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Composite Beams Using Newly Developed H-Shaped Steel with Protrusions

Poutres composites employant des profilés nouveaux en H avec saillies

Verbundträger aus neuentwickelten H-Stahlprofilen mit Oberflächenerhebungen

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SUMMARY

For steel-concrete composite structures an H-shaped steel with high shear bond performance to concrete by forming protrusions on its outer flange surface has been developed. The configuration of protrusions was determined as a result of many push-out tests, to find out the most effective configuration. The applicability of this H-shape steel to composite beam construction has been confirmed by full-scale model tests and field tests.

RÉSUMÉ

Pour les structures composites en acier-béton, on a mis au point les profilés en H avec une bonne adhésion transversale au béton en formant des saillies sur ses larges rebords extérieurs. Dans cette mise au point on a effectué un grande nombre d'essais d'extrusions afin de déterminer la meilleure configuration des saillies. De plus, la possibilité d'application de ce profilé en H aux poutres composites de bâtiments a été également confirmée au cours d'essais de modèle en vraie grandeur ainsi que d'essais sur le terrain.

ZUSAMMENFASSUNG

Für Stahl-Betonverbundkonstruktionen sind H-Stahlprofile entwickelt worden, welche auf der Flanschaussenseite Oberflächenerhebungen zur Steigerung der Schubverbundwirkung aufweisen. Die Anordnung der Oberflächenerhebungen wurde durch viele «Anstossversuche» bestimmt, um zur leistungsfähigsten Lösung zu gelangen. Die Eignung dieser H-Stahlprofile für Verbundträger in Hochbauten wurde durch Versuche im Massstab 1:1 und Feldmessungen bestätigt.

1. INTRODUCTION

Steel and concrete composite beams are widely used in bridge and building structures throughout the world. From the structural point of view, the mechanism of transfering shear stress at the interface of steel and concrete is the most important aspect. The flat surface of structural steel shapes, for example,does not exhibit any significant bond performance at all. A substantial number of shear connectors are required to be studded when beams are designed as steel and concrete composite beams. An extensive research and development work has been carried out by authors to introduce new concept of composite beams using new structural H-shapes, "Embossed H-Shapes". They have series of protrusions on their flange surfaces.

This paper reports the results of experimental research works carried out to fully investigate the hehavior of these composite beams formed by "Embossed H-Shapes". The bond characteristics of protrusions was investigated firstly by performing a number of push-out tests. The concept of shape factor for optimum configuration of protrusions has been introduced. The successful method to produce "Embossed H-Shapes" has been developed in the mean time as the result of several trial productions. Eleven full scale model specimens of different length were constructed and subjected to structural testings. The concept was then applied to several building steelworks as their sub-beams, and field tests were conducted there.

2. BOND CHARACTERISTICS

2.1 Test procedures

Twenty specimens for push-out tests were prepared. The protrusions were formed by machining flange surfaces this time. Line-type and dot-type protrusions as shown in Fig.1 were studied. The effect of parameters such as height (h), width (w_1,w_2), interval (i_1,i_2), rising angle (Θ) of protrusions and concrete strength (Fc) was investigated. Details of these parameters and some of corresponding results of push-out tests are summarized in Table 1. Figure 2 illustrates the test specimens and procedures. The vertical load is applied statically and the slip between steel and concrete slab is detected by dial gauges. During the vertical loading, the pressure of 0.3 N/mm^2 was constantly applied to the interface between the steel and the concrete by the horizontal clamping apparatus.

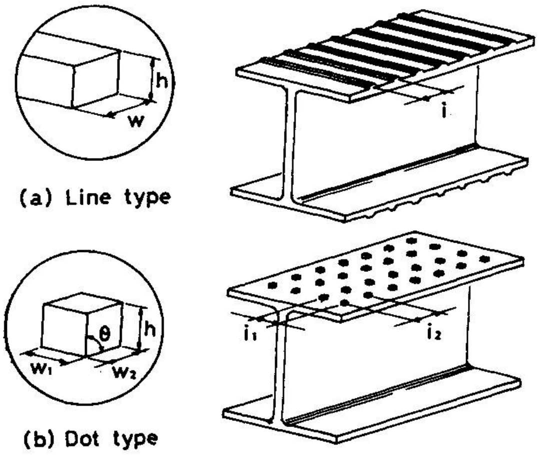

Fig.1 Type of protrusions of push-out test

2.2. Test results

Typical load-slip curves observed are compared in Fig.3. Maximum shear bond strength (τ_{max}) tabulated in Table 1 is in the form of the uniform stress acting over the whole matting area of steel to concrete. The deformation capacity(δ_{90}) is defined as the slip observed at the load of 90% of Pmax after the experiencing ultimate load Pmax.

