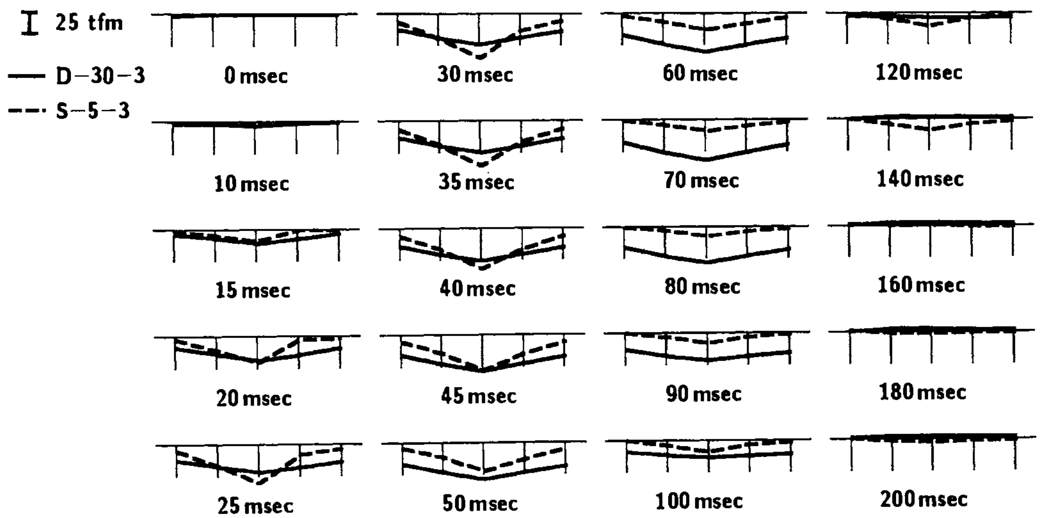

Fig. 3. Sectional distribution of girder bending moment at the mid span.

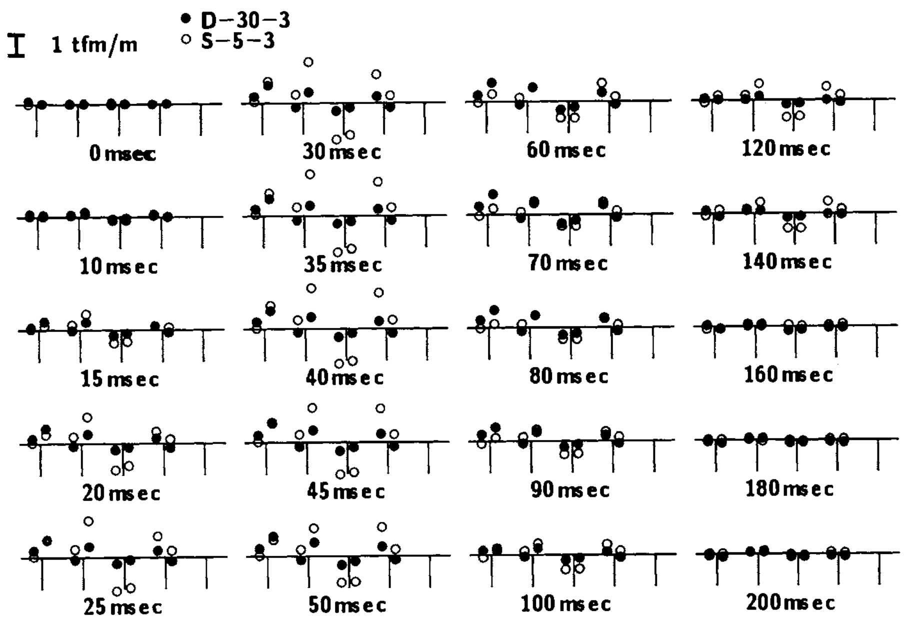

Fig. 4. Sectional distribution of flange bending moment at the mid span.

respectively . The three-layered absorbing system (D-30-3) used here might have reduced the load share ratio of the impacted girder more than 15 % comparing with the single layered sand cushion (S-5-3). This low load share ratio in the case using the three-layered absorbing system must be due to its high dispersibility of impact force.

