

EXPERIMENTAL AND ANALYTICAL INVESTIGATION ON FAILURE BEHAVIOR OF STEEL PLATE – HPFRC COMPOSITE BEAMS

Yasuhiko Sato (1), Ryosuke Shionaga (2) and Yoshihiko Nakamura (3)

(1) Hokkaido University, Sapporo, Japan

(2) IHI corporation, Tokyo, Japan

(3) IHI Infrastructure Systems Co., Ltd.

Abstract

In this study, direct shear tests of HPFRC - steel plate composite elements are conducted so as to evaluate shear stress – relative displacement curves of the interfaces. Besides three-point loading experiments of the HPFRC - steel plate composite beams were conducted. In those experiments, kinds of resins and shear keys and its combinations applied in the interface are chosen as parameters. In this paper, how the interface affects the mechanical behaviour of the composite elements and beams is discussed. Furthermore, Finite Element Analyses, in which the shear stress – relative displacement curves found in the direct shear tests were installed, are performed to examine the failure mechanism of the composite beams. The paper describes that the ultimate load of the HPFRC and the steel plate composite beams is determined by interface failure and the FE analysis can predict the behaviour reasonably.

Résumé

Dans cette étude des essais de cisaillement direct de dalles composites BFUP / tôle en acier sont réalisés afin de déterminer les contraintes de cisaillement et les déplacements relatifs à l'interface acier BFUP. Par ailleurs, des essais de flexion trois points de barreau composite BFUP / plaque acier ont été réalisés. Dans ces essais, plusieurs sortes de résine de connexion et/ou de connecteurs sont testées. Cet article expose comment l'interface affecte le comportement mécanique des éléments composites. En outre, des analyses par éléments finis, dans lequel la loi de comportement contrainte de cisaillement / courbes de déplacement relatifs trouvés dans les essais de cisaillement direct sont effectuées afin d'examiner le mécanisme de rupture des éléments composite. L'article montre que la charge ultime de la dalle composite BFUP / acier est déterminée par la rupture de l'interface et que l'analyse par éléments finis fournit une prévision correcte du comportement de la structure.

1. INTRODUCTION

Countermeasure of orthotropic steel decks is one of worldwide issues for developing sustainable society. Several researches have been done so as to improve durability and serviceability of bridge decks before now [1][2]. In Japan, a few years ago, fatigue cracks in orthotropic decks were found [3] and the mechanism of the damage has been investigated [4]. Repairing and/or strengthening of the orthotropic steel decks are now urgent issue as well as other advanced nations. To prevent severe damage in the old orthotropic steel decks, in general, SFRC overlay with 50 to 80 mm thickness is applied in practice [5]. However there are some issues of concern on speed of construction and long-term bond behavior of the interface between the SFRC and the steel deck.

Authors have developed High Performance Fibre Reinforced Concrete (HPFRC), which contains rapid curing ability and somewhat lower flow ability based on the mixture that we have developed as a reinforcing material for reinforced concrete members [6], under the assumption that the HPFRC will be cast on a steel deck with relatively greater bridge plate slope. The HPFRC has 1 vol.% of 13 mm straight steel fibres and compressive strength of around 30 N/mm² at 3 hours and 80 N/mm² at 28 days.

In this study, direct shear tests of HPFRC - steel plate composite elements are conducted so as to evaluate shear stress – relative displacement curves of the interfaces. Besides three-point loading experiments of the HPFRC - steel plate composite beams were conducted. In those experiments, kinds of resins and shear keys and its combinations applied in the interface are chosen as parameters. In this paper, how the interface affects the mechanical behaviour of the composite elements and beams is discussed. Furthermore, Finite Element Analyses, in which the shear stress – relative displacement curves found in the direct shear tests were installed, are performed to examine the failure mechanism of the composite beams.

