EFFECTIVENESS OF COHESION ON HORIZONTAL SHEAR TRANSFER FOR COMPOSITE PRESTRESSED CONCRETE GIRDERS

Yoshiki Tanaka[1]
Jun Murakoshi[1]
Hiroshi Yasumori[2]
Hiroshi Asai[2]
Sadaaki Nakamura[2]

Abstract

To improve design and construction of composite prestressed concrete girders, a mechanism of shear transfer at the horizontal interface was reexamined. In the research, interface shear tests of three girders were conducted. The slip loads due to interface shear failure of the composite girders were well estimated using a method based on cohesive strength for joints between concrete. In particular, it was found that the influence of the normal stress due to loading should be considered for estimating the slip load of the girders.

Introduction

Composite prestressed concrete girders are one of reasonable tools for construction of highway bridges. Late 1950, Portland Cement Association (PCA) carried out a series of tests for the structural type.[1,2] In 1960, tentative recommendations for design and construction of the structures were presented based on various research including the PCA's research project.[3] Recently, wide flange type precast girders available to reduce the number of girders are favorably applied for providing lower construction cost of the composite prestressed concrete girders. The wider flange can reduce the shear stress acting on the horizontal interface. But according to current Japanese specifications, the minimum interface reinforcement ratio of 0.2 % may be likely to require rather more reinforcing bars across the interface.[4,5] From this viewpoint, researchers reexamined the shear transfer mechanism for the composite girders. To date, for addressing shear transfer of concrete-concrete composite girders, a number of push-off tests[1,6,7] and beam tests[1,2,7-11] were presented. But each contribution of cohesion, shear friction and dowel action in the shear transfer behavior has not sufficiently been apparent. In the research program conducted by the authors, contribution due to dowel action was examined in detail. Subsequently, the contribution due to cohesion and shear friction was discussed.[12] The research revealed that for composite girders requiring the interface reinforcement ratio lower than 0.5 % and monolithic behavior, cohesion between concrete should be taken into account for estimating shear resistance of the interface. As a part of the examinations, interface shear tests of three composite prestressed concrete girders were conducted.[13]

[1] Public Works Research Institute, Japan
[2] Japan Prestressed Concrete Contractors Association

This paper shows the test results of the three girders and provides an estimation method for the slip load of the composite girders.

Provisions on Interface Shear Strength for Composite Girders

The design interface shear strength for composite concrete girders prescribed in the AASHTO, LRFD Highway Bridge Design Specifications,[14] Eurocode2 (EN)[15] and Japanese specifications[16] are shown in Fig. 1 in relation to the clamping stress $p \cdot f_y$, where p is the interface reinforcement ratio (= A_s / A_c); f_y is yield point of reinforcing bars across the interface; A_s is area of the reinforcing bars; A_c is area of the contact surface. As a reference, results of various push-off tests[4,6,8,17-20] were also plotted. The line for the Japanese specifications was drawn using the allowable shear strength τ_{ba} based on the allowable stress design method, being seemingly conservative. Several factors like load and resistance factors provide difficulty of comparison between provisions. From Fig. 1, it can be seen that the design interface shear strength increases with $p \cdot f_y$.

Previous Research

The shear friction theory proposed by Birkeland et al.[21]and Mast[22] ignores effectiveness of cohesion on the shear resistance between concrete. Mast addressed that wide variation of the shear strength of specimens with low reinforcement ratio was caused by cohesion.[22] Whereas, Paulay et al. presented that adequate construction joint with clean and rough surface can develop sufficient shear capacity corresponding to monolithic concrete.[23] For adequate interface shear design of composite prestressed concrete girders having relatively large area of the contact surface, cohesion should not be ignored, rather characteristics of cohesion should be examined definitely.

Figures 2a and 2b schematically show each contribution due to cohesion, shear friction and dowel action on load-slip displacement curves drawn based on a result of a push-off test conducted by researchers.[12] Since most of the test results shown in Fig. 1 were obtained from tests of specimens with large reinforcement ratio, it was supposed that the load-slip behavior of those tests corresponded to that shown in Fig. 2a and that the slip displacement at the maximum load was significant. As shown in Fig. 2a, the influence of cohesion was likely to be ignored even if bond was valid.

A relationship between the shear strength and the reinforcement ratio based on data obtained from Hanson's push-off tests with the rough interface (roughness was around 9.5 mm) [1] is shown in Fig. 3. It can be seen that the shear strength was almost constant below the reinforcement ratio of 0.6 %. The figure indicates that behavior of specimens with the reinforcement ratio less than 0.6 % corresponded to that shown in Fig. 2b illustrating significant performance of cohesion.

It is known that a type of finishing and the roughness of the contact surface influences the cohesive strength (bond strength).[1] The brush-finished surface or the rough surface using chemical retarder is usually applied to the interface of Japanese composite prestressed concrete girders. In Fig. 4, test results of specimens having the brushed or comb-scratched contact surface and the reinforcement ratio of 0.1 or 0.2 % are shown in relation to the measured roughness R_{zj} of the contact surface.[5] The roughness R_{zj} is defined as a depth between upper and lower peaks, which are averages of the five maximum peaks. For normalizing similarly to plasticity of concrete, the shear strength was divided by the cylinder strength f'_c. When compared with the normalized shear strength v_u / f'_c of monolithic concrete ranging from 0.13 to 0.22 for no normal stress,[24] the v_u / f'_c values of the brash-finished interface was significantly smaller. Even this level of the shear strength, typical behavior of these specimens was similar to that shown in Fig. 2b.

