Zeitschrift: IABSE congress report = Rapport du congrès AIPC = IVBH Kongressbericht

Band: 9 (1972)

Artikel: Fatigue strength of steel plates with a stud shear connector for application to continuous composite beams

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DOI: https://doi.org/10.5169/seals-9552

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Fatigue Strength of Steel Plates with a Stud Shear Connector for Application to Continuous Composite Beams

Résistance à la fatigue de plaques d'acier avec goujons de cisaillement employées dans la construction de ponts mixtes continus

Ermüdungsfestigkeit von Stahlplatten mit Schubdübeln bei der Anwendung durchlaufender Verbundträger

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1. Introduction

The static and fatigue behaviors of non-prestressed continuous composite beams, which are steel and concrete composite constructions along the entire length of structure without prestressing into concrete slab in negative moment regions, have been nearly clarified by the several experimental studies 1),2),3). However, a question in connection with the fatigue resistance of the tension flange in the regions where the beam passes over an interior support and which is subjected to repeated negative moments, has not completely been solved yet.

With respect to this problem, two types of fatigue tests have been conducted until now. Namely, one is a flat plate test by using specimens which consist of a flat plate and of one or more studs welded to it, and the other is a beam test for model composite beams subjected to negative moment. However, there were some defects in both of the test methods to obtain the S-N relationships on fatigue resistances of plates with a stud shear connector. First, in all of the flat plate tests which were conducted in the past, the fatigue strength of the plate was obtained under the condition where the stud was not subjected to any shear force, against the fact that the studs in composite beams act as shear connectors between steel beam and concrete slab. On the other hand, in the beam tests, a S-N relationship for any shear stress level could not be obtained, since it was not easy to vary arbitrarily the combination of flexural tensile stress in a tension flange with shear stress on a stud shear connector.

Now, in order to improve the above-mentioned defects in both tests and to obtain exact S-N relationships on fatigue resistances of plates with a stud shear connector, the authors have carried out the flat plate fatigue tests by using a new testing device which could make a pulsating shear force act on a stud in the same phase as a cyclic extensions applied to a plate. Moreover, static and fatigue tests were conducted with other three types of specimens, which were plain plates, plates with a stud removed and plates with a bare stud, in order to estimate the influences of welding and geometrical discontinuity caused by a stud upon static and fatigue resistances of plates.

In this paper, an outline of these experiments is described and the test results are provided and compared with the results 3) of beam tests done by the authors.

2. Description of Specimens and Test Procedure

2.1 Description of test specimens

Structural carbon steel SS41 by JIS (the Japanese Industrial Standards) designation and high-strength quenched and tempered low alloy structural steel SM58Q by JIS were used in the fabrication of plates for test specimens, and the steel material of the studs corresponded to SS41 grade. Chemical composition and mechanical properties of these base materials indicated in mill sheet, are given in Table 1.

The whole test program for SS41 and SM58Q steels was broken down into seven different test series including three static tests, respectively. The dimensions of each specimen for these test series are shown in Fig. 1. Cross-sectional dimensions in parallel portion of plates were the same through all of the test series, and the shape and length of plates were identical in each of the SA through SC, A through C, and D series.

The fatigue tests were as follows:

A Series: The purpose of this series of tests was to obtain a basic S-N curve for plain plate of base material with mill scale under pulsating tension stress cycles.

B Series: In order to estimate the effect of welding on the base materials, the geometrical discontinuity caused by the upset around the root of stud was made to disappear by cutting off the stud and grinding down to the surrounding plate surface.

C Series: The function of this series was to determine a S-N curve for plates under the condition that a stud was not subjected to any shear forces, namely the state of a bare stud.

D Series: This series were intended to find out the effect of transmission of shear force through the stud shear connector at the same time when the plate is being subjected to a primary tension.

The static tensile strength of A through C series was checked by means of three static tests, SA, SB and SC series, respectively.

The authors have to mention that the experiments for SS41 steel have been carried out as planned, but for SM58Q steel, only the tests of SA, SB, SC and C series have been finished until now and the remains are being continued.

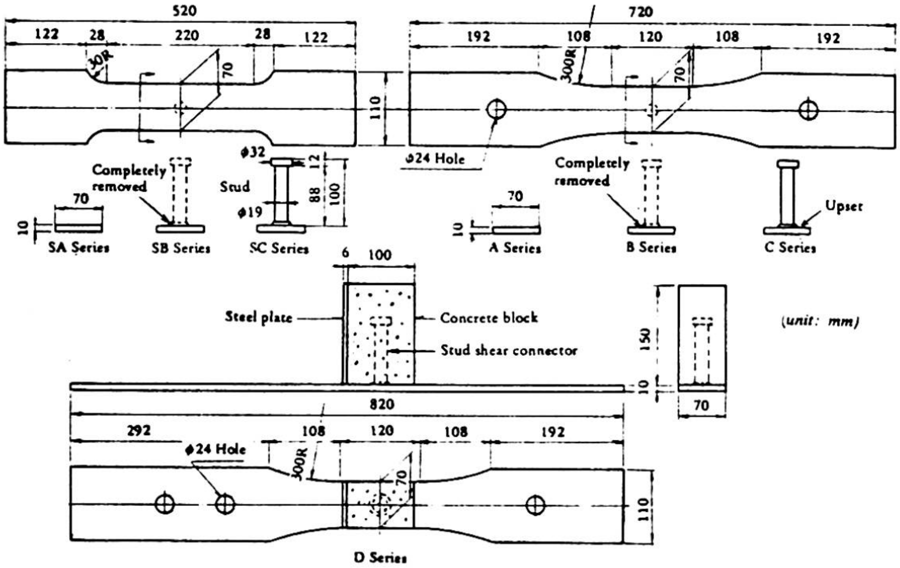


Fig.1 Dimensions of test specimens.

