STRENGTHENING EFFECT ON PRESTRESSED CONCRETE MEMBERS AFFECTED BY ALKALI-SILICA REACTION (ASR)

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Abstract

Shear strengthening effect was studied experimentally for prestressed concrete (PC) beams affected by alkali silica reaction (ASR), using seven PC specimens (height 300 mm × width 300 mm × length 2000 mm). The purposes of this study were to verify the effects of ASR deterioration and stirrup rupture on shear strength of concrete members and shear strengthening effects of three proposed methods. It is known that retrofitted strengthening members are subjected to residual expansion with the progress of ASR deterioration after the execution of strengthening. Loading test was carried out in this study with the effects of such residual expansion taken into account to verify the effectiveness of the proposed shear strengthening techniques.

Keywords: ASR, stirrup rupture, shear strength, shear strengthening, prestressed concrete (PC) beam

1 INTRODUCTION

It was reported previously that reinforcing bar rupture attributable to concrete expansion was found at bends or pressure welds in concrete structures affected by alkali-silica reaction (hereinafter referred to as ASR) [1]. Although there have been no reports that any shear strength reduction occurred in the prestressed concrete (PC) superstructures due to the rupture of reinforcing bars, it is urgently needed to address this issue and develop effective countermeasures.

There were numerous problems to be solved before establishing strengthening methods for ASR-affected PC members. It was necessary to collect basic data and take practical actions. Japan Prestressed Concrete Contractors Association formed an ASR countermeasure study committee and, in coordination with other organizations, carried out several series of experimental studies for better understanding of long-term properties, residual prestress, volume effect, shear strength and many other issues [2,3,4,5,6].

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This paper reports results of a part of that project in which major focus was placed on shear strength of ASR-affected PC members and effects of different strengthening methods. This is an update for the previous report on the plan of this experiment [3] presented at the 13th ICAAR conference.

In this experiment, PC beam specimens were exposed outdoors for a long term to allow ASR deterioration to occur in them, three different strengthening methods were applied to them for improved shear strength, and shear loading test was carried out to verify their strength. The strengthening was executed in the middle of the expansion stage, so that effects of residual expansion, which was one of the characteristic problems for ASR, were taken into account in the loading test.

2 OUTLINE

2.1 Specimen types, shape and dimensions

There were seven specimens with different combinations of the following factors: normal (non-reactive) aggregates or ASR reactive aggregates; with or without ASR deterioration; with or without stirrups; rupture of stirrups; and with or without shear strengthening. Table 1 and Figure 1 show the outline of the specimens, and Table 2 shows the specimen types. The shape and configuration of the specimens were determined so that the data may be mutually complemented with those from a similar study currently conducted by the other group. The specimens were evaluated through comparative examination of the experimental results as described in Table 3.

2.2 Selection of shear strengthening methods

The following three methods were selected for examination as shear strengthening for ASR-affected PC girders with ruptured stirrups, giving consideration to operability in actual construction and capability of visual inspection after the application: vertical external cable method; large-eccentricity external cable method; and continuous fiber sheet method. Figure 2 shows schematic views of shear strengthening on PC girders, and Figure 3 shows structural diagrams of the strengthened specimens.

Strengthening design was determined based on Equation (1) of design shear strength for beams specified in the Japan Society of Civil Engineers Standard Specifications for Concrete Structures [7]. The strengthening amount was set so that the strength of individual strengthening members would compensate for Vsd or Vped, taking into account the effects of residual expansion by ASR after the strengthening.

$$Vyd = Vcd + Vsd + Vped \quad (1)$$

where, Vyd: design shear strength of beam; Vcd: shear strength of the concrete; Vsd: shear strength of the shear strengthening members; and Vped: vertical component of effective tensile force in the longitudinal tendon.

Vertical external cable method (II-5)

Prestressing steels were arranged vertically and prestress was applied for shear strengthening, in anticipation of the restraining effect on expansion and improved shear strength of the shear strengthening members (Vsd).

Large-eccentricity external cable method (II-6)

This method was an application of the external cable method commonly used for flexural strengthening. Prestressing steels were externally placed with a large eccentricity in anticipation of the improved component strength in the shear direction (Vped).

