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LOAD-DISPLACEMENT RELATIONSHIP OF PLATE SHAPE SHEAR CONNECTOR IN STEEL-CONCRETE COMPOSITE STRUCTURES

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With the aim to study the deformation and to estimate the capacity of plural shear connectors in steel-concrete composite structure, a series of specimens with various number of plate shape shear connectors were tested by direct pull-out test. Shear connectors in between the ones nearby loaded end and free end exhibit an unique load-longitudinal displacement relationship. The effects of spacing, thickness and height of shear connector on this relationship were studied. Two simple equations obtained by empirical formulation of the load-longitudinal displacement relationship predict the capacity of plural shear connectors satisfactorily.

Keywords : *shear connector, longitudinal displacement, load, load carrying capacity*

1. INTRODUCTION

In steel-concrete composite structure, shear connectors are required for transfer of shear force in between concrete and steel element in order to develop the composite action. For some particular types of structure such as open sandwich and sandwich composite structures as shown in **Fig.1**, which consists of concrete as core and steel plate as facing, shear connectors are provided for stiffening the structural steel plate which also acts as formwork, apart from merely strengthening the member. In this type of structure, shear connector such as T, L and plate shape rib are considered to have edge over ordinary headed stud shear connector.

It is important to understand the behavior and capacity of shear connectors as basic knowledge for design of composite structure. Shear transfer capacity of shape shear connector has been studied and well understood[1),2)], however, research on plate shape shear connector in which the deformational constraint of steel bed plate is small can hardly be seen. One of the related research was conducted by Ueda and Chin[3),4)]. They had carried out a series of test on single plate shape shear connector and further developed an equation to estimate the capacity of shear connector. They suggested that the equation is also applicable to group shear connectors where the capacity can be predicted conservatively. However, this is not yet clarified.

In practice, a group of shear connectors are usually arranged along the plate anchorage in structure. In this case, the load carrying capacity of each shear connector may possibly be affected by its neighboring shear connectors and therefore, the capacity of the entire plural shear connectors system may as well be affected.

It was with this in mind that this study was focused on plural shear connectors. The load-longitudinal displacement relationship of each shear connector along plate anchorage was investigated, and effort is also put into working out a way to estimate the capacity of plural plate shape shear connectors.

2. EXPERIMENT

(1) Description and preparation of specimens

The experimental work of this investigation was performed by direct pull-out test. All together, nine specimens were tested. The details of specimens are given in **Fig.2** and **Table 1**. The thickness and width (b) of the steel bed plate for all specimens were the same, 6 mm and 150 mm respectively, but the length varied with the number of shear connectors provided. In all nine specimens, plate shape shear connectors were used. The number (n), thickness (t_{sc}) and height (h_{sc}) of shear connectors are listed in **Table 1**. The spacing (S) of shear connectors in all specimens was 100 mm except in Specimen SS-6 which was 150 mm. Shear connectors were welded perpendicularly to steel bed plate. Concrete with maximum aggregate size of 5 mm was cast in the direction normal to the plane of steel bed plate. The concrete portion for all specimens was reinforced identically and was of the same cross section, i.e. 150 mm×300 mm.

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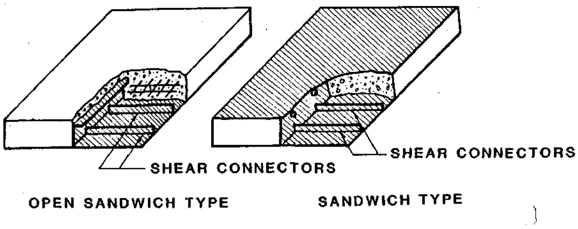

Fig.1 Open sandwich and sandwich composite structures.

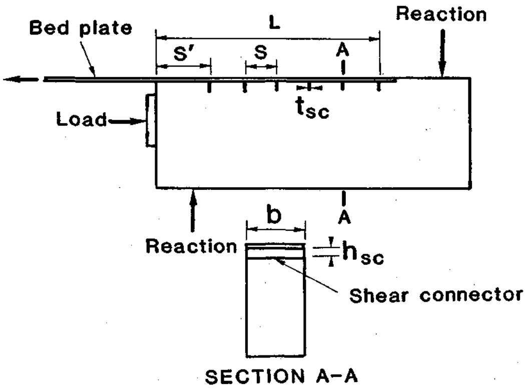

Fig.2 Details of specimens.