Table 1. Chemical composition and mechanical properties of base materials

Material	Chemical Composition (wt.%)						Mechanical Properties		
	C	Si	Mn	P	S	Cu	Y. P. (kg/mm^2)	T. S. (kg/mm^2)	Elong. (%)
SS41 Plate	0.17	0.04	0.77	0.009	0.031	——	30	45	32
SM58Q Plate	0.14	0.36	1.21	0.019	0.012	0.03	63	66	26
Stud	0.17	0.01	0.69	0.011	0.033	——	28	43	30

All of the plates for test specimens were fabricated from a large steel plate (10 x 1600 x 4100 mm) of which surface condition was as-received with mill scale. After the both sides of all plates were machined to specified dimensions, each specimen for SB, SC, and B through D series was provided with a single stud (ϕ 19 x 100 mm) at the center of plate by the same welding procedure that the weld current was 2,000 amps. and arc time 32/60 cycles for SS41 steels, and 1,700 amps. and 36/60 cycles for SM58Q steels.

For specimens of SB and B series, after stud welding, the studs were completely removed and ground down to approximately the same thickness as the surrounding plate.

In the case of specimens for D series, the stud was encased in a concrete block of 70 x 150 x 100 mm, as shown in Fig. 1, in order to secure similar stress conditions as observed in actual composite beams. After a grease had been placed on the plate surface in order to remove steel-concrete bond, the high-early-strength concrete, of which mean compressive strength at a week was about 320 kg/cm^2, was cast around the stud. In this way, it was expected that all of the applied shear force could be transmitted through the stud to the plate.

2.2 Test procedure

All of the fatigue tests were conducted with a Losenhausen-type fatigue testing machine of a maximum capacity of 40 tons for dynamic load, and all of the static tests were carried out with an Amsler-type universal testing machine of a maximum load capacity of 200 tons.

2.2.1 A, B and C Series

The fatigue tests for these series were conducted under the conditions of partial tension-to-tension stress cycles with the minimum load of 1 ton and with a constant loading speed of 500 cycles per minute for SS41 steels and 340 cycles per minute for SM58Q steels.

2.2.2 D Series

In this test series, a new shear loading device with a fatigue testing oil jack (maximum dynamic load capacity = 10 tons) was attached to a primary Losenhausen-type fatigue testing machine, so that the pulsating shear force could be acted on a stud which was welded to a plate, in the same phase as the pulsating tension of the plate.

A schematic diagram for this loading method for combined stress is shown in Fig. 2.
A tensile force was applied to the plate with the Losenhausen-type fatigue testing machine in the same manner as an ordinary tensile fatigue test, and moreover, simultaneously the stud was

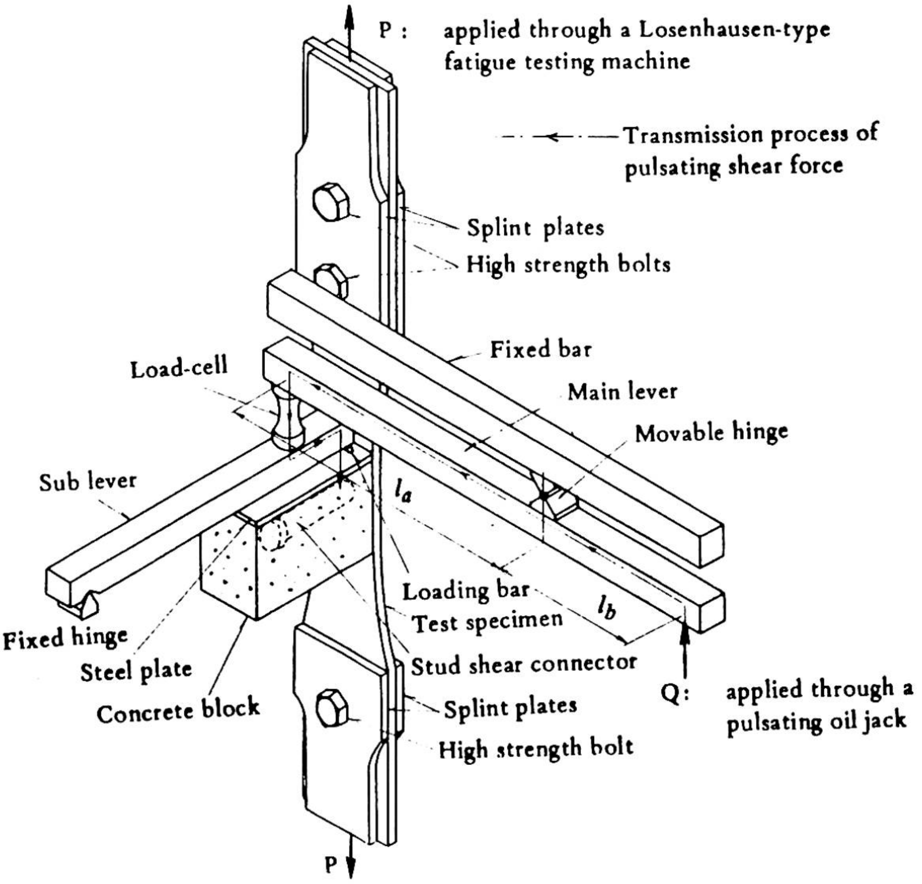
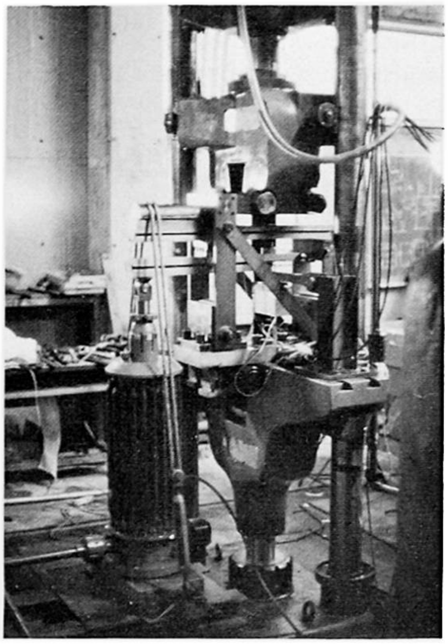


Fig. 2 Schematic diagram for combined stress loading method.

loaded through two levers of a shear loading device with an another oil jack through which pulsating loads were applied with a pulsator belonging to a primary testing machine. Fig. 3 shows a view of testing in progress.

