신구콘크리트 계면의 전단강도 측정을 위한 정하중 및 피로하중 보실험

Beam Tests for Static and Fatigue Interface Shear Strength between Old and New Concretes

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요　약

신구콘크리트 계면(접합부)의 전단강도 측정을 목적으로 보시험체를 사용한 정하중 및 피로하중의 재하 실험이 수행되었다. 총 13개의 시험체중에서 정적재하실험을 통하여 5개 시험체의전단강도를 측정하였고, 8개의 시험체는 2,000,000회 또는 3,000,000회의 반복하중을 가력한 후 전단강도를 측정하였다. 실험변수는 접합부거칠기, 전단보강철근 및 신구콘크리트간 부착력의 유무이었다. 정적재하실험에서, 접합부가 거칠면서 콘크리트간 부착력이 존재한 시험체의 경우, 평균전단강도는 61kgf/cm^{2}이었다. 유사한 조건의 시험체에 3,000,000회의 전단하중을 가력한 피로하중실험에서 접착부의 열화현상은 나타나지 않았다. 이때 반복가력된 최대전단응력은 20kgf/cm^{2}으로 전단강도의 약 1/3수준이었다. 접합부가 거칠게 처리되지 않은 시험체와 접합부는 거칠지만 콘크리트간 부착력이 인위적으로 제거된 시험체의 경우에는 전단보강철근을 사용하여도 피로하중에 의한 접합부의 열화현상이 나타났다.

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Abstract

Interface shear strength of concrete under static loading and deterioratiion of interface strength by fatigue loading in shear were experimentally investigated using composite beam test specimens. Thirteen beams were constructed. Five composite beams were tested statically until interface delaminations were observed in the static tests. Seven composite beam and one monolithically cast beam were subjected to two to three million cycles of fatigue load. Test variables were interface roughness, interface shear reinforcement, and presence of interface bond. The average interface shear strength of the composite beams with bonded-rough interface was 6,060 kPa. No interface delamination was observed after cycling for the composite beams with bonded-rough interface and interface bond was not influenced by repeated application of the shear stress of 2,000 kPa(about 1/3 of the static interface shear strength). Smooth interface and unbonded-rough interface with shear reinforcement deteriorated under repeated shear loading.

Keywords: concrete; interface shear strength; fatigue; shear connector; interface roughness; bonded-rough interface; unbonded-rough interface.

1. Introduction

In structual repair or strengthening of existing reinforced concrete structures, new concrete is often placed on top surface of existing reinforced concrete beams or slabs to increase the structural capacity. Full transfer of shear across the interface between the old and new concretes must develop for a composite action to occur when the strengthened member is subjected to flexural forces. In structual rehabilitation of existing reinforced concrete bridge decks using bonded concrete overlay, where a new layer of concrete is place on top of existing reinforced concrete slabs, deterioration of the interface strength by repeated loading in shear can be expected as the slabs are subjected to high cycle fatigue loading under traffic.

Interface shear strength under static loading and deterioration of interface strength by fatigue loading in shear were experimentally investigated using 13 composite beam test specimens in the current study.

The interface shear strength of concrete has often been studied using push-off tests. Hanson,(2) for example, studied the effect of interface roughness and stirrups crossing the interface in improving shear transfer at connections between precast beams and cast-in-place slabs. Maximum shearing stress of 3,450 kPa for bonded-rough interface was measured. Hanson also conducted tests on T-shaped girders in addition to push-off specimens. It was concluded that the push-off tests gave a good representation of the character of the stress-slip curves for the girders tested. The push-off test results by Mattock et al.(3,4)indicated that the interface shear strength was a function of the amount of the shear reinforcement in that the change in strength, size, and spacing of the reinforcement affected the strength. Paulay et al.(5) investigated the principal mechanism of shear resistance along horizontal construction joints crossed by the reinforcement in cast-in-place concrete construction, such as shear walls. The contribution of dowel action, surface preparation, and reinforcing content on the shear strength of the construction joints was determined. The joint strength in shear was between 3,450 kPa and 4,800 kPa in specimens with bonded-rough surfaces. Saemann and Washa(6) tested 42 composite beams. Test results showed that the interface shear strength increased as the surface roughness and the reinforcement ratio increased.

