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論　文

[2203] Shear-Fatigue Behavior of Steel-Concrete Sandwich Beams without Web Reinforcement

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1. INTRODUCTION

Steel–concrete sandwich member is a type of composite member in which core concrete is sandwiched by steel skin plates as shown in Fig.1. The flexural capacity and also the shear capacity[1] of this type of members have been thoroughly investigated under static loading conditions. Therefore, the design code for steel–concrete sandwich structures has been proposed recently[2]. However, there is a lack of the experimental data regarding the strength of this type of members under fatigue loading conditions. Therefore, this study investigates the shear–fatigue behavior of steel–concrete sandwich beams which are not provided with web reinforcement.

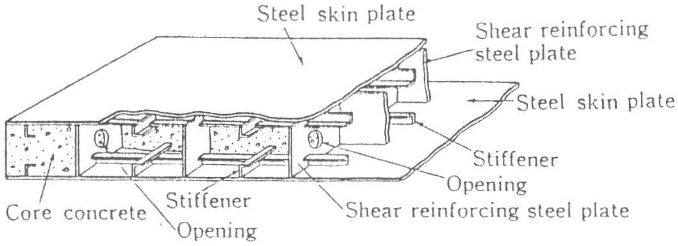

Fig.1 Steel–concrete sandwich member

2. OUTLINE OF THE EXPERIMENTAL WORK

Experimental work was carried out for the steel–concrete sandwich beam shown in Fig.2, which has a span length of 265 cm and a cross section of 25×40 cm. The shear span to effective depth ratio (a/d) is equal to 3.0. The thickness of the upper and lower steel plates is 16 mm. The average compressive strength of concrete is 270 kgf/cm^2. The yield strength of the steel plates is equal to 4000 kgf/cm^2. The sandwich beam is not provided with web reinforcement. Shear connectors (steel angles 40×4 mm) are provided at the interface between the concrete and the steel plates. The steel angles are welded to the steel plates. The beam was designed in such a way that the flexural capacity is much higher than the shear capacity to avoid fatigue fracture of the tensile steel plate which was indicated in previous study[3].

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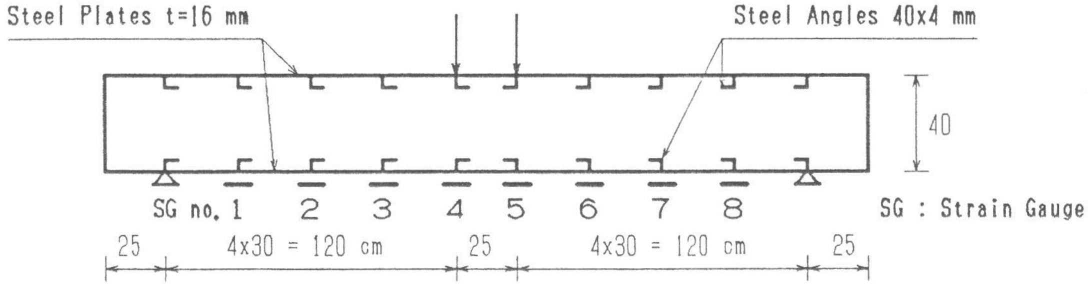


Fig.2 Setting of test beam & locations of strain gauges

Tests were carried out for four specimens. Specimen no.1 was tested under static monotonic loading while the other three specimens were tested under fatigue loading. In the fatigue tests, the specimens were loaded statically during the first hundred cycles and then loaded dynamically with 240 cycles per minute until failure. The minimum fatigue load (P_{min}) was kept constant at 2.0 tons, while the maximum fatigue load (P_{max})was chosen to be 13 tons for specimen no.2, 16 tons for specimen no.3, and 19 tons for specimen no.4. For specimen no.2, fatigue failure did not occur until $2x10^6$ cycles and therefore the maximum load was increased to 22 tons. The mid–span deflections, the strains in the steel plates, and the crack growth were measured with increasing the number of loading cycles (N) (i.e., 1, 10, 100, 10^3, 10^4, 10^5 cycles,...,etc.)[4],[5].

3. FINITE ELEMENT ANALYSIS

A nonlinear finite element method computer program (WCOMR)[6] was used to analyze the steel–concrete sandwich beam shown in Fig.2. The finite element mesh of the beam is shown in Fig.3. The constitutive models for concrete and steel elements are given in references [6] and [7]. Bond elements are provided to simulate the interface between the concrete and the lower steel plate. A linear bond stress–slip relationship was adopted as a constitutive law for the bond elements[7]. Enforced displacements are given at the loading point as shown in Fig.3.