The fatigue tests were conducted in combined pulsating stress cycles with the minimum tensile load of 1 ton for the plate, and with the constant shear stress range for the stud, which was about 2 or 4 kg/mm^2 in this test program. The loading speed was held approximately 340 cycles per minute through all of the specimens.



(a) Setup of fatigue testing machine

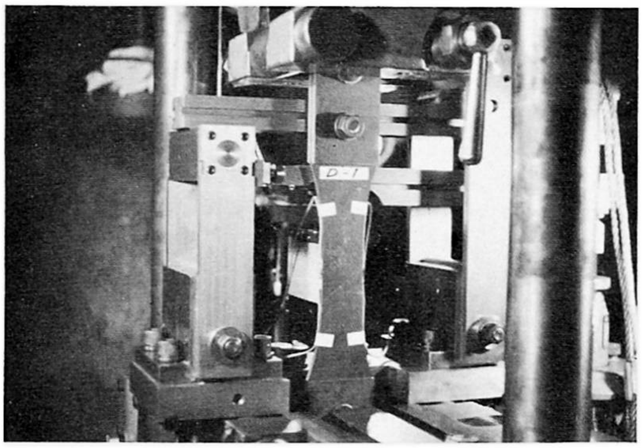


Fig. 3 Fatigue test of D series in progress.

3. Test Results and Discussions

3.1 Static tests

The results of static tests which are presented in Table 2, indicate that the stud welding and the geometrical variation of plate surface did not so much influence either on the stress at the yield point or on the ultimate tensile strength of a base material. The fractures in SB and SC series occurred in the base material at about 5 cm apart from the stud welding point.

The above-mentioned facts held true for the both of mild steel SS41 and high-strength steel SM58Q.

Table 2. Results of static tension tests

Test Series	SS 41			SM 58Q		
	Y. P. (kg/mm^2)	T. S. (kg/mm^2)	Elong. (%)	Y. P. (kg/mm^2)	T. S. (kg/mm^2)	Elong. (%)
SA	27.7	46.2	30.7	56.2	63.9	19.9
SB	27.1	45.2	30.7	55.9	64.6	20.8
SC	26.3	44.8	29.1	56.8	65.0	20.3

3.2 Fatigue tests

The results of fatigue tests are presented in the form of S-N diagram in Fig. 4, on the basis of log-log relationships between a nominal applied tensile stress range in the smallest cross-section of plate and a number of cycles to failure. The figure indicates that the results showed amazingly little scatter, so that a relatively small number of tests were able to give a remarkable indication of the fatigue resistance for each test series.

3.2.1 A Series

From the results of A series for SS41 steels shown in Fig. 4, as the fatigue strength 36.4 and 26.3 kg/mm^2 at 10^5 and 2 x 10^6 cycles, respectively, could be obtained by an extrapolation of the data on a straight line. Although a few number of specimens in this series were tested, these values coincide fairly well with the results reported in Ref. 8), namely the values of 33.8 kg/mm^2 at 10^5cycles and 26.8 kg/mm^2 at 2 x 10^6 cycles for 50 % survival.