Table 1 Details of specimens.

Specimen	n	t_{SC} mm	h_{SC} mm	S' mm	S mm	L mm	f_c' MPa
SN-2	2	2.3	20	200	100	300	31.0
SN-4	4	2.3	20	200	100	500	22.2
SN-5	5	2.3	20	100	100	500	23.9
SN-6	6	2.3	20	100	100	600	21.4
SN-7	7	2.3	20	200	100	800	28.5
SN-8	8	2.3	20	200	100	900	28.2
SS-6	6	2.3	20	150	150	900	23.6
ST-10	10	1.2	20	100	100	1000	21.6
SH-10	10	1.2	40	100	100	1000	19.3

Note; n : Number of shear connector
t_{SC} : Thickness of shear connector
h_{SC} : Height of shear connector
S' : Length of concrete in front of shear connector nearby loaded end
S : Spacing of shear connector
L : Anchorage length
f_c' : Concrete compressive strength

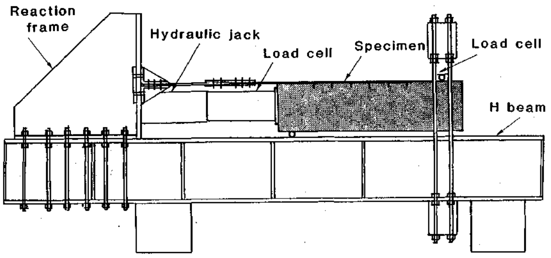

Fig.3 Experimental set-up.

In order to remove the friction that may possibly be induced in between concrete and steel bed plate, smooth tape was stuck on the inner surface of bed plate in contact with concrete portion. The elimination or at least reduction of friction in this way enabled the performance of the shear connectors themselves to be appraised with greater reliability.

The specimens were air cured under room temperature at 20°C and were tested at an average concrete age of two weeks. Three concrete cylinders were cast with each specimen and cured under the same condition.

(2) Instrumentation and test procedure

The experimental set-up is shown in **Fig.3**. The specimens were tested on a huge H beam which sat on two levelled concrete blocks. The steel bed plate was fixed to a rigid reaction frame which itself was tightened by prestressing bars to the H beam. Load was applied by an hand operated hydraulic jack placed between the specimen and reaction frame and the magnitude of applied load was measured by an electrical load cell. The center of load was 120 mm from the top of specimen. Roller supports were used as vertical reactions to counter the small moment developed when load was applied. The setting-up was carried out carefully so that the specimen was truely level. In order to determine the load borne by each shear connector and its displacement, four strain gages were mounted to bed plate, two on each face of bed plate, at the center position between each shear connector. The longitudinal displacement of shear connector nearby free end was measured by two highly precise electrical transducers and the average value was adopted as displacement of the free end shear connector. The longitudinal displacement of the shear connector nearby loaded end also measured. Data were recorded at every load interval of 2.5 kN.

3. TEST RESULTS AND DISCUSSION

(1) Failure mode

Similar failure mode was observed in all the specimens tested, in which progressive failure process took place. When applied load was increased up to certain value, first crack was developed in the concrete portion from the tip of shear connector near loaded end. However, at this stage, the specimen was still able to resist more load. As load was further increased, cracks were generated from neighboring shear connectors and propagated toward the free end. When plate

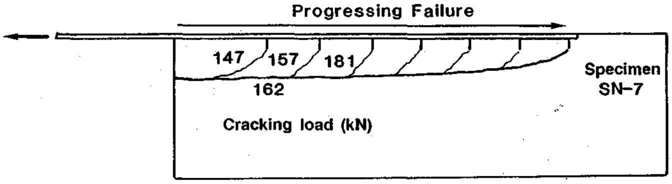

Fig.4 Failure mode of specimens.

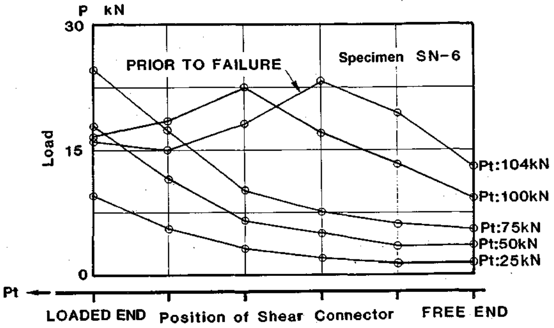

Fig.5 Load distribution along plate anchorage for various loading steps.