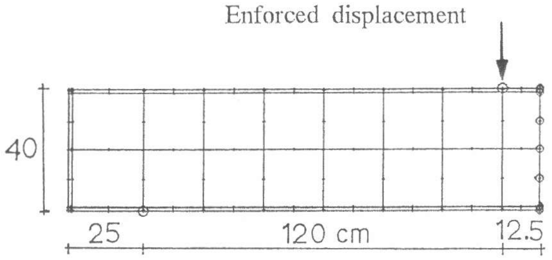


Fig.3 The finite element mesh

4. RESULTS AND DISCUSSION

At first, the sandwich beam was tested under static monotonic loading. The sandwich beam was also analyzed under static monotonic loading by

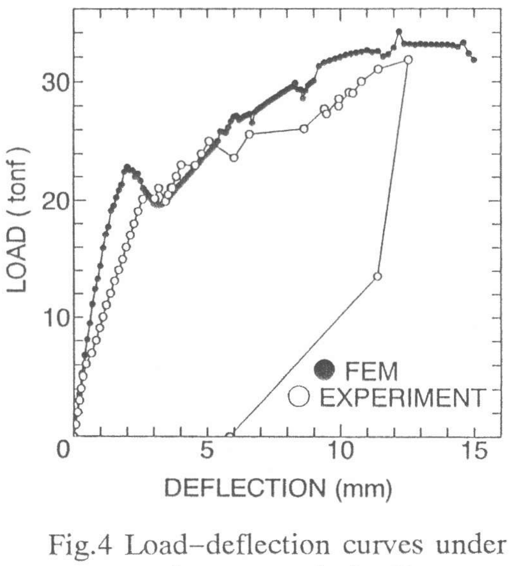
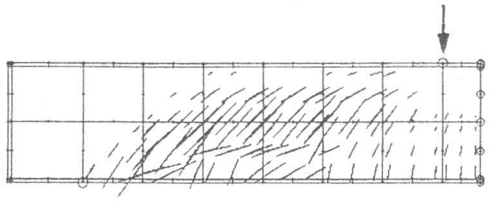
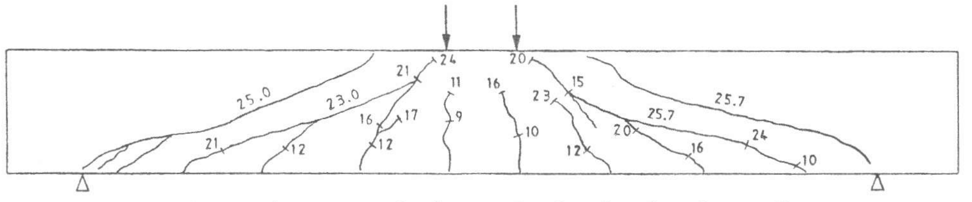


Fig.4 Load–deflection curves under static monotonic loading

using the finite element method. The experimental as well as the analytical load–deflection curves are shown in Fig.4. It is observed that the load increases with high stiffness until about 23.0 tons. At this load, main diagonal cracking occurs. This could be illustrated by the crack patterns in Fig.5. Then, the load–deflection curve increases further with small stiffness until the ultimate failure load which is about 32.0 tons.



a) Finite element analysis (load= 23 tonf)
lines indicate the value of the
principal tensile strain
(scale: 1mm = 160×10^{-6})



b)Test (numbers indicate the load value in tonf)
Fig.5 Crack patterns under static monotonic loading