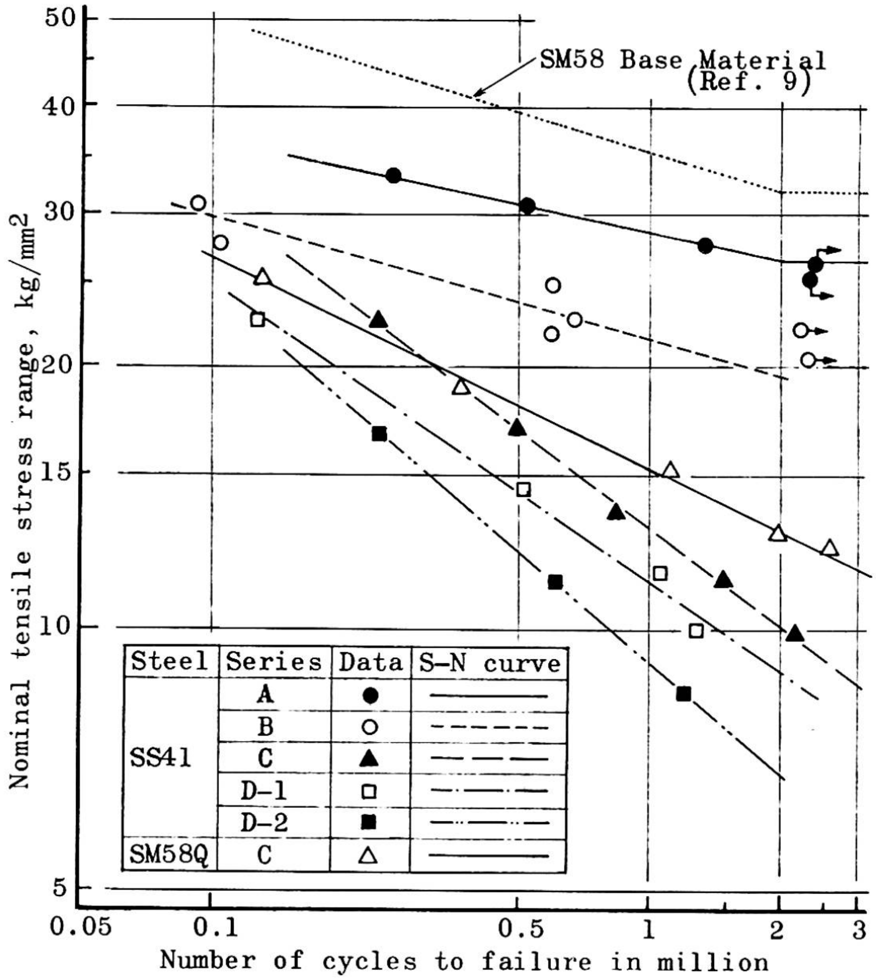


Fig. 4 Fatigue test data on S-N diagram.

3.2.2 B Series

An indication of the effect of welding may be obtained by comparing the results of the A and B series for SS41 steels. In Fig. 4, it is observed that the S-N curve for B series is situated about 5 to 6 kg/mm^2 in terms of the fatigue strength below that for A series, and this difference would be caused by some effects of welding--- for example, stress concentration produced by weld defects which will occur in a welded part during the welding process, residual stress, change of materials in heat-affected zone and so on. In this test series, however, it may be considered that the stress concentration due to weld defects had a larger influence on fatigue strength compared with the other factors. Because, in visual inspection of fracture surface for B series specimens after the fatigue tests, it was observed that the fatigue fracture had initiated at the location of so-called blow-hole for two among five fractured specimens (see Fig. 5(a)), and at a part of lack of fusion for the rest.

And besides, from this fact, it is considered that the results for B series have somewhat scattered, since the degree of stress concentrations produced by the weld defects may delicately depend upon the type or nature of such defects as their shape, orientation and size, etc.

3.2.3 C Series

(a) SS41 Steels

From the results of C series as shown in Fig. 4, it is clear that the geometrical discontinuity at the root of stud has a large influence on the fatigue resistance of plates with a stud. In other words, the slope of S-N curve for C series is more steeper than that for A or B series, and the fatigue strength decreases rapidly as the cycles increase, resulting in about 40 % of that for A series and about 50 % of that for B series, at 2 x 10^6 cycles.

In all of the specimens for C series, a fatigue crack initiated at either one of the upset edges closest to the ends of plate, and propagated more rapidly toward the both sides of plate. In visual inspection of fracture surface after the fatigue tests, such internal defects as observed in B series, were not found out at all. From these matters, it is clear that the influence of internal defects is not so great as the geometrical effect of stud. In the case of the presence of a stud, accordingly, it can be concluded that the fatigue strengths of plate with a stud will depend upon mainly the degree of stress concentrations at the root of stud, and properties of the base metal in heat-affected zone including residual stresses. In this test program, unfortunately the individual effect of these factors upon fatigue strength of plate could not be studied in detail, but would be investigated in future.

(b) SM58Q Steels

In Fig. 4, the S-N curve given in Ref. 9) for the plain plate fatigue tests of JIS SM58 steels with mill scale, is also drawn for comparing with the results of this series, since the tests of A series for this steel have not been conducted until now.

It is seen that the fatigue strengths of C series for SM58Q steels at any cycle lives drop down equally by about 40 % of those for plain plate, resulting in nearly the same value as for SS41 steels, while a large difference in static tensile strength between both steels is indicated in Table 2. This may be caused by a fatigue characteristic of high-strength steel, that is, a high notch sensitivity for stress concentrations.

From the fact that the conditions of initiation and propagation of a fatigue crack was nearly the same as the case of SS41 steels, it may be slso persisted that this reduction in fatigue strength would be caused by the reason above-mentioned for SS41 steels with a stud.

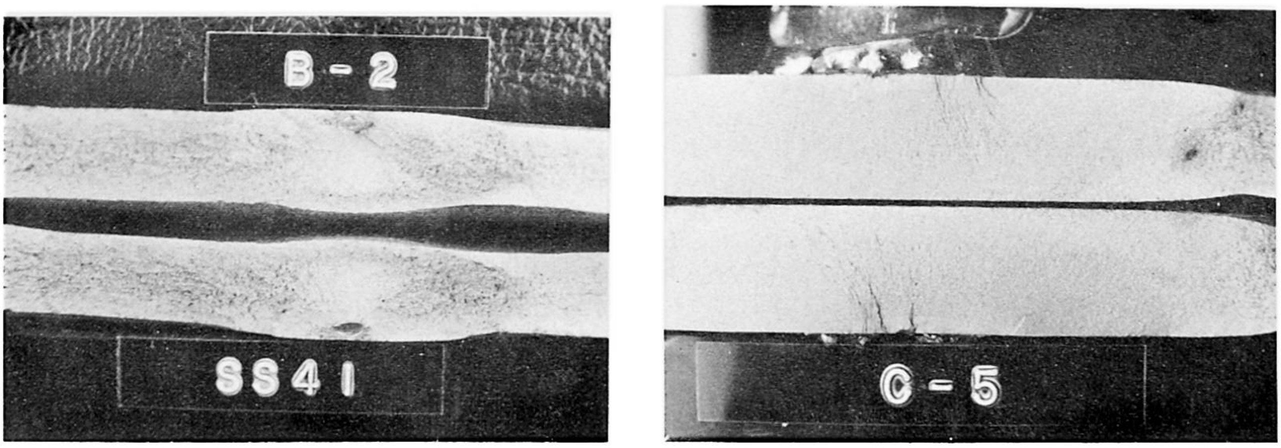
(c) Comparisons with other investigations

In Table 3, the fatigue strengths obtained from the S-N curve for C series of SS41 and SM58Q steels are compared with those obtained from the flat plate tests made by other investigators4),5),6). It is indicated that, in spite of the differences in materials, number of stud attached to a plate, shape and size of specimens and so on, there is an excellent agreement among the results, although the present results for SM58Q steels were somewhat larger than the others.

