(９) Analytical study on shear strength of steel-concrete full and open sandwich beams

鋼コンクリートフルおよびオープンサンドイッチはりのせん断耐力に関する解析的研究

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This paper presents nonlinear FEM calculation results of both full and open sandwich beams failing in shear. In the FEM analysis factors for the shear strength of sandwich beams, such as concrete strength, tension steel plate amount, web plate amount, web plate yield strength, and shear span to depth ratio, are taken as variables. It is shown analytically how each factor affects the concrete contribution and the web plate contribution to the ultimate shear capacity. Furthermore, the analytical results are compared between cases of full and open sandwich beams so as to show what are the difference in how the factor affects the shear capacity and why the shear capacity of full sandwich beam is greater than that of open sandwich beam.

Key Words: steel-concrete sandwich beam, shear strength

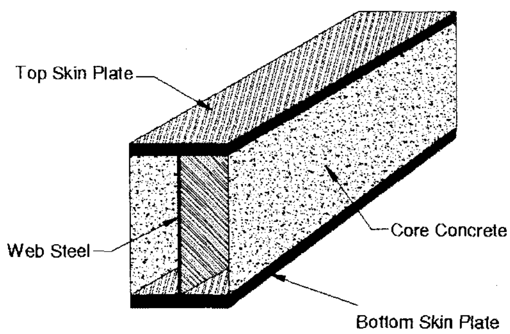
1. Introduction

It is generally true that steel-concrete composite members can easily attain high shear strength in comparison with steel members. This is because a significant concrete contribution to the shear strength can be expected. The shear strength of composite members, however, is mostly estimated empirically like reinforced concrete members. Steel-concrete sandwich members are no exception. JSCE Design Code for Steel-Concrete Sandwich Structures[1)] shows design equations for shear strength of full sandwich members based on experimental results, however they are rather conservative[1), 2)]. There is no commonly used design formula available for shear strength of open sandwich members, although it can be estimated conservatively by a way similar to that for reinforced concrete member.

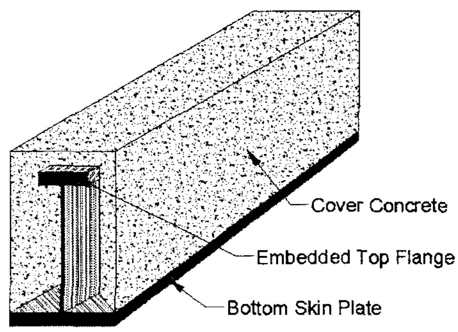
This paper presents results of nonlinear finite element analysis on shear failure of full and open sandwich members with full web (see Fig.1). The FEM results show effects of various factors on the shear strength as well as the difference in shear strength development between the full and open sandwich members. It is believed that the information presented in this paper is useful to develop a more rational shear strength prediction method for sandwich members.

2. Finite Element Analysis

The finite element analysis was conducted using a program for nonlinear plane stress problem, which is originally a version of WCOMR for analysis of steel-concrete sandwich members[3)] and then has been revised and extended at Hokkaido University. Three types of elements are prepared; concrete element, steel element and bond link element. The concrete element contains nonlinear constitutive models in both compression and tension and cracks are modeled by a smeared way. The steel model considers strain



(a) Full sandwich member



(b) Open sandwich member

Fig.1 Full and open sandwich member with full web hardening after yielding. The bond link element is inserted between the concrete and steel element to represent interface mechanics including one through shear connector. The shear connector modeled is L-shaped steel shear connector and its constitutive model is the one derived in a previous study[4].

The element mesh is illustrated in Fig.2. The bond link element is inserted only between tensile steel plate and concrete. This means that slips in compression zone are assumed to be negligible. The elements for the full web are not connected with the concrete elements at the same location, which means that force transfer between the steel full web and the concrete is negligible. The buckling of the steel plate is not considered.