2. Preparation for Tests

2.1 Test Setup

A new composite beam test setup was designed in which the interface was subjected to shear stresses by application of the vertical force on a simple beam. A test beam is shown in Fig. 1. The plan view of the beam shows the location of the contact region. The area other than the contact surface was unbonded using 5-mm-thick foam core board. The neutral axis (N.A.) of the uncracked section which was in the base beam moved into the overlay after development of flexural cracks. Fig. 2 shows the equilibrium of forces acting on a cracked half beam. A couple consisting of the compression (C) and the tension forces (T) acting on the overlay and on the longitudinal reinforcing steel is shown in Fig. 2 (a). The average interface shear stress (τ) can be quantified by measuring the strains in the longitudinal reinforcing steel, finding the tension force, and dividing by the interface area as shown in Fig. 2(b);

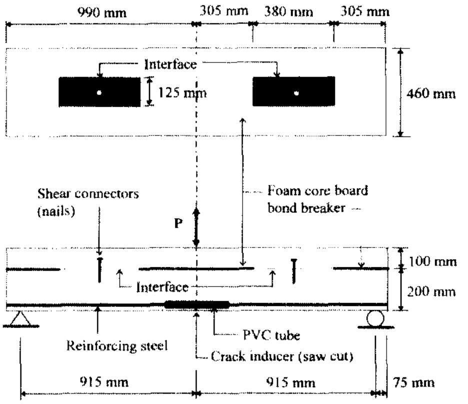
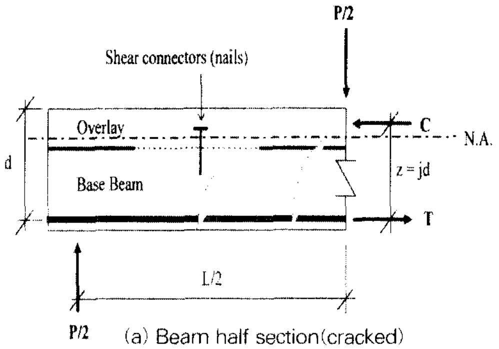
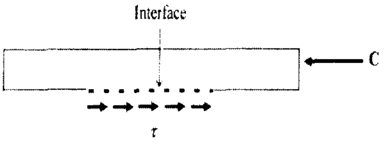


Fig. 1 A composite test beam



(a) Beam half section(cracked)



(b) Free-body of overlay left of point load

Fig. 2 Method of calculating interface shear stresses

$$\tau = \frac{C}{ab} = \frac{T}{ab} \qquad (1)$$

where a, b = length (380 mm) and width (125mm) of interface, respectively. It was assumed that friction between the two concrete in the unbonded region would be very small and could be neglected.

2.2 Test Specimens

Fig. 3 shows the steel cages made for the base beams. Five U.S. # 4 bars(diameter = 13 mm) were used for the longitudinal reinforcement. The middle 250-mm portion on three reinforcing bars was unbonded and strain gages were installed on the bars in the unbonded region as shown in Fig. 3. Relatively heavy shear stirrups were used to provide beam shear strength.

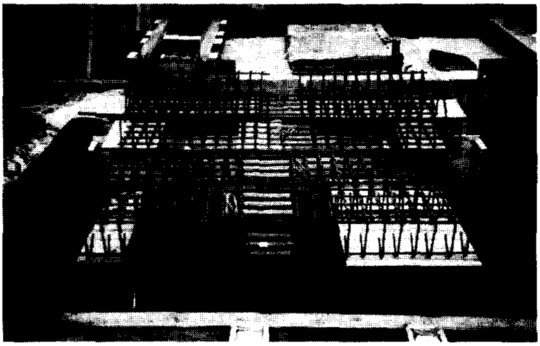
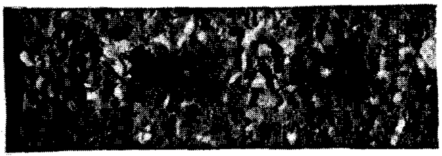