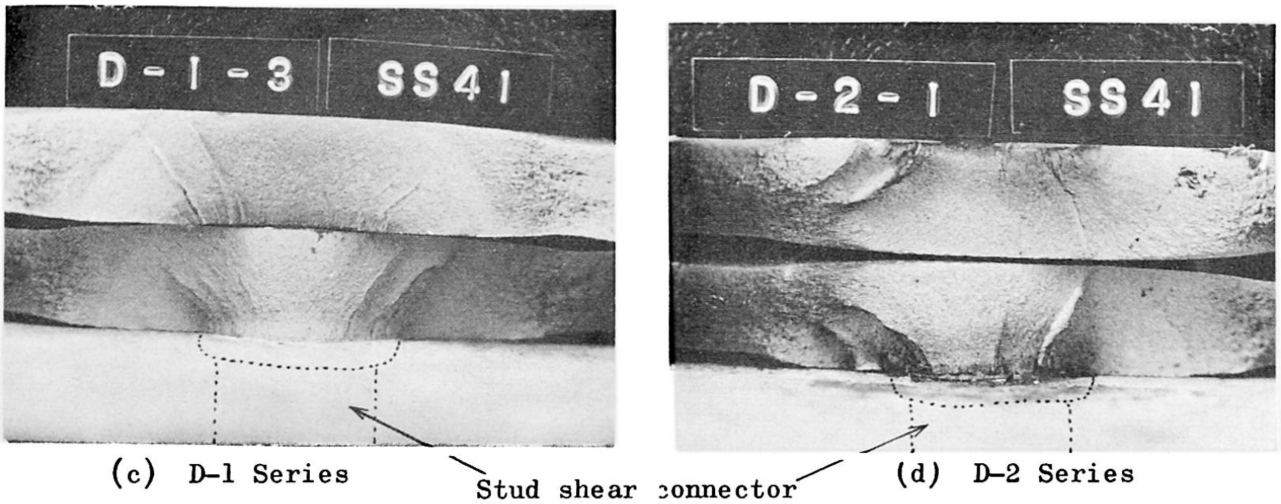
Typical fracture surfaces after the fatigue tests for each of the test series are shown in Fig. 5. Fig. 5(a) for B series shows a typical fracture surface with a blow-hole at which the fatigue crack initiated. In Fig. 5(b) for C series, it is seen that the fatigue crack initiated just close at the edge of upset and propagated uniformly and approximately perpendicular to the plate surface.

Table 3. Comparisons of fatigue strength of plate with studs

Name	Material	Fatigue Strength, kg/mm^2		Number of stud welded to a plate
		N=500,000	N=2,000,000	
Authors	JIS SS41	16.8	10.1	one stud
	JIS SM58Q	18.2	13.0	
T. Wakabayashi et al.5)	JIS SS41	18.0	11.0	one stud
	JIS SM58	15.5	10.0	
K.A.Selby et al.4)	ASTM A7F A441	16.6～20.4	10.0～12.5	one or more studs, transversely
W. Roshardt6)	DIN St37	16.0	11.0	three studs, longitudinally
	DIN St60 St70	17.5	10.0	



(a) B Series (b) C Series



(c) D-1 Series (d) D-2 Series

Fig. 5 Typical fatigue fracture surfaces in each test series.

3.2.4 D Series

In order to estimate the influence of shear force acting on a stud shear connector upon a tensile fatigue resistance of plate under combined stress conditions, a number of S-N curves must be obtained at various different levels of constant shear stress range. In this test program for SS41 steels, the fatigue tests were carried out under two different stress levels, that was, approximately 2 kg/mm^2 and 4 kg/mm^2 with a maximum deviation of ± 5 % in the average shear stress range acting on a nominal cross-section of stud, and each test series was distinguished as D-1 or D-2, respectively. The test results are plotted in Fig. 4 with the shear stress range as a parameter.

All of the specimen in this series failed due to propagation of a fatigue crack which had initiated at the upset edge closest to the side of applied shear force. A typical fracture surface is shown in Figs. 5(c) and (d). As compared with Fig. 5(b), it is seen that the fracture surface in D series includes a narrow region where a crack has propagated along the fusion line on account of the presence of shear force acting on the stud, while the fatigue crack in C series has propagated approximately perpendicular to the plate surface and formed a relatively flat fracture surface.

By comparing three S-N curves for C, D-1 and D-2 series as shown in Fig. 4, it is noticed that the fatigue strength of plate at any cycle life reduces gradually as the shear stress range increases, and it can be considered that this phenomenon may be reasonable. Then, in order to clarify how the tensile fatigue strength of plate would be influenced by a shear force acting on a stud, the authors tried to apply the test results to various criteria of failure that are generally used in the case of combined alternating bending and torsion in the same phase.

The fatigue strengths at 2×10^6 cycles for C, D-1 and D-2 series, which were obtained from the S-N curves shown in Fig. 4, and the result of push-out tests, which were primarily conducted to determine the shearing strength of shear connectors under pure shears, reported in Ref. 7) are plotted on the so-called fatigue limit diagram under combined stresses in Fig. 6, in which the curves calculated corresponding to various theoretical criteria of failure10) are also indicated. As seen in Fig. 6, the present test results including those for push-out test are not applicable to any curves, and accordingly the phenomenon of reduction in the fatigue strength of plate could not be interpreted fully and satisfactorily with the usual criteria of failure. The following factors may be considered as the main reasons for this: the difference in combined loading conditions of normal and shear stress, for example, the one is bending and torsion, and the other is tension and shearing; the difference in the estimation of fatigue strength, namely, the one is an endurance limit and the other is a fatigue strength at 2×10^6 cycles; the effect of stud welding and stress concentration at the root of stud in the present specimens; and so forth. Therefore, a definite experimental hypothesis for fatigue failure of plate with a stud under combined stress cycles, could not be obtained within a limit of the present test program lacking sufficient informations. Supplementary fatigue tests for other shear stress levels are being continued to make clear this phenomenon.