Continuous fiber sheet method (II-7)

Continuous fiber sheets were adhered to the side and bottom surfaces of the specimens as shear strengthening, anticipating improved shear strength of the shear strengthening members (Vsd).

2.3 Experiment schedule

Figure 4 shows the flow of the experiment. The specimens to be strengthened were checked for the presence and development of ASR deterioration during the outdoor exposure, and shear strengthening was executed at a proper timing (about one year from manufacture) to allow for residual expansion by ASR after the application. The specimens were exposed outdoors for further progress of ASR deterioration before carrying out the loading test.

3 SHEAR LOADING TEST

3.1 Objectives

The objectives of the loading test were as follows:

1) verify the effects of the presence or absence of ASR deterioration on shear strength;
2) verify the effects of the presence or absence of stirrups and the effects of rupture of the stirrups on shear strength; and
3) verify the effects of the shear strengthening members retrofitted to the ASR-affected specimens in the presence of residual expansion by ASR.

3.2 Loading test plan

Figure 5 shows the loading positions and steps. Loading positions were where a/d (ratio of shear span to effective depth) = 3. Load was increased to 100 kN in 20 kN increments and removed. After applying two cycles of this, load was increased again to 100 kN in 20 kN increments and then up to breaking point in 50 kN increments.

Since this experiment aimed at verifying the shear strengthening effects by comparison of shear strength, it was necessary to ensure shear failure at least in specimen II-4 which had no stirrups. For that purpose, prestress in each specimen was adjusted before the loading test to a level where stress due to the prestress in the bottom fiber was 3 N/mm^2 [3].

3.3 Loading test results

Breaking load and failure mode

Photo 1 shows individual specimens after the failure. Table 4 and Figure 6 show the calculated values and experimental results in comparative manner.

Specimens II-4 and II-6 failed in shear mode, and others failed in flexure mode.

Breaking load levels were higher than calculation results in all specimens. Breaking load of II-4 which failed in shear mode was 1.4 times the calculated value (by the Mcr method equation [3]). This ratio was almost consistent with that reported in a previous study by Tamura et al. [8]. This justifies the application in this experiment of the existing calculation equation in which effects of cracks and other damage by ASR deterioration were ignored. However, care should be taken in applying the equation in future studies because uncertainties may exist in dimensions, degree of cracking or fluctuations in concrete strength due to ASR deterioration in existing structures. It is necessary to establish a new calculation method capable of evaluating ASR deterioration properly.

Failure observed in this study occurred as follows: ASR deterioration cracks which initiated at the preloading stage grew in width and length with the increase in applied load; more cracks initiated and propagated; and concrete eventually failed along the cracks. Fracture surfaces extended through to the end in II-4 and II-6 which failed in shear mode. This was likely due to longitudinal cracks generated at the preloading stage. Figure 7 shows the load displacement curves for all specimens.

4 SUMMARY

The findings of this study are discussed below, following the evaluation systems shown in Table 3.

Effects of ASR deterioration

Effects of ASR deterioration were examined by comparing specimens II-1 and II-2. Both specimens failed in flexural mode, with breaking load of II-2 being about 7% lower than that of II-1 (control: 2P = 594 kN, ASR-reactive: 2P = 552 kN). This reduction was attributed to the deterioration by ASR. The loading test was carried out in three steps, and II-1 and II-2 exhibited similar load displacement curves in the third step where ultimate load was applied. However, effects of reduced rigidity were observed in the first and second steps where serviceability limit state load was applied. These findings coincided with the results of an experimental study on the long-term behavior of ASR-affected PC members [2]. Displacement in II-1 increased after 80 kN as shown in the load displacement curves, which was likely due to initiation and development of flexural cracks. Such an increase in displacement due to flexural cracks was not found in II-2 which already had numerous cracks due to ASR deterioration at the preloading stage. This suggested that the effects of reduced rigidity due to these cracks appeared during the initial loading. The load displacement curves for the second loading step revealed that displacement increased in both specimens from the levels under the initial load (Figure 8). This was likely due to the decrease in rigidity attributable to the flexural cracks which occurred during the initial loading. The difference in displacement increase ratio between 17% in II-1 and 30% in II-2 was attributed to the presence or absence of ASR deterioration cracks.