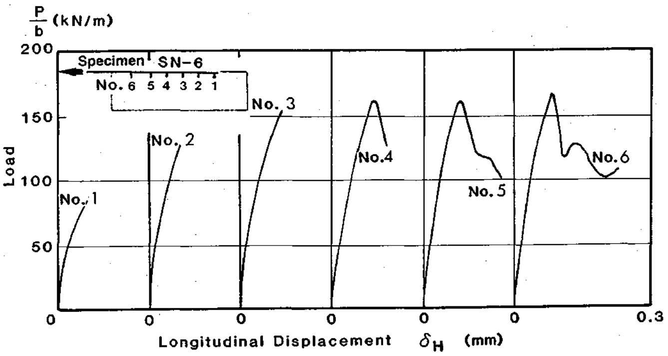

Fig.6 Load-longitudinal displacement relationship of shear connectors along plate anchorage.

anchorage reached its ultimate capacity, the steel bed plate and contacted concrete suddenly split from the specimen as an unit, as shown in **Fig.4**.

(2) Distribution of load along plate anchorage

An equal magnitude tensile force was produced in steel bed plate when load was applied to the concrete portion of specimen by hydraulic jack and this force was then distributed to the shear connectors along plate anchorage. **Fig.5** shows the load distribution among shear connectors for Specimen SN-6 at various loading steps (P_t). Load carried by each shear connector (P) was calculated by multiplying the difference of strain values infront and behind the shear connector, to the cross sectional area and Young's Modulus of bed plate. At each loading step, shear connectors nearby loaded end carry larger load and this reduces towards the free end. Similar pattern of load distribution occurs when applied load is increased. However, the load distribution varies when applied load is increased to a higher state. As an example, the load distribution prior to failure in **Fig.5** shows decrease of load for shear connectors nearby loaded end while load borne by shear connectors nearby free end is still increasing. This indicates that at the moment just before failure of the specimen, some shear connectors nearby loaded end had already reached its ultimate capacity and went to softening, while the rest nearby free end were still below the capacity of shear connector.

This progressive failure process is also demonstrated in **Fig.6** which shows the load-longitudinal displacement relationship of each shear connector along plate anchorage up to just before failure of

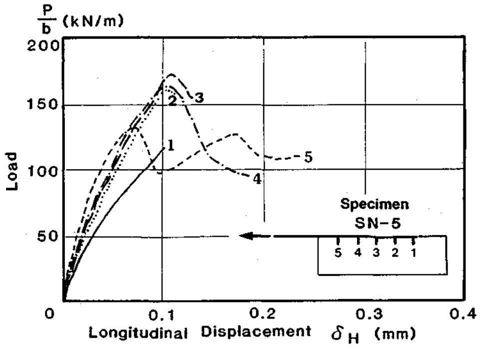

Fig.7 Effect of boundary condition on load-longitudinal displacement relationship.

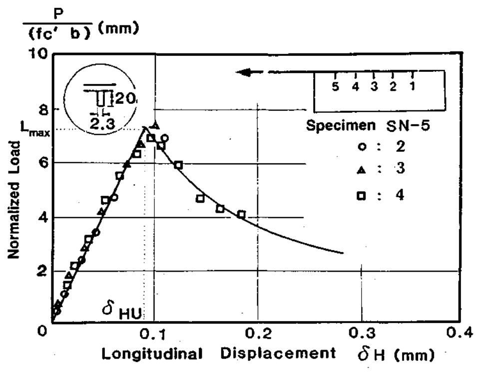

Fig.8 Unique load-longitudinal displacement relationship of internal shear connectors.

Specimen SN-6. The longitudinal displacement is defined as the displacement of shear connector relative to its original position in the loading direction. The longitudinal displacement of the free end shear connector was determined by direct measurement. For the immediate neighboring shear connector, the longitudinal displacement was obtained by adding the free end shear connector's longitudinal displacement and the elongation of bed plate in between these two shear connectors. The longitudinal displacements of the following shear connectors were calculated by the same method.