Fig. 3 Beam reinforcement

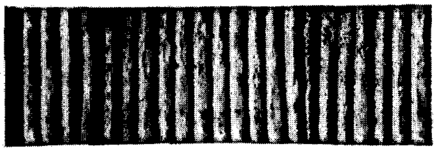
A total of 13 beams was constructed for tests and special powder-driven nails were used as shear connectors. Nails were approximately 120 mm long and 10 mm in diameter and were installed into a predrilled hole using a special powder-driven actuator which makes use of an explosive charge.[1]

Three different degrees of interface roughness were tested: very rough V-shaped grooved interface, rough heavily shotblasted interface, and relatively smooth troweled interface. V-shaped grooves were created on the top surface of two base beams while concrete was still fresh to produce very rough interfaces. Two other beams had smooth trowel finished interfaces. The interfaces of all other beams were heavily shotblasted. The contact area was 475 cm^2 on each side of the beam. One or two nails were used across the interface on each side of eight composite beams to provide interface shear reinforcement ratios (ρ_s) of 0.18% and 0.36%, respectively. Fig. 4(a) and (b) show the interface preparation before overlay placement for the beams with heavy shotblasting and two nails and for beams with V-shaped grooves and no nails. Two thin layers of general purpose grease were applied to the heavily shotblasted contact surfaces of two base beams to create unbonded interfaces.

One "monolithically" cast beam (a beam



(a) Heavy shotblasting



(b) V-shaped grooves

Fig. 4 Interface preparation

with a depth equal to the beams with overlays) was constructed which served as a control beam. A reduced shear section was created by inserting a horizontal foam core template during concrete placement when the concrete lift reached 200 mm measured from the bottom of the form. Table 1 is a summary of the test variables.

Table 1 Summary of test program

Specimen index	Number of nails	Interface preparation	Interface bond	Interface reinf. ratio(%)	Fatigue cycles (x1,000)	Test type
M0-1	—	—	—	—	3,000	F[3]
V0B-1	0	Grooved[1]	Bonded	—	—	S[4]
V0B-2	0	Grooved	Bonded	—	—	S
H0B-1	0	Shotblasted	Bonded	—	3,000	F
H0B-2	0	Shotblasted	Bonded	—	—	S
H1B-1	2	Shotblasted	Bonded	0.18	3,000	F
H1B-2	2	Shotblasted	Bonded	0.18	—	S
H2B-1	4	Shotblasted	Bonded	0.36	3,000	F
H2B-2	4	Shotblasted	Bonded	0.36	3,000	F
H1U-1	2	Shotblasted	Unbonded	0.18	2,000	F
H2U-2	4	Shotblasted	Unbonded	0.36	2,000	F
N1B-1	2	T.F.[2]	Bonded	0.18	2,000	F
N1B-2	2	T.F.	Bonded	0.18	—	S

1:Grooved=V-shaped grooves to maximum deth of 6mm.
2:T.F.=trowel finish.
3: F=statically load to failure after completion of fatigue cycling
4: S=statically loaded to failure without cycling

2.3 Materials

The stress vs. strain relationship of the reinforcing steel was determined from coupon tests. Four stress vs. strain plots were used to determine the tension force in the reinforcing steel based on strain readings. The 28-day compressive strengths of the base beam and the overlay were 37 MPa, and 32 MPa respectively. The maximum size of the river gravel aggregates used for the beams and the overlays was 20 mm. The base concrete was moist cured under wet burlap and plastic sheets for seven days. Overlays were cured under a plastic sheet for three days.

2.4 Test Procedure

Five composite beams were tested statically until interface delaminations were observed in the static tests. A vertical line load was applied slowly at the beam midspan until interface delamination was observed. The loading rate was approximately 4.5 kN per minute. Interface shear stresses were determined by directly measuring the strains in the longitudinal reinforcing steel and using Eq. 1.