Effects of stirrup rupture

Effects of stirrup rupture were examined by comparing II-2 and II-3. Both II-2 and II-3 failed in flexural mode, without any difference in their ultimate strengths. Because of this, effects of stirrup rupture on ultimate shear strength were not identifiable. However, larger displacement in II-3 was obvious in the load displacement curves as compared to II-2 (Figure 9).

Effects of stirrups

Effects of stirrups were examined by comparing II-2, II-3 and II-4. Specimens II-2 and II-3 failed in flexural mode, and II-4 which had no stirrups failed in shear mode. Although quantitative determination was not possible due to the difference in failure mode, it was demonstrated that stirrups contributed to the shear strength under ASR deterioration, irrespective of the presence or absence of rupture (Figures 9 and 10).

Shear strengthening effects

Shear strengthening effects were examined by comparing individual strengthened specimens against non-strengthened II-4. II-5 and II-7 exhibited similar tendencies in all measurement items and improvement in shear strength. The results further demonstrated that II-6 had a great contribution not only to improvement in shear strength but also improvement in flexural strength. The three strengthening methods examined in this study were proved effective in shear strength improvement in the presence of residual expansion due to ASR deterioration (Figure 11).

5 REFERENCES

[1] Japan Society of Civil Engineers (2005): Report of the Sub-committee on Countermeasures for Damage due to Alkali Silica Reaction - Fracture of Reinforcing Steels in Concrete Structures Damaged by ASR. Concrete Library: No. 124 (in Japanese).

[2] Hiroi, Y., Manabe, H., Ihaya, T., Ookubo, T. and Miyagawa, T. (2008): Experimental Study on the Long-Term Properties of Prestressed Concrete Members Affected by Alkali-Silica Reaction (ASR). 13th ICAAR Conference Proceedings: 754-763.

[3] Nishimura, K., Muroda, K., Kobayashi, Y., Taniguchi, H. and Miyagawa, T. (2008): Experimental Study on Shear Strength and Reinforcement of PC Members Affected by Alkali-Silica Reaction (ASR). 13th ICAAR Conference Proceedings: 290-299.

[4] Japan Prestressed Concrete Contractors Association (2009): ASR Countermeasure Study Committee Report (in Japanese).

[5] Okuyama, K., Ookubo, T., Ihaya, T. and Hiroi, Y. (2010): Experimental Study on the Properties of Prestressed Concrete Specimens Affected by ASR (Part 1) - Report of ASR Countermeasure Study Committee, Japan Prestressed Concrete Contractors Association. Prestressed Concrete: Vol. 52: No. 3: 61-70 (in Japanese).

[6] Nishimura, K., Jodai, K., Yokoyama, T. and Muroda, K. (2010): Experimental Study on the Properties of Prestressed Concrete Specimen Affected by ASR (Part 2) - Report of ASR Countermeasure Study Committee, Japan Prestressed Concrete Contractors Association. Prestressed Concrete: Vol. 52: No. 5: 37-45 (in Japanese).

[7] Japan Society of Civil Engineers (2005): Standard Specifications for Concrete Structures - 2007, Design: 132-141.

[8] Tamura et al. (2003): A study on shear strength evaluation for PC beams with rectangular cross section. Prestressed Concrete: Vol. 45: No. 6: 101-110.

TABLE 1: Outline of the specimens

Specimen dimensions	0.300 × 0.300 × 2.000 m
Prestressing steel bars	Two (2) installed at 1/3 of the member height; 26 mm diameter
Compressive stress	10 N/mm² introduced in the bottom fiber by prestressing
Stirrups	Provided at a shear strengthening ratio of about 0.5% (for specimens with stirrups only)

TABLE 2: Combinations of factors

	II-1	II-2	II-3	II-4	II-5	II-6	II-7
	Non-strengthened	Non-strengthened	Non-strengthened	Non-strengthened	Strengthened	Strengthened	Strengthened
Exposure period	3 years	3 years	3 years	3 years	3 years	3 years	3 years
Execution of strengthening	--	--	--	--	April 2006	April 2006	April 2006
Loading test	July 2008	July 2008	July 2008	July 2008	July 2008	July 2008	July 2008
Prestressing	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ASR deterioration	No	Yes	Yes	Yes	Yes	Yes	Yes
Stirrups	Yes	Yes	Yes (broken)	No	No	No	No
Shear strengthening	No	No	No	No	Yes	Yes	Yes
Remarks	Control	ASR-reactive	ASR-reactive, with ruptured stirrups	ASR-reactive, without stirrups	Vertical external cables	Large-eccentricity external cables	Continuous fiber sheets