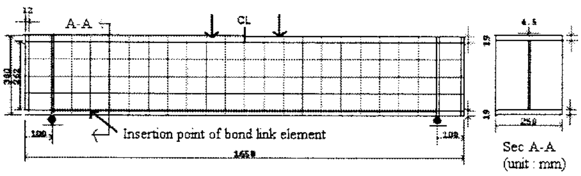


Fig.2 Element mesh

3. Prediction of Shear Strength of Sandwich Beams

In order to see reliability of the finite element analysis the calculated results of shear strengths of full and open sandwich beams are compared with experimental results[5), 6)] as shown in Table 1. The experimental parameter is full web ratio for both full and open sandwich beam cases. The calculated results underestimate the experimental results slightly, however we consider that the accuracy level is acceptable.

4. Concrete and Steel Contribution to Shear Strength

As a composite member, contribution of both concrete and steel to shear strength is expected in a sandwich beam. The contribution of concrete and steel can be shown by internal stresses at shear failure. The location at which the internal stresses are examined is chosen in such a way that the critical concrete zone causing shear failure is included. Thick solid lines in Fig.3 are considered path for examining the concrete internal stresses. Each line consists of a vertical line which goes through the critical concrete compression zone (or zone for concrete crushing) and an arch representing a major diagonal crack. We choose the path along which the depth of the compression zone is the minimum. The path for examination of the steel internal stresses consists of a diagonal line in web plate connecting two points at which the concrete path intersects and two vertical lines in top and bottom steel plates (see Fig.4).

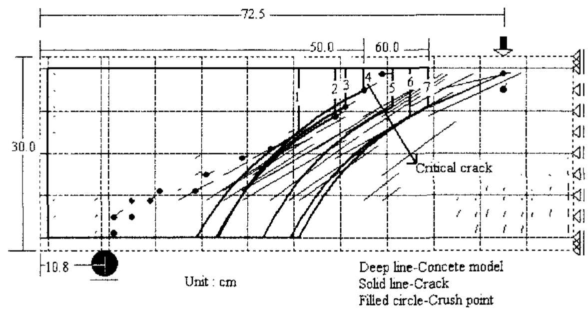


Fig.3 Path for examination of concrete contribution

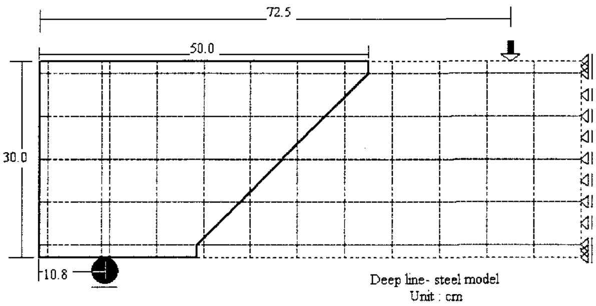


Fig.4 Path for examination of steel contribution

The internal concrete stresses along the path are considered separately for the critical compression zone and the diagonal cracking zone. The internal stress in the compression zone is mostly principal compressive stress, while the internal stress in the diagonal cracking zone is mostly stresses transferred at crack by aggregate interlocking. It was found that the contribution of the diagonal cracking zone is greater than that of the compression zone because the area of the diagonal cracking zone is larger than that of the compression zone. The contributions of the top and bottom steel plates are negligibly small compared with that of the full web plate, because not only the area but also the stress of the full web plate are much greater than those of the top and bottom plates. Therefore only the full web contribution is considered in the following section.

Table 1 Comparison of experimental results and FEM results

Specimen	Type	Material properties and proportions					Shear strength		
		a/d	f'_c (MPa)	f_{wy} (MPa)	p_s (%)	p_w (%)	Exp (kN)	FEM (kN)	Exp/FEM
expBN2	Full	2.12	26.00	319	6.54	1.20	603	555	0.920
expBN3	Full	2.12	24.71	324	6.54	1.80	722	654	0.906
expBN4	Full	2.12	24.40	342	6.54	2.40	796	755	0.948
expH327	Open	2.02	34.31	249	8.03	2.13	330	300	0.909
expH457	Open	2.02	34.31	249	8.03	3.00	381	351	0.921
expH607	Open	2.02	34.31	249	8.03	4.00	426	361	0.847

Note: a/d is shear span to depth ratio, f'_c is concrete strength, f_{wy} is yield strength of web plate, p_s is tensile steel plate ratio, and p_w is full web plate ratio.