Researchers applied the modified Cowan theory to estimate the shear strength due to cohesion for composite concrete specimens.[12] As an example, a relationship between the normalized shear strength v_u / f'_c and the normalized normal stress σ_n / f'_c for the brush-finished interface is illustrated in Fig. 5. The theory presented by Hofbeck et al.[25] was re-modified (an angle of an inclined line OA was assumed to be constant as $\tan^{-1}(1/2)$ regardless of shape of specimens). The estimation method was verified by comparison with data of both monolithic and composite concrete. In this paper, the cohesive strength of girders is estimated using the theory. To simplify for calculation, the figure shows two regression lines. For σ_n / f'_c less than 0.15, the shear strength is governed by a tensile strength of the interface. Note that the tensile strength does not mean that of either concrete. On the other hand, for σ_n / f'_c more than 0.15, the shear strength is governed by a compressive or bearing strength of inferior concrete.

With regard to behavior of interface failure of composite reinforced concrete girders subjected to monotonic flexure loading, Hanson[1] described as follows; bending cracks rapidly propagated after cracking, followed by slipping along the interface. But the slipped area did not reach the end of the girder since a diagonal shear crack of web preceded. Whereas, composite prestressed concrete girders tested by PWRI and JPCA late 1990s[8] failed due to the slip along the interface reaching the end of the girders. Diagonal shear cracks near the support point seemed to be prevented by prestressing force.

Based on results of composite reinforced concrete girders carried out by Loov and Patnaik,[10] the influence of width of the contact surface on the slip load due to interface shear failure is shown in Fig. 6. It can be seen that the slip load was proportional to the width. The result inferred that the cohesion dominated the slip load of the girders.

Test Setup

Details and parameters of specimens are shown in Fig. 7 and Table 1. All specimens were composite prestressed concrete girders. For Beam I, a width of web or the contact surface was 150 mm; #3 bars were arranged across the interface at a bar spacing of 225 mm (Fig. 8). For Beam II, the width of web was 1.5 times as large as that of Beam I, while a cross section area of steel bars across the interface equaled to that of Beam I. The reinforcement ratios of Beam I and Beam II are 0.21 % and 0.14 %, respectively. For Beam III, concrete keys with a size of 30 mm x 50 mm x 150 mm at a spacing of 450 mm were installed instead of the reinforcing bars across the interface (Fig. 9). In addition, extra reinforcing bars and concrete keys were added at the other side of shear span in every specimen for improving the shear strength as the fixed side (Table 1). All areas of the contact surfaces including top of concrete keys were finished by brushing as shown in Figs. 10 and 11. The roughness of the contact surface was determined using a laser displacement transducer set on a linearly-running table. Target cylinder strengths of web and flange were 50 N/mm^2 and 30 N/mm^2. High early strength portland cement was used. All specimens were made of the same batch of concrete for web and flange, respectively. The measured cylinder strengths of concrete at age of beam tests are shown in Table 2. Mechanical properties of reinforcing bars and tendons are shown in Table 3. The interface was once trowelled just after placing. Brush-finishing was applied two hours after placing. Web concrete was cured by wet covering. Prestressing was introduced to the web at age 10 days, followed by grouting immediately. The prestressing force was controlled as being 0.21 P_{su} at age of test, where P_{su} is the ultimate tensile strength of tendons. Flange concrete was cast at age 24 days of the web. Subsequently the specimens were cured by wet covering for seven days including heating for three days in winter, followed by staying in room temperature until age of loading tests. A loading scheme is shown in Fig. 7. A loading jack of 3000 kN was used. Prior to the slip of the interface, each specimen was monotonically loaded. Following unloading after the slip, it was loaded again to observe final failure of the slipped girders.

Test Results

Load-displacement curves at midspan are shown in Fig. 12. The cracking load due to bending was monitored by strain gages installed on the bottom of web concrete. Bending cracks propagated to 50 mm below the interface at a load of 550 kN in Beam I and Beam III. Similarly, it occurred at a load of 600 kN in Beam II. The yielding load was determined by measuring strains on longitudinal reinforcing bars. Beam I and Beam III was not yielded prior to slipping. But the longitudinal reinforcing bars in Beam II were yielded before slipping, so that the curve was somewhat influenced. Failure of Beam I just after slipping is illustrated in Fig. 13. The slip due to interface shear suddenly took place. At the slip, a slipped area was observed from most of the pure bending area to the end of the girder similarly to the results of the former tests using symmetrical girders as previously described[8]. While it does not appear in this figure, small bending cracks were observed under the opposite side of the flange. Beam I and Beam III was slipped at the test side. But the slip of Beam II unexpectedly occurred at the fixed side having the additional concrete keys. The curve of Beam III was similar to that of Beam I prior to the slip. The slip load of Beam II was 1.6 times as large as that of Beam I or Beam III.

At reloading, the load-displacement curve crossed a point at just after slipping. Rapid increase of displacement was observed after passing through the point. All specimens collapsed due to compressive failure of the web with spalling of side cover concrete. The slipped area was not expanded by reloading.

After the loading test a flange section of Beam III was cut off. The slipped surface of the flange is shown in Fig. 14. Coarse aggregates were observed in the surfaces of concrete keys failed along the interface. A part of flange concrete was hollowed out at a loading point. In the other area, trace of the blush-finished surface was observed. A significant difference of failure type between the hollowed area and the other area was found. The difference inferred that a large normal force due to loading influenced the shear resistance of the interface.