Note: period for residual expansion: approximately two years

TABLE 3: Evaluation systems
II-1 – II-2 = effects of ASR deterioration
II-2 – II-3 = effects of stirrup rupture
II-2 – II-4 = effects of stirrups
II-5,6,7 – II-4 = shear strengthening effect

TABLE 4: Calculation results vs. experimental results (in kN)

		II-1	II-2	II-3	II-4	II-5	II-6	II-7
		Control	ASR-reactive	Ruptured stirrups	No stirrups	Vertical external cables	Large-eccentricity external cables	Continuous fiber sheets
Calculation	Mcr ⇳ Mcr × 1.5	218.1 ⇳ 296.7	201.8 ⇳ 272.2	199.0 ⇳ 268.0	141.2 ⇳ 211.8	300.0 ⇳ 367.9	238.1 ⇳ 306.6	234.6 ⇳ 306.4
	Flexural strength	267.3	219.1	219.1	219.1	219.1	381.0	219.1
Experiment	Breaking load (2P)	593.7	552.1	546.0	395.1	502.5	698.8	504.8
	Breaking load (P)	296.9	276.1	273.0	197.6	251.3	349.4	252.4
	Failure mode	Flexural	Flexural	Flexural	Shear	Flexural	Shear	Flexural
	vs. Mcr	--	--	--	1.4	--	--	--

