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New evaluation and modeling procedure for horizontal shear bond in composite slabs

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ABSTRACT

A new method for modeling the horizontal shear bond in steel deck-concrete composite slabs is proposed. The method considers the slab slenderness as the strength parameter that affects the accuracy of horizontal shear bond modeling. A calculation procedure called the Force Equilibrium method is developed to generate shear bond stress versus end slips relationship (shear bond property) from bending tests. An interpolation procedure is also presented to estimate the shear bond property curves for slabs of varying slenderness using two sets of bending test data. The shear bond property curves are applied to connector elements of finite element models to model the horizontal shear bond behavior in composite slabs. The results of this study show that the shear bond of composite slabs under bending varies with the slenderness parameter, and hence influences the slab strength and behavior, as well as affecting the accuracy of the finite element analyses. The finite element analyses conducted on slabs with different slenderness utilizing a single shear bond property, which are not varied according to the slenderness parameter, may lead to either safe or unsafe results, depending on the geometry of the slabs.

1. Introduction

A composite slab comprised of structural concrete cast on cold-formed profiled steel deck is the most popular type of floor system used in steel framed buildings. In most practical cases, the behavior and strength of a composite slab is governed by horizontal shear bond at the interface of the steel deck and the concrete. The strength of the horizontal shear bond depends on many factors, among which include the shape of the steel deck profile, type and frequency of embossments, thickness of steel sheeting, arrangement of load, length of shear span, thickness of concrete, strain in the steel sheeting, support friction, natural clamping due to curvature under bending and type of end anchorage.

Because of these many influencing factors, it is not possible to provide representative design values that can be applied to all slab conditions. Hence, present design procedures for steel deck reinforced composite slabs, namely the m–k, the partial shear connection (PSC), and the multi linear regression methods, use data from full scale bending tests [1–4]. Design methods based on full scale tests are expensive and time consuming. As a less expensive alternative, finite element (FE) analysis can be conducted to replace the full scale bending tests. In the FE analysis, it is also not possible to model the influencing factors mentioned above separately due to lack of quantitative information of their contributions to the shear bond strength. A practical alternative is to model the horizontal shear bond by obtaining the necessary properties through elemental tests.

Correct modeling of the interaction behavior between the steel deck and the concrete, in the form of horizontal shear bond stress versus end slip relationship,[1] is the most important factor that affects the accuracy of the results. In previously reported studies, connector or spring elements were typically used to represent the horizontal shear interaction. The elements' material property was modeled by assigning horizontal shear bond–end slip curves. The relationships were obtained from direct shear tests such as push off tests [5–7], pull out tests [9,10], slip block test [8] or just an assumed relationship [11]. Because of the nature of the direct shear test configurations, the effect of curvature due to slab bending and the shear span to effective depth ratio, herein referred

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[1] Also used interchangeably with "shear bond–end slip curve" or "shear bond property" in this paper.

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to as the *slenderness*,[2] could not be considered. The slenderness could not be considered when an assumed relationship was used.

Daniels and Crisinel [9,10] reported that FE results only resembled the real slab behavior for long span slabs, but were underestimated for short span tests. Similar to the results reported by Daniels and Crisinel [9,10], An [8] found that the FE results were in good agreement with the long span slab tests but underestimated the capacity of the short slabs. Using an assumed shear bond–end slip curve for the interaction elements, Tenhovuori and Leskela [11] analyzed composite slabs of different slenderness to study the horizontal shear resistance behavior. Even though the accuracy of the FE results were not verified, a general relationship between the shear bond strength and the slenderness parameters could be deduced where the shear bond strength had increased with the increasing concrete thickness and had decreased with increasing shear span lengths.

Veljkovic [5,6] used variable shear bond–end slip curve in his FE study. To obtain a correct simulation, the shear bond–end slip curve was modified several times during the analysis according to strain level in the steel sheeting. The modification had to be made by applying a reduction function to the original shear bond–end slip curve because the shear bond strength was found to decrease with increasing strain in the steel sheeting. The reduction function was obtained from push–pull tests developed by the same author. The test setup was similar to push off tests except that the steel sheeting was put under tensile strain while the concrete was pushed over it. High strain in the steel sheeting reduced the resistance of the embossment interlock. Using variable shear bond properties, the analysis results were found to represent more closely the actual behavior of the real slabs.

As demonstrated by Veljkovic, it is apparent that the inaccuracy of the FE models for short span slabs as reported by Daniels and Crisinel [9,10] and An [8] was attributed to the use of an unchanged shear bond–end slip curve in the interface element. With a correct combination of material and concrete cracking properties, the FE models may simulate the behavior of long span slabs very well. However the use of the same shear bond–end slip curve in the FE model will always underestimate the *compact* slabs because of the fact that the actual shear bond strength increases with decreasing slenderness, as that shown by Tenhovuori and Leskela [11].

This paper deals with modeling of variable slenderness composite slabs using the FE method. The main focus is on the use of variable shear bond–end slip curves to model the interface behavior of the slabs. The shear bond–end slip curves were varied in accordance with the slab slenderness. To incorporate the slenderness effect, the shear bond–end slip curve cannot be derived from push off or pull out tests, but must be from bending tests. A method to calculate the shear bond property from bending test data is first derived. Using the method, graphs of shear bond stresses versus end slips are then generated. Small scale bending test data as reported in [12] are used in this study. The calculated results are validated by comparing the maximum stresses obtained from the graphs with the maximum stresses calculated using the PSC method available in [3]. Then the calculated shear bond–end slip curves are assigned to the connector elements of the FE models to simulate the interaction behavior between the steel sheeting and the concrete and the accuracy of the analysis results are analyzed. The FE modeling and analyses are performed using ABAQUS/Explicit module. Variable slenderness slabs are analyzed and finally the results are compared against the test data.