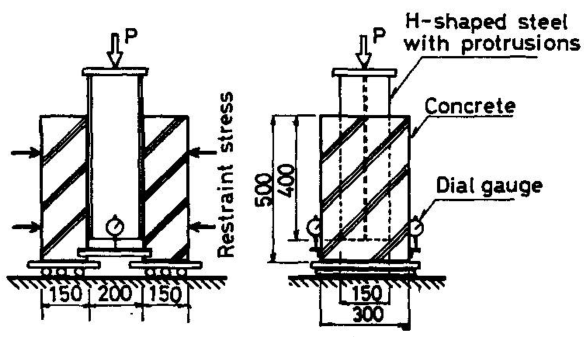

Fig.2 Test procedure of push-out test

The failure occurred in the concrete surface in all specimens. Two types of failure mode were observed. They are illustrated in Fig.4. One is the shearing failure and another is bearing failure [1]. Failure mode of each specimen is also listed in Table 1.

2.3. Discussion

The failure modes and the bond characteristics can be expected to be explained by introducing the concept of shape factor (As/Ab) of protrusions, where Ab is bearing area of the protrusions and As is their shearing area as illustrated in Fig.5 [2].

Fig. 6 shows the relationship between the bond strength in terms of concrete strength(τ_{max}/Fc) and the shape factor (As/Ab). It is seen in this figure that the bond strength increases as the shape factor decreases. The failure mode changes at the shape factor of about 9. The shearing failure occurs when (As/Ab) is less than 9 and the bearing failure does otherwise.

Fig. 7 shows the deformation capacity δ 90 in relation to the shape factor. It is seen there that the shearing failure is associated with very little deformation capacity. This phenomenon is also illustrated in Fig. 3 by curves L-2 and D-8, which indicate that the load decreases abruptly right after reaching the Pmax. The successful bond characteristics with stable bond strength cannot be expected in the range where shape factor (As/Ab) is less than 9 when shearing failure always occures in brittle nature.

The rising angle (θ) showed little influence on the shear bond strength if the rising angle is greater than 60° (D-10 in Table 1). It could also be said that all the other parameters than As/Ab, such as the type of protrusions, do not exhibit significant influences on the bond strength. It has been concluded therefore that the optimum configuration of protrusions can be expected when their shape factor lies in the range of 10 to 20.