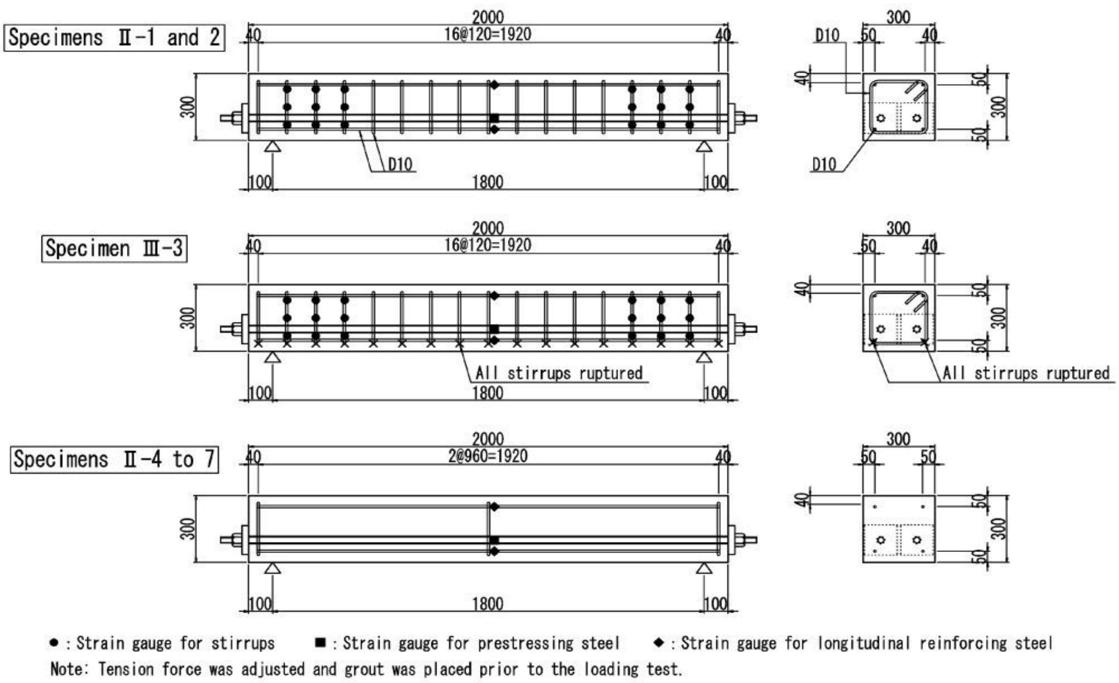


FIGURE 1: Structural diagrams of the specimens

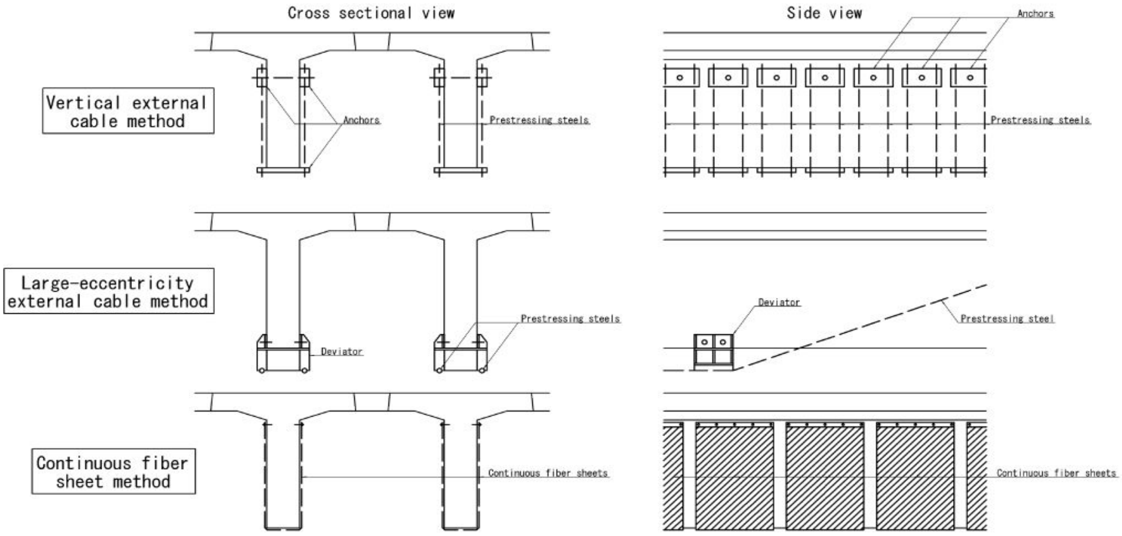


FIGURE 2: Schematic views of the strengthening methods

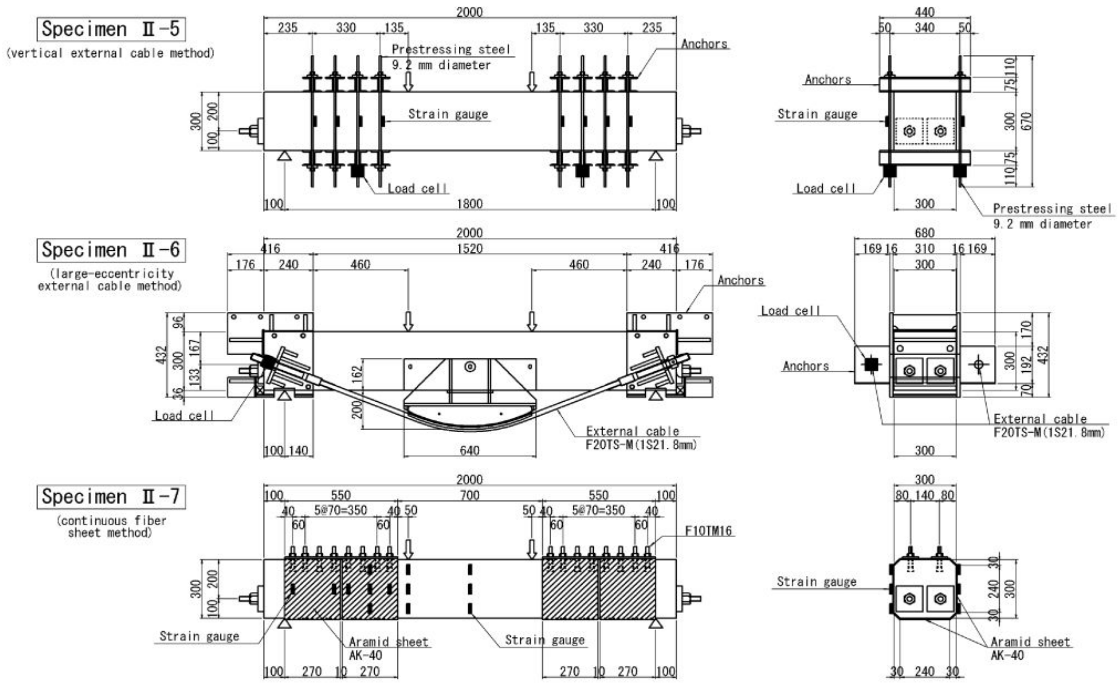


FIGURE 3: Structural diagrams of the strengthened specimens

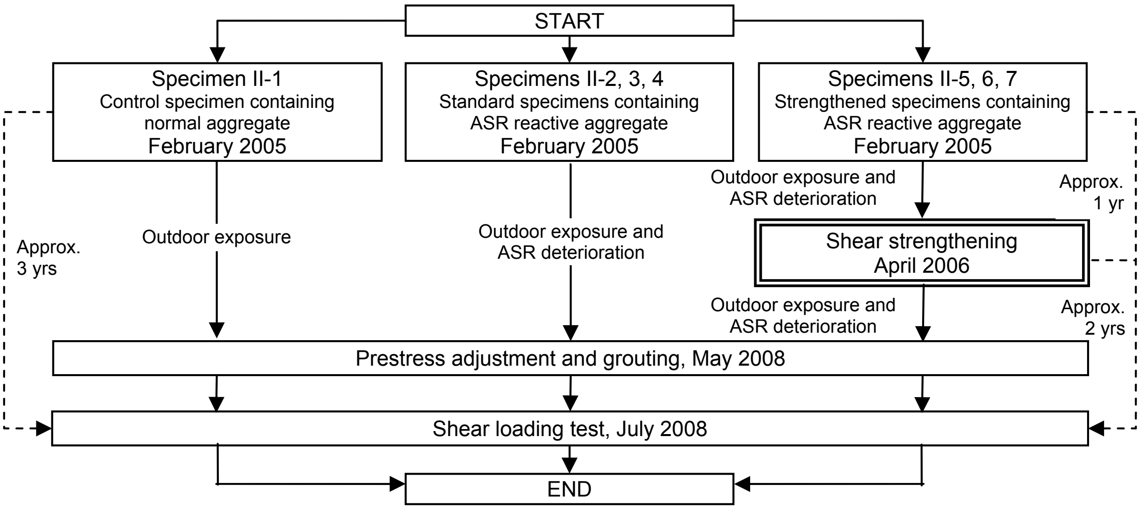


FIGURE 4: Flow of the experiment

