Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 60 (1990)

Artikel: Forces on the studs in a steel plate and concrete slab

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DOI: https://doi.org/10.5169/seals-46460

Forces on the Studs in a Steel Plate and Concrete Slab

Effort sur les goujons de dalles mixtes acier-béton

Dübelkräfte in Verbundplatten

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SUMMARY
A steel plate and concrete composite slab, made of prefabricated thin steel deck with headed studs and in situ cast concrete, has been used for bridge decks. To verify that the stud-force characteristics are an important design factor of such a slab, we have carried out two-point loading tests and three-dimensional finite element analysis. As a result, it was found that most of stud shearing force is carried at the welded base, and that the body of the stud is subjected almost to only axial tensile force due to uplift, with noticeable magnitude.

RÉSUMÉ
Les dalles mixtes acier-béton, constituées de plaques préfabriquées en acier mince avec goujons à tête et béton coulé sur place, on été utilisées pour les tabliers de pont. Le comportement de l'effort sur la liaison acier-béton, qui est un important facteur pour le dimensionnement de ces dalles, est ici vérifié au moyen d'une double charge ponctuelle et d'une analyse d'éléments finis tridimensionnels. Les résultats ont montré que la force de cisaillement est plus marquée à la base soudée du goujon et que le corps du goujon est le plus souvent uniquement soumis à une force de traction axiale; ces efforts sont notablement élevés.

ZUSAMMENFASSUNG
Verbundplatten, die aus Stahlprofilblechen mit Schubdübeln (Kopfbolzen) und Ortbeton bestehen, finden oft Anwendung in Brückendecks. Experimentelle Untersuchungen und numerische Vergleichsrechnungen zur Erklärung der Charakteristik der Schubdübelkräfte, welche für die Bemessung von Verbundplatten wichtig sind, werden vorgestellt. Die Ergebnisse zeigen, dass die Dübelschubkräfte am angeschweissten Dübelfuss am grössten sind und dass im Dübel selbst wenstliche Zugkräfte vorhanden sind.

1. INTRODUCTION

A steel plate and concrete composite slab (often called Robinson slab), which is made of prefabricated thin steel deck with headed studs and in situ cast concrete, has been used for bridge decks. It has an excellence both in strength and durability, and its application can be found in the Tancarville bridge, France [1], and a bridge on the Tokyo metropolitan expressway, Japan [2], for example.

In such a slab, studs are used as a shear connector to transmit shearing forces on the interface between steel plate and concrete, in order to make the slab carry external load effectively as a composite structure. The studs are key elements having serious influence on the performance of the composite slabs and, therefore, it becomes necessary for a rational design on the slab to evaluate the shearing forces and the axial forces that are caused by slip and uplift acting on the studs [3]. Unfortunately, there has been no established method to estimate those forces on the studs in the slab.

The final goal of this study is to reveal the stud-force characteristics of a steel plate and concrete composite slab. For the sake of this, firstly, two-point loading tests have been conducted for simply supported composite beam specimens. Secondly, three dimensional finite element analyses have been carried out. Finally, through the experimental results and the numerical ones obtained, the characteristics of stud-forces have been examined.

2. EXPERIMENT

2.1 Test specimens

The test specimens were 160 cm long, 30 cm wide and 18cm high in concrete as shown in Fig.1. Parameters varied in the specimens were as follows: 1) Thickness of steel plate, 2) Diameter and height of studs and 3) Spacing of stud arrangement. Several view studs with narrow slits to measure stud-forces were arranged within a shear span (see Figs.1 and 2). Except C series specimens, natural bond between concrete and steel plate was excluded by placing a thin vinyl film between them. The details of the specimens with their material properties are listed in Table 1.

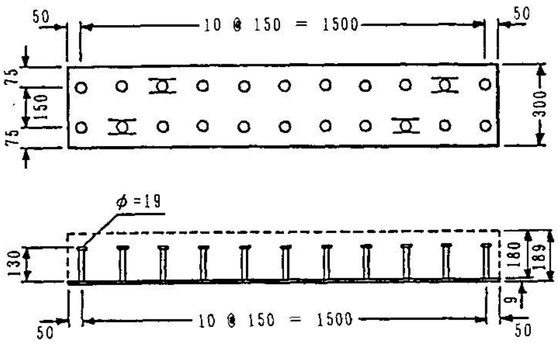


Fig.1 A Typical Test Specimen (unit:mm)