Shear Resistance due to Cohesion Considering Normal Stress

When compared between Beam I and Beam II, a difference of the interface width linearly influenced the slip loads despite the same cross section area of reinforcing bars. In addition, the slip load of Beam I with the reinforcing bars across the interface was approximately as much as that of Beam III without reinforcing bar. From the results, the slip loads of three specimens seemed to be dominated by cohesion of the interface. This result corresponded to the results of various push-off tests indicating that the interface shear strength for the reinforcement ratio less than about 0.5 % depended on cohesion.

To determine the normal stress on the interface of the specimens, 3D-elastic FEM analysis using a monolithic model was carried out for each beam. Figure 15 shows a distribution of the normal stress acting on the top of web obtained from the analysis for Beam III at the slip load. In the figure, the normal stress distribution was averaged in width, being normalized by f'_c. In Fig. 16, a distribution of the normalized shear strength v_u / f'_c estimated using Fig. 5 and Fig. 15 is shown. It can be seen that around center of the shear span, even the tensile normal stress slightly occurred, the shear strength was still effective. Subsequently, the shear resistance force at the interface due to cohesion was estimated by integrating the distribution of v_u / f'_c from a loading point to a support point as shown in Fig. 16 and multiplying by the width of interface. Following that, the slip load corresponding to the shear resistance force was calculated based on elastic analogy. The results are shown in Table 4. The estimated slip loads well agreed with the test results. It was recognized that the slip loads of three specimens was caused by cohesion of the interface. To understand a degree of the influence of the normal stress, the slip loads ignoring the normal stress are shown in Table 4. The slip loads were approximately 1.7 times (1 / 0.60) of the ignored slip load. From the result, it was found that the influence of the normal stress should be taken into account for the estimation.

For the brush-finished interface like the specimens as shown in Fig. 5, the normalized normal stress σ_n / f'_c more than 0.15 yields compressively-dominated failure. Although the normalized normal stress σ_n / f'_c was less than 0.15 in all slipped area as shown in Fig. 15, the failed surface of Beam III shown in Fig. 14 indicated that the hollowed area at a loading point seemed to be slipped due to the compressively-dominated failure. A potential eccentricity of local stress distribution under loading was likely to yield the type of failure.

Assuming that the shear strength of the concrete keys corresponded to monolithic concrete, the effect of concrete keys was estimated using the above method. The estimated slip load for Beam III with concrete keys is shown with parentheses in Table 4. The result of calculation shows as if the concrete keys were effective, but test data did not show such effect of the concrete keys. The test results were obtained from that the slip load of Beam III with concrete keys was similar to that of Beam I without concrete key, and that the slip of Beam II was observed on the fixed side with concrete keys. In the research by Hanson[1], it was observed that concrete keys installed on the rough interface were not effective, while the concrete keys with smooth surface were apparently effective. The similar phenomenon seemed to happen in these girder tests.

Roll of reinforcing bars across interface

Since the shear resistance of the interface in the composite prestressed concrete girders depended on cohesion, reinforcing bars across the interface were ineffective for providing the maximum shear resistance and rigidity prior to the slip. Nevertheless, cohesive failure of joints in concrete is mostly vulnerable and irreversible, requiring some considerations against unexpected actions during construction and service.[21,22]

For small contact area available to slip slightly, like bearing joints of precast concrete beams in building subjected to earthquake, the reinforcement is adequately arranged according to the requirement based on the shear friction theory. On the other hand, for large contact area like the composite prestressed concrete girders, contribution of shear friction requiring the reinforcing bars seemed to be invalid. But the provision of the minimum reinforcement ratio requires relatively large area of reinforcement in proportion to the contact area. From the above results, it is obvious that the reinforcement has rare opportunity to play a role for preventing the slip along the interface. Thus, the provision seems not to be always appropriate, while being conservative. Particularly, for the wide flange type precast girders providing a wider area of the interface, the working shear stress along the interface decreases with the width. It is likely to say that the provision of the minimum reinforcement ratio is too conservative for the wide flange type of the composite girders. It is reasonable for satisfying the design of interface shear that web stirrups required for the shear resistance of a monolithic girder are extended to flange across the interface and adequately anchored.

Conclusions

For reexamining shear transfer of the composite prestressed concrete girders, interface shear tests of three specimens of girder type were conducted. In addition, an estimation method of the slip load due to cohesion was provided, being considered the influence of the normal stress on cohesion. The estimated slip loads due to cohesion incorporating the normal stress well corresponded to the slip loads obtained from the tests. Similarly to the previous results of push-off tests that shear failure of the interface with low reinforcement ratio depends on cohesion (bond) between concrete, the shear failure of three girders with the reinforcement ratio less than 0.2 % were dominated by cohesion. In contrast with the push-off tests, the normal stress acting on the interface should be taken into account for predicting the slip loads of the composite girder specimens.

Recommendations

The interface shear resistance V_u for composite prestressed concrete girders should be taken as:

$$V_u = k_c \cdot f'_{cd} \cdot A_c \qquad (1)$$

where:

k_c = cohesion factor (= v_u / f'_c, corresponding to vertical axis of Fig. 4 and 5)
for rough surface using retarder, $k_c = 0.05$
for brash-finishing, $k_c = 0.035$
The values were determined based on test data[8] shown in Table 5.

f'_{cd} = design cylinder strength of concrete (N/mm^2, inferior side of concrete)

Since large slip displacement already occurred when the maximum performance of the reinforcement across the interface would exhibit, contribution of the reinforcement was not included in Eq. (1). The influence of the normal stress on the interface shear resistance is significant. But since the interface shear strength is sufficiently obtained even using Eq. (1) not considering the normal stress when compared with current Japanese design as shown in Fig. 1, the influence was ignored in the equation. The reinforcement across interface should be taken into account as described above.