2. OUTLINE OF EXPERIMENTS

2.1 HPFRC used

To make the HPFRC, normal Portland cement, fine aggregate, silica fume, expansion agent, steel short fibres, and tap water were mixed with a forced mixing type mixer. The fine aggregates were inland sand and the maximum aggregate size was 5 mm. The length of straight steel fibres was 13 mm and the diameter was 0.16 mm. The tensile strength of fibres was above 2000 N/mm².

The target flow of fresh state and compressive strength at 28 days based on the JIS standard test were set to 110 -140 mm and 80 N/mm², respectively. The average of the observed flow values was about 120 mm and compressive strengths at 3 hours and 28 days were above 30 and 80 N/mm² respectively.

2.2 Outline of direct shear test

Direct shear tests were conducted. Overall view of the test is shown in Photo 1. The load was applied on a front face of the HPFRC by a



Photo 1 Overall view of direct shear test

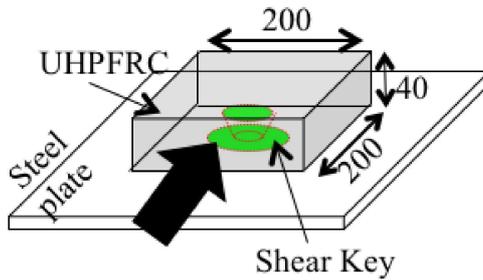


Figure 1 Specimen of direct shear test

hydraulic jack as shown in Fig.1 and relative displacement between the HPFRC and the steel plate was measured by transducers.

HPFRC with 40 mm thickness was casted on a steel plate with 12 mm thickness where a resin and/or a shear key were placed on the plate to unite as a composite structure. In this study, five HPFRC-steel plate elements with different interfaces where types and combinations of resins and/or shear keys

were varied were prepared as shown in Table 2. Amount of resin in all cases was controlled by weight

Table 2: Details of specimens for direct shear test and experimental results

	Shear key-Plate Interface		Resign for HPFRC-Plate Interface	Maximum load (kN)	Failure mode*1
	Shear Key	Resign			
I1	–	–	R1	56.8	UP1
I2	–	–	R2	28.1	UP2
I3	A	R3	–	37.2	SP
I4	B	R3	–	38.8	SP
I5	C	R3	–	18.0	SP

*1 UP1 : cohesion failure on HPFRC surface, UP2 : adhesion failure of resign,
 SP : resign failure between shear key and steel plate

Table 3: Young's modulus of resigns used

	Kinds of resign	Young's modulus (N/mm ²)
R1	Epoxy	2770
R2	Epoxy	2000
R3	Acrylate	1200

Type	A	B	C
Bolt	M16 bolt with POM	M16 bolt with POM	M16 Flat Head Bolt with POM
Plate	3.2mm thick	2.3 mm thick	2.3 mm thick with pre-cut

Figure 2: Types of shear keys

The types of resin and Young's modulus are shown in Table 3. The resins R1 and R2 were used as an adhesive between the HPFRC and steel plate while the resin R3 was used as adhesive between the shear key and the steel plate. In this study, three kinds of shear keys shown in Fig.2 were used. Shear keys A, B, and C have a polyoxymethylene resin covering material at a bolt head. In a circular steel plate of shear key C, some pre-cut were installed radially with the view to prevent rapid propagation of interface delamination between the circular steel plate of the shear key and the steel plate.

2.3 Outline of three-point loading experiment

The three-point loading tests were carried out to evaluate capacities of HPFRC-steel plate composite beams. In this study, five composite beams with the interfaces examined in the direct shear test were prepared as shown in Table 4. The size of specimen is 2.4 m long, 0.4 m width, and 52 mm overall thickness consists of 40 mm thickness HPFRC and 12 mm thickness steel plate as shown in Fig. 3. In specimens No.3 to No.5, six shear keys were attached by a resin with the space of 400 mm in an axial direction. The load was applied monotonically at the center of span and the mid-span deflection was measured by a transducer.