2.2 Loading system

The elevation of two-point loading test is illustrated in Fig.2. The specimens were simply supported and were loaded statically

Table 1 Details of Test Specimens

No.	Name	Stud			Steel Plate				Concrete		
		Dia. (mm)	Height (mm)	Spacing (mm)	Thick. (mm)	f_{su} (MPa)	E_s (MPa)	ν_s	f_c' (MPa)	E_c (MPa)	ν_c
1	A-19-100	19	130	100	9	4.18×10^2	2.21×10^5	0.312	2.65×10	2.21×10^4	0.173
2	A-19-150	19	130	150	9	4.18×10^2	2.21×10^5	0.312	2.65×10	2.21×10^4	0.173
3	A-19-214	19	130	214	9	4.18×10^2	2.21×10^5	0.312	2.65×10	2.21×10^4	0.173
4	A-19-300	19	130	300	9	4.18×10^2	2.21×10^5	0.312	2.65×10	2.21×10^4	0.173
5	B-13-150	13	100	150	6	4.46×10^2	2.05×10^5	0.274	2.39×10	2.42×10^4	0.187
6	B-19-150	19	130	150	9	4.20×10^2	1.96×10^5	0.284	2.39×10	2.42×10^4	0.187
7	C-13-150	13	100	150	6	4.46×10^2	2.05×10^5	0.274	2.39×10	2.42×10^4	0.187
8	C-19-150	19	130	150	9	4.20×10^2	1.96×10^5	0.284	2.39×10	2.42×10^4	0.187

Note) Only specimens of C series have natural bond on the interface between steel plate and concrete.

along the two lines across their width adjusted the ratio of a shear span length to a effective height (a/d) to be 2.5 causing a shear failure at their ultimate state.

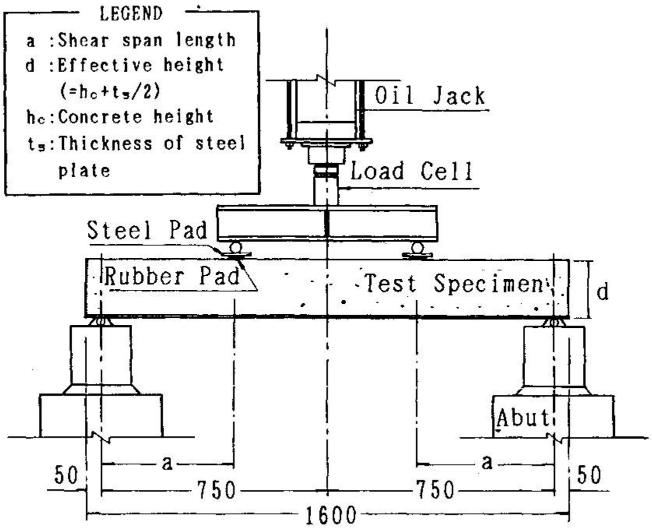
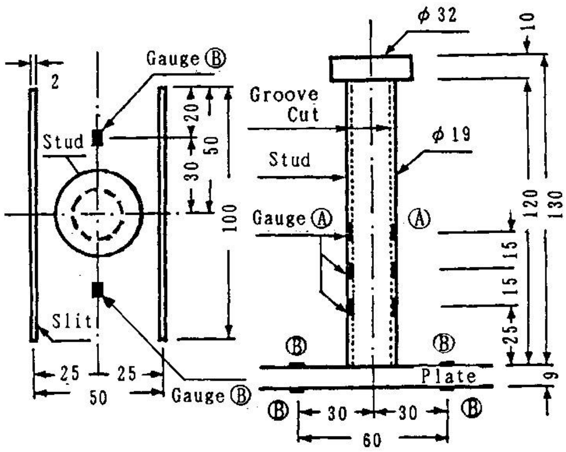


Fig.2 Two-Point Loading Test Set Up

2.3 Measurement of stud-forces

An special attention to measure of stud-forces was paid. A view stud to measure in detail the stud-forces is shown in Fig.3. Namely, the stud-forces were measured in the two ways. One was on a group of strain gauges Ⓐ in Fig.3, embedded in a groove cutting the body, that is the trunk, of stud, which was to set to investigate both the intensities of shearing and tensile force due to slip and uplift. The other was on an another group of gauges Ⓑ, attached on a steel plate with narrow slits in its span direction, which was used to measure the intensity of the whole shearing force of stud including the welded base by considering equilibrium condition of membrane tensile forces of steel plate. In addition, it is noted that the slits are used to exclude an interference of neighboring studs.