(3) Relationship of load and longitudinal displacement of shear connector

Typical load-longitudinal displacement relationship is illustrated in **Fig.7**. Longitudinal displacement of shear connector increases with load in a nearly proportional relationship up to the capacity or maximum load of shear connector. Crack developed from the tip of shear connector when the maximum load is reached. Sudden decrease of load accompanying by continuous increase of longitudinal displacement beyond this point shows that the shear connector is losing its ability to resist load.

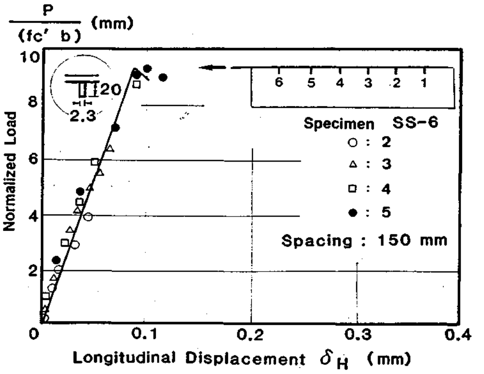

Fig.9 Effect of spacing of shear connector on load-longitudinal displacement relationship.

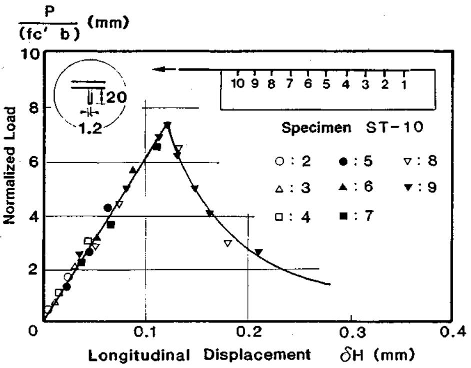

Fig.10 Effect of thickness of shear connector on load-longitudinal displacement relationship.

Also shown in **Fig.7**, load-longitudinal displacement relationships of shear connector at loaded end, free end and shear connectors in between them are quite different among each other. These differences are probably due to different boundary conditions. The shear connector at loaded end was exposed to direct influence of applied load from hydraulic jack. On the other hand, the shear connector at free end was bound to smaller transverse constraint in the direction normal to the plane of bed plate. As a result, the free end shear connector was more easier to displace under the same load as compared to other shear connectors. The boundary conditions of the shear connectors between the shear connector at loaded end and free end were similar, hence, their load-longitudinal displacement relationship were found to be unique as shown in **Fig.8**. This unique load-longitudinal displacement relationship is identical to all the specimens in Series SN which were provided with shear connectors having the same dimensions.

Taking into account the effect of concrete strength of the specimens in Series SN, it was found that the load sustained by each shear connector is

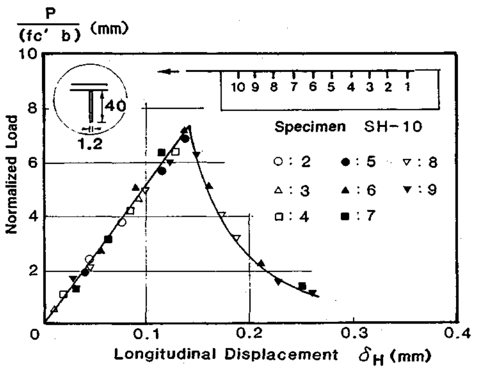

Fig.11 Effect of height of shear connector on load-longitudinal displacement relationship.

Table 2 Parameters of Equation (1)

Specimen	Geometry of Shear Connector			Equation's Parameter			
	t_{SC} mm	h_{SC} mm	S mm	L_{max} mm	δ_{HU} mm	K	c
Series SN	2.3	20	100	7.33	0.09	81	0.9
SS-6	2.3	20	150	9.40	0.09	104	-
ST-10	1.2	20	100	7.33	0.12	61	2.0
SH-10	1.2	40	100	7.33	0.14	52	3.0

most suitable to be normalized by f_c' as represented by y-axis in **Fig.8**. Also, the load carried by each shear connector increases with its width, therefore load per unit width of shear connector were obtained by dividing the load by the width (b) of shear connector.