[2] In this paper the composite slab *slenderness* is defined as the ratio of the shear span length to the effective depth of the concrete, which is measured from the top fiber to the centroid of the steel deck. The inverse of the slenderness is referred to as *compactness*. Hence for a relative comparison, a *slender slab* is long span and thin concrete cover while a *compact slab* is short and thick.

2. Proposed method for generating shear bond property

An [8] used the Force Equilibrium method to calculate horizontal shear force–slip relationship from block bending tests. However An's procedure is only suitable for a test type where the moment arm is fixed such as the block bending test. A new derivation of this method is presented here for application to bending tests. The method is derived based on the following assumptions, which are in part made based on the observation from bending tests reported in [12] and from classical bending theory:

- The relative slip is uniform along the shear span hence the distribution of horizontal shear stress is also uniform along the shear span.
- The neutral axis of the composite section is always above the deck top flange and it moves upwards as the crack and the end slip increase. As a result, the compressive force in the concrete moves upward accordingly.
- Slip is only dominant at the failing end, while at the non-failing end, slip is small and negligible.
- The difference of curvatures between the concrete and the steel deck after the slip has occurred is small and hence are assumed equal.
- Due to slip, two neutral axes exist and therefore the steel deck is always taking a fraction of load by bending about its own axis.
- Steel deck is assumed to behave elastically and remain fully effective up to a maximum load.
- Plane section remains plane and normal to neutral axis.
- Concrete stress in tension is neglected.
- Small displacement theory is valid.

A free body diagram of a composite slab section tested with two-point loads is shown in Fig. 1(a). The friction force at the support is not included in the diagram and its contribution to the shear bond resistance is assumed to be intrinsically included in the shear bond force, F. The corresponding strain and internal force distributions at the critical sections are depicted in Fig. 1(b) and (c). At any instance, i during the test, the horizontal shear force F_i is equal to the axial force, T_i in the steel deck. At the partial interaction phase, the steel deck can also take a fraction of the applied load by bending about its own axis. The remaining bending resistance in the steel deck is denoted by M_{ri}. Neglecting the concrete self weight, the horizontal shear force, F_i can be calculated by taking moment about the compression force, C;

$$F_i = T_i = \frac{\left(\frac{P_i}{2} L_s - M_{ri}\right)}{z_i} \quad (1)$$

where

P_i = total applied load

L_s = shear span length

z_i = moment arm between tension and compression force.

Moment can be related to curvature by $\frac{M}{E_s I_s} = \frac{1}{R}$. From the geometry of Fig. 2, the curvature is $\frac{1}{R} = \frac{\delta_1 + \delta_2}{L_s(L - 2L_s)}$. Therefore, from the moment–curvature relationship, M_{ri} in Eq. (1) can be determined by;

$$M_{ri} = \frac{\delta_{1i} + \delta_{2i}}{L_s\,(L - 2L_s)} E_s I_s \quad (2)$$

where

δ_{1i} and δ_{2i} = measured deflections at load point 1 and 2 (Fig. 2)

E_s and I_s = Modulus of elasticity and moment of inertia of the steel deck.

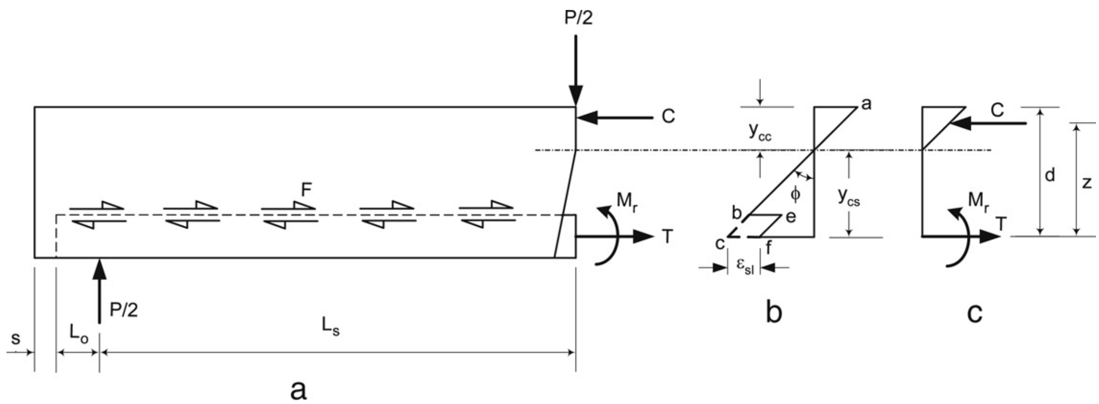

Fig. 1. Slab at partial interaction phase (a) Free body diagram of the critical section, (b) Strain distribution diagram, (c) Stress and internal force diagram.

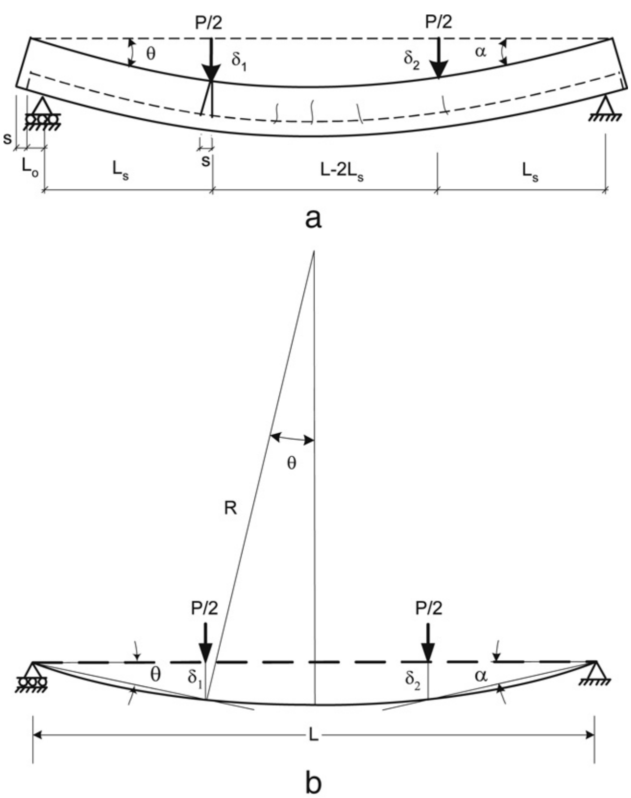

Fig. 2. Slab under bending, (a) At cracking mode, (b) Deflection and curvature of the deck.