(a) Plane View (b) Side View

Fig.3 Details of a View Stud

3. FINITE ELEMENT ANALYSIS

In the composite structures considered here, the studs were arranged discretely as shown in Fig.1 and transmitted forces locally at their welded base whose areas were extremely smaller than the whole area of the interface. It seemed, therefore, to require some three dimensional analyses to reveal the characteristics of stud-forces theoretically. Thus we have carried out analyses by using the three dimensional finite element model outlined in Fig.4, in which steel plate and concrete were idealized to 20 nodes hexahedral isoparametric elements and stud-forces were taken into account as a transmission force having three directional components on the interface. To fulfill the compatibility conditions between steel plate and concrete, a point matching technique was used as in Reference [4], considering both nonlinear force-displacement relations at stud points and nonlinear stress transmission characteristics at other points than those, namely being of continuity in compression and separation in tension.

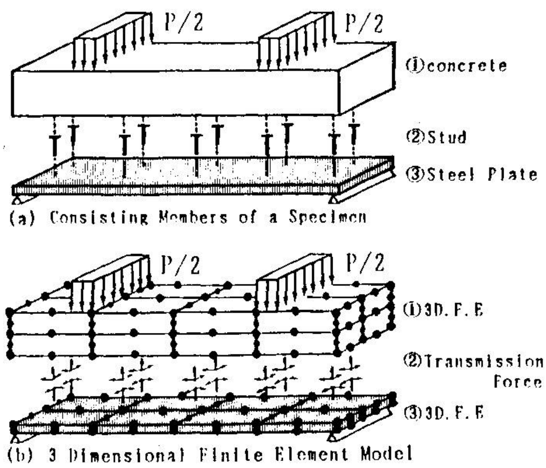


Fig.4 Numerical Model

Table 2 Stud-Force in Elastic Region

No.	Name	x (mm)	Shearing Force:S(N)						Tensile Force:N(N)				
			Exp.		Numer.				Exp.	Numer.			
			Sb	St	S1	S1/Sb	S2	S2/Sb	N	N1	N1/N	N2	N2/N
1	A-19-100	100	1069	-	1520	1.42	1196	1.12	49	127	2.91	98	2.16
		200	843	-	1490	1.76	1167	1.39	-	-	-	-	-
		300	922	-	1040	1.13	961	1.05	-	-	-	-	-
2	A-19-150	150	1589	-	1942	1.23	1530	0.96	-	-	-	-	-
		300	902	-30	1706	1.88	1353	1.50	118	196	1.58	147	1.18
3	A-19-214	214	2697	180	2892	1.08	2001	0.74	677	431	0.64	294	0.44
		428	951	-	1667	1.75	1304	1.38	-	-	-	-	-
4	A-19-300	300	1824	127	2991	1.62	2089	1.13	490	539	1.10	373	0.75
5	B-13-150	150	824	-108	1559	1.88	1108	1.34	-108	177	-1.63	127	-1.19
		300	677	-59	1363	2.03	981	1.46	98	157	1.69	118	1.21
6	B-19-150	150	1795	-137	1824	1.02	1481	0.82	333	206	0.61	167	0.49
		300	1118	-108	1608	1.43	1314	1.17	402	206	0.50	157	0.38
7	C-13-150	150	265	-10	1559	5.72	1108	4.07	0	177	∞	127	∞
		300	167	0	1363	8.11	981	5.83	10	157	23.1	118	16.7
8	C-19-150	150	1383	-177	1824	1.32	1481	1.07	10	206	34.7	167	27.8
		300	1344	-118	1608	1.19	1314	0.97	20	206	10.0	157	7.65

Note) x refers to the distance of the view stud from the supported edge.
Exp. and Numer. refer to the experimental results and the numerical ones, respectively.

4. RESULTS

4.1 Stud-forces in elastic region

Table 2 summarizes stud-forces obtained through the experiments and the finite element analyses in elastic region before concrete cracking when the total intensity of applied load: P was 9.8kN (=1tf). In this table, Sb, St and N indicate the shearing forces measured at the base of studs, shearing and tensile forces measured on the body of studs, respectively and Sb can be regarded as whole shearing forces of studs. Further, the table also shows the results of numerical analysis executed in a 1/4 space model with 3402 degrees of freedom in total. On these results, letter S and N refer to the shearing and tensile force of studs, and numeral 1 attached to them means those when the rigidity of studs was taken as infinity and numeral 2 when it was assumed to be equal to the initial rigidity of the shearing force and slip curve proposed by Ollgaad et al [5].