The load-longitudinal displacement relationship was found to be affected by the spacing of shear connector. In Specimen SS-6 where the shear connectors were spaced at 150 mm rather than 100 mm as in Series SN, its load-longitudinal displacement relationship as illustrated in **Fig.9** is different from the latter's in **Fig.8**. Increasing the spacing of shear connector results in higher capacity or maximum load of the shear connector.

Fig.10 shows the effect on the load-longitudinal displacement relationship when the thickness of shear connector is decreased to about half of those in Series SN. Comparing **Fig.8** and **Fig.10**, thinner shear connector displaces more easily under the same load than thicker shear connector which is stiffer up to the maximum load of shear connector.

On the other hand, the load-longitudinal displacement relationship in **Fig.11** shows that higher shear connector displaces more as compared to lower shear connector with equal thickness until the maximum load is reached. Nevertheless, the maximum load of shear connector was found to be unaffected by thickness and height. This is because failure of shear connector is controlled by concrete strength rather than the thickness and height of shear connector.

(4) Capacity of plural shear connectors

It was understood earlier that plural shear connectors fail progressively and softening behavior is exhibited in load-longitudinal displacement relationship, therefore the capacity of plural shear connectors cannot be obtained from direct product of capacity of single shear connector and number of shear connectors existing along plate anchorage. A load-longitudinal displacement model is necessary to be formed in order to estimate the capacity of plural shear connectors. Formulating the unique load-longitudinal displacement relationship in **Fig.8** empirically with two following simple equations:

$$\left.\begin{aligned} P/(f_c' b) &= K\delta_H && \text{for } \delta_H \leqq \delta_{HU} \\ P/(f_c' b) &= L_{\max}(\delta_{HU}/\delta_H)^c && \text{for } \delta_H > \delta_{HU} \end{aligned}\right\} \cdots(1)$$

where, $L_{\max}$: capacity of single shear connector
δ_{HU} : longitudinal displacement corresponding to $L_{\max}$
K, c : constants

and the parameters of the equation as tabulated in **Table 2**, the load-longitudinal displacement relationship and further, the capacity of plural shear connectors based on splitting failure mode can be estimated.

Using the unique model, total load-total displacement relationship of each specimen can be calculated. For example, when the free end shear connector displaces at certain amount of longitudinal displacement, the corresponding load sustained by the free end shear connector can be determined from the model. This load equals the tensile force in steel bed plate in between the free end shear connector and the shear connector next to it. Following this, longitudinal displacement of the second shear connector can be known from the summation of the free end shear connector's longitudinal displacement and the elongation of steel bed plate. The load of the second shear connector can therefore be valued based on the model. By the same way, calculation is continued up to the loaded end.

Taking into consideration of the possible effect of different boundary condition at the loaded end on the behavior of plate anchorage, the loaded end shear connector is not considered. Total load can now be obtained from the summation of load carried by each shear connector in front of the loaded end shear connector, while total displacement equals the longitudinal displacement of shear connector, just in front of the loaded end shear connector. Based on the similar procedure, iteration is done for various input values of free end

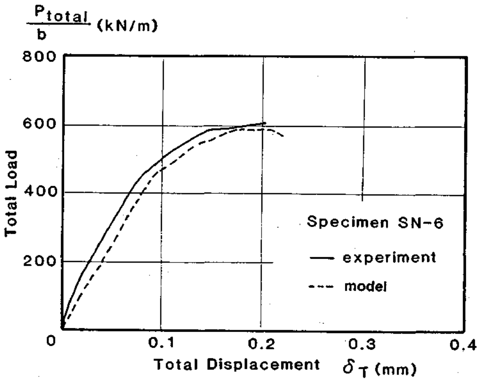

Fig.12 Relationship between total load and total displacement.

Table 3 Comparison between load carrying capacity of plural shear connectors from test results and calculations.