Moment arm, z_i in Eq. (1) is an unknown parameter to be determined approximately from test data. Its value depends on the location of the composite section neutral axis, which at partial interaction, moves upward as the load increased. The first location of the composite neutral axis, y_{cc}, is at the tip of the first crack in the concrete. It then moves upward as the end slip and vertical deflection increase while the load is added. The value of y_{cc} at first cracking is calculated based on cracked section analysis of full interaction as indicated by line *abc* of Fig. 1(b). The calculation can follow Eq. B-1 of [1];

$$y_{cc} = d\left\{\left[2\rho n + (\rho n)^2\right]^{\frac{1}{2}} - \rho n\right\} \tag{3}$$

where

$d =$ effective depth of slab section

$\rho =$ ratio of steel area to effective concrete area, $\rho = A_s/(bd)$

$n =$ modular ratio $= E_s/E_c$.

Thereafter, y_{cc} reduces or the composite neutral axis moves upward as the crack length, y_{cs} increases. From the geometry as shown in Fig. 2(a), the crack length at instant *i*, can be estimated by;

$$y_{csi} = \frac{s_i L_s}{(\delta_{1i} + \delta_{2i})} \tag{4}$$

where

$s_i =$ measured end slip.

Therefore,

$$y_{cci} = d - y_{csi}; \quad 0 \le y_{cci} \le h_c \tag{5}$$

where

$h_c =$ concrete cover above deck top flange.

The moment arm is therefore;

$$z_i = d - \frac{1}{3} y_{cci}. \tag{6}$$

3. Bending test and calculation of the shear bond property

Test diagrams, specimen details and test parameters used in this study are shown in Figs. 3 and 4 and Table 1 [12].

Each test data point was applied to Eq. (1) through (6) to obtain the horizontal shear bond force. The values were then divided by the deck surface areas along the shear spans to obtain the shear bond stresses. The values were plotted against the corresponding end slips that were measured in the tests. A typical relationship between shear bond stress and end slips is shown in Fig. 5. To validate the proposed calculation method, the maximum shear bond stress obtained from the graphs for all test data were compared with the maximum values calculated using the PSC method available in [3]. The comparison is tabulated in Table 2. The results show good agreement between the two methods.

The Force Equilibrium method proposed here is derived for use with two-point load bending tests of composite slabs. The method was tested and validated using data from small scale bending tests of composite slabs made using trapezoidal deck only. No verification was made for slabs using other types of deck. However because of the generality of the method, the authors believe that it can be applied to composite slabs made with other types of deck profiles, embossment and end details, provided separate bending tests are conducted for each detail.

Table 1
Test parameters.

Specimen #	Deck depth (mm)	Deck moment of Inertia (mm^4/m)	Sheeting thickness (mm)	Fy (MPa)	Fu (MPa)	Specimen length measured from center of support (mm)	Shear span (mm)	Total concrete thickness (mm)	Conc. Comp. strength $f'c$ (MPa)
1	76	1280 922	0.9	370	440	2440	810	190	35
2	76	1280 922	0.9	370	440	3350	1020	125	35
3	76	1708 351	1.2	330	440	2440	810	190	35
4	76	1708 351	1.2	330	440	3960	1320	125	31
5	76	2157 630	1.5	350	410	1220	410	190	35
6	76	2157 630	1.5	350	410	2440	810	190	31
7	76	2157 630	1.5	350	410	3050	970	190	35
8	76	2157 630	1.5	350	410	3660	1120	125	35
9	76	2157 630	1.5	350	410	4270	1320	125	31
10	51	570 816	0.9	360	430	2130	710	165	35
11	51	570 816	0.9	360	430	2740	970	100	31
12	51	760 633	1.2	340	410	2130	710	165	35
13	51	760 633	1.2	340	410	3350	1070	100	35
14	51	961 374	1.5	320	400	2130	710	165	35
15	51	961 374	1.5	320	400	3660	1170	100	31

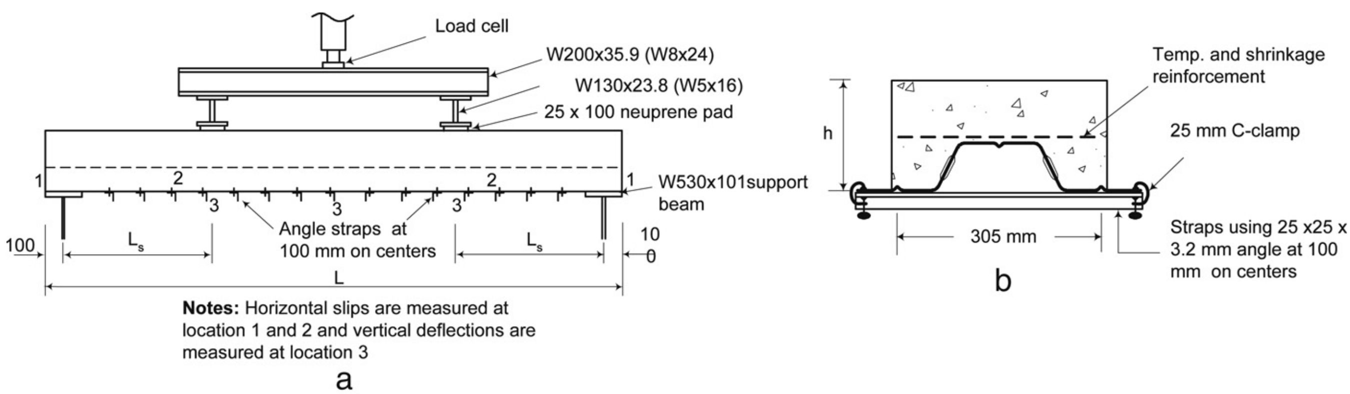

Fig. 3. Small scale bending test (a) Elevation, (b) Cross section.