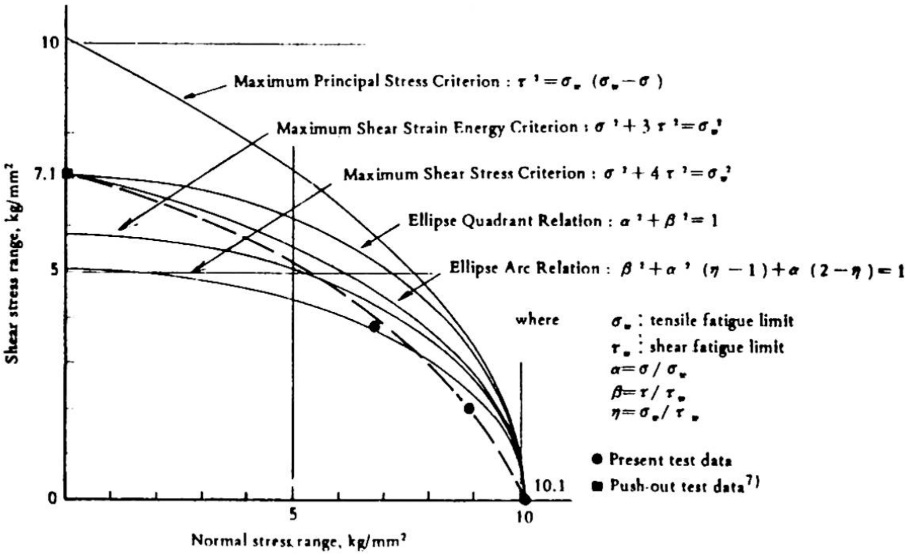


Fig. 6 Comparison of test data with various criteria of failure.

4. Comparison with the Results for Beam Tests

4.1 Summary of the beam tests

The experimental study on composite beams subjected to repeated negative moment was conducted as a part of investigations to clarify the fatigue behavior in negative moment regions of non-prestressed continuous composite beams, and its results were reported in Ref. 3) by the authors.

The test program was carried out on sixteen beam specimens which were divided into seven types, as shown in Table 4, according to location of loading, diameter of longitudinal reinforcing bar, and spacing and type of shear connectors. Cross-sectional dimensions, details of shear connectors, span length and location of applied load are shown in Fig. 7.

Table 4. Summary of test beams

Beam	No.	Diameter of longitudinal reinforcements	Spacing and type of shear connectors (cm)		Loading condition
E 1	2	D 13 mm	40	Stud	Two points
E 2-1	2	D 16	30		
E 2-2	2	D 16	60		
E 2-3	2	D 16	10		
E 3	2	D 19	20		
H 1	3	D 16	30	Stud	One point
H 2	3	D 16	45	Block	

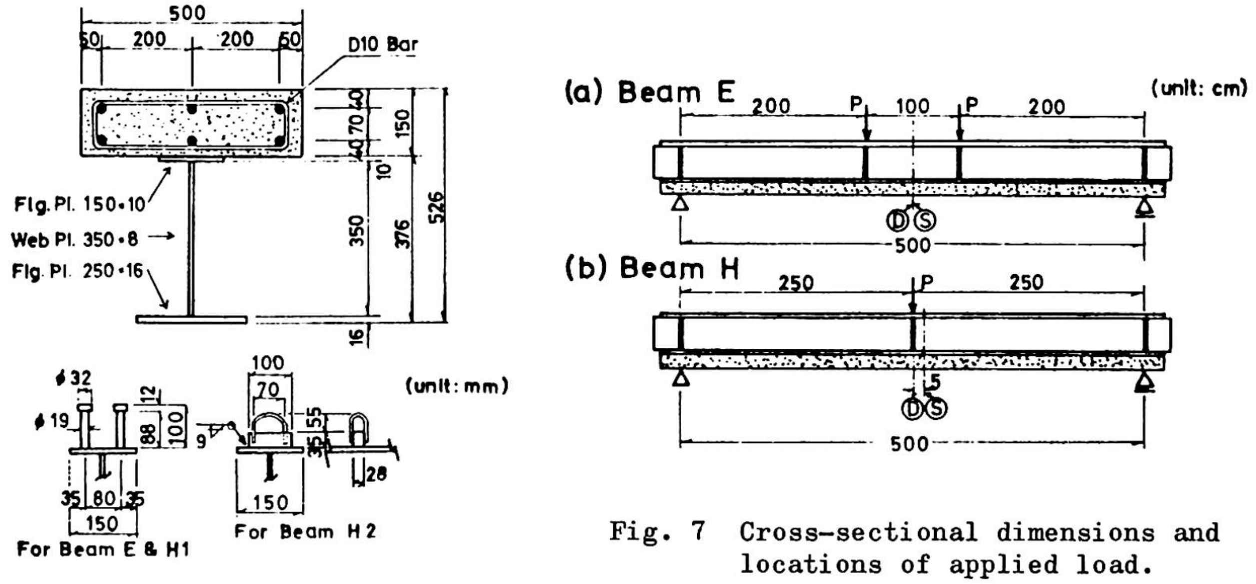


Fig. 7 Cross-sectional dimensions and locations of applied load.