First, the experimental values of C series specimens with natural bond on their interfaces were lower than those of B series ones having the same properties as C series except a point without natural bond. It was obvious that the natural bond carried some part of transmission forces on the interface. Second, with a comparison of the numerical values to the experimental ones, the former was in fair agreement with the latter, excluding C series owing to the natural bond, and another point to be emphasized is to give theoretical and experimental evidence on the appearance of tensile force in studs, which is attributed to the nonlinear stress transmission characteristics of the interface between concrete and steel plate already mentioned.

Last, the shearing forces measured on the body of studs: St were very small below 1/10 of the whole shearing forces: Sb corresponded. This result suggests that almost all shearing forces were transmitted at the welded bases of studs and also that the numerical modeling on stud-forces used here could be verified, in which stud forces were replaced as the transmission forces at the interface. Furthermore, on the body of studs, the tensile force: N was superior to the shearing force: St corresponded. In particular, some of N had a considerable magnitude beyond 20% of the whole shearing forces: Sb.

4.2 Theoretical consideration on the tensile force of stud in elastic region

Figure 5 shows an example of the contact area on the interface between steel plate and concrete, as a result of the elastic analysis. It can be seen that the contact area extended toward the center of span in the vicinity of each point of studs arranged. It is most likely because the steel plate was subjected to a local bending moment due to stud shearing force. It seems, therefore, that the local bending moment: M due to shearing force: S caused separation in one side and contact in another side from the stud position, and thus the tensile force: N was yielded on the stud as a reaction against the compressive force: C transmitted on the contact area as illustrated roughly in Fig.6.

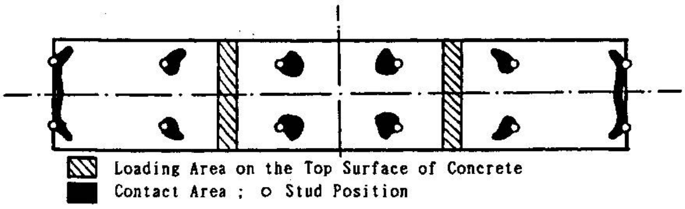


Fig.5 Contact Area on a Interface

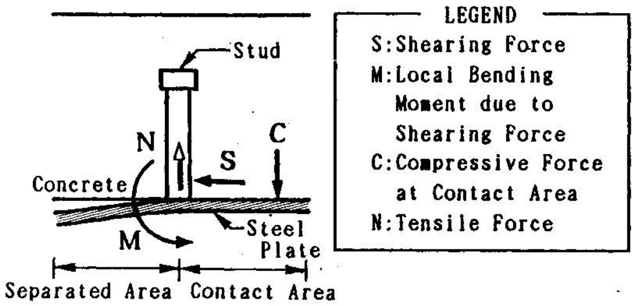


Fig.6 Mechanism of the Tensile Force in Elastic Region

4.3 Inelastic behavior of stud-forces

Initial cracking loads and ultimate loads observed are listed in Table 3. All specimens failed in the same mode referring to shear bond failure with fatal diagonal cracks.

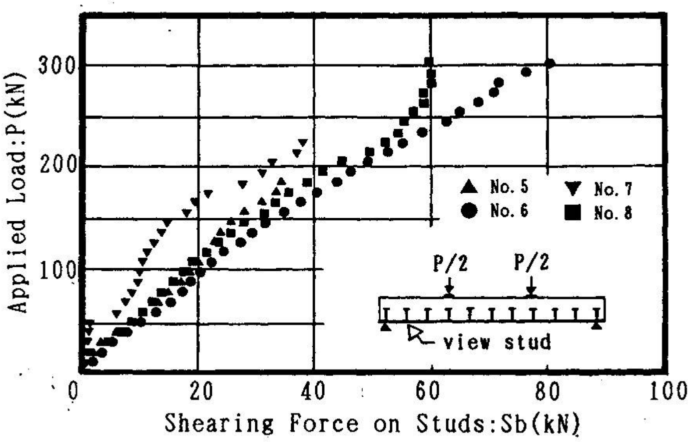


Fig.7 Shearing Forces at the Base of Studs

Figures 7, 8 and 9 show the behavior of stud-forces measured up to failure. The influence of natural bond was not noticeably larger than that in elastic region. Comparing the behavior between in Figs.7 and 8, it can be mentioned that the tensile force of studs was not so large before the cracking of concrete approximately at 50kN of the load intensity, however afterwards it increased rapidly, while the shearing force of studs gradually increased from beginning except the specimen No.7 with natural bond. This tendency seems to be caused by cracking or local crushing of concrete surrou-