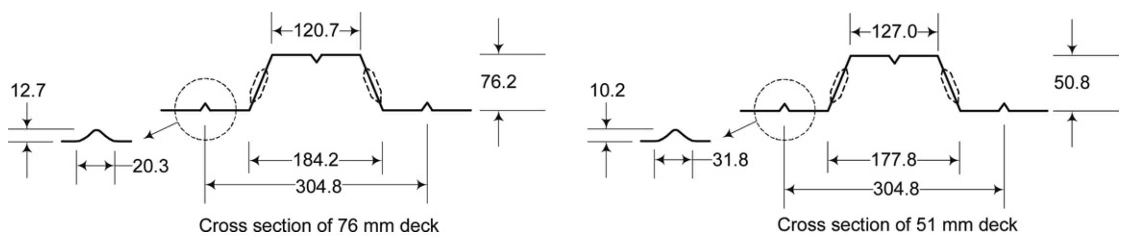

Fig. 4. Deck cross section and dimensions.

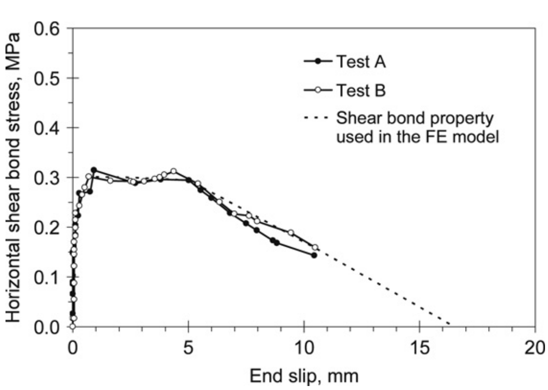

Fig. 5. Typical shear bond property (results of Test #6).

4. Finite element analysis

Quasi-static three-dimensional nonlinear FE analyses were carried out using ABAQUS/Explicit 6.3 to demonstrate the effect of slab slenderness on the shear bond property of composite slabs. The concrete was modeled with the brick element, C3D8R, and the steel deck was modeled with the shell element, S4R. The interaction between the steel deck and the concrete was modeled using the connector element, CONN3D2. The concrete material and steel sheeting properties were assumed based on the literature review [13–16,6] and the values are given in Tables 3 and 4. The connector element property was assigned with the horizontal shear bond curve that was calculated from the bending test data using the Force Equilibrium method as discussed in the preceding section. The curve obtained from specimen #6 is shown in Fig. 5 and this specimen was used as the basis for FE model development. The results of the FE analysis conducted on specimen #6 are shown in Fig. 6. The detail procedure of the quasi-static analysis carried out in this study is discussed in [17].

The shear bond–end slip curves for Specimen #5 to #9 were calculated from test data using the proposed Force Equilibrium method. The specimens for these tests were built on the same deck profile but having different slenderness. The results of two tests for

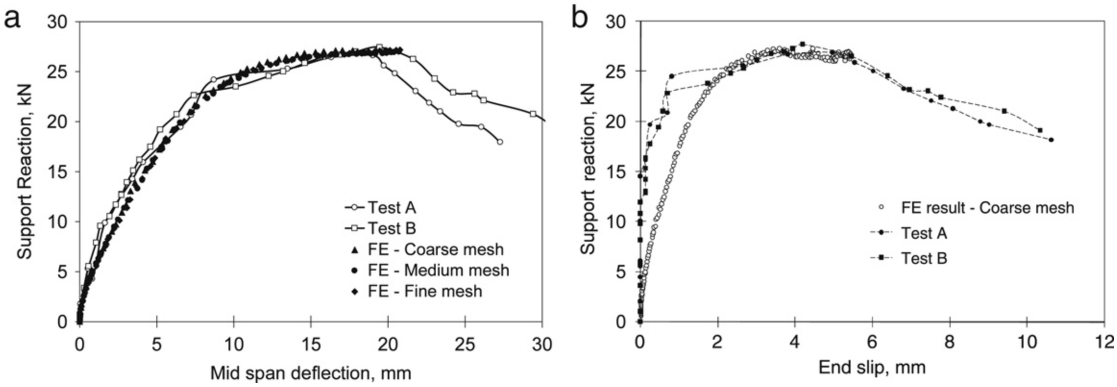

Fig. 6. Results of FE analysis for specimen #6. (a) Load vs Mid span deflection, (b) Load vs End slip.

Table 2
Comparison of maximum shear bond stress, τ between PSC and Force Equilibrium Method (FM).