Table 4: List of composite beam specimens and results

Beam specimen	Interface	Maximum load (kN)		P_{exp}/P_{FEM}
		Exp.	FEM	
No.1	I1	66.6	26.6	2.05
No.2	I2	21.6	49.7	0.43
No.3	I2+I5	36.9	51.3	0.74
No.4	I3	17.0	14.3	1.19
No.5	I4	21.6	16.1	1.34

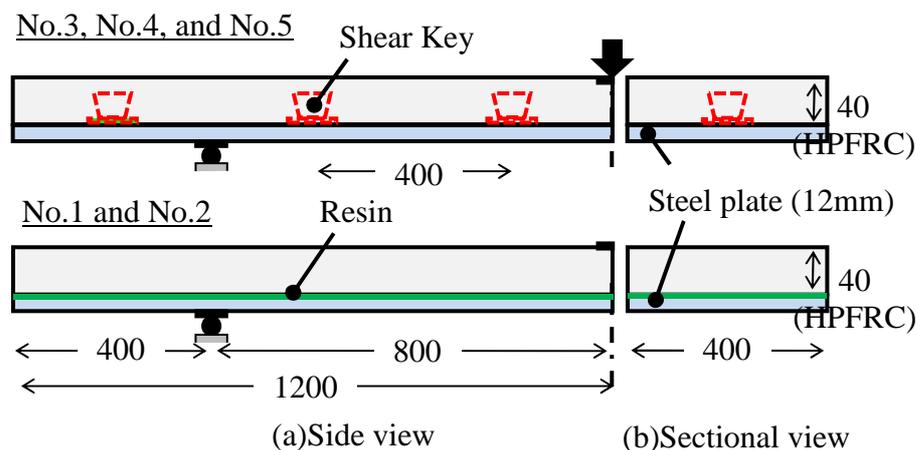


Figure 3: Composite beam specimen (a half span)

3. EXPERIMENTAL RESULTS

3.1 Results of direct shear test

The failure mode and the maximum load observed are shown in Table 2. The shear stress and relative displacement curves of all specimens are shown in Fig.4. The shear stress is the value where applied load was divided by bonded area 40 X 40 mm.

In specimens I1 and I2 without any shear key, the cohesive failure of HPFRC surface and the adhesive failure on the steel plate were found respectively. In other specimens with the shear key, interface failure between shear key and steel plate was found.

The specimens I5 with the shear key which has the precut circular plate show rather ductile behavior than others. Although those specimens have the similar shear key, the shear strengths are greatly different. Among the specimens, the bonding method using epoxy resin between the HPFRC and the steel plate shows higher performance.

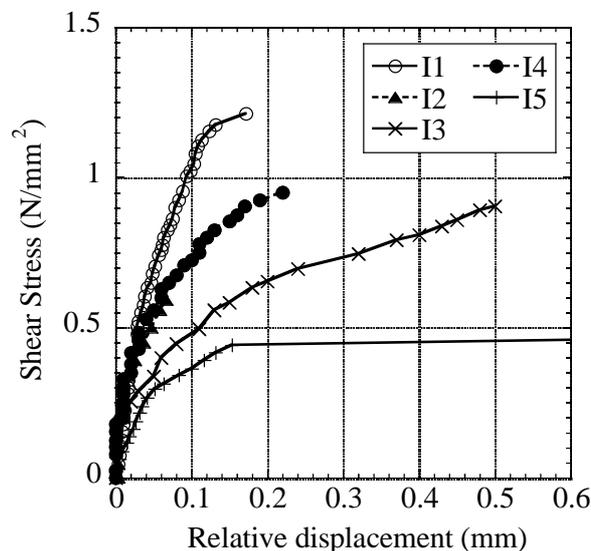


Figure 4: Relationships between shear stress and relative displacement

3.2 Results of beam test

The failure mode and the maximum load of the composite beams are shown in Table 4. In all specimens, visible flexural nor shear cracks in HPFRC could not be founded at any load step and finally interface delamination between the panel and the plate was observed. Especially the delamination failure in the specimens with shear keys was caused by interface failure between shear keys and the steel plate.