Seven composite beams and one monolithically cast beam were subjected to two to three million cycles of fatigue load. Sinusoidal cyclic loading was applied at the beam midspan on top of the overlay. Testig frequency was 6 Hz. The average vertical load and the loading amplitude were 56 kN and 24kN. The interface shear stresses, determined using Eq. 1, typically ranged between 2,000 kPa and 860 kPa during cycling. Cycling was stopped after each one-half million cycles. Beam midspan deflection, reinforcing steel strains, and interface slips were measured to determine deterioration of composite action as the beams were statically loaded to the maximum fatigue load.

2.5 Testing Equipment and Instrumentation

The Material Testing System (MTS) had a fatigue-rated capacity of 250 kN. Vertical load, loading amplitude, and cyclic frequency were controlled by a servo-controller. The beam midspan deflection was monitored using a linear potentiometer with 0.025 mm accuracy supported on a stand beneath the base beam. Interface slips between the overlay and the base beam were monitored using dial gages with 0.0025mm accuracy and liner potentiometers. A dial gage and a liner potentiometer were installed at each end of the beam. Sampling rate was 20 data sets per second.

3. Test Results

3.1 Static Test Results

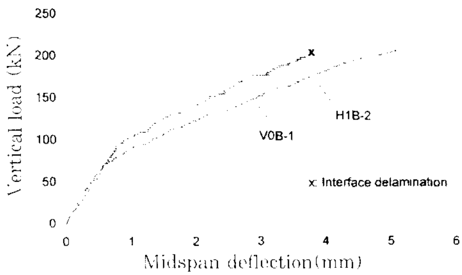
Table 2 is a summary of the beam static test results. The test results of specimens *V0B-1* with very rough grooved interface and no nails and ***H1B-2*** with rough heavily shotblasted interface and one nails across the interface on each side of the beam (ρ_s = 0.18%) are shown in Fig. 5. Applied load vs. beam midspan deflection and load vs. strains in the longitudinal reinforcing steel are shown in Fig. 5. The flexual stiffiness and the development of reinforcing steel strains in the two beams were similar. Each beam was preloaded before the static test to produce flexural cracks which initiated at the beam bottom fibers and progressed upward typically ending in the overlay (Fig. 6). The interface on one end of ***V0B-1*** delaminated at an applied load of 202 kN as shown in Fig. 7. The interface shear stress was 5,930 kPa at failure. A sudden

Table 2 Summary of static test results: Values at interface delamination

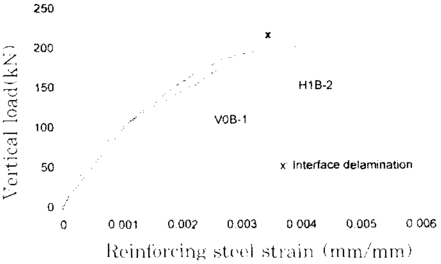
Specimen index	Vertical load (kN)	Midspan deflection (mm)	Reinf. steel strain (%)	Interface slip		Interface shear stress (kPa)
				East (mm)	West (mm)	
V0B-1	202	3.7	0.34	0.09	**0.21**[2]	5,930
V0B-2	205	8.7	0.78	**0.04**	**0.45**	6,350
H0B-2	166	4.6	0.32	0.25	**0.43**	5,910
H1B-2[1]	209	5.2	0.53	0.07	**0.13**	6,070
N1B-2	74	1.4	0.07	0.08	**0.15**	1,870

1 : No interface delamination occurred : values are given at maximum vertical loading of 209kN.

2 : Delaminated interface(*Italocized* and **bold**).



(a) Load vs. deflection



(b)Load vs. reinforcing steel strain

Fig. 5 Beam static tests: Very rough grooved interface with no nails (V0B-1) and rough shotblasted interface with nails (H1B-2, ρ_s = 0.18%)