5. Effect of Each Factor on Shear Strength

In this study concrete compressive strength, tension steel plate ratio, full web plate ratio, yield strength of full web plate, and shear span to depth ratio are taken as factors for the shear strength of sandwich beams. A number of full and open sandwich beams with various combinations of the considered factors were analyzed by the nonlinear finite element program to see effects of each factor on the shear strength.

5.1 Effect of concrete strength

The contribution of the concrete compression zone increases almost linearly with the concrete strength in both full and open sandwich beams (see Figs.5 and 6). Similarly the contribution of the diagonal cracking zone increases with the concrete strength for both full and open sandwich beams. Consequently the overall concrete contribution increases with the concrete strength. The increment in the contribution is slightly greater in open sandwich beams.

The full web plate contribution shows quite different tendency. The contribution slightly decreases with the concrete strength.

The concrete strength increases the shear strength of sandwich beams mainly due to the increase in the concrete contribution.

5.2 Effect of tension steel plate ratio

The internal stress in the concrete compression zone at shear failure increases with tension steel plate ratio but its depth decreases. As a result, the contribution of the compression zone decreases. The internal stress in the diagonal cracking zone does not change much with the tension steel plate ratio. The overall concrete contribution increases only slightly with the tension steel plate ratio.

The full web plate contribution does not change significantly with the tension steel plate ratio. The contribution of the top and bottom steel plates increases with the tension steel plate ratio.

The tension steel plate increases slightly the shear strength of sandwich beams because of the slight increase in both concrete and steel contributions.

5.3 Effect of full web plate ratio

The contribution of both compression zone and diagonal cracking zone does not change significantly. However, the full web plate contribution increases significantly due to increase in both corresponding area (ratio) and average stress at ultimate.

Consequently the full web plate ratio increases the shear strength significantly.

5.4 Effect of yield strength of full web plate

The yield strength of full web plate less likely affects the concrete contribution, however the average stress of the full web at shear failure increases with the yield strength. As a result, the shear strength increases with the yield strength of the full web plate.

5.5 Effect of shear span to depth ratio

The contribution of the concrete compression zone increases rather significantly with decrease in the shear span to depth ratio. However, the change in the contribution of the diagonal cracking zone is less significant.

The full web steel contribution increases in open sandwich beams with decrease in the shear span to depth ratio, while that in full sandwich beams does not increase but slightly decrease (see Figs.7 and 8).

Consequently the shear strength of open sandwich beams increases with decrease in the shear span to depth ratio, however that of full sandwich does not.

6. Difference in Shear Strength Development between Full and Open Sandwich Beams

It is known that the shear strength of a full sandwich beam is greater than a comparable open sandwich beam. The finite element analysis in this study, in which internal stresses in concrete and steel at shear failure are shown in detail, clearly discloses why the full sandwich beams can develop the greater strength. The average stresses in the critical compression zone and the full web plate are greater in the full sandwich beams (see Figs.5-8). The greater stress in the compression zone may be due to the better confinement provided by the compression steel plate. This confinement can increase ultimate strain of the concrete resulting in increase in the strain of the full web plate at the shear failure. Thus, the contribution of the full web plate can increase.

7. Conclusions

Based on the nonlinear finite element analysis, the shear strength development mechanism of full and open sandwich beams is clarified as follows:

(1) Since the shear failure is caused by concrete compression failure (diagonal compression failure), the shear strength increases with the concrete strength.

(2) The amount and yield strength of full web plate increases the shear strength since they increase the full web plate contribution. However, they do not affect much the concrete contribution.

(3) Decrease in the shear span to depth ratio increases the shear strength of open sandwich beams since it increases both concrete and full web plate contributions. However it does not increase the shear strength of full sandwich beams since the full web plate contribution decreases.

(4) The shear strength of full sandwich beams is greater than that of open sandwich beams since the contributions of both concrete and full web plate are greater due to the better confinement by the compression steel plate.