Steel materials of all test specimens were structural carbon steels of JIS SS41 grade for steel beams and for stud shear connectors, deformed bars of SD30 at JIS for longitudinal reinforcements. At these fatigue tests, such phenomena were observed that a fatigue crack initiated at the upset edge of shear connectors and then propagated through the tension flange to which the shear connectors were attached.

In the present paper, the authors have rearranged the test data of beam tests by taking into account the so-called dynamic effects of repeated load due to an interaction of the applied dynamic load and inertia force of the beam, in calculating flexural fiber or shear stresses which occurred in the beams. Because, the effects were not considered for the arrangements of beam test results at the time when the Ref. 3) was published, resulting in a large underestimation for calculating the stresses.

The modified results for beam tests are plotted in Fig. 8 and compared with those for C and D series of SS41 steels.

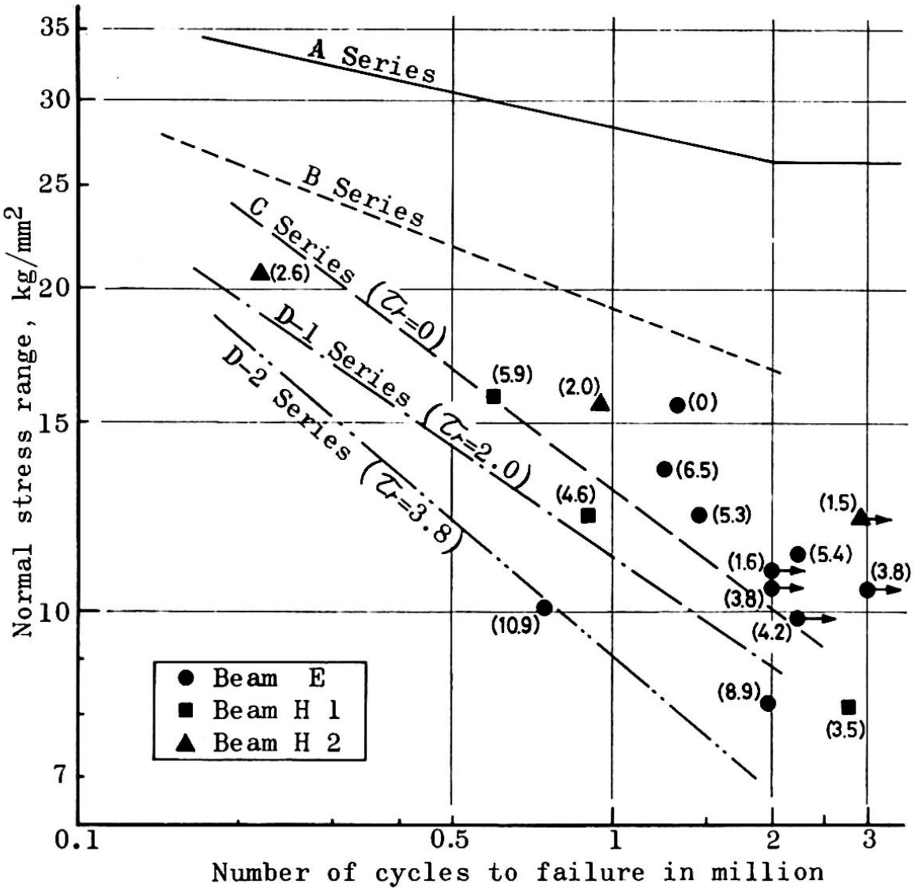


Fig. 8 Comparisons of the results for beam and plate tests in terms of normal tensile stress range.

4.2 Comparisons with the results of beam tests

In Fig. 8, the results for flat plate tests of SS41 steels are indicated in the forms of S-N curve, and these for beam tests are plotted by means of three kinds of marks. The numerals in parentheses express the shear stress range τ_r in kg/mm^2, which acted on a shear connector in each beam specimen. While shear connectors for H2 specimens were different from those for E and H1 specimens, the results for H2 beams were dealt with, for reference, together with those for E and H1 beams in the following discussions.

As shown in this figure, the most of the results for beam tests scatter widely on the right of S-N curves for C, D-1 and D-2 series. When paying attension to the value of τ_r which was indicated in the parentheses, such a tendency is observed that, with a few exceptions, at any normal stress range, the fatigue life for the data for smaller τ_r becomes longer than that for those for larger τ_r. From this fact, it would be understood at least qualitatively that, as seen in the flat plate tests, the fatigue strength of tension flange to which the shear connectors were attached is not a little influenced by the shear force which acted on shear connectors.

Next, the authors have tried to evaluate the both test results by means of the plane principal stress occurred at the base of stud. A principal stress σ_p consisting of normal stress σ_x, namely, a flexural fiber stress in tension flange for beam specimens or a nominal tensile stress in the cross-section for plate specimens, and of an average shear stress in the stud τ_{xy}, as shown in Fig. 9, were considered for the evaluation. A flexural stress in the root of the stud σ_y was excluded out of this principal stress, since its exact estimation had not been made yet.

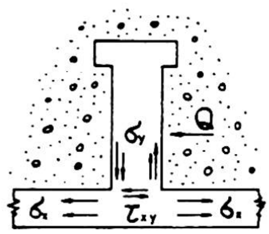


Fig. 9 Stress condition at base of stud.

The data for C, D-1 and D-2 series of plate tests and those for beam tests are plotted in Fig. 10 with the marks of black square and dot, respectively, and further, two scatter bands including the most part of each group are indicated by vertical or horizontal hatchings. As seen in the figure, all of the both test results are included in either comparatively nallow scatter band with the exception of a few data.