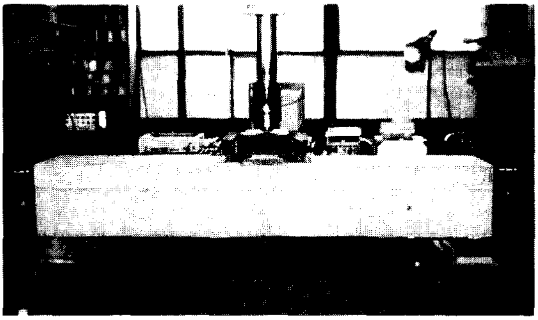


Fig. 6 Flexural cracking after preloading

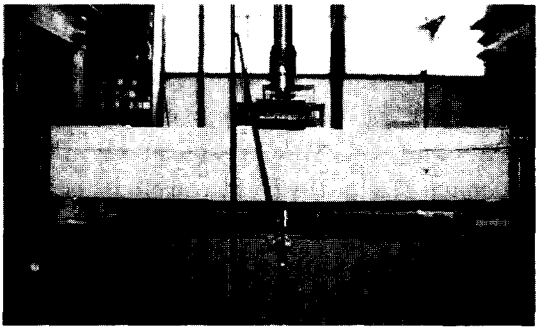
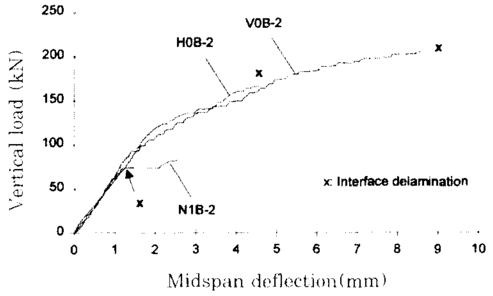


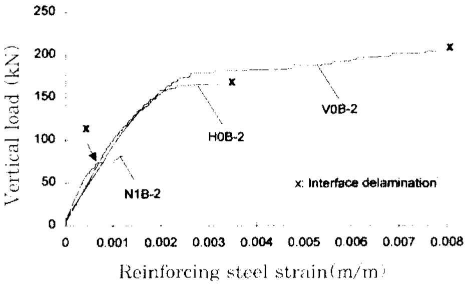
Fig. 7 Delaminated interface

delamination failure was observed. No delamination failure developed in ***H1B-2*** under vertical load which reached 209 kN. The interface shear stress was 6,070 kPa at the maximum load when the main bars yieled.

The static test results of three additional beams are shown in Fig. 8. Two beams, V0B-2 and H0B-2, had grooved and heavily shotboasted interfaces, respectively, with no nails while the third beam, N1B-2, had smooth troweled interface with one nail across the interface on each side of the beam (ρ_s = 0.18%). The load vs. beam midspan deflection plots in Fig. 8(a) show that the initial flexural responses of the two beams with the rough interface and no nails were similar. Interface delamination occurred at a vertical load of 205 kN in V0B-2. The interface shear stress at failure was 6,350 kPa. The interface shear stress at failure was 5,910 kPa for H0B-2. The interface slips at failure were on the order of 0.4 mm for both beams (Table2). The load vs. reinforcing steel strain plot in Fig. 8(b) also show that the responses of the two composite beams were similar. The average interface shear strength of three beams(***V0B-1***, ***V0B-2***, and ***H0B-2***) with bonded-rough interface and no nails was 6,060 kPa.



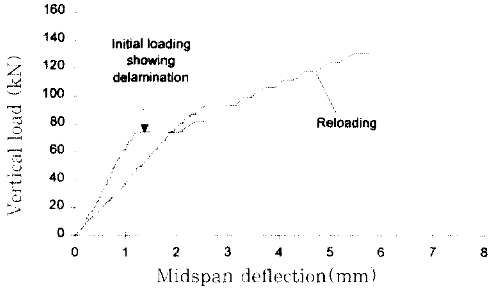
(a)Load vs. deflection



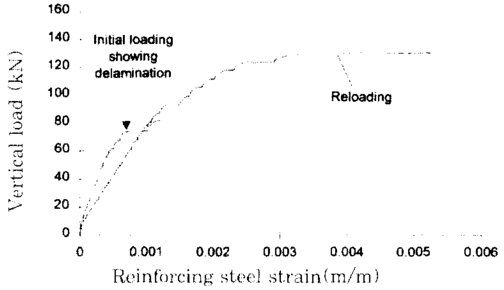
(b)Load vs. reinforcing steel strain

Fig. 8 Beam static test: Rough interfaces with no nails (V0B-2,H0B-2) and smooth interface with nails (NIB-2, ρ_s = 0.18%)