Acknowledgments

This research was conducted in the cooperative Research on Connections of Precast Prestressed Concrete Elements for Bridges by PWRI and the Japan Prestressed Concrete Contractors Association (JPCA) in FY2005-2006.

References

1. Hanson, N.W., *Horizontal shear connections, Precast-prestressed concrete bridges*, PCA Bulletin D35, May 1960.
2. Mattock, A.H. and Karr, P.H., *Precast-prestressed concrete bridges 4. Shear tests of continuous girders*,

PCA Bulletin D45, 1961.
3. ACI-ASCE Committee 333, Tentative recommendations for design of composite beams and girders for buildings, *Journal of ACI*, 57-12, pp.609-628, December 1960.
4. Abe, H., Takechi, T. and Nakashima, T., Experimental study for shear strength of the interface between concrete beam and deck with PC composite bridges, *Proc. of 14th Symposium on Developments in Prestressed Concrete*, pp.147-150, November 2005. (in Japanese)
5. PWRI and JPCA, *Cooperative Research Report on Connections of Precast Prestressed Concrete Elements for Bridges, Part I*, PWRI Cooperative Research Report No. 362, Tsukuba, Japan, February 2007. (in Japanese)
6. Otofuji, K., Sasado, M., Hamamoto, T., Mikoshiba, M. and Onishi, S., Study on the joint face of composite concrete girder, *Journal of Japan Prestressed Concrete Engineering Association*, 9-2, pp.8-18, April 1967. (in Japanese)
7. Anderson, R.A., Composite designs in precast and cast-in-place concrete, *Progressive Architecture*, 41-9, pp.172-179, Sep. 1960.
8. PWRI and JPCA, *Cooperative Research Report on Labor-Saving of Design and Construction of Concrete Bridges, Part II Study on Composite Prestressed Concrete Girders*, PWRI Cooperative Research Report No. 215, Tsukuba, Japan, December 1998. (in Japanese)
9. Saemann, J.C. and Washa, G.W., Horizontal shear connections between precast beams and cast-in-place slabs, *Journal of ACI*, pp. 1383-1409, Nov. 1964.
10. Loov, R.E. and Patnaik, A.K., Horizontal shear strength of composite concrete beams with rough interface, *PCI Journal*, 39-1, pp.48-69, Jan.-Feb. 1994.
11. Patnaik, A.K., Behavior of composite concrete beams with smooth interface, *Journal of Structural Engineering*, ASCE, 127-4, pp.359-366, April 2000.
12. PWRI and JPCA, *Cooperative Research Report on Connections of Precast Prestressed Concrete Elements for Bridges, Part II Behavior of Dowel Reinforcing Bars and Studs*, PWRI Cooperative Research Report No. 370, Tsukuba, Japan, March 2008. (in Japanese)
13. PWRI and JPCA, *Cooperative Research Report on Connections of Precast Prestressed Concrete Elements for Bridges, Part III Shear Transfer of Composite Concrete Girders*, PWRI Cooperative Research Report No. 383, Tsukuba, Japan, March 2008. (in Japanese)
14. LRFD Bridge Design Specifications, 4th ed., AASHTO, 2007.
15. Eurocode 2: *Design of concrete structures* Part 1.1: General rules and rules for buildings (EN1992-1-1), 2004.
16. Japan Road Association, *Specifications for Highway Bridges, Part III*, 2002. (in Japanese)
17. Mattock, A.H. and Hawkins, N.W., Shear transfer in reinforced concrete-Recent research, *PCI Journal*, pp.55-75, March-April 1972.
18. Walraven, J.C. and Reinhardt, H.W., *Theory and experiments on the mechanical behavior of cracks in plain and reinforced concrete subjected to shear loading*, Heron, Vol.26, 1981.
19. Walraven, J.C., Frenay, J. W. and Pruijssers A., Influence of concrete strength and load history on the shear friction capacity of concrete members, *PCI Journal*, pp.66-84, Jan.-Feb., 1987.
20. Okada, T., Study on shear transfer across concrete joint interfaces, *Proceedings of JSCE*, No. 502, Japan Society for Civil Engineers, pp. 73-82, 1994.11. (in Japanese)
21. Birkeland, P.W. and Birkeland, H.W., Connections in precast concrete construction, *Journal of ACI*, pp.345-368, March 1966.
22. Mast, R.F., Auxiliary reinforcement in concrete connections, *Proceedings of ASCE*, ST6, pp.1485-1504, June 1968.
23. Paulay, T., Park, R. and Phillips, M.H., Horizontal construction joints in cast-in-place reinforced concrete, *Shear in Reinforced Concrete*, ACI SP-42, Vol.2, pp.599-616, 1974.
24. Ito, S., Ono, T. and Ueno, H., On the shearing strength of concrete, *Reports for PWRI*, No. 100, pp.133-143, 1959.1. (in Japanese)
25. Hofbeck, J.A., Ibrahim, I.O. and Mattock, A.H., Shear transfer in reinforced concrete, *ACI Journal*, pp.119-128, February 1969.