Specimen	Test	τ by PSC (MPa)	τ by FM (MPa)	PSC/FM
1	A	0.210	0.214	0.98
	B	0.205	0.223	0.92
2	A	0.221	0.178	1.24
	B	0.135	0.144	0.94
3	A	0.204	0.236	0.86
	B	0.224	0.250	0.90
4	A	0.181	0.157	1.15
	B	0.188	0.155	1.21
5	A	0.600	0.597	1.00
	B	0.467	0.483	0.97
6	A	0.301	0.314	0.96
	B	0.316	0.312	1.01
7	A	0.270	0.288	0.94
	B	0.217	0.235	0.92
8	A	0.244	0.228	1.07
	B	0.248	0.219	1.13
9	A	0.198	0.178	1.11
	B	0.217	0.185	1.18
10	A	0.266	0.294	0.90
	B	0.236	0.272	0.87
11	A	0.163	0.141	1.16
	B	0.149	0.151	0.99
12	A	0.287	0.307	0.94
	B	0.314	0.353	0.89
13	A	0.239	0.213	1.13
	B	0.240	0.263	0.91
14	A	0.443	0.469	0.94
	B	0.390	0.434	0.90
15	A	0.286	0.243	1.18
	B	0.319	0.264	1.21
		Mean		1.02
	Standard deviation			0.12

Table 3
Mechanical and brittle cracking properties of concrete used in the FE model.

Concrete properties	Values
Density	2400 kg/m^3
Elasticity modulus	24.8 GPa
Poisson ratio	0.2
Cracking failure stress	2.07 MPa
Mode I fracture energy	73.56 N/m
Direct cracking failure displacement	1.27×10^{-5} m
2 segment tension stiffening model	Remaining direct stress, Direct cracking displacement. 2.07 MPa, 0 mm 0.62 MPa, 0.022 mm 0 MPa, 0.140 mm
Post cracking shear behavior model	Power law with 2.0 power factor 0.4% maximum crack opening strain for coarse mesh. The value was adjusted proportionately according to characteristic mesh size for models with different mesh sizes.

Table 4
Steel properties used in the FE model.

Steel properties	Values
Density	7800 kg/m^3
Elastic modulus (flanges)	203.4 GPa
Yield stress (flanges)	345 MPa
Elastic modulus (web)	101.7 GPa
Yield stress (web)	173 MPa

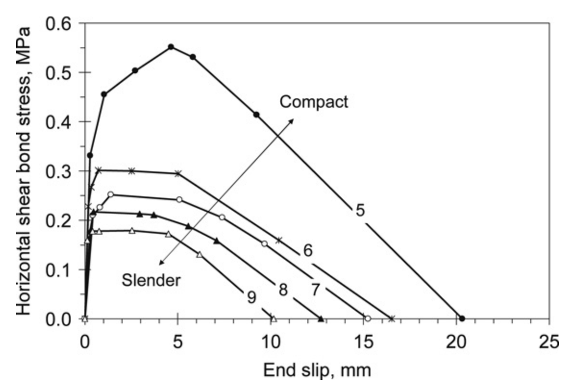

Fig. 7. Horizontal shear bond properties for Specimen #5 to #9.

each specimen were averaged, simplified and plotted as Curves 5 to 9 in Fig. 7.

FE analyses were carried out for models of Specimen #5, #7, #8 and #9 using the corresponding shear bond properties as plotted in Fig. 7. Other material properties were unchanged. The results of the analysis were plotted for each model and labeled as Curve A in the load–deflection graphs as shown in Fig. 8. The graphs indicate that the FE results generally agree well with the test data for slabs of varying slenderness.

As depicted in Fig. 7, the shear bond–end slip relationships vary with the slab slenderness. It can be seen that the stresses and slips are larger for more compact slabs and the values are smaller for more slender slabs. On the other hand, the end slip for full interaction slabs does not occur and hence it can be safely assumed that the shear bond–end slip curve for the full interaction slab is located along the vertical axis. From here, it can be seen that the shear bond property depends on the slab slenderness. For the partial interaction slabs, the shear bond property is unique and is not interchangeable with different slenderness slabs. The FE analyses indicate that the accurate result for a particular slab can only be obtained when the shear bond–end slip property from the beam of the same slenderness is used.