Figure 5 shows the relationships between load and mid-span deflection. The specimens with shear keys show ductile behaviour while the specimens without the shear keys shows a brittle manner. This tendency is very similar to that in the direct shear test. However the magnitude relation in capacity is unlike shear strengths observed in the direct shear test. It must be noted that a shear key in the beam covers area of 400 X 400 mm which is two times larger than the area in the direct shear test. The further discussion on the capacity of the beams will be conducted in next chapter with the comparison with finite element analysis.

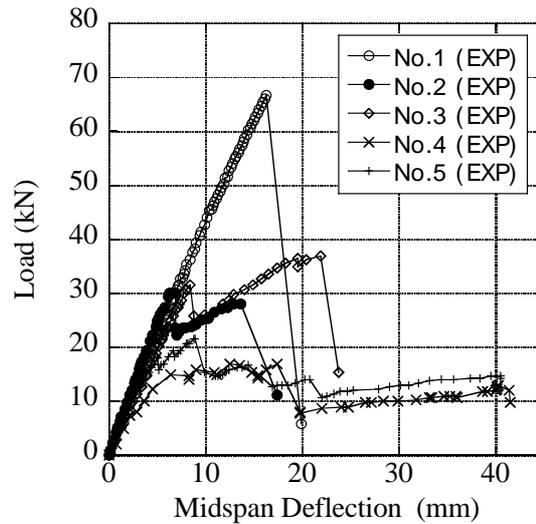


Figure 5: Relationships between load and mid-span deflections

4. ANALYTICAL INVESTIGATION USING FINITE ELEMENT ANALYSIS

4.1 Finite element program and constitutive laws

In this study, analyses were carried out with a 3D nonlinear FE program named CAMUI [7], which was created by laboratory of engineering for maintenance system at Hokkaido University. A solid element containing 20 nodes and 8 gauss integration points is used in this program. A nonlinear concrete and steel model was implemented for the element. A sixteen-node isoparametric interface element was also applied. In this study, interface elements are prepared between HPFRC and steel elements as shown in Fig. 6. In the interface elements, the shear stress – relative displacement curves in 400 mm X 400 mm area, shown in Fig. 7, are installed. The curves were obtained based on the shear stress and relative displacement relations observed in the direct shear test with the bonding area of 200 mm X 200 mm. Fig. 8 shows the relationships between tensile stress and crack width for HPFRC [6] used in the analysis.

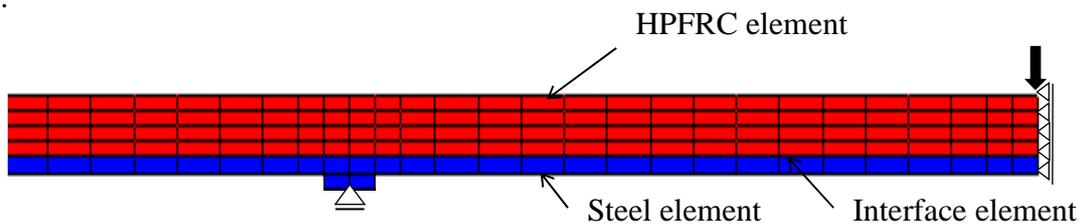


Figure 6: Finite element mesh

4.2 Load-displacement curves and ultimate load

Figure 9 shows the relationships between applied load and mid-span deflection predicted by the FE program. The maximum loads in the analysis and the ratio of analytical and experimental ultimate loads are shown in Table 4. In the case of specimens with shear keys, overall trend seems to be the same as experimental results. However the analytical maximum loads of the specimens without shear key are very different from the experimental results. The