Table 1 Parameters of specimens

<table>
<tr><th rowspan="3">Specimen</th><th rowspan="3">Span (mm)</th><th rowspan="3">Height (mm)</th><th rowspan="3">Width of web (mm)</th><th colspan="6">Interface</th></tr>
<tr><th rowspan="2">Width b (mm)</th><th colspan="2">Fixed side</th><th colspan="2">Test side</th><th rowspan="2">Type of finishing</th></tr>
<tr><th>Reinforce -ment ratio (%)</th><th>Spacing of concrete keys (mm)</th><th>Reinforce -ment ratio (%)</th><th>Spacing of concrete keys (mm)</th></tr>
<tr><td>Beam I</td><td rowspan="3">3500</td><td rowspan="3">600</td><td colspan="2">150</td><td>0.21</td><td>450</td><td>0.21</td><td>none</td><td rowspan="3">Brushing</td></tr>
<tr><td>Beam II</td><td colspan="2">225</td><td>0.14</td><td>450</td><td>0.14</td><td>none</td></tr>
<tr><td>Beam III</td><td colspan="2">150</td><td>0.21</td><td>225</td><td>0</td><td>450</td></tr>
</table>

note: 1. Reinforcement ratio p = Cross section area of a reinforcing bar / (b x (bar spacing))
2. Size of concrete key : 30 mm x 50 mm x b

Table 2 Cylinder strength of concrete at age of beam tests (N/mm^2)

Specimen	Flange	Web
Beam I	39.6	54.1
Beam II	40.7	50.6
Beam III	42.1	55.2

Table 3 Properties of reinforcing bars and tendon

Size	Yield point (N/mm^2)	Tensile strength (N/mm^2)	Modulus of elasticity (kN/mm^2)	Remarks
#3	370	517	194	across interface
#4	354	501	197	stirrups and others
#7	394	565	195	longitudinal bars
Dia. 32 mm	1132	1164	207	tendons

Table 4 Comparison of test results with the calculated slip load due to cohesion

Specimen	Beam I	Beam II	Beam III
Calculated shear resistance force due to cohesion, kN	873	1259	924 (989)
Calculated slip load $P_{u,cal}$, kN	601	926	631 (675)
Measured slip load $P_{u,ex}$, kN	591	957	620 (620)
$P_{u,ex}$ / $P_{u,cal}$	0.98	1.03	0.98 (0.92)
Calculated shear resistance force due to cohesion ignoring normal force, kN	515	794	548
Calculated slip load ignoring normal force $P_{u,cal2}$, kN	355	584	374
$P_{u,cal2}$ / $P_{u,cal}$	0.60	0.61	0.60
Measured roughness of contact surface, R_{zj}, mm	0.73	0.91	0.82

note: The cylinder strength of flange was applied for the calculation, being lower than that of web.
Parentheses indicate results of calculation considering influence of concrete keys.

Table 5 Samples of cohesion factor k_c (= v_u / f'_c)

Type of finishing	Average	S.D.	Minimum	Number of data
Brushing	0.037	0.014	0.023	18
Brushing, delayed	0.066	0.013	0.048	6
Retarder	0.051	0.007	0.047	6
Trowelling	0.023	0.003	0.020	6

note: These data were obtained from push-off tests conducted by PWRI and JPCA(1998).[8]

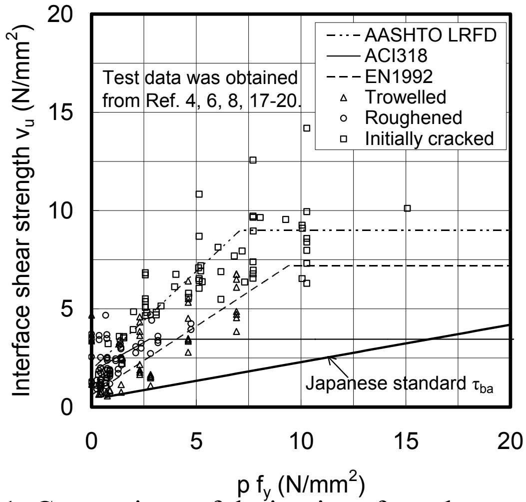
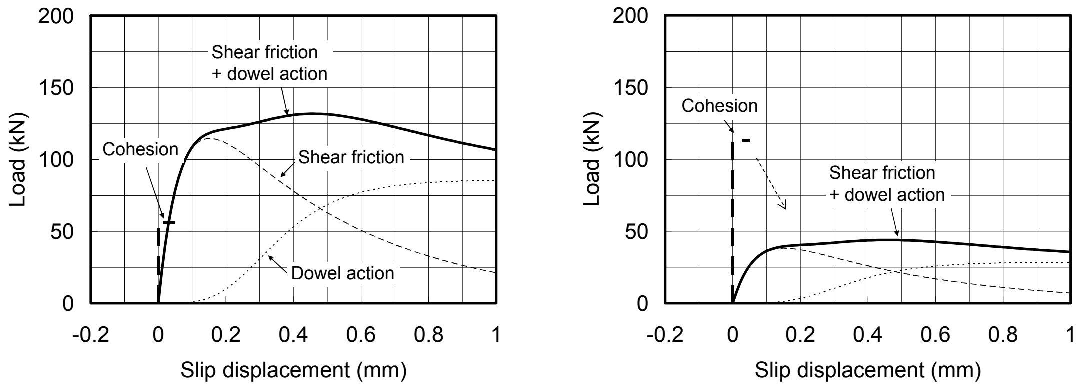