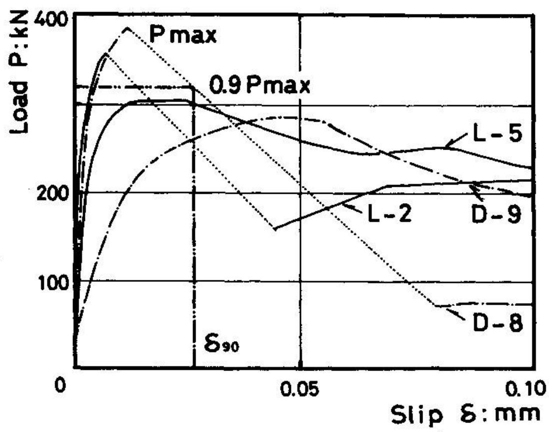

Fig.3 Typical load-slip curves

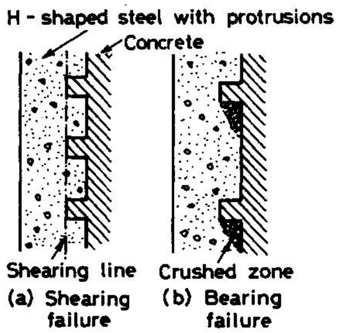

Fig.4 Failure modes

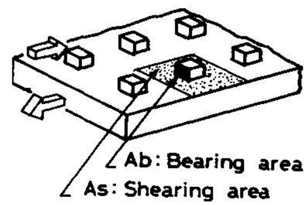

Fig.5 Shape factor As/Ab

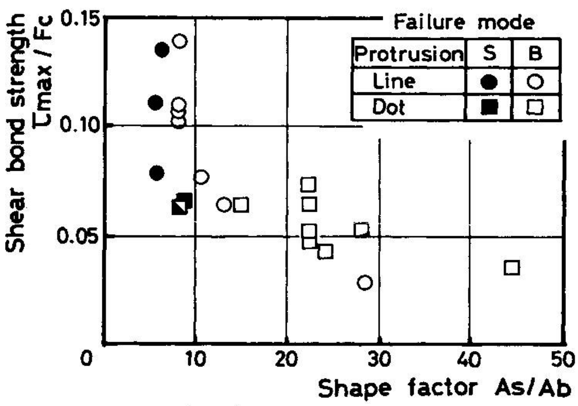

Fig.6 Bond strength

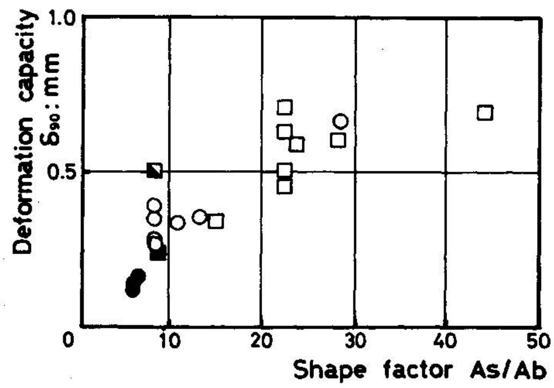

Fig.7 Deformation capacity

Specimen	Protrusions: Height h (mm)	Protrusions: Interval $i(i_1 \times i_2)$ (mm)	Protrusions: Width $w(w_1 \times w_2)$ (mm)	Shape factor As/Ab	Concrete strength F_c (N/mm^2)	Bond strength τ_{max} (N/mm^2)	Deformation cap. δ_{90} (mm)	Failure mode*1
L-1	2	15	3	6.0	31.8	2.48	0.12	S
L-2	2	15	3	6.0	25.6	2.88	0.14	S
L-3	2	20	3	8.5	25.6	2.62	0.27	B
L-4	2	20	3	8.5	25.6	3.57	0.35	B
L-5	2	20	3	8.5	25.6	2.73	0.39	B
L-6	2	25	3	11	25.6	1.99	0.34	B
L-7	2	30	3	13.5	25.6	1.64	0.42	B
L-8	2	60	3	28.5	31.8	0.98	0.66	B
L-9	3	30	4.5	8.5	25.6	2.81	0.29	B
L-10	6	50	1.0	6.7	36.3	4.90	0.17	S
D-1	3	15x15	4.5x4.5	15.2	31.8	2.04	0.34	B
D-2	3	18x18	4.5x4.5	22.5	36.9	1.88	0.51	B
D-3*2	3	18x18	4.5x4.5	22.5	20.2	0.94	0.46	B
D-4	3	18x18	4.5x4.5	22.5	20.2	1.30	0.71	B
D-5*2	3	15x30	15x4.5	8.5	20.2	1.23	0.50	B+S
D-6	3	20x20	4.5x4.5	28.1	31.8	1.67	0.60	B
D-7	3	25x25	4.5x4.5	44.8	31.8	1.13	0.69	B
D-8	5	20x20	7.5x7.5	9.2	31.8	2.13	0.27	S
D-9	5	30x30	7.5x7.5	22.5	31.8	2.32	0.64	B
D-10*3	3	18x18	6.2x6.2	23.7	36.9	1.52	0.63	B

Note : *1, In failure mode, S is shearing failure and B is bearing failure
*2, D-3 and D-5 have staggered protrusions
*3, D-10 has protrusions with the rising angle Θ=60°

Table 1 Specimens and test results of push-out test

3. CONFIGURATION OF PROTRUSIONS OF EMBOSSED H-SHAPES

Interpreting the test results explained so far, the final configuration of protrusions to be roll-formed on the Embossed H-Shapes has been determined as shown in Fig. 8. The shape factor, As/Ab, of the protrusions is about 16. Embossed H-Shapes available at present from Sumitomo are in the form of universal beams whose flange width is 200mm and their height range from 300mm to 600mm, being commonly applied to the sub-beams of the structural steelworks in various buildings. Portions of flange surfaces about 50 mm from their edges are prepared flat without protrusions, so that they can easily support the ends of steel decks of cold formed light gauge sheets which in turn act as the concrete forms.