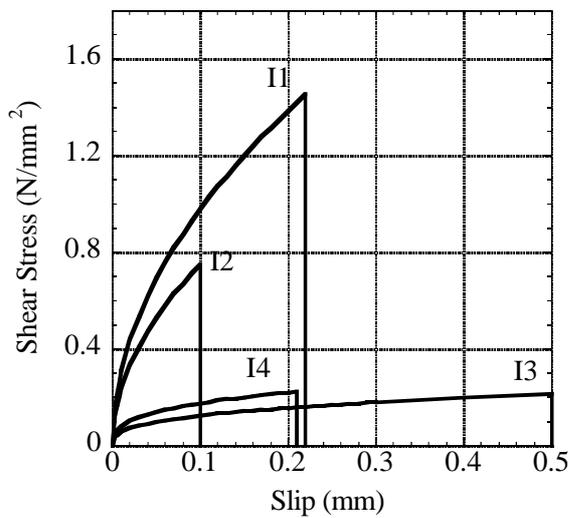


Figure 7: Interface models for FEM

experimental maximum load in specimens No.1 and No.2 are 2.5 and 0.43 times of the analytical capacity, respectively.

At casting of HPFRC in specimen No.1, the resin put on steel plate was started to move as shown in Photo 2. As a result, thickness of resin became non-uniform distribution. The result may affect the delamination strength of interface between the HPFRC and the steel plate.

4.3 Failure mechanism

Figure 10 shows shear stress distributions in interface elements in analysis and shear stresses observed in the experiment. The experimental shear stresses are calculated using strains attached on a side face of steel plate. In the analysis, the load was dropped immediately after the shear stress reached to the strength at 800 mm from the plate end where is the middle of the shear span. Because HPFRC has very high tensile strength, delamination between HPFRC and steel plate would dominate over the beam behaviour before flexural or shear failure occurs.

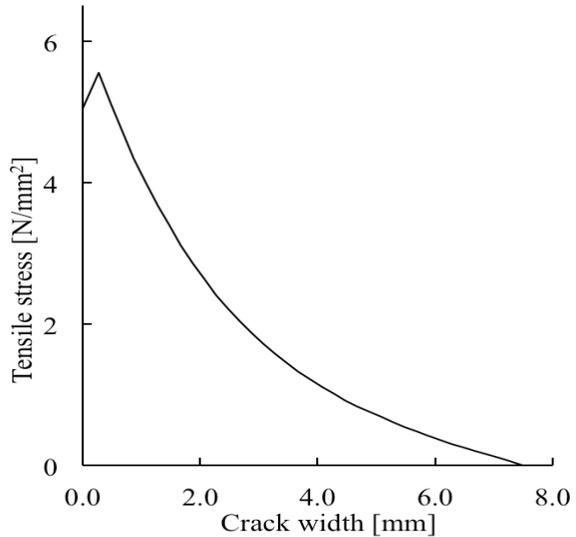


Figure 8: Tension model for HPFRC

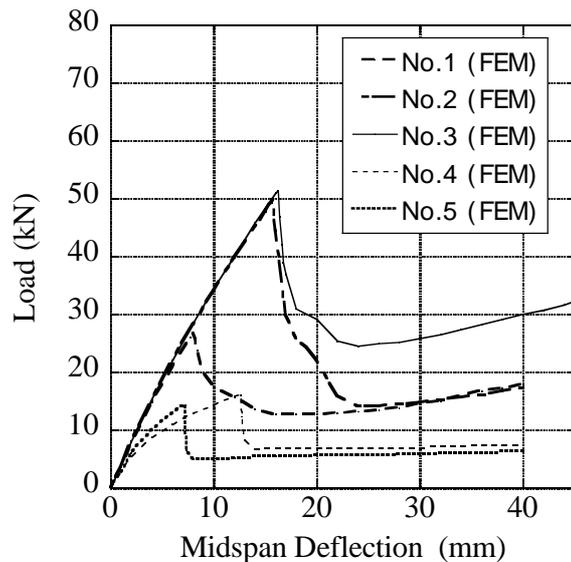


Figure 9: Relationships between load and midspan deflections (FEM)



Photo 2: Resin flow at HPFRC casting

5. CONCLUSIONS

The following findings are obtained in the experimental and analytical examinations.