Fig. 1 Comparison of design interface shear strengths

note: Rough interface, normal concrete, f'_c = 30 N/mm², f_y = 345 N/mm² for drawing the lines



(a) p = 2.7 % (b) p = 0.4 %

Fig. 2 Influence of interface reinforcing ratio on contribution due to cohesion, shear friction and dowel action[12]

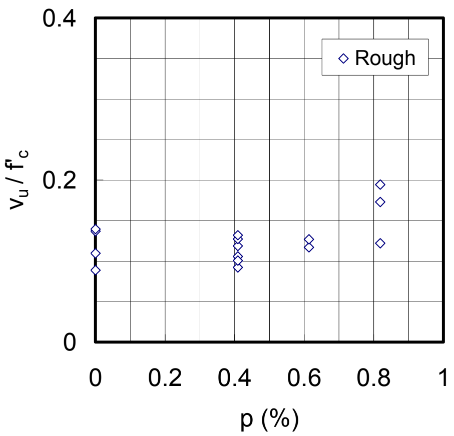


Fig. 3 Relationship between p and v_u/f'_c obtained from Hanson's results[1]

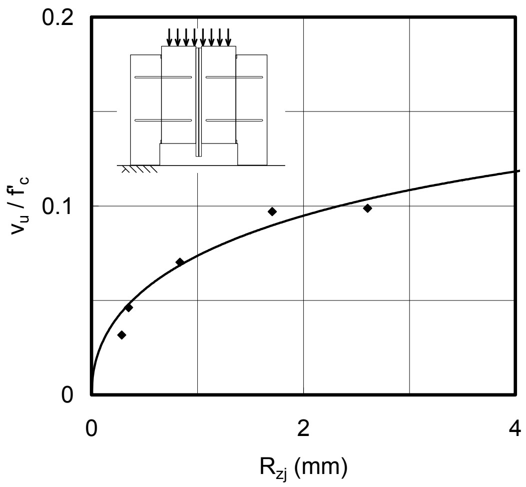


Fig. 4 Results of push-off tests of specimens with various roughness of contact surface, p = 0.1 - 0.2 % [5]

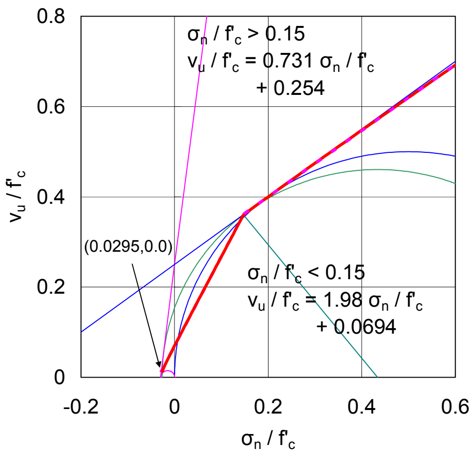


Fig. 5 Relationship between shear strength and normal stress for brash-finished contact surface based on the modified Cowan theory[12]

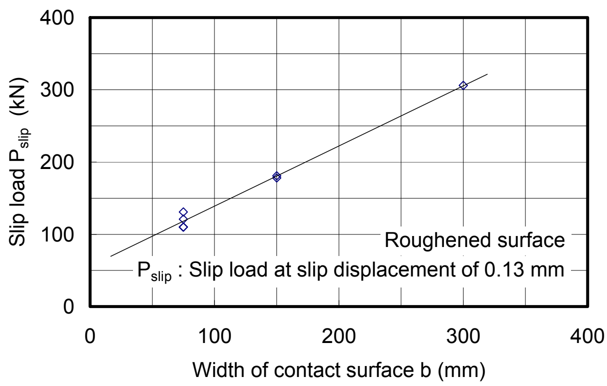


Fig. 6 Influence of width of contact surface on slip load
Data was obtained from Loov and Patnaik(1994).[10]