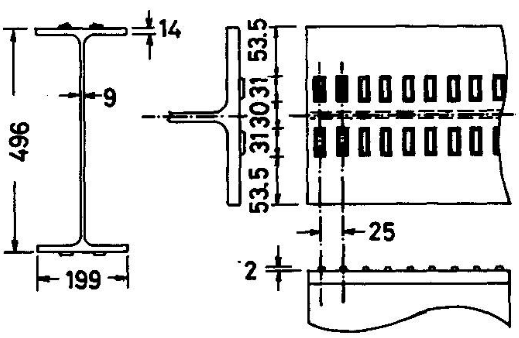

Fig.8 Embossed H-shape

4. APPLICABILITY OF EMBOSSED H-SHAPE TO COMPOSITE BEAMS

4.1 Bond strength of Embossed H-Shapes in composite beams

4.1.1 Specimen and test procedure

The higher bond stress is expected in composite beams than in push-out tests, because greater restraint force exists by pressing concrete slab vertically to the flange surface. Therefore, the shear bond strength of Embossed H-Shapes was investigated in the form of composite beams with short bending span, which are illustrated in Fig. 9. The specimens were designed to have failed in bond failure before the yield of concrete or steel occurred. The upper half of Table 2 tabulates the parameters of six test specimens prepared. The methods of concrete placement and concrete characteristics are the main parameters. The sixth specimen, NA-1, was included for the purpose of comparison. This was a composite beam with a usual plain universal shape and shear connectors studded onto it, and with the same section as DA-2. Both NA-1 and DA-2 were formed with light gauge steel decks (JIS-ALM12). The deflection of beams, the slip between steel shapes and concrete slab and the strain distribution over several cross sections were the items measured during these short span tests.

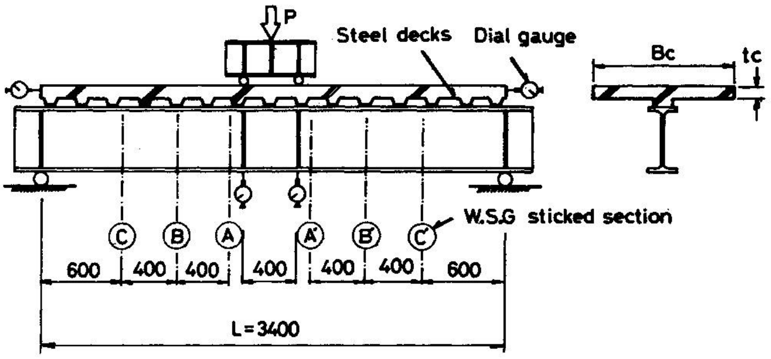

Fig.9 Short span test

Specimen		RC-slab Width B_c (mm)	Thick-ness t_c (mm)	Steel deck*1	Concrete Sort*2	F_c (N/mm²)	Test results Maximum load P_{max} (KN)	Slip load P_s (KN)	Shear bond Strength τ_{max} (N/mm²)	$\frac{\tau_{max}}{F_c}$
Short span test	DA-1	1500	90	non	N	28.9	967	431	4.08	0.142
	DA-2	"	85	ALM-12	N	27.5	984	470	4.19	0.152
	DA-3	"	90	non	N	19.9	843	372	2.74	0.138
	DA-4	"	90	non	L1	23.7	872	402	3.19	0.135
	DA-5	"	90	non	L2	29.8	804	392	3.53	0.118
	NA-1	"	85	ALM-12	N	27.3	1101	-	-	-
Ordinary span test	DB-1	2800	85	ALM-12	N	23.3	607	607	4.56	0.196
	DB-2	"	90	non	N	18.2	568	372	3.21	0.176
	DB-3	"	50	ALM-12	N	17.5	631	441	2.63	0.150
	NB-1	"	85	ALM-12	N	29.8	768	-	-	-
	DC-1	"	90	non	N	22.8	735	395	3.70	0.162

Note : *1, ALM-12 deck is a JIS-Standard deck with 1.2mm in thickness and 75mm in web height.
*2, N is normal concrete. L_1 and L_2 are light weight aggregate concrete with the specific gravity of 1.8 and 1.6, respectively.

