論文 A Study on the Fatigue Strength of Steel-Concrete Sandwich Beams with Shear Reinforcement

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ABSTRACT: Static and fatigue loading tests were carried out for steel-concrete sandwich beams which are provided with shear reinforcing steel plates. Under static loading, the sandwich beam indicated a shear compression failure mode. However, under fatigue loading, the sandwich beams indicated two failure modes, namely the crushing of concrete between the diagonal cracks and the fatigue fracture of the steel plates either the lower flange plate or the shear reinforcing steel plates. The S-N relationship for the different failure modes is presented. The fatigue strengths of the shear reinforcing and the flange plates in the beam are also compared with the fatigue strengths in air.

KEYWORDS: fatigue strength, steel-concrete sandwich beams, shear reinforcement

1. INTRODUCTION

The steel-concrete sandwich member is composed of core concrete, flange steel plates, shear reinforcing steel plates, and shear connectors (i.e., steel angles) as shown in Fig.1. The sandwich members have many practical applications in various structures such as tunnels, bridge decks, marine structures, etc. Marine structures are subjected to wave forces repeatedly. Bridge decks are also subjected to traffic loads repeatedly. These repetitive loads may result in progressive cracking and sometimes crushing of the core concrete if the load amplitude is sufficiently large. The sandwich member has also many weldings between the steel plates. These weldings may result in fatigue fracture of the steel plates. However, there have been few researches regarding the fatigue strength of steel-concrete sandwich members[1,2]. This paper presents an experimental study on the fatigue strength of steel-concrete sandwich beams with shear reinforcement.

2. OUTLINE OF TESTS

Experimental works were carried out for the steel-concrete sandwich beam shown in Fig.1, which had a span length of 1.69 m and a cross section of 150 × 300 mm. The sandwich beam was tested by two symmetrical concentrated loads, and the shear span to effective depth ratio (a/d) was equal to 2.40. The thickness of the upper and lower flange plates was 16 mm. As shown in Fig.1, the right and the left shear spans were provided with a shear reinforcing steel plate of 100 mm in width and 6 mm in thickness. This shear reinforcing plate was placed at the center of the shear span parallel to the member axis. Hereafter, this shear reinforcing plate will be called as the "tie plate". The compressive strength of the concrete was

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15 MPa. The yield strength of the steel plates was 400 MPa. Steel angles of 30 × 30 × 3 mm size were used as shear connectors which were welded to the flange plates. Tests were carried out for six specimens. The first specimen was tested under static monotonic loading while the other five specimens were tested under fatigue loading. In the fatigue tests, the specimens were loaded dynamically with 240 cycles per minute in a sinusoidal waveform until failure.

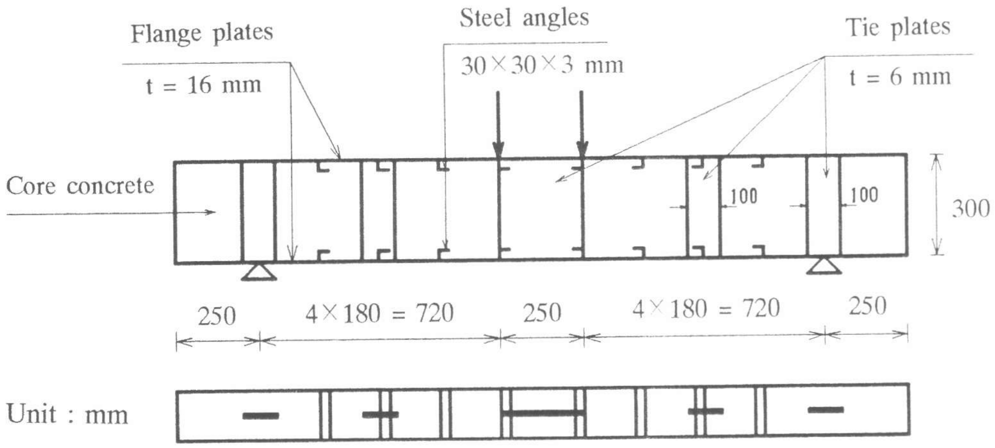
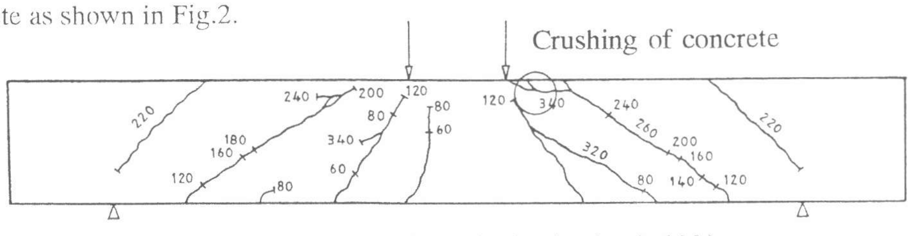