Test results of ***NIB-2*** which had a smooth troweled interface are also shown in Fig. 8. A significantly different flexural behavior was obtained. Interface delamination occurred at a significantly lower vertical load when compared with those of the beams with the rougher interfaces. The interface delamination



(a) Load vs. delfection



(b) Load vs. reinforcing steel strain

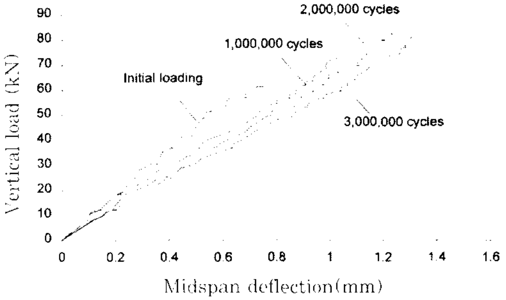
Fig. 9 Beam static test: Smooth interface with nails (NIB-2, ρ_s = 0.18%)

occurred at a very low load of 74 kN even though nails were used to strengthen the smooth interface. The interface shear stress at failure was 1,870 kPa which was only 31% of the average for the bonded-rough interface (6,060 kPa). ***N1B-2*** was unloaded after the initial delamination occurred and then reloaded. The two different loading curves are shown in Fig. 9 which indicate the loss of composite action due to the delamination. Test results revealed that a smooth interface with nails (ρ_s = 0.18%) was not as effective as a bonded-rough interface without nails in maintaining composite section under shear loads.

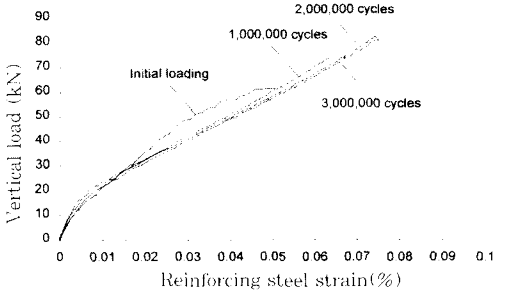
3.2 Fatigue Test Results

A "monolithically" cast beam, ***M0-1***, was first subjected to three million fatigue cycles. Changes in beam midspan deflections, reinforcing steel strains, and interface slips were measured to determine the possible deterioration of composite action after each one-half million cycles as the beam was statically loaded up to the maximum fatigue load of 80 kN (or maximum interface shear stress of 2,000 kPa). Test results revealed that the strength of the artificially created interface (reduced shear section) of the "monolithically" cast beam was unaffected by the repeated loading.

Four composite beams with bonded-rough shotblasted interface were subjected to three million fatigue cycles. The interfaces were heavily shotblasted. No nails were used for ***H0B-1***. One nail was used across the interface in each side of ***H1B-1*** (ρ_s = 0.18%). Two nails were used on each end of two other beams, ***H2B-1*** and ***H2B-2*** (ρ_s = 0.36%). Test results of ***H2B-1*** are shown in Fig. 10 for the initial loading and loading after each one million cycles. The beam midspan deflection slowly increased with increasing number of cycles as shown in Fig. 10(a) probably due to the development of flexural and web shear cracks in the beam. The reinforcing steel strains and interface slips, however, remained almost the same which indicated that the composite action was fully maintained throughout the cycling. Based on beam midspan deflection, reinforcing steel strain, and interface slip readings, it was concluded that the interface strengh was not influenced by cycling. Similar observations were made from the fatigue tests of three other beams. The beam midspan deflection, reinforcing steel strains, and interface slips did not change significantly after three million fatigue cycles.