Table 2 Specimens and test results of composite beam test

4.1.2 Test results and discussions

The load slip curves are shown in Fig. 10. The conventional beam, NA-1, shows a ductile behavior, but the slip occurs in the early stage of loading, see Fig.10, so that it's initial rigidity is lower than DA-2 with Embossed H-Shape. Although the behavior of Embossed-H composite beams is less ductile after the initial slip of concrete occurred on the flange surface of steel shapes, the complete composite action with no slip movement can be expected before then.

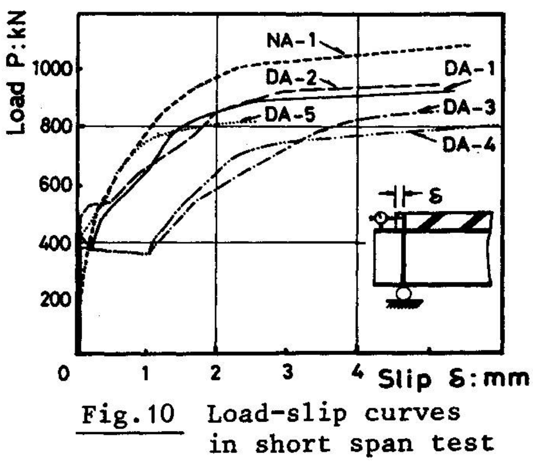

Fig.10 Load-slip curves in short span test

The maximum shear bond stress (τ_{max}) of Embossed H-Shapes is calculated by dividing the increments of axial force of the steel cross-section by the resisting area which, in turn, is the multiple of the incremental beam length times protruded width of 100mm, see Fig. 8, indifferent of the method of concrete placement with or without cold formed steel forms. The results are also tabulated in Table 2. The maximum shear bond strength (τ_{max}) of Embossed H-Shapes is plotted against concrete strength (Fc) as shown in Fig.11. A linear relationship ($\tau_{max} = 2\times Fc/15$) can be observed, and by utilizing this and certain value of factor of safety, a design method can be formulated. For Japanese domestic application, the factor of safety of two (2) was adopted.

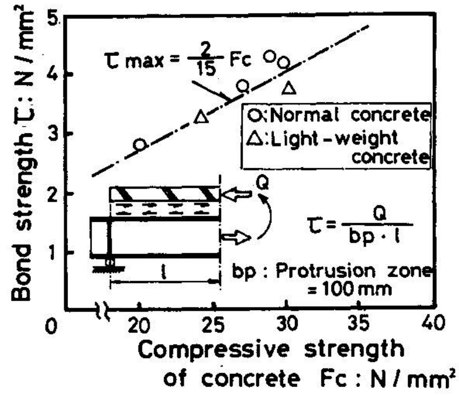

Fig.11 Relation between concrete strength and bond strength

4.2. Full-scale model tests

4.2.1 Specimen and test procedure

Five full scale composite beam with ordinary length of sub-beams were prepared. Specimen configurations are illustrated in Figs. 12 and 13. The lower half of Table 2 tabulated the details of these specimens.