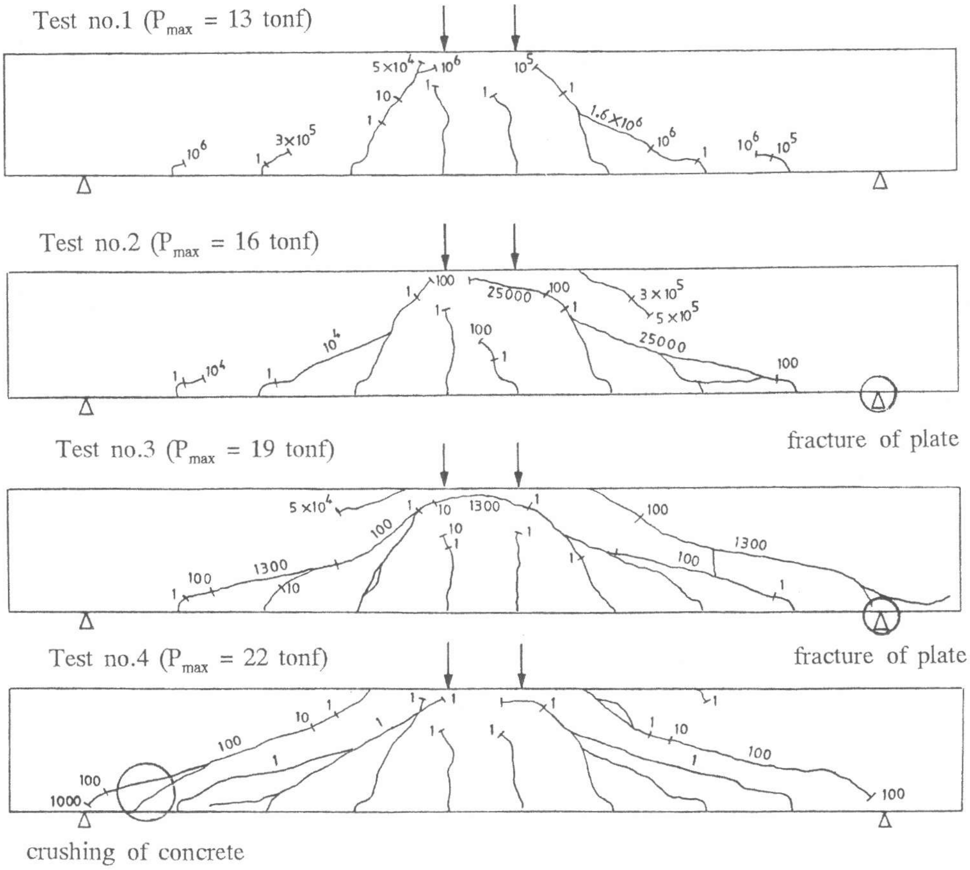
Four fatigue tests were carried out. The maximum fatigue load (P_{max}) was chosen to be 56.5%, 69.6%, 82.6%, and 95.6% of the main diagonal cracking load (P_{cr} = 23.0 tonf). The results of the fatigue tests are summarized in Table 1. The crack patterns of the sandwich beam under fatigue loading are shown in Fig.6. The numbers written on the crack patterns indicate the number of fatigue loading cycles (N). In all the fatigue tests, it is observed that diagonal cracks initiate at the locations of the shear connectors and then the propagation of these cracks increases with increasing the number of loading cycles (N). In the fatigue test no.1 (P_{max}= 13 tonf), fatigue failure did not occur until $2x10^6$ cycles. In the fatigue test no.2 (P_{max}= 16 tonf) and the fatigue test no.3 (P_{max}= 19 tonf), fatigue failure was caused by fracture of the tensile steel plate at the supporting point. In the fatigue test no.4 (P_{max}= 22 tons), fatigue failure occured due to crushing of concrete between diagonal cracks in the vicinity of the support. These fatigue failure modes are also illustrated in Fig.6. The obtained S–N relationship for the sandwich beam is shown in Fig.9 in which the full circle indicates the non–failure case, the white circle indicates the fracture of plate failure case, and the square indicates the crushing of concrete failure case. In the fatigue test no.2 and no.3, after the formation of the main diagonal cracks, the part of the lower steel plate between the support and the second outer shear connector was subjected to local bending deformations because of the restraint from the support. Also, the largest slip between the concrete and the lower steel plate was observed in this part. Thereafter, the steel plate was fractured at the supporting point which is a weak point since the shear connector is welded to the plate. Fig.7 illustrates the relationship between the number of loading cycles (logN) and the mid–span deflections of the beam. In the fatigue test no.2, no.3, and no.4, there is some increase in the mid–span deflection because of the formation of the main diagonal cracks. However, in the fatigue test no.3, there is much bigger increase in the mid–span deflection after 10^4 cycles (see Fig.7) which may be caused by the initiation of steel crack at the location of the support. Fig.8 illustrates the relationship between the number of loading cycles (logN) and the strain ranges in the lower steel plate of the beam. In general, the strain ranges in the lower steel plate are approximately constant throughout the fatigue tests. However, after the formation of the main diagonal cracks, the strain range increases at the locations near the supports (i.e.,SG no.1 and SG no.8)(see Figs.2, 6, and 8).