Specimen	Pu(test) kN	Pu(cal) kN
SN-2	20	34
SN-4	72	65
SN-5	81	84
SN-6	90	88
SN-7	130	124
SN-8	150	131
SS-6	112	92
ST-10	98	99
SH-10	94	95

Note

Pu(test): Capacity of plate anchorage excluding the shear connector nearby loaded end

Pu(cal) : Capacity of plate anchorage predicted by proposed unique model

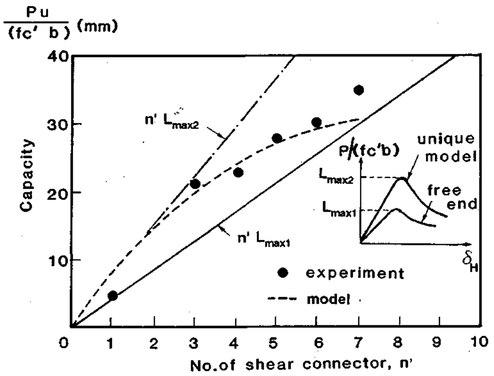

Fig.13 Relationship between load carrying capacity of plural shear connectors and number of shear connector for Series SN.

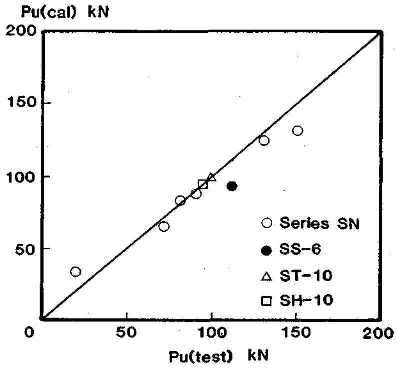

Fig.14 Comparison between capacity of plural shear connectors from calculations and test results.

longitudinal displacement, until the total load at the final shear connector considered starts to decrease. The maximum total load obtained is the calculated capacity of plural shear connectors. Relationship of total load and total displacement of plate anchorage from experiment and calculation using the unique model for specimen SN-6 are compared in **Fig.12**. The calculated values agree quite well with experimental data.

The calculated and experimental capacity of plural shear connectors for various specimens are listed in **Table 3**. The results show that the unique load-longitudinal displacement model can be employed to estimate the capacity of plural shear connectors satisfactorily. The only exception is Specimen SN-2 with just two shear connectors. This is believed to be affected by the free end boundary condition, in which the capacity of free end shear connector was reached at the moment just before failure of the specimen and that the capacity or maximum load of free end shear connector was lower than internal shear connectors. However, in other specimens with longer plate anchorage where more shear connectors were available, load carried by the free end shear connector was smaller than its capacity at the moment just before failure of the specimen. Consequently, the influence of the free end boundary condition on the capacity of plural shear connectors in this case seems to be small and negligible.

Fig.13 illustrates the relationship between the capacity of plural shear connectors and number of shear connector (*n'*) for Series SN in which the loaded end shear connector is excluded. The results derived from unique load-longitudinal displacement model estimate the capacity of plural shear connectors better than that obtained by multiplying the capacity of single shear connector and number of shear connector.

Obviously, the capacity predicted by simple multiplication method ($n'L_{max2}$) using maximum load of unique load-longitudinal displacement model is overestimated. On the other hand, the values determined by maximum load of free end shear connector L_{max1} insteads of L_{max2} is conservative. However, as the number of shear connector is increased, the capacity of plural shear connectors is approaching the values of $n'L_{max1}$.

The calculated and experimental capacity of plural shear connectors of all the specimens are compared in **Fig.14**. The results show that the proposed unique load-longitudinal displacement model can predict the capacity of plural shear connector quite well.

4. CONCLUSIONS

(1) The load-longitudinal displacement relationship of shear connectors along plate anchorage is unique except the shear connector at loaded end and free end which are under different boundary conditions.

(2) Progressive failure process occurs in plural shear connectors system.

(3) A simple model obtained by empirical formulation of the unique load-longitudinal displacement relationship predicts the capacity of plural shear connectors satisfactorily.

(4) Capacity of single shear connector increases with spacing.

(5) Thinner shear connector displaces more as compared to thicker shear connector when equal load is carried.

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鋼コンクリート合成構造における板鋼シアコネクタの荷重-ずれ関係

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鋼コンクリート合成構造における板鋼シアコネクタのせん断荷重-ずれ変形関係を求め，複数あるシアコネクタのせん断耐力を算定する一方法を表した．実験パラメーターは，シアコネクタの個数，間隔，厚さ，高さである．荷重端と自由端間の各シアコネクタの荷重-変形関係は同じ関係式で表されることを明らかにし，実験結果から求めたその関係式を用いることにより精度良くせん断耐力が算定できることを示した．