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MECHANICAL INTERLOCKING CAPACITY OF COMPOSITE SLABS

BY

R. M. Schuster* and W. C. Ling**

SUMMARY

This paper presents an ultimate interlocking capacity (shear-bond) expression for composite slabs based on end-slip of the shear span occurring prior to ultimate load, where the shear-bond mode of failure is considered to be the result of the breakdown of the mechanical interlocking capacity between the steel deck and concrete of the composite slab. A total of 168 laboratory performance tests of eight different product types were used to substantiate the ultimate interlocking capacity (shear-bond) expression developed. In comparing the computed with the corresponding experimental results, a ± 15% correlation was obtained in all of the investigated cases.

INTRODUCTION

A most efficient and economical lightweight floor system is created by compositely integrating the structural properties of concrete and formed steel decking (corrugated or ribbed). The steel deck performs the dual role of functioning as a form for the wet concrete during construction and as positive reinforcement for the slab under service conditions. This combination of compositely integrating the structural properties of concrete and steel decking is termed "Composite Slab Construction". See Reference 13 for a detailed description and discussion of the numerous inherent attributes of composite slabs. To develop this composite action (mechanical interlocking capacity), the steel deck must be able to resist horizontal shear and prevent vertical separation between the concrete and steel deck. This is commonly achieved by mechanical interlocking devices and in some cases by the geometric shape of the steel deck profile. The most common composite deck systems on the market today utilize a fixed pattern of indentations or embossments or both (mechanical interlocking devices) to develop the necessary composite action between the concrete and steel deck.

Since composite slab systems failing in shear-bond do experience end-slip prior to ultimate load, this paper presents the development of an ultimate interlocking capacity (shear-bond) expression, where the shear-bond mode of failure is considered to be the result of the breakdown of the mechanical interlocking capacity between the steel deck and concrete of the composite slab. This approach is different from the existing ultimate shear-

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bond expressions which are based on the assumption that the failure crack is caused by excessive principal tension stresses in the concrete.

INTERLOCKING CAPACITY (SHEAR-BOND)

Review of Shear-Bond Expressions

Composite slab testing at Iowa State University (9) indicated that the primary mode of failure was due to the combined action of shear and moment, resulting in a shear-bond type of failure. A shear-bond mode of failure was identified by the formation of an approximately diagonal crack at ultimate load under or near one of the two symmetrically placed concentrated line loads. At failure, sudden end-slip of the shear span between the steel deck and concrete was experienced, causing complete loss of composite action within the affected shear span portion. No end-slip was experienced prior to ultimate load with any embossment-type composite slab system tested. Curve 1 of Fig. 1 illustrates this behavior on a typical load-deflection curve for the embossment-type composite slab systems tested. Since no end-slip occurred prior to ultimate load and the potential failure crack was almost invisible until failure, Schuster (10) developed the first ultimate shear-bond expression for composite slabs based on the assumption that the failure crack was caused by excessive principal tension stresses in the concrete. The resulting equation, Eq. 1, is a linear relationship of the ultimate shear-bond capacity, containing two unknown coefficients that have to be evaluated from laboratory performance tests.

$$\frac{V_u}{bd} = m\frac{\sqrt{f'_c}\, d}{L'} + kp \qquad (1)$$