The fatigue life for the main diagonal cracking was predicted by using the finite element method. As a primary trial, the analysis procedure was based upon reducing the tensile strength of concrete with increasing the number of loading cycles (N)[8]. Fig.10 illustrates the predicted and the experimental S–N relationships for the main diagonal cracking of the sandwich beam.

Table 1. Results of the fatigue tests

Specimen No.	f_c' (Kg/cm^2)	Fatigue test No.	P_{max} (tonf)	P_{min} (tonf)	P_{max} / P_{cr} (%)	Fatigue life (cycles)	Failure mode
2	290	1	13.0	2.0	56.5	2,000,000	NF[1)]
3	290	2	16.0	2.0	69.6	624,221	FS[2)]
4	230	3	19.0	2.0	82.6	120,081	FS[2)]
2	290	4	22.0	2.0	95.6	79,948	WC[3)]

1) NF : no fatigue failure until 2,000,000 cycles
2) FS : fracture of the lower steel plate at the supporting point (see Fig.6)
3) WC : diagonal web crushing (crushing of concrete between diagonal cracks in the vicinity of the support)(see Fig.6)


Test no.1 (P_{max} = 13 tonf)

Test no.2 (P_{max} = 16 tonf)

fracture of plate

Test no.3 (P_{max} = 19 tonf)

fracture of plate

Test no.4 (P_{max} = 22 tonf)