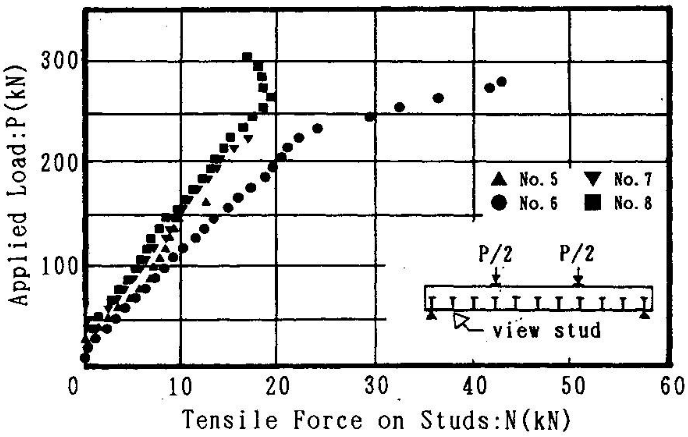


Fig.8 Tensile Forces at the Body of Studs

nding studs, which made the stress distribution change around studs. Furthermore, at the ultimate state, the magnitudes of the tensile force attained up to 30-50% of those of the whole shearing forces. Figure 9 shows a comparison of the shearing forces measured on the body: St to the base: Sb of stud in specimen No.6. In contrast with the tensile forces mentioned above, the ratio of Sb to St sustained to be below about 10% constantly up to failure. Results of elastic analyses are also drawn in Fig.9; broken lines refer to those when the ratio of the two elastic moduli: n (=Es/Ec) was 15.

5. CONCLUSION

Concluding remarks on the characteristics of the stud-forces in a steel plate and concrete composite slab through the experimental and the numerical studies are summarized as follows:

1. Almost all stud shearing force were carried at the welded base of studs, and the body of stud was hardly subjected to shearing force.
2. The body of studs was subjected almost to only a axial tensile force, the magnitude of which was about 10% of that of the whole shearing force in elastic region and attained to 30-50% of that at ultimate state.
3. A mechanism of the presence of tensile forces on studs in elastic region before cracking of concrete has been theoretically examined, and the numerical results of stud forces taking account of the mechanism were in fair agreement with the experimental ones.

Table 3 Cracking Load:Pcr and Ultimate Load:Pu

No.	Name	Pcr (kN)	Pu (kN)
1	A-19-100	88	260
2	A-19-150	69	211
3	A-19-214	29	284
4	A-19-300	69	196
5	B-13-150	39	186
6	B-19-150	29	309
7	C-13-150	59	226
8	C-19-150	49	304

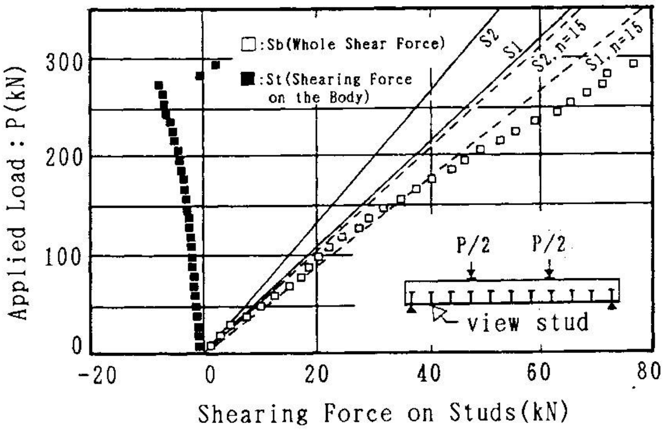


Fig.9 Shearing Forces at the Base and the Body of Studs

ACKNOWLEDGMENTS

We would like to thank Messrs. K.Watanabe and T.Asaka, former graduate students of Osaka City University, for their help in numerical computation.

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