In the direct shear test and the beam test of HPFRC-steel plate composite members, the bonding method using epoxy resin between the HPFRC and the steel plate shows higher performance. However the delamination strength is very affected by thickness of the resin.

3D finite element analyses with interface models derived from the direct shear test can simulate the composite beam behaviour reasonably.

The ultimate load of the HPFRC and the steel plate composite beams is determined by interface failure before flexural or shear failure does take place, because the HPFRC has high tensile strength.

ACKNOWLEDGEMENTS

The authors would like to express their appreciation to Mr. Ryota Naruse and Mr. Daisuke Yamazaki who are former students at laboratory of engineering for maintenance system, Hokkaido University, for supporting experiments and analyses.

REFERENCES

- [1] N. Krstulovic-Opara, A. R. Haghayeghi, M. Haidar, and P. D. Krauss, Use of conventional and high-performance steel-fiber reinforced concrete for bridge deck overlays, *ACI Material Journal*, Vol.92, No.6, pp.669-677, 1995.
- [2] P. Buitelaar, R. Braam, and N. Kaptijn, 'Reinforced high performance concrete overlay system for rehabilitation and strengthening of orthotropic steel bridge decks', 2004 Orthotropic bridge conference, USA, pp.384-401.
- [3] A. Tabata, Y. Takada, and Y. Horie, 'Inspection and reinforcement for fatigue damages on orthotropic steel deck bridge', Technical Note of PWRI, No.4089, pp.205-216, 2007
- [4] C. Miki, H. Suganuma, M. Tomizawa, F. Machida, 'Cause study on fatigue damage in orthotropic steel bridge deck', *Journal of JSCE*, No.780, pp.57-69, 2005 (in Japanese)
- [5] J. Murakoshi, N. Yanadori, and H. Ishii, 'Research on steel fiber reinforced concrete pavement for orthotropic steel deck as a countermeasure for fatigue', Technical Note of PWRI, No.4089, pp.359-372, 2007
- [6] R. Shionaga, Y. Sato, and J. C. Walraven, 'Study on tensile behavior of high performance fiber reinforced mortar with reinforcing bar', *Journal of JSCE*, E2, Vo.66, No.4, pp.366-379, 2010
- [7] R. Takahashi, Y. Sato, K. Konno, and T. Ueda, '3D nonlinear punching shear simulation of steel-concrete composite slab', *Journal of Advanced Concrete Technology*, Vol.3, No.2, pp.297-307, 2005

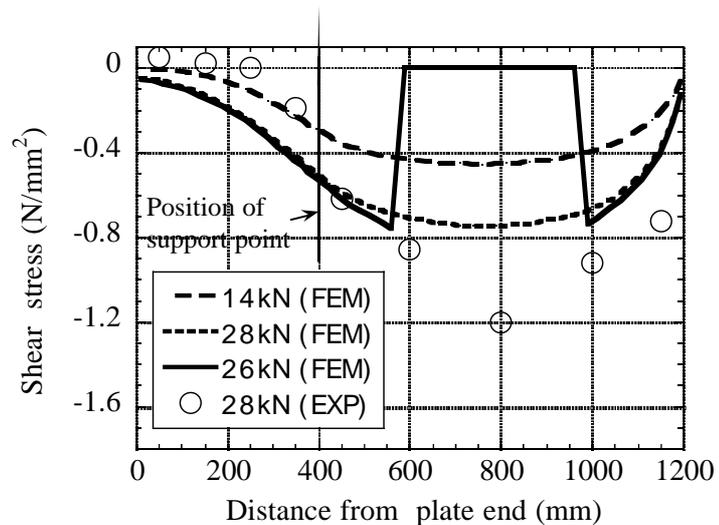


Figure 10 : Shear stress distributions