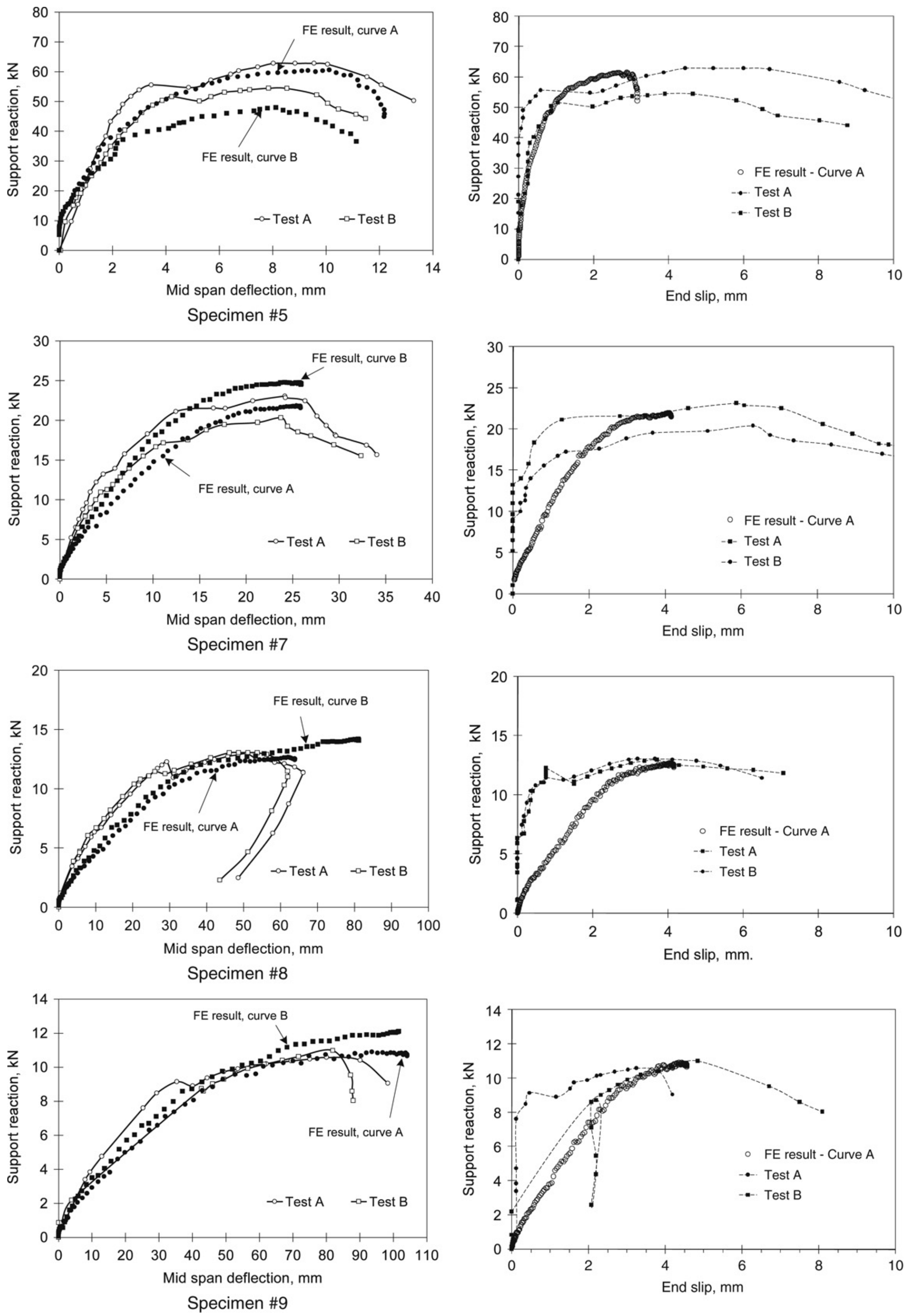

Fig. 8. Comparison between FE results and test data for specimen #5, #7, #8 and #9 — Left : Load vs. Mid span deflection; Right: Load vs. End slip.

To further illustrate this finding, analyses were performed again on the same models but only using shear bond property, Curve #6. The results are labeled as Curves B in the load–deflection graphs of Fig. 8. It can be seen that the models underestimate the capacity of more compact slab (model #5) but overestimate the slenderer slabs (model #7, #8 and #9). The graphs also show that the differences between the analysis and test results are smaller for the more slender slabs. It should be noted that the corresponding end slip values from FE analysis did not differ appreciably between Curve A and B. Hence, the end slip results for Curve B were not plotted here for clarity.

It is evident from the results presented above that with the right combination of material properties, the use of single shear bond property in composite slab modeling may produce good results for one particular slab geometry, but it may not be accurate when the slab slenderness is changed. It is important to stress the points highlighted in the background section that all FE studies of composite slabs performed by previous researchers used a single shear bond–end slip curve, which was obtained from the same test philosophy, i.e. *push off* or *pull out* tests. While their results showed general agreement between the analysis and test results, none of the reports provide information regarding the accuracy of the analysis for slabs of variable slenderness.

5. Linear interpolation method for predicting the shear bond property

It has been shown in the above sections that the shear bond property of a composite slab is geometry dependent. The correct property must be used to model a particular slab in the numerical analysis, so that an accurate prediction of the slab strength and its behavior can be obtained. If this is the case, FE modeling of composite slab would become uneconomical because tests are needed for every slab before they can be correctly modeled. If all tests had already been conducted, the FE analysis would no longer be required. Considering this, for the method described to be of practical significance, it is necessary to establish a method for estimating the shear bond property that is applicable to variable slenderness slabs without a need for too many tests.

Linear interpolation was used for estimating the shear bond–end slip curve for slabs of different slenderness. The interpolation was conducted using shear bond–end slip curve of two bending test results: one compact and one slender specimen. The linear relationship was assumed based on the fact that the load carrying capacities of slabs of any slenderness built on the same deck profile vary linearly with the slab compactness, L_s/d. This is shown by the m–k equations in [3]:

$$\frac{V}{bd} = m\frac{A_s}{bL_s} + k$$

$$V = mA_s\frac{d}{L_s} + bdk \qquad (7)$$

where V is the shear force. Based on this information, other points below the maximum value on the shear bond–end slip curves were also assumed to be related linearly. As such they could be estimated by linear interpolation between two known curves derived from the bending tests. The interpolation of all points on the shear bond–end slip curve followed the same proportion as for the maximum shear bond stresses.

To illustrate the interpolation procedure, consider the shear bond stress–end slip curves from specimen #5 and #9 as shown in Fig. 7. The shear bond–end slip relationship for specimen #7 is to be determined by interpolation using these two curves. The interpolation method is depicted graphically in Fig. 9. The maximum shear stress, τ_3 that lies on Curve #7 is first obtained from the linear regression line of the maximum stresses of specimen #5 and #9. After knowing τ_3 the corresponding slip, s_3 can be determined by linear interpolation between the maximum points of Curves #5 and #9 whose coordinates are (s_1, τ_1) and (s_2, τ_2) respectively. The next nearest point on Curve #7 is assumed to lie along the straight line between the next nearest points on curves #5 and #9. The position of this point is at an equal proportion as for the maximum stress points calculated before,

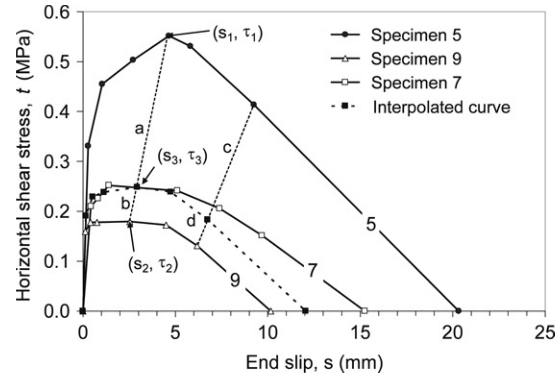

Fig. 9. Approximation of the shear bond stress–slip Curve #7 by linear interpolation using Curve #5 and #9.