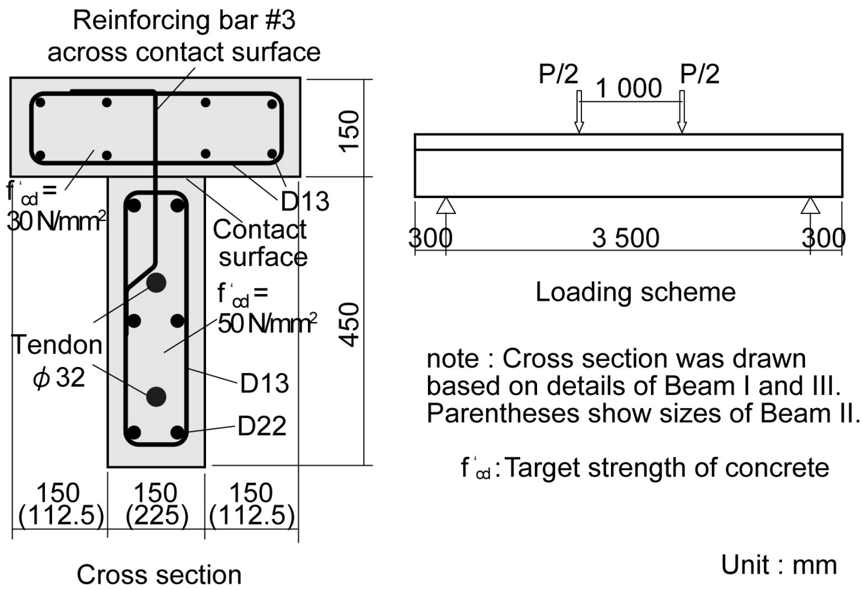


Fig. 7 Details of specimen

Fig. 8 Reinforcing bars across contact surface

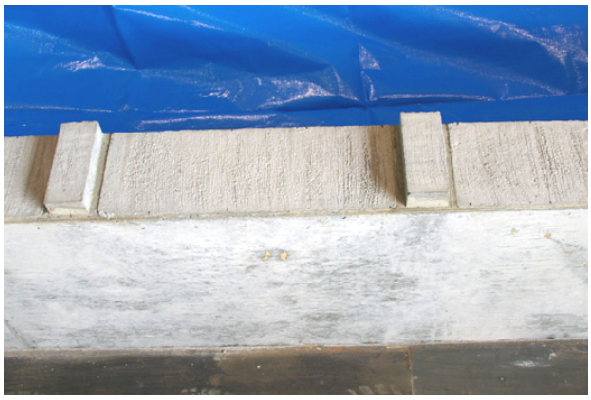


Fig. 9 Concrete keys

Fig. 10 Brushing with typical Japanese bloom

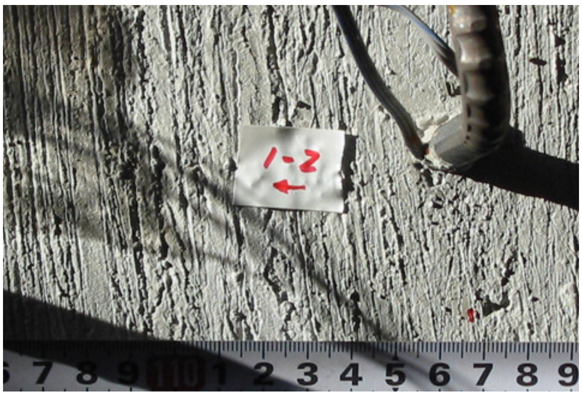
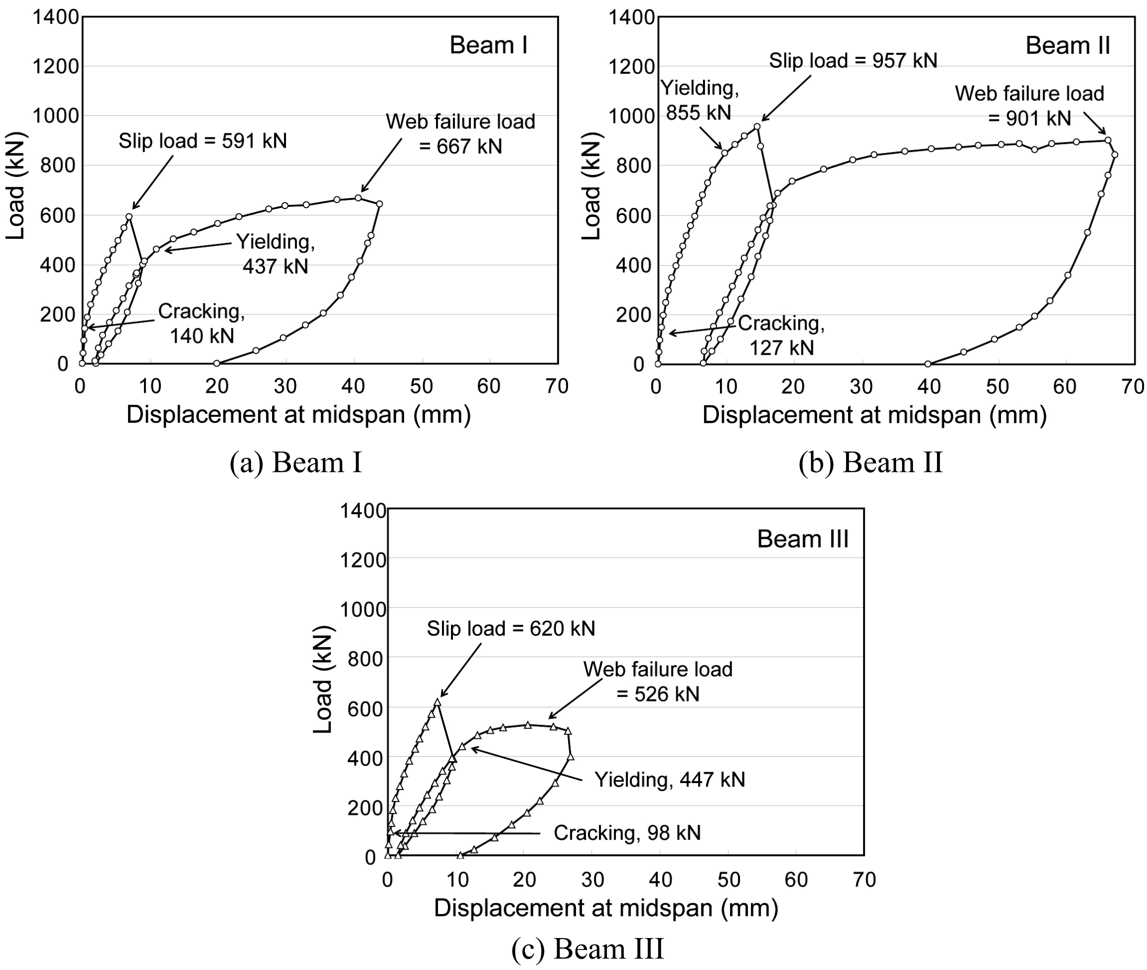