3.2 Bending moment of flange

Figure 4 shows the bending moments of flange at the intersection of the flange and the web in both cases of D-30-3 and S-5-3. In this figure, a bending moment was plotted on the side of flange where the bending tension stress was generated. A positive and a negative moment were specified for the tension stress generating in the lower and the upper fiber of flange, respectively. The features on the positive and/or negative bending moment distribution in both cases were almost the same. However, the bending moments in the case of D-30-3 were distributed with an average value less than 1 tfm/m over the whole girders. On the other hand, in the case of S-5-3, the bigger bending moment was generated at G3 and the inner flanges of G2 and G4. It seems that these results came out from the reasons mentioned above: the three-layered absorbing system (D-30-3) could disperse an impact load over the absorbing system, but, the single layered sand cushion (S-5-3) could not disperse an impact load effectively and the impact load was concentrated near the falling weight dropped area. The absolute maximum bending moments in the cases of D-30-3 and S-5-3 are 1.0 tfm/m and 2.0 tfm/m, respectively.

Usually, the flange of PC girder was designed for negative bending moment assuming a cantilever beam with unit width fixed at the edge of web. However, since the bending moments took almost the same negative and positive values, the flange must be designed against alternative bending moments.

4 CONCLUSIONS

To confirm the performance of a three-layered absorbing system, the dynamic and elastic behavior of a prototype PC multi-girder with absorbing system under the impact loading were experimentally studied. In this study, two type absorbing systems were applied for comparative study: a three-layered absorbing system (composed of a 50 cm thick sand layer (top), a 20 cm thick RC core slab and 100 cm thick EPS blocks (bottom)), and a single layered 90 cm thick sand cushion. The results obtained from this study are summarized as follows:

1. Based on the girder bending moment of the impacted girder, the absorbing capacity of the three-layered absorbing system was 6.7 times superior to that of the single layered sand cushion for the same impact energy input.
2. By using the three-layered absorbing system, more than 15 % load share ratio of the impacted girder can be reduced than the case using the single layered sand cushion.
3. In the case using the single layered sand cushion, the flange moment concentrated at the falling weight dropped area and became big. However, the three-layered absorbing system can produce a uniform and reduced flange bending moment.

REFERENCES

Aravindan, P.K. and Kurian, E. 1993. Low velocity hard impact studies on reinforced concrete slabs. Transactions of the 12th International Conference on SMIRT, Vol. JH12/5, p. 303-308.

Geiss, M. and Freund, H.-U. 1993. Dynamic loading of a reinforced cylindrical vessel by an internal detonation. Transactions of the 12th International Conference on SMIRT, Vol. JH12/5, p. 315-320.

Kishi, N., Nakano, O., Matsuoka, K.G. and Nishi. H. 1993a. Field test on absorbing capacity of sand cushion. Journal of Structural Engineering, JSCE, Vol. 39A, p. 1587-1597, in Japanese.

Kishi, N., Nakano, O., Mikami, H., Matsuoka, K.G. and Sugata, N. 1993b. Field test on shock-absorbing effect of three-layered absorbing system. Transactions of the 12th International Conference on SMIRT, Vol. J, p. 357-362.

Mikami, H., Kishi, N., Matsuoka, K.G. and Nomachi, S.G. 1991. Dynamic behavior of concrete slabs reinforced by braided AFRP rods under impact loads. Transactions of the 11th International Conference on SMIRT, Vol. J, p. 45-50.

Nakano, O., Kishi, N., Matsuoka, K.G. and Yoshimura J. 1992. Development of 3-layered shock-absorbing system. Proceedings of the International Symposium on Impact Engineering, p.725-729.