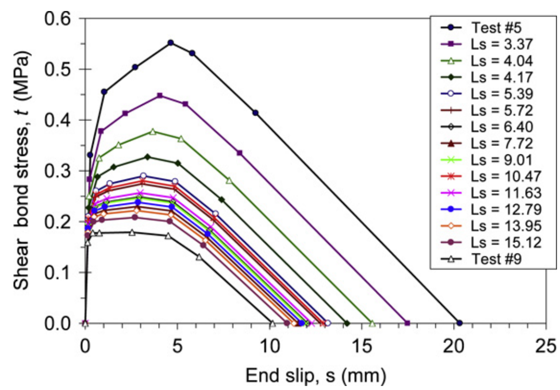

Fig. 10. Shear stress–slip property for the 76 mm (depth) – 1.5 mm (sheet thickness) slab of variable slenderness.

such that $\frac{a}{b} = \frac{c}{d}$. By linear interpolation the coordinate of the new points can be calculated. Likewise, other points on Curve #7 can be determined in a similar manner. For comparison, the shear bond–end slip curve for specimen #7 obtained from tests data also drawn in Fig. 9. As depicted in the figure, both curves especially the portions up to the maximum value are in good agreement. The difference between the interpolated and the calculated curves beyond the maximum value will not influence the analysis results significantly because in most analyses, the information beyond the maximum load is of limited value.

6. Application of the shear bond model in the FE element analysis

The shear bond–end slip curves of specimen #5 and #9 were used to estimate the shear bond property for a series of different slenderness slab models using the linear interpolation method as discussed above. Some of the model geometries were similar to the tested specimens. Several other models were chosen arbitrarily so that their slenderness values would fill the gaps between the tested slenderness. The interpolated shear bond property curves for these slabs are shown in Fig. 10. Finite element analyses were performed on these models utilizing the same material properties as in the preliminary model development. The analysis results in the form of maximum support reaction due to applied load versus the slenderness are plotted in Fig. 11. Test data are also plotted in the same figure for comparison. The curves fitted to both data series using power function are very close, indicating that the FE models using interpolated shear bond property curves are accurate.

Two other slab groups that utilized 51 mm deep with 0.9 mm sheet thickness and 76 mm deep with 1.2 mm sheet thickness

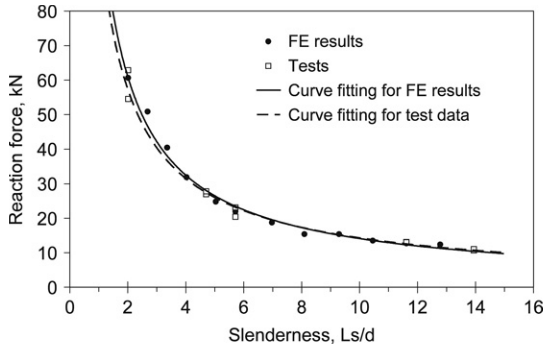

Fig. 11. Tests data and FE results for the 76 mm (depth) – 1.5 mm (sheet thickness) slab with variable slenderness.

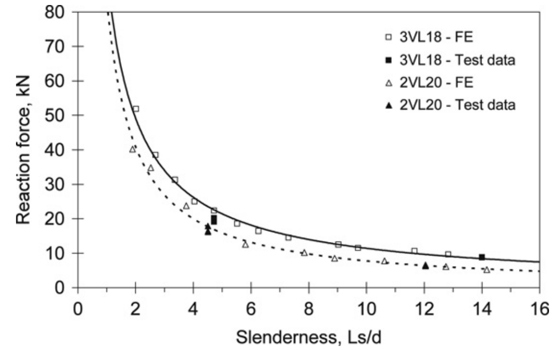

Fig. 13. FE results for slab models using 76 mm (depth) – 1.2 mm (sheet thickness) and 51 mm (depth) – 0.9 mm (sheet thickness) deck with variable slenderness.

decks were analyzed in the same manner, where the shear bond property curves were interpolated and extrapolated from specimens #10 and #11, and specimens #3 and #4 respectively. Their curves are shown in Fig. 12. For models that were more compact and more slender than the tested specimens, the curves were also obtained by extrapolation. The FE results for both slab groups are shown Fig. 13. The result curves follow the same trend and comparable well with each other.

7. Summary and conclusions

A procedure referred to as the Force Equilibrium method was developed for calculating the shear bond in composite slabs from bending test data. The procedure was used to produce the shear bond–end slip relation. The accuracy of the method was validated by comparing the results with the established PSC method. An interpolation procedure was also proposed to predict the shear bond properties of slabs with varying slenderness from only two sets of bending test data. Quasi-static FE modeling and analysis were conducted to illustrate the effect of varying shear bond properties on the accuracy of the FE models. In the FE models, connector elements were used to represent the shear bond between the steel deck and the concrete. The shear bond properties that were obtained from the proposed calculation procedure were assigned to the connector elements.