crushing of concrete

Fig.6 Crack patterns under fatigue loading

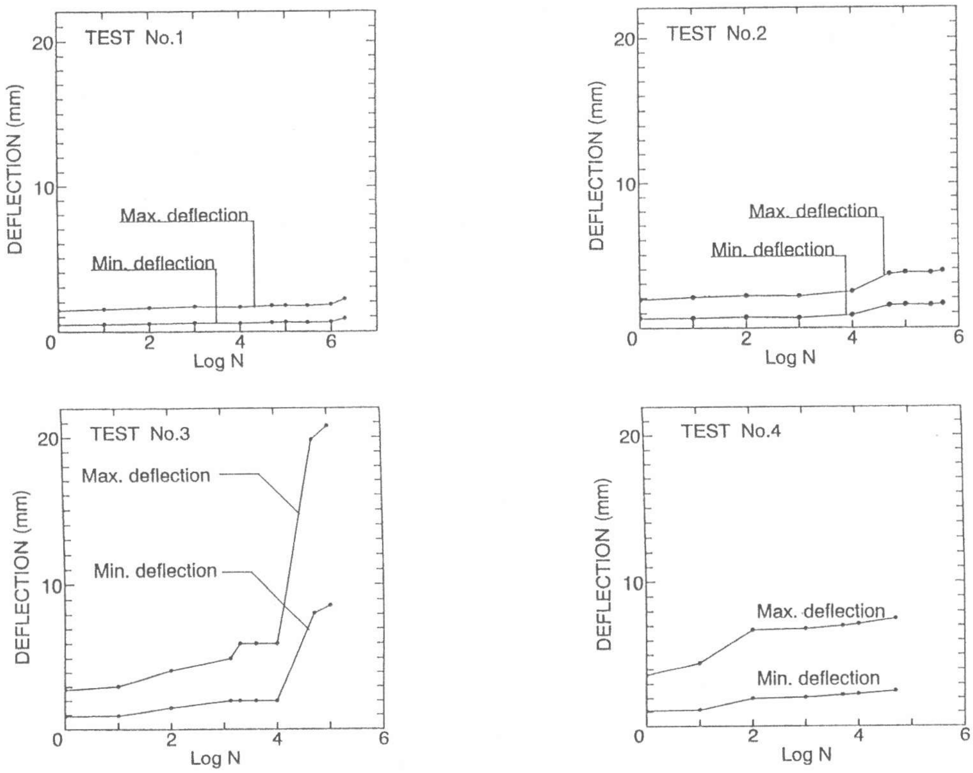


Fig.7 Relationship between log N & the mid-span deflections

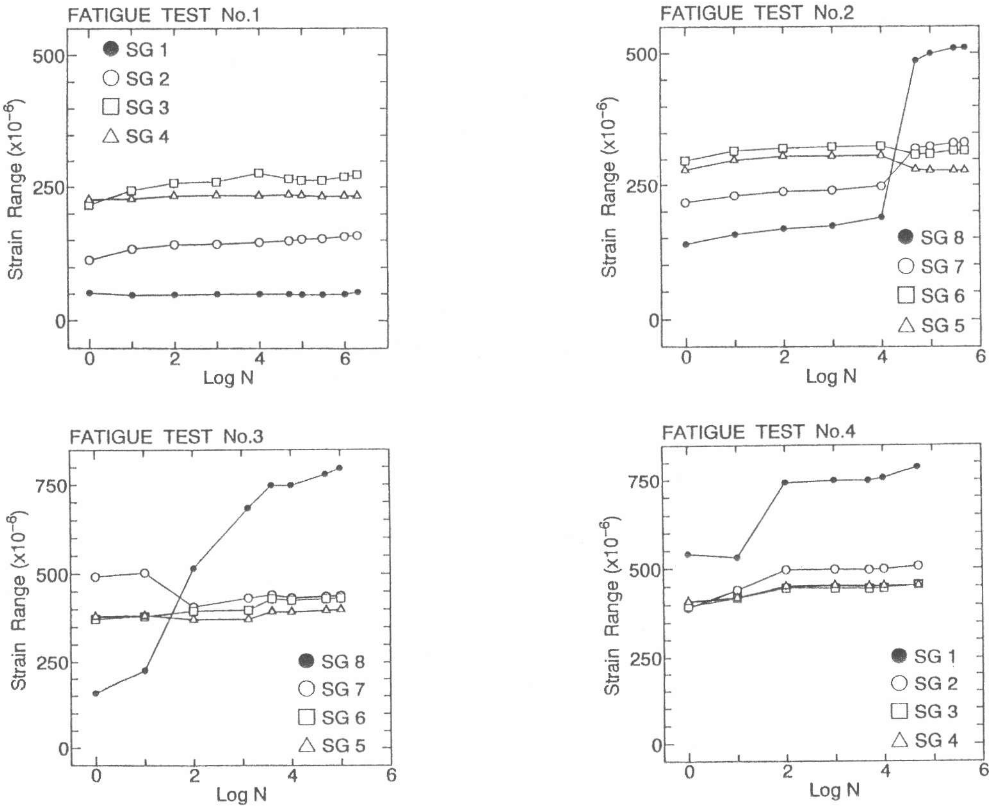


Fig.8 Relationship between log N & the strain ranges in the lower steel plate

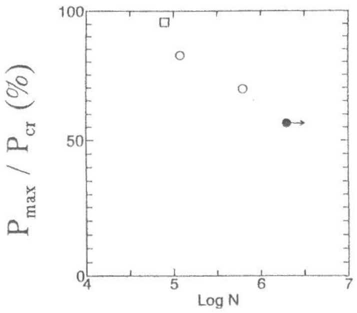


Fig.9 S–N relationship for the sandwich beam

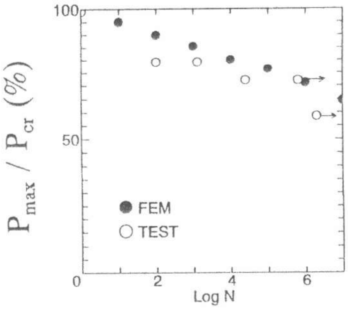


Fig.10 S–N relationships for the main diagonal cracking of the sandwich beam

5. CONCLUSIONS

1) The sandwich beam investigated in this study indicates a shear failure mode under static loading, which is characterized by main diagonal cracks. Under fatigue loading, diagonal cracks initiate at the locations of the shear connectors and then the propagation of these cracks increases with increasing the number of loading cycles (N).

2) For large maximum fatigue load (P_{max} = 95.6% of P_{cr}), the failure mode is crushing of core concrete between diagonal cracks, but for smaller loads (P_{max} = 82.6% and 69.6% of P_{cr}), the failure mode is fracture of the tensile steel plate at the supporting point.

3) The fatigue life for the main diagonal cracking was predicted by using the finite element method in which an experimental S–N relationship was applied to reduce the tensile strength of concrete.

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