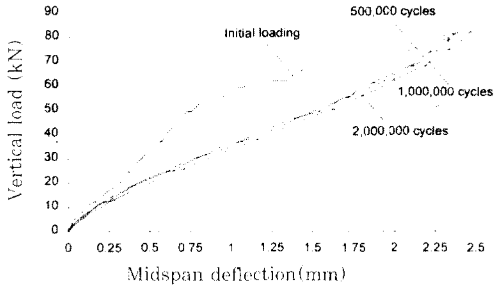
(a)Load vs. deflection



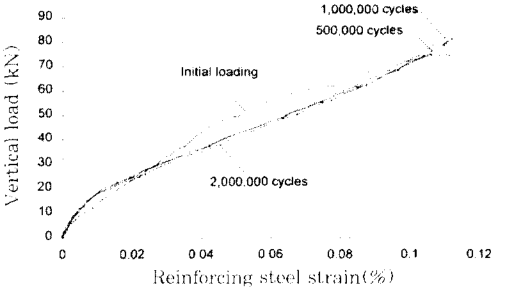
(b) Load vs. reinforcing steel stain

Fig. 10 Beam fatigue tests: Bonded-rough interface with nails (H2B-1, ρ_s = 0.36%)

N1B-1 had smooth troweled interface and one nail was used across the interface on each side of the beam (ρ_s = 0.18%). The interface strength was very low and, although both interface failed during the preloading, loading was applied for two million cycles. Test results are shown in Fig. 11 for inital loading and for static loading after 0.5, 1, and 2 million cycles. The beam midspan deflection and the reinforcing steel strains at initial loading were significantly larger than those of the beams with the bonded-rough interface indicating the loss of composite action due to the delamination. The change in the beam deflections between the initial loading and loading after one-half million cycles was large as shown in Fig. 11(a) which suggested additional deterioration of the interface due to cycling.



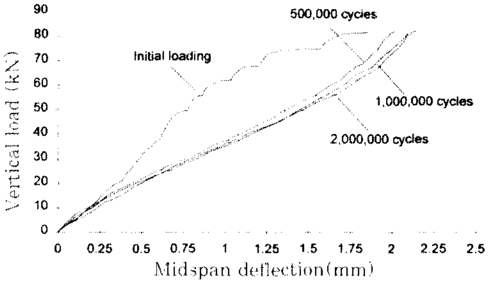
(a) Load vs. deflection



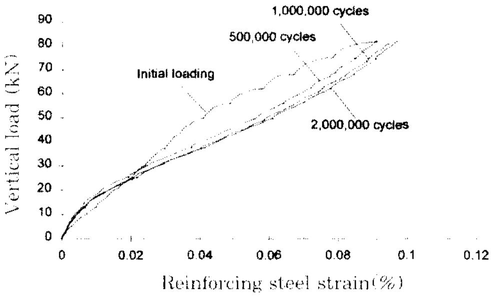
(b) Load vs. reinforcing steel strain

Fig. 11 Beam fatigue tests: Bonded-smooth interface with nails (NIB-1, ρ_s = 0.18%)

Two beams with unbonded-rough interface with nails were subjected to two million fatigue cycles. The interface of both beams were heavily shotblasted. One and two nails were used across the unbonded interface on each side of *H1U-1* (ρ_s = 0.18%) and *H2U-1* (ρ_s = 0.36%), respectively. Test results are shown in Fig. 12 for *H1U-1* for the initial loading and loading after 0.5, 1, and 2 million cycles. Beam midspan deflection and reinforcing steel strains of the unbonded beam were significantly larger than those of the beams with the bonded-rough interfaces which suggests that the interface of the unbonded beam with nails did not maintain the full composite section after cycling. Similar test results were obserbed in *H2U-1.*



(a) Load vs. deflection



(b) Load vs. reinforcing steel strain

Fig. 12 Beam fatigue tests: Unbonded-rough interface with nails (H1U-1, ρ_s = 0.18%)

3.3 Post-Fatigue Static Test

All beams with bonded-rough interfaces were statically tested after cycling since no iterface delaminations were observed during the cycling. Test results are summarized in Table 3. High interface strengths determined in the post-fatigue static tests indicated that the fatigue cycling did not significantly influence the interface strength as shown in Table 3. It needs to be noted, however, that the interface shear strength of ***H0B-1*** (4,800 kPa) was only 81% of that in the companion beam, ***H0B-2*** (5,910 kPa). Strength of the bonded-rough interface (without nails) may have deteriorated under fatigue loading but needs further study.