The following conclusions can be drawn from the study:

1. The proposed Force Equilibrium method enables the calculation of the horizontal shear bond stress in composite slabs using two-point bending test data. The maximum shear bond stress obtained using the method is comparable with that calculated using the Partial Shear Connection (PSC) method. The Force Equilibrium method has an advantage in that it also can produce the horizontal shear bond stress–end slip relation. This property is useful for numerical analysis.
2. The behavior and magnitude of the shear bond depend on the slenderness of the slabs. For slender slabs the shear bond and the end slip magnitudes are relatively small compared to more compact slabs. The change of the shear bond behavior is also less sensitive for the slender slabs compared with the more compact ones.
3. The load carrying capacity of composite slabs is a function of the slenderness parameter, L_s/d which is agreeable with the already established m–k method. Hence, the shear bond property is unique to the slab in accordance with the slenderness parameter.
4. Because the shear bond property is unique for the slab in accordance with the slenderness parameter, the property of the elements used to model the horizontal shear interaction in the FE analysis must be changed in accordance with the slenderness of the slab model. In this way, the accuracy of the FE analysis can be improved. If a single shear bond property curve is assigned to the interaction elements, as was done using push off tests by many previous researchers, the FE analysis can be accurate for a particular slab geometry only, but underestimating the more compact slabs and overestimating the slenderer slabs.
5. Only two sets of bending tests are required to provide good shear bond modeling properties for various slenderness models. One set of tests should be compact specimens and the other set slender specimens. For other slenderness slabs, the shear bond properties can be determined using the proposed linear interpolation or extrapolation from the two sets of test data. Other parameters that contribute to the shear bond property such as sheeting strain, support friction, natural

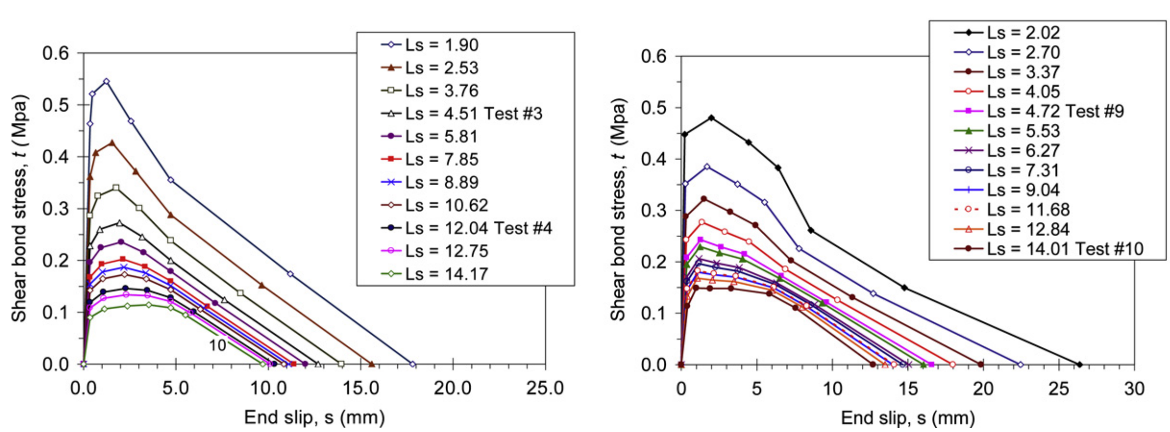

Fig. 12. Interpolations of shear bond properties for specimens made of 51 mm (depth) – 0.9 mm (sheet thickness) (left) and 76 mm (depth) – 1.2 mm (sheet thickness) (right) decks.

clamping and curvature have already been included implicitly in the shear bond property obtained from bending tests, hence their effects can be ignored in the FE model.

References

[1] ASCE. Standard for the structural design of composite slabs. ANSI/AASCE 3–91. American Society of Civil Engineers. New York, 1992.
[2] BS-5950. Structural use of steelwork in building — Part 4: Code of practice for design of composite slabs with profiled steel sheeting. British Standard Institution. London, 1994.
[3] Eurocode 4. Design of composite steel and concrete structures. Part 1.1. General rules and rules for buildings. EN 1994-1-1:2004. European Committee for Standardization. Brussels, 2004.
[4] CSSBI. Standard for composite steel deck. CSSBI 12M - 96. Canadian Sheet Steel Building Institute; 1996.
[5] Veljkovic M. Longitudinal shear capacity of composite slabs. In: Nordic steel construction conference'95. 1995.
[6] Veljkovic M. Behavior and resistance of composite slabs. Ph.D thesis. Lulea (Sweden): Lulea University of Technology; 1996.
[7] Patrick M, Poh KW. Controlled test for composite slab design parameters. In: IABSE symposium. Brussels, Belgium — Mixed Structures. Including New Materials. 1990. p. 227–31.
[8] An L. Load bearing capacity and behavior of composite slabs with profiled steel sheet. Ph.D. dissertation. Sweden: Chalmers University of Technology; 1993.
[9] Daniels BJ, Crisinel M. Composite slab behavior and strength analysis. Part I: Calculation procedure. Journal of Structural Engineering, ASCE 1993;119(1): 16–35.
[10] Daniels BJ, Crisinel M. Composite slab behavior and strength analysis. Part II: Comparisons with test results and parametric analysis. Journal of Structural Engineering, ASCE 1993;119(1):36–49.
[11] Tenhovuori A, Leskela MV. Longitudinal shear resistance of composite slabs. Journal of Constructional Steel Research 1998;46(1–3): Paper 319.
[12] Abdullah, Easterling. A new small scale testing method for composite slabs. Journal of Structural Engineering, ASCE 2007;133(9):1268–77.
[13] Abaqus online documentation. Version 6.3-1. Pawtucket (RI): Hibbitt, Karlsson and Sorenson Inc.; 2002.
[14] Alfaiate J, Pires EB, Martins JAC. A finite element analysis of non-prescribed cracks propagation in concrete. Computers & Structures 1997;63(1):17–26.
[15] Hillerborg A, Modeer M, Peterson PE. Analysis of crack formation and crack growth in concrete by means of fracture mechanics and finite elements. Cement and Concrete Research 1976;6:773–82.
[16] Veljkovic M. Interaction between concrete and sheeting in composite slabs. S-971 87 LULEA. Lulea (Sweden): Lulea University of Technology, Division of Steel Structures; 1994.
[17] Abdullah R, Paton-Cole VP, Samuel Easterling W. Quasi-static analysis of composite slab. Malaysian Journal of Civil Engineering 2007;19(2):91–103.