Fig. 11 Brush-finished surface



(a) Beam I

(b) Beam II

(c) Beam III

Fig. 12 Load - displacement curves

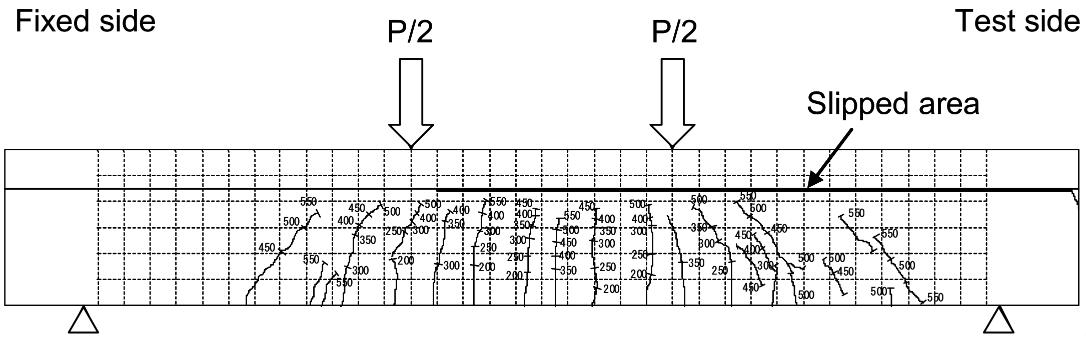


Fig. 13 Failure of Beam I just after slipping

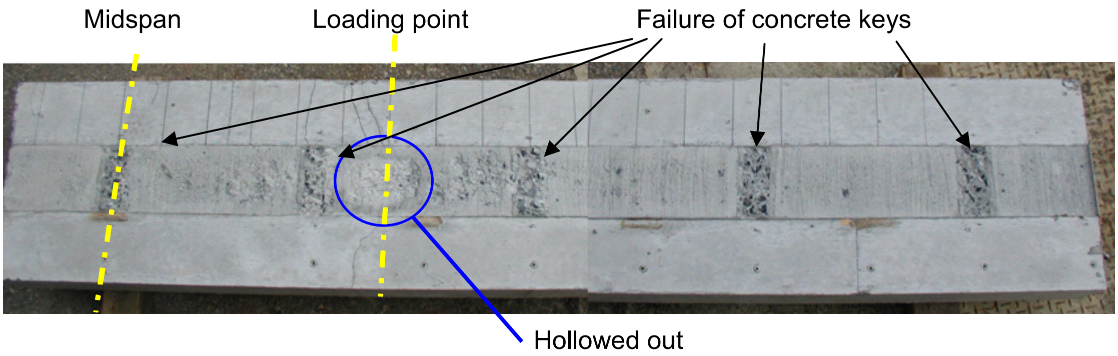


Fig. 14 Contact surface of flange after test, Test side of Beam III

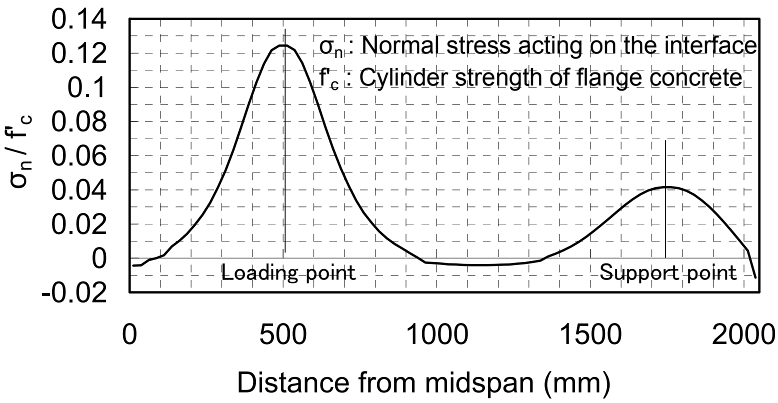


Fig. 15 Distribution of normal stress acting on the interface
at the maximum load of 620 kN, Beam III

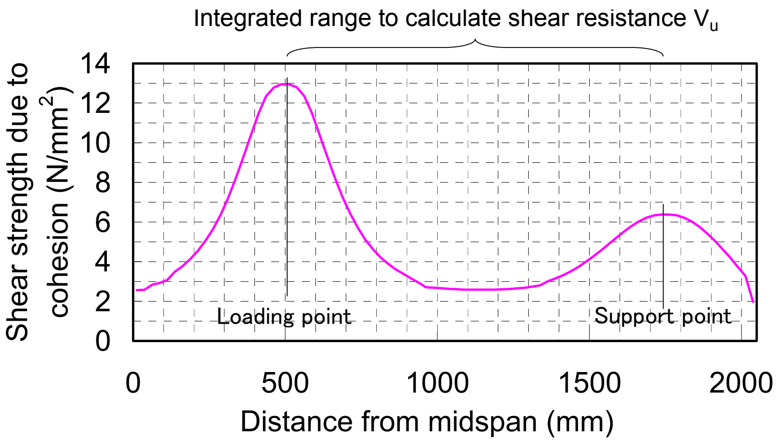


Fig. 16 Distribution of shear strength due to cohesion
at the maximum load of 620 kN, Beam III