Table 3 Post-fatigue static test results: Values at interface delamination

Specimen index	Vertical load (kN)	Midspan deflection (mm)	Reinf. steel strain (%)	Interface slip		Interface shear stress (kPa)
				East (mm)	West (mm)	
M0-1	191	6.9	0.81	**0.37**[2]	**0.54**	6,390
H0B-1	148	3.8	0.18	0.05	**0.35**	4,800
H1B-1	214	11.0	1.23	0.20	**0.42**	6,890
H2B-1	222	17.4	1.23	0.12	**0.52**	6,900
N2B-2[1]	233	16.2	–[3]	0.18	0.27	–[3]

1 : No interface delamination occurred ; values are given at maximum vertical loading of 233kN,

2 : Failed interface(*Italocized* and **bold**).3: Not measure due to strain gage failure.

4. Discussion of Test Results

It must be noted that the interface shear strengths determined in the current study are considerably higher than those published previously. Hanson[(2)] for example, suggested a maximum shearing stress of 3,450 kPa for bonded-rough interfaces. Interface shear strengths were between 3,450 kPa and 4,800 kPa in specimens with bonded-rough surface in a study by Paulay et al.[(5)] Higher interface shear strengths determined from direct strain measurements in the current study seem to indicate that true interface shear strength may be higher than that previously published, although the current test results have to be interpreted carefully due to limited number of tests.

5. Conclusions

Test results of beams revelaled that roughening the interface before placement of the overlay was required to provide high interface shear strength. Shear connectors also helped strengthen the interface (more than 3% improvement when 0.18% shear reinforcement was provided). The performance of unbonded-rough or bonded-smooth interfaces with shear reinforcement, however, was not as effective as a heavily shotblasted interface without reinforcement.

The composite beam static tests resulted in the following conclusions:

1. The average of interface shear strength of three composite beams with bonded-rough interface and without shear connectors (*V0B-1*, *V0B-2*, and *H0B-2*) was 6,060 kPa;
2. Interface shear strength of a beam with heavily shotblasted interface and no shear connectors (*H0B-2*) was 5,910 kPa;
3. Average of the interface shear strengths in two beams with very rough V-shape grooved interface and no shear connectors (*V0B-1* and *V0B-2*) was 6,140 kPa, which was 4% higher than that of a beam with heavily shotblasted interface and no shear connectors;
4. Interface shear strengths in a beam with heavily shotblasted interface and with 0.18% shear reinforcement (*H1B-2*) was higher than 6,070 kPa, which was more

than 3% improvement over that of a beam without reinforcement; and

5. Shear strength of the bonded-smooth interface with 0.18% shear reinforcement (*N1B-2*) was only 31% of a similar test beam with heavily shotblasted interface.

The fatigue test results of beams revealed the following:

1. No interface delamination was observed after cycling for all beams with bonded-rough interfaces after three million fatigue cycles;

2. The interface bond of three beams with heavily shotblasted interface with 0.18% or 0.36% shear reinforcement (H1B-1, H2B-1, and H2B-2) was not influenced by the application of the repeated shear stresses for maximum interface shear stress of 2,000 kPa, which was about 1/3 of the static interface shear strength;

3. The interface shear strength of H0B-1 subjected to cycling, however, was only 81% of the in that companion beam, H0B-2 tested without cycling. although a strong conclusion cannot be presently drawn due to limited number of tests, strength of the heavily shotblasted interface without shear reinforcement may deteriorate under fatigue loading;

4. Deterioration of composite action of an unbonded-smooth interface with 0.18% shear reinforcement (N1B-1) under repeated shear loading was found after one-half million cycles;

5. Composite action of unbonded-rough interface with 0.18% and 0.36% shear reinforcement (*H1U-1* and *H1U-2*) also deteriorated under repeated shear loading; and

6. An unbonded-smooth or unbonded-rough interface with shear connectors was not as effective as a bonded-rough interface without shear shear connectors in maintaining composite section under repeated shear loads.

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