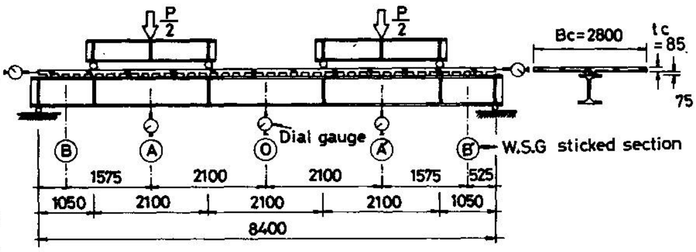

Fig.12 Ordinary span test in simple beam

Dimensions and cross-sectional properties of the specimen DB-1 are the exact duplication of composite sub-beams recently constructed in Japan, utilizing Embossed H-Shapes of mild steel. The concrete slab was placed on the light gauge steel deck, JIS-ALM12. The concrete of the specimen DB-2 was placed over the usual and supported concrete form, without using steel deck. The specimen DB-3 is with steel deck but its slab is thinner than DB-1. NB-1 is the specimen of conventional composits beam by a plain universal beam, the size of which is the same as that of DB-1, with shear connectors studded on its flange surface. The cross-section of DC-1 is the same as that of DB-2, but this was tested under the condition of seemingly continuous beam. The same sections are connected at both ends of the DB-2 specimen, as shown in Fig. 13. This is the configuration of usual sub-beams, connected to main girders with high-strength bolts. Nearly central span of sub-beams at both ends of the specimen DC-1 was restricted from any upward deflection, so that some negative bending moment occurred at the location of connections to girders. Load were applied as illustrated in these figures and measurements obtained were the deflection of beams, the slip between the steel shape and concrete slab and strains at various cross-sections.

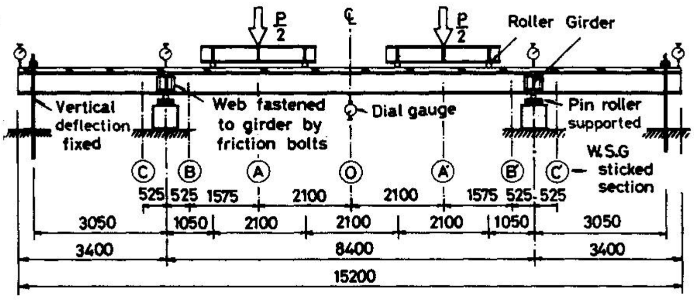

Fig.13 Ordinary span test in continuous beam

4.2.2. Test results and interpretations

Figure 14 illustrates the load-deflection relationships of two specimens, DB-1, a composite beam with an Embossed H-Shape and NB-1, a composite beam with an ordinary universal beam with shear connectors. Pys there is the calculated load at which the steel shapes in the composite cross section yield. Pub is the shear strength calculated for Embossed H-beam, DB-1, using the results of short span tests (τ max = 2x Fc/15). Both specimens were subjected to repeated loading up to Pys for six cycles. The same characteristics as observed in short span tests can be confirmed also in this figure. Studded beam, NB-1, starts to loose its rigidity at the load much less than Pys, and residual deflection is accumulated during six repetitions of cycle loading. Embossed H-beam DB-1, on the other hand, maintains its initial rigidity even when Pys is reached. It can be concluded that, at least in the elastic range, composite beams with Embossed H-Shapes behave in the same manner as, or rather more rigidly than those with ordinary beams and shear connectors.

Specimens DB-2 and DC-1 are compared in Fig. 15. Some cracks appeared in the concrete slab at the location over the steel connections to girders at fairly early stage thus loosing the rigidity of the continuous slab specimen, DC-1. The behavior of this beam then becomes similar to that of DB-2, a simply supported beam, and nearly at Pys the slip between steel and concrete was observed both in DB-2 and DC-1, as was seen in above mentioned test of DB-1. Many slip-like saw shapes seen in the curve of DC-1 are attributed to the frictional slips occurred at high-strength bolts connecting a sub-beam to main girders. Throughout the whole test period, the curve of DC-1 stayed higher than DB-2.

The behavior of DB-3, the specimen with thinner concrete slab, is illustrated in Fig.16. The shear bond strength of this specimen was designed much less than Pys, the yield of steel, and this was confirmed in the behavior of the test beam. No other significant failures anticipated due to thinner concrete slabs were observed during the test.