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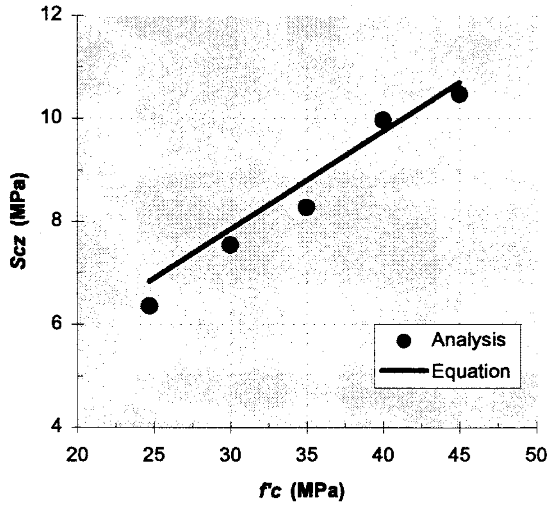

Fig.5 Concrete compression zone contribution in full sandwich beam (Equation: regressed line)

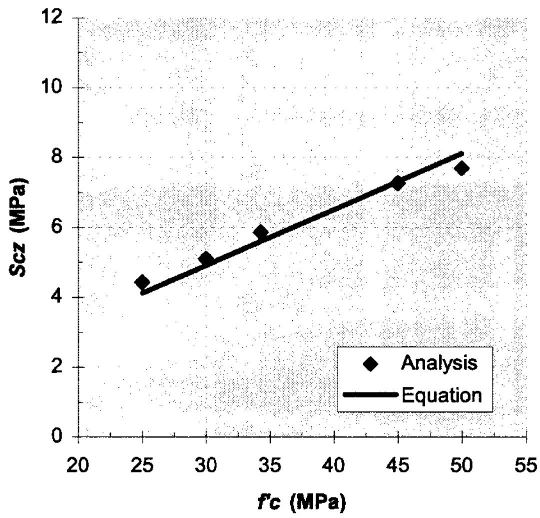

Fig.6 Concrete compression zone contribution in open sandwich beam (Equation: regressed line)

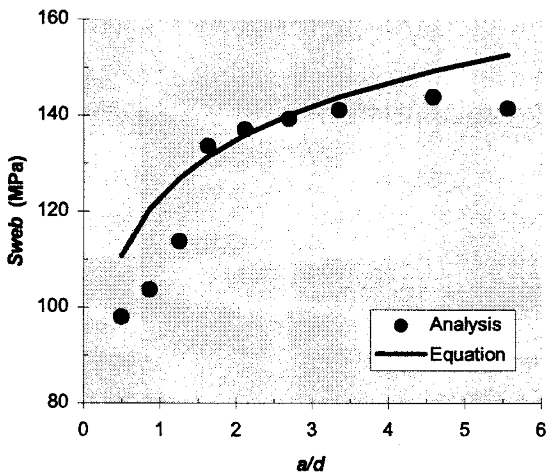

Fig.7 Full web plate contribution in full sandwich beam (Equation: regressed line)

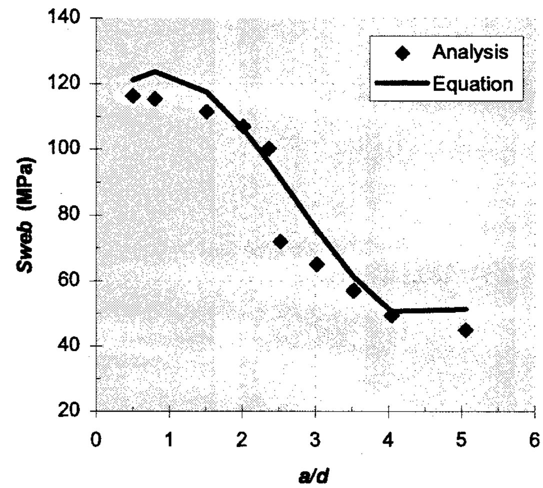

Fig.8 Full web plate contribution in open sandwich beam (Equation: regressed line)