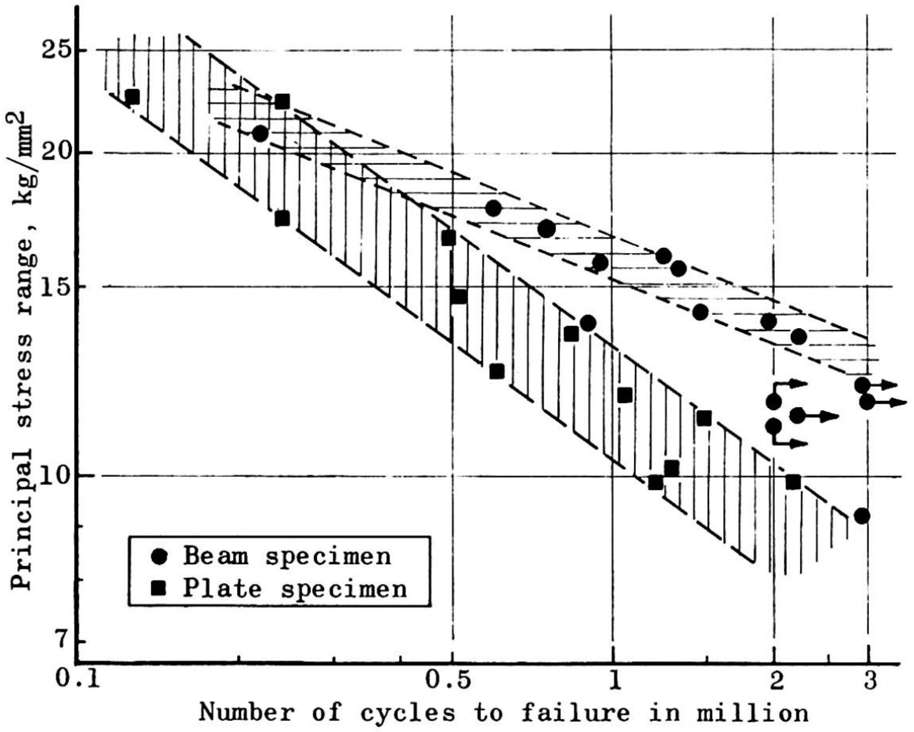


Fig. 10 Comparisons of the results for beam and plate tests in terms of principal stress.

The breadth of scatter band for plate tests are somewhat wider than that for beam tests. This may be explained by the following two reasons. First, such a difficulty of shear loading method existed that the plate would be subjected to not only an axial tensile force, but a slight additional bending moment in the plane due to an eccentricity of shear loading, although the loading point of shear force was kept as close as possible to the plate surface, about 4 mm. Second, the test results for C, D-1 and D-2 series were not applicable to the maximum principal stress criterion, as seen in Fig. 6.

Besides, the interpretation on a few exceptions which appeared in the results for beam tests, has not been completed yet.

In Fig. 10, it is observed that the scatter band for beam tests is located above that for the plate tests, and the differences of fatigue strength between the both bands become larger as the cycle life increases, while they nearly coincide with together at about 200,000 cycles. In the beam specimens, the stress in a tension flange is redistributed to longitudinal reinforcements which were embeded in concrete slab and acted fully effectively after the fatigue crack propagated through the tension flange, and also the shear stress on the stud is redistributed to adjacent studs even if the fatigue crack occurred in the tension flange at some studs. Hence, the speed of propagation of fatigue crack was very slow, especially when the load was smaller, and the fatigue cycle life of beam specimens will become longer. Against this fact, in the flat plate tests, the condition of the tests was very severe, compared with that of the beam tests on account of no redistribution of any stresses. Therefore, there is no doubt that the results for flat plate tests are on the safe side for an actual design of tension flange in negative moment regions of non-prestressed continuous composite beams.

In this manner, the both results for beam and flat plate tests may be interpreted fairly well by considering the principal stress, but, it is still in question why the fatigue failure of a plate in tension with stud shear connectors did not satisfy the maximum principal stress criterion.

5. Conclusions

The main conclusions of this investigation may be summarized as follows:

(1) In the static tensile tests, the stud welding and the geometrical variation of plate surface did not so much influence on either the yield point or the ultimate tensile strength of the base material of either SS41 and SM58Q steels.

(2) The fatigue strength of plate with a stud shear connector was influenced mainly by the stress concentration caused by a geometrical discontinuity at the root of stud, and accordingly the fatigue failure occurred at the edge of the upset.

(3) The fatigue strength of plates with a bare stud reduced remarkably compared with that of the base material, resulting in less than about 40 % at 2 x 10^6 cycles, namely, approximately 10.1 kg/mm^2 in the stress range for SS41 steels, and about 40 %, 13.0 kg/mm^2 for SM58Q steels.

(4) The fatigue tests conducted by using a new testing device, have produced very reasonable results relating with the tensile fatigue strength of plate. Namely, the pulsating shear force reduced the fatigue strength of plate below that for the plate with a bare stud, and as the result, the nominal tensile stress range at 2 x 10^6 cycles was lowered down to about 8.9 kg/mm^2 for the shear stress range of 2.0 kg/mm^2 and about 6.8 kg/mm^2 for that of 3.8 kg/mm^2.

(5) The informations which were obtained from the combined stress fatigue tests of flat plate with a stud shear connector, would be applicable to the evaluation of fatigue tests for the beam specimens.

(6) When the results for flat plate tests were compared with those for beam tests in terms of plane principal stress consisting of normal and shear stresses, the fatigue cycle life for the latter was longer than that for the former in general. This may be mainly due to the redistribution of stresses in beam specimens after a fatigue crack was initiated.

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SUMMARY

The experiments are described primarily in order to study the influence of stud welding upon fatigue resistance of a plate in tension, and also to obtain information on the S-N relationship for the plate to which a stud-type shear connector is attached, under such a stress condition as tension in the plate and shear on the stud. Then, the test results are discussed in relation with the fatigue behavior of steel and concrete composite constructions in a negative moment.