Fig.1 Geometry of the sandwich beam

3. BEHAVIOR OF THE SANDWICH BEAM UNDER STATIC LOADING

At first, the sandwich beam was tested under static monotonic loading. The crack pattern of the sandwich beam is shown in Fig.2. The ultimate failure load (P_u) was equal to 362.7 kN. The failure mode of the beam was a shear compression failure which is characterized by diagonal cracking and crushing of concrete as shown in Fig.2.



(numbers indicate the load value in kN)
Fig.2 Crack pattern under static monotonic loading

4. BEHAVIOR OF THE SANDWICH BEAM UNDER FATIGUE LOADING

Fatigue tests were carried out for five sandwich beams. The minimum fatigue load (P_{min}) was kept constant at 5.5% of the static strength of the beam (P_u). The maximum fatigue loads (P_{max}) were equal to 52.5%, 68.3%, 81.1%, 90.4%, and 96.1% of the static strength of the beam (P_u). The results of the fatigue tests are illustrated in Table 1. In fatigue test no.1 $(P_{max} = 52.5\%$ of $P_u)$, fatigue failure occurred due to fracture of the lower flange plate as shown in Fig.3a. The strain measurements have indicated that the part AB of the lower flange plate was subjected to local bending deformations (see Figs.3a and 3b). These local bending deformations result in a concentration of the tensile stresses at point W which is the welding point between the tie plate and the lower flange plate (see Fig.3b). Therefore, fatigue crack

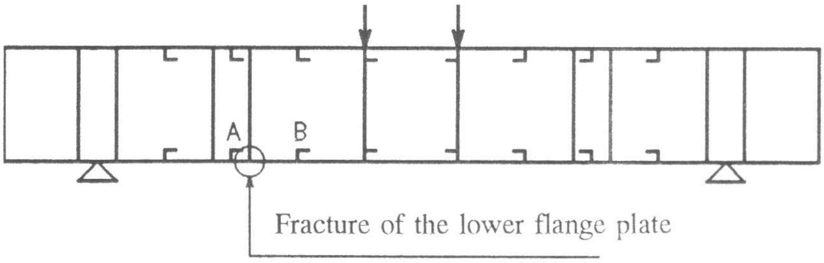
Table 1 Results of the fatigue tests

Fatigue test no.	P_{min} / P_u (%)	P_{max} / P_u (%)	Fatigue life (cycles)	Failure mode
1	5.5	52.5	310,799	FP[1]
2	5.5	68.3	13,724	TP[2]
3	5.5	81.1	4662	TP[2]
4	14.3 5.5	86.0 90.4	6000 2100	TP[2]
5	5.5	96.1	70	CC[3]

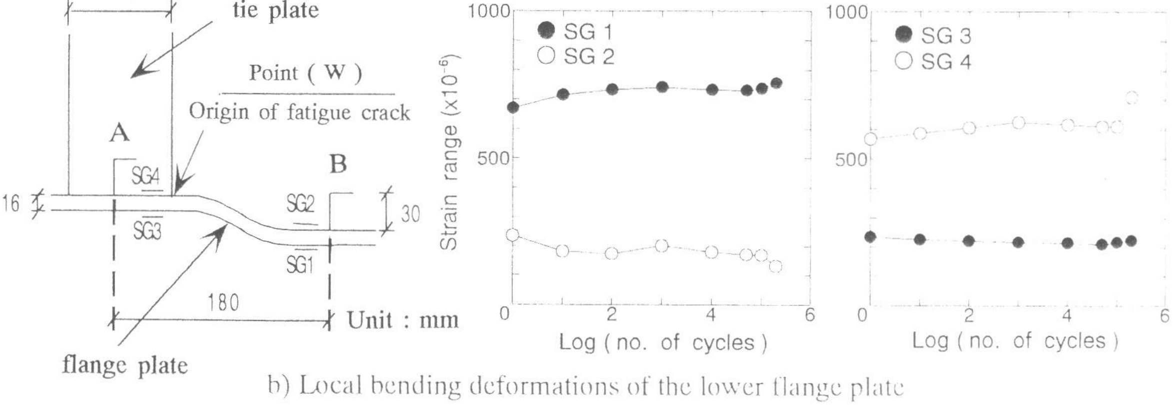
1) FP : Fracture of the lower flange plate

2) TP : Fracture of the tie plate. 3) CC : Crushing of the concrete

originated from point W and then this crack propagated in the lower flange plate with increasing the number of cycles *(N)* until complete fracture occurred. In fatigue test no.2 (P_{max} = 68.3% of P_u), the sandwich beam failed due to crushing of concrete in the vicinity of the loading point as shown in Fig.4a. Thereafter, the concrete was removed and a fatigue crack of 50 mm in length was found to propagate in the tie plate (see Fig.4b). In fatigue test no.3 (P_{max} = 81.1% of P_u), the sandwich beam failed due to crushing of concrete in the vicinity of the loading point as shown in Fig.4a. Thereafter, the concrete was removed and the tie plate was found to be completely fractured (i.e., completely separated from the lower flange plate) (see Fig.4c). In fatigue test no.4, the sandwich beam was subjected to 6000 cycles during which the fatigue load was fluctuating between a minimum value of (P_{min} = 14.3% of P_u) and a maximum value of (P_{max} = 86% of P_u). Thereafter, the load range was increased to be fluctuating between a minimum value of (P_{min} = 5.5% of P_u) and a maximum value of (P_{max} = 90.4% of P_u). Then, fatigue failure occurred after 2100 cycles with the higher load range (i.e., P_{min} = 5.5% and P_{max} = 90.4% of P_u). In this test, the sandwich beam failed due to crushing of concrete in the vicinity of the loading point as shown in Fig.4a. Then, the concrete was removed and a fatigue crack of 10 mm in length was found to propagate in the tie plate (see Fig.4d). In fatigue tests no.2, no.3, and no.4, the failure mode of the sandwich beam is considered to be fracture of the tie plate. That is because the fatigue crack occurs in the tie plate at first and then new diagonal crack originates from the shear connector at point C (see Fig.5) and propagates



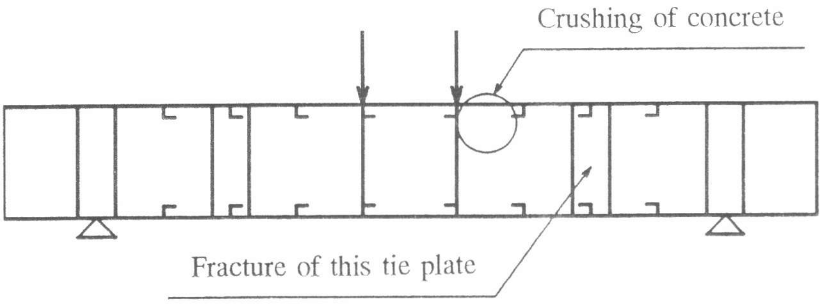
a) Failure mode of the sandwich beam



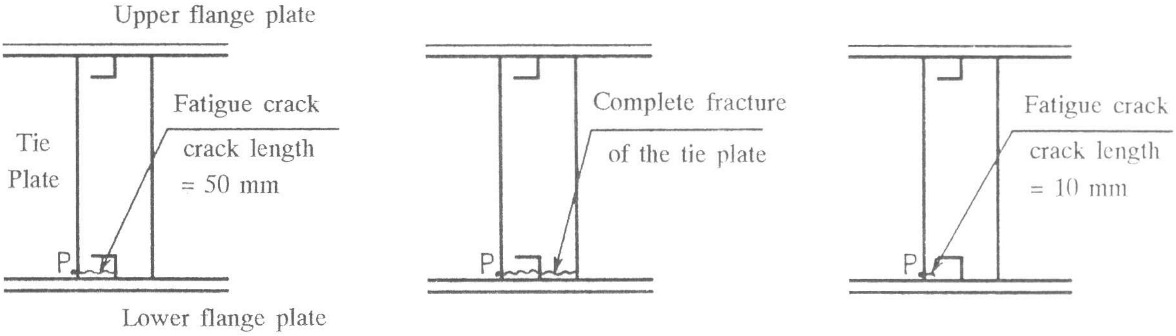
b) Local bending deformations of the lower flange plate

Fig.3 The failure mode in fatigue test no.1 (P_{max} / P_u = 52.5%)

towards the loading point. Therefore, the deflection of the beam increases and finally the crushing of the concrete takes place. It is observed that the fracture of the tie plate occurs always at the welding part between the tie plate and the lower flange plate. Also, the fatigue crack starts always from point P which is the most tensioned point in the tie plate (see Figs.4b, 4c, and 4d). This could be illustrated by the relationship between the number of loading cycles *(N)* and the strain ranges in the tie plate as shown in Fig.6. In fatigue test no.5 ($P_{max} = 96.1\%$ of P_u), the sandwich beam failed due to crushing of concrete in the vicinity of the loading point. Then, the concrete was removed and the tie plate was found to be sound (i.e., no fatigue crack has occurred in the tie plate). Therefore, in fatigue test no.5, the failure mode of the beam is considered to be crushing of concrete. The S-N relationship of the sandwich beam is shown in Fig.7. Note that the fatigue life of the beam at ($P_{max} / P_u = 90.4\%$) is plotted by two points connected with a dotted line, the first point at 2100 cycles and the second point at 8100 cycles. The first point neglects the effect of the 6000 cycles with ($P_{max} = 86\%$ of P_u) and ($P_{min} = 14.3\%$ of P_u). On the other hand, the second point considers the effect of the small load range ($P_{max} = 86\%$ and $P_{min} = 14.3\%$ of P_u) exactly the same as the effect of the big load range ($P_{max} = 90.4\%$ and $P_{min} = 5.5\%$ of P_u). Hence, the actual fatigue life of the beam is locating between 2100 cycles and 8100 cycles.



a) Failure mode of the sandwich beam

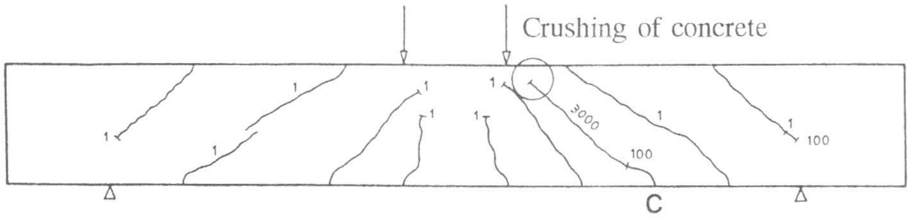


b) Fracture of tie plate (fatigue test no.2)

c) Fracture of tie plate (fatigue test no.3)

d) Fracture of tie plate (fatigue test no.4)

Fig.4 The failure mode in fatigue tests no.2, no.3, and no.4



(numbers indicate the number of loading cycles)

Fig.5 Crack pattern of the sandwich beam in fatigue test no.3

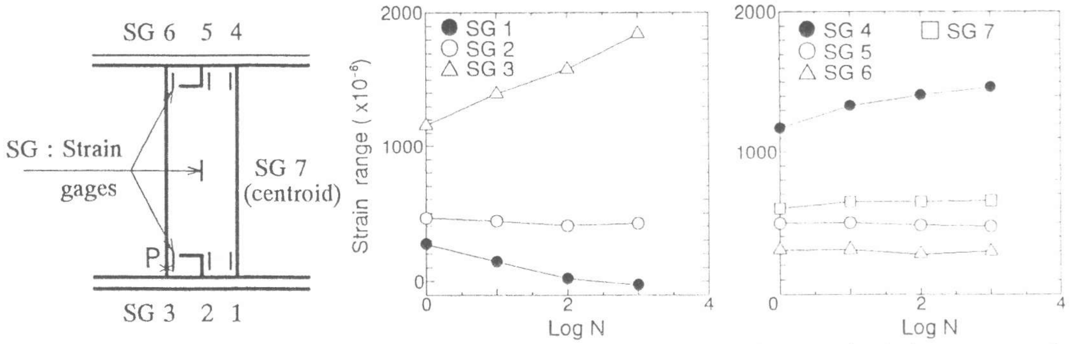


Fig.6 The relationship between *(logN)* and the strain ranges in the tie plate in fatigue test no.3

5. FATIGUE STRENGTHS OF TIE PLATE AND LOWER FLANGE PLATE

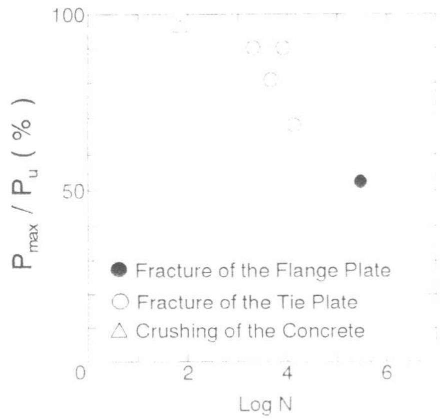


Fig.7 The S-N relationship of the beam

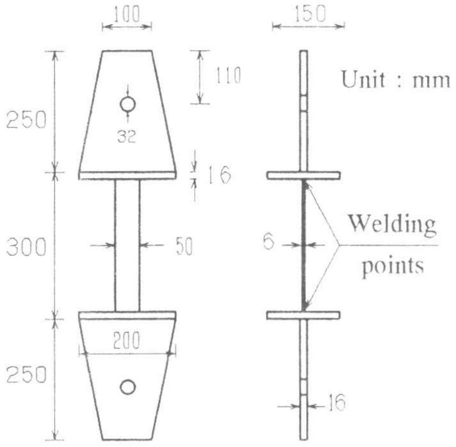
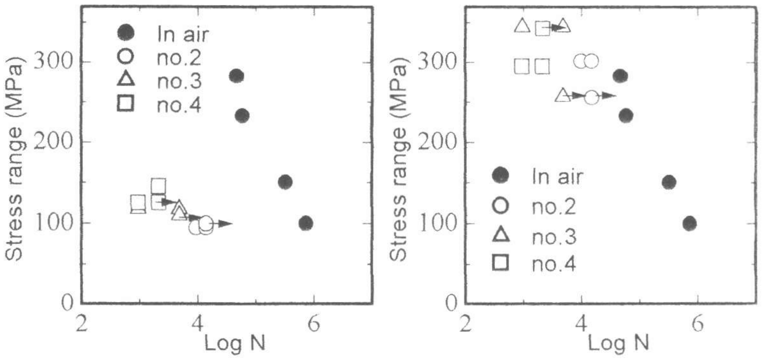


Fig.8 Tie plate specimen for the tensile fatigue test

Tensile fatigue tests were carried out for a number of tie plate specimens in air. The tested tie plate specimen is shown in Fig.8 which had a width of 50 mm and a thickness of 6 mm. The specimen had a yielding point of 400 MPa and a tensile strength of 550 MPa. As shown in Fig.8, the tie plate specimen was welded at its both ends to horizontal steel plates of 16 mm in thickness. These horizontal steel plates correspond to the upper and lower flange plates in the sandwich beam. The specimens were tested for different tensile stress ranges. Figure 9a illustrates a comparison between the S_r-N relationship of the tie plates in air and the S_r-N relationship of the tie plates in the sandwich beam. The S_r-N relationship of the tie plates in the beam was plotted using the stress range at the centroid of the tie plates (see Fig.6) in order to exclude the effect of the shear deformations of the tie plates. The S_r-N relationship of the tie plates in the beam was plotted using the data from fatigue test no.3. In Fig.9a, the fracture of the tie plate in the beam is plotted by two points connected with a dotted line. It means that the fracture of the tie plate has occurred between these two numbers of cycles. The fatigue strength of the tie plates in the beam was found to be weaker than the fatigue strength in air. This is because of the shear deformations of the tie plates in the beam. These shear deformations result in additional tensile stresses at the welding parts between the tie plates and the flange plates as shown in Fig.6, which in turn result in reducing the fatigue life of the tie plates. Figure 9b illustrates another comparison between the S_r-N relationship of the tie plates in air and the S_r-N relationship of the tie plates in the sandwich beam. In this figure, the S_r-N relationship of the tie plates in the beam was plotted using the stress range at point P (see Fig.6) which is the most tensioned point in the tie plates. Hence, Fig.9b takes into account the effect of the shear deformations of the tie plates. The difference between the stress range plotted in Fig.9a and the corresponding stress range plotted in Fig.9b indicates the additional stress range induced in the tie plate due to the shear deformations. Note that the stress range at point P is in good agreement with the S_r-N relationship in air.

Also, tensile fatigue tests were carried out for a number of flange plate specimens in air[3]. Figure 10 illustrates a comparison between the S_r-N relationship of the flange plate in the beam and the S_r-N relationship in air. The S_r-N relationship of the flange plate in the beam was plotted using the stress range at point W (see Fig.3b) which was the origin of the fatigue crack in the flange plate. The stress range at the corresponding point in the right side of the beam is also plotted. The stress range at point W takes into account the effect of the local bending deformations of the flange plate. However, there is still some gap between the stress range at point W and the S_r-N relationship in air. This gap may be caused by the shear transfer between the concrete and the lower flange plate.



a) Stress range at the centroid b) Stress range at point P

Fig.9 Comparison between the S_r-N relationship of the tie plates in the beam and the S_r-N relationship in air

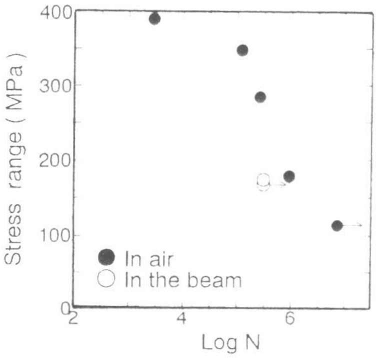


Fig.10 Comparison between the S_r-N relationship of the flange plate in the beam and the S_r-N relationship in air

6. CONCLUSIONS

1) The sandwich beam investigated in this study indicates a shear compression failure mode under static loading. This failure mode is characterized by diagonal cracking and crushing of concrete.

2) For a maximum fatigue load (P_{max}) ranging between 41.8% and 90.4% of the static strength of the sandwich beam, the failure mode of the beam is fracture of the steel plates either the lower flange plate or the shear reinforcing steel plates. However, for a very large maximum load (P_{max} = 96.1% of the static strength), the failure mode of the beam is crushing of concrete.

3) The fatigue strength at the welding part of the tie plates in the beam was found to be weaker than the fatigue strength in air. This is because of the shear deformations of the tie plates in the beam.

4)The fatigue strength at the welding part of the lower flange plate in the beam is weaker than the fatigue strength in air because of the local bending stresses and the shear transfer between the concrete and the flange plate.

Fatigue strength (or S-N curve) for three failure modes of the sandwich structure as well as fatigue strengths of the flange and tie plate in the sandwich structure, which should be quantified for fatigue design of the sandwich structure, will be reported in another paper by the authors.

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