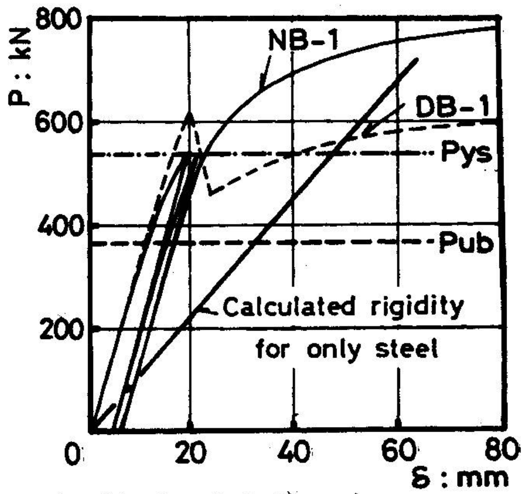

Fig.14 Load-deflection curves of DB-1 and NB-1

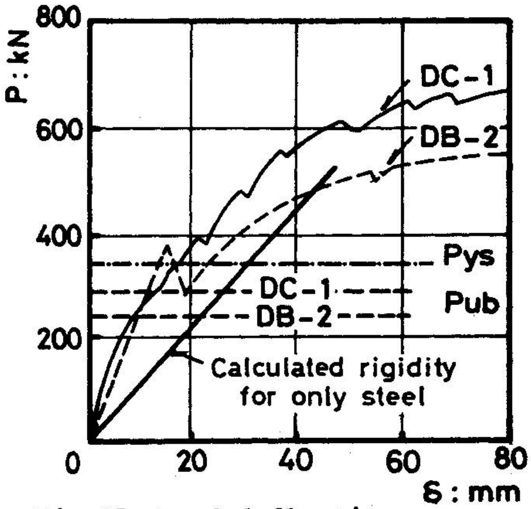

Fig.15 Load-deflection curves of DB-2 and DC-1

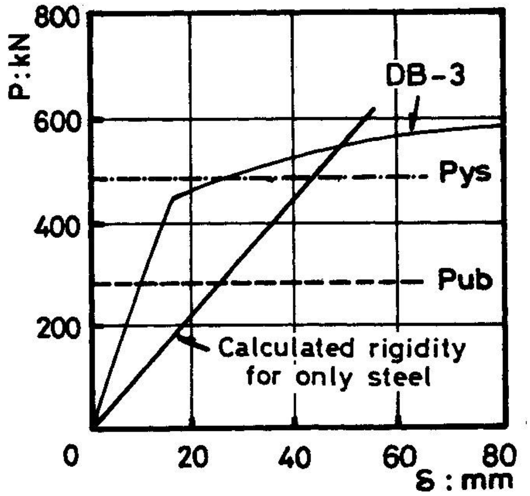

Fig.16 Load-deflection curves of DB-3

The shear bond strength of these composite beams is also tabulated in Table 2. These figures are somewhat higher than those obtained by short span tests. Slip loads at which the initial slips occur in these beams are also higher than those in short span tests. It is seen that in short span tests the load applied is rather concentrated,while it is more uniform in these full scale model tests. Therefore,the shear bond strength is considered to be greater when the concrete slab is pressed down onto the flange surface more effectively. From this point of view, the optimum condition exists in the beams loaded by uniformly distributed loads. The shear bond strength obtained by short span tests is, therefore, considered to stay in safety side, when this is used in the design formula for the conditions of uniformly distributed load.

Higher rigidity of floor beams offers less vibration. Vibration problems of floor beams are getting more strict nowadays. Steel and concrete composite construction increases the rigidity of frame members and thus decreases the vibration troubles. Factor of increase in its rigidity over the simple steel construction is said to be 2 to 3 [3]. About ten buildings have been constructed so far using Embossed H-Shapes as sub-beams. Number of field tests up to their design load were performed in some of these buildings. The results were compared with those of laboratory tests described in this report, and the applicability of Embossed H-Shapes was further confirmed successfully. The use of the Embossed H-shaped for composite construction exhibits large economic advantages in addition to the simplification of field works.

5. CONCLUSIONS

(1) Universal beams (Embossed H-Shape) which exhibit substantial shear bond performance with concrete have been developed by roll-forming protrusions on their flange surfaces in univesal mills.

(2) Extensive Push-out tests have revealed that the most dominant factor to affect the shear bond characteristics is the shape factor (As/Ab) It has been found out that, as the shape factor decreases, the shear bond strength increases but that there exists the lower bound of the shape factor below which no ductility of bond characteristics can be expected.

(3) The configuration of protrusions to be roll-formed on the flange surface of the Embossed H-Shapes has been determined by the results obtained by these extensive push-out tests.

(4) The shear bond strength has been investigated by full scale composite beams with Embossed H-Shapes and the results have been formulated as $\tau_{max} = 2 \times Fc/15$.

(5) It has been confirmed further, for example by several field tests, that the composite beams with Embossed H-Shapes exhibit the complete composite behavior at least in the elastic range untill the bond stress reaches its ultimate strength.

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