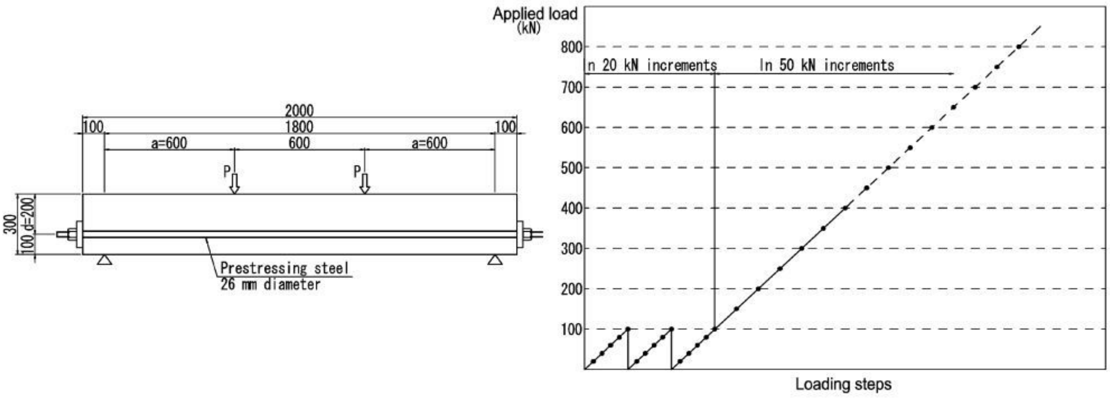


FIGURE 5: Loading positions and steps

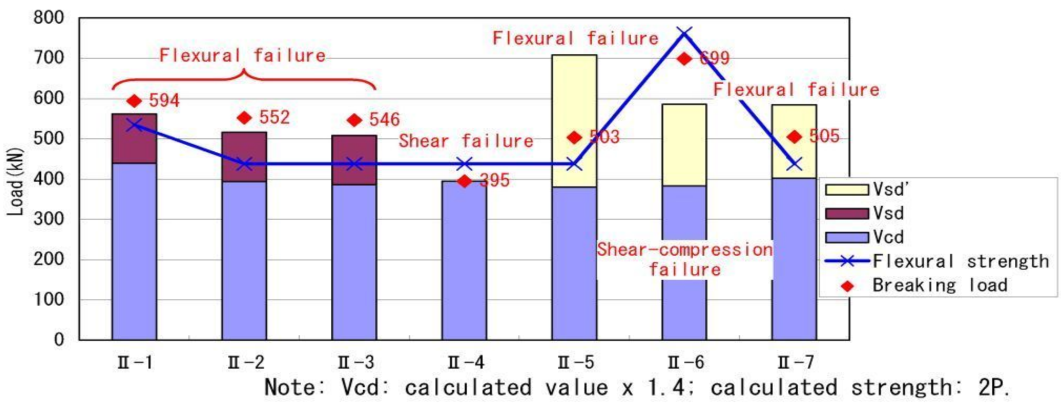


FIGURE 6: Calculated strengths and actual breaking loads

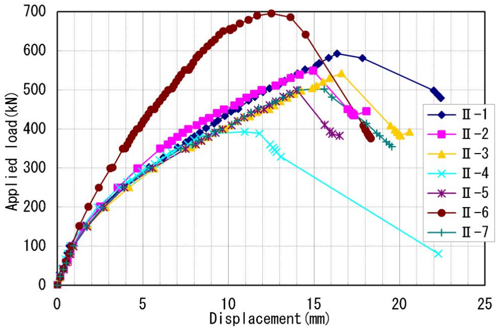
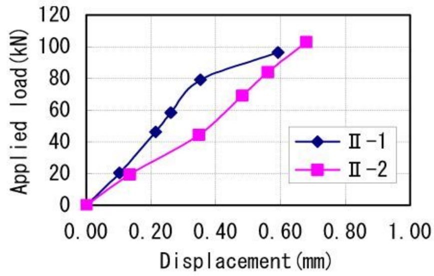
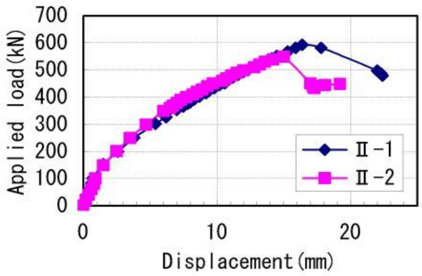


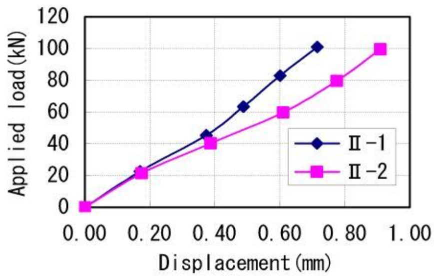
FIGURE 7: Load-displacement curves



b) Serviceability limit state load (1st step)



a) Ultimate limit state load



c) Serviceability limit state load (2nd step)

FIGURE 8: Load-displacement curves (II-1 and 2)

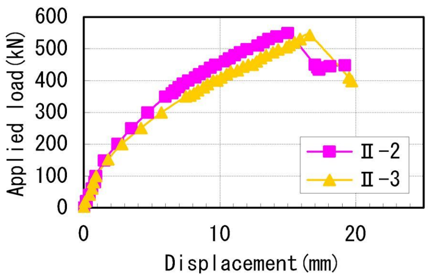


FIGURE 9: Load-displacement curves (II-2 & 3)

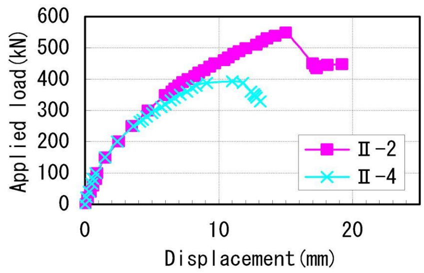


FIGURE 10: Load-displacement curves (II-2 & 4)

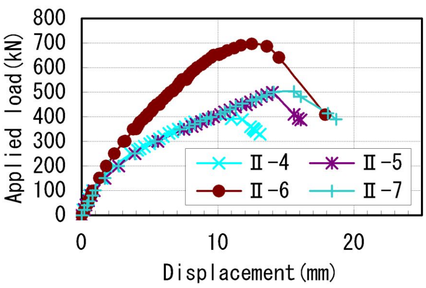


FIGURE 11: Load-displacement curves (II-4 to 7)

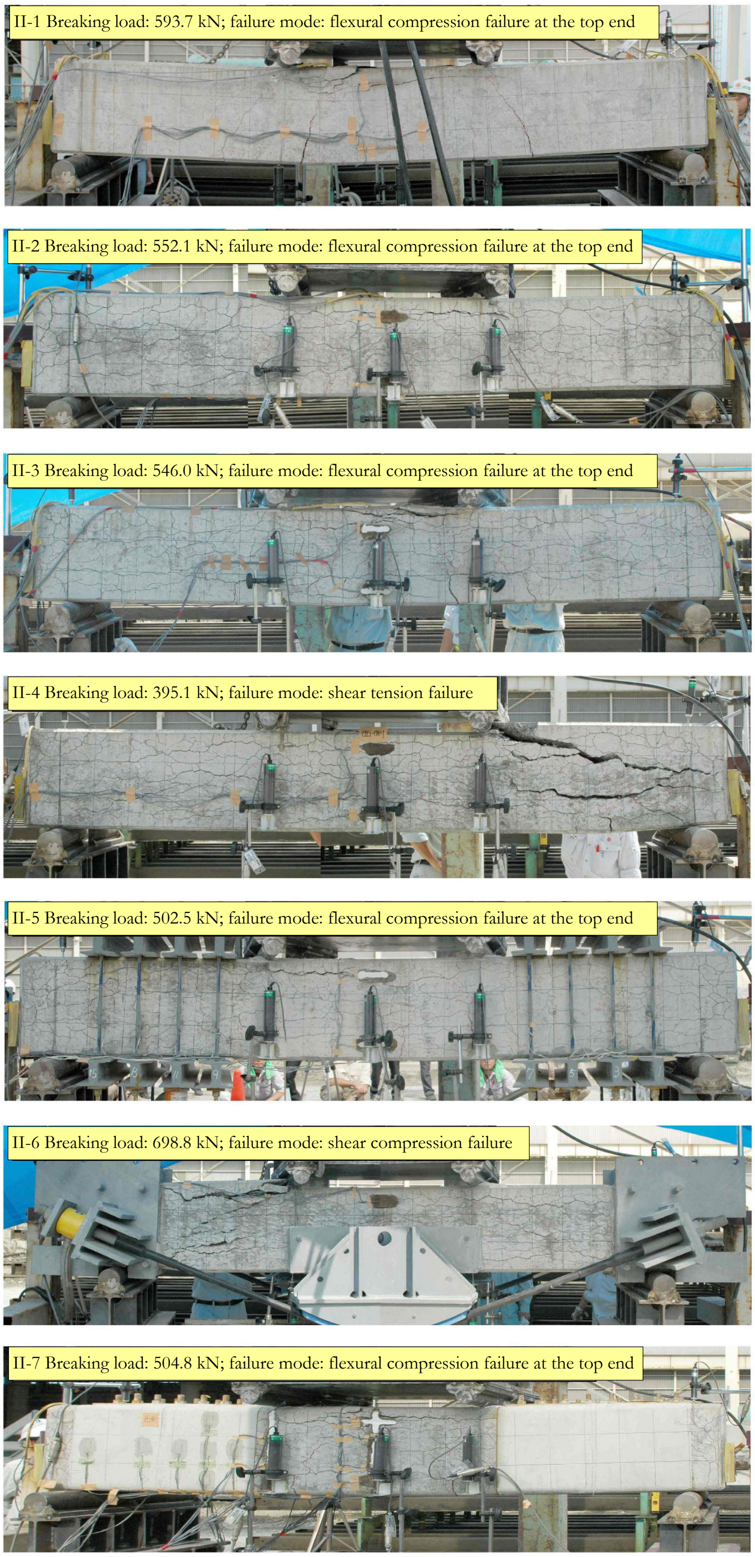


PHOTO 1: Pictures showing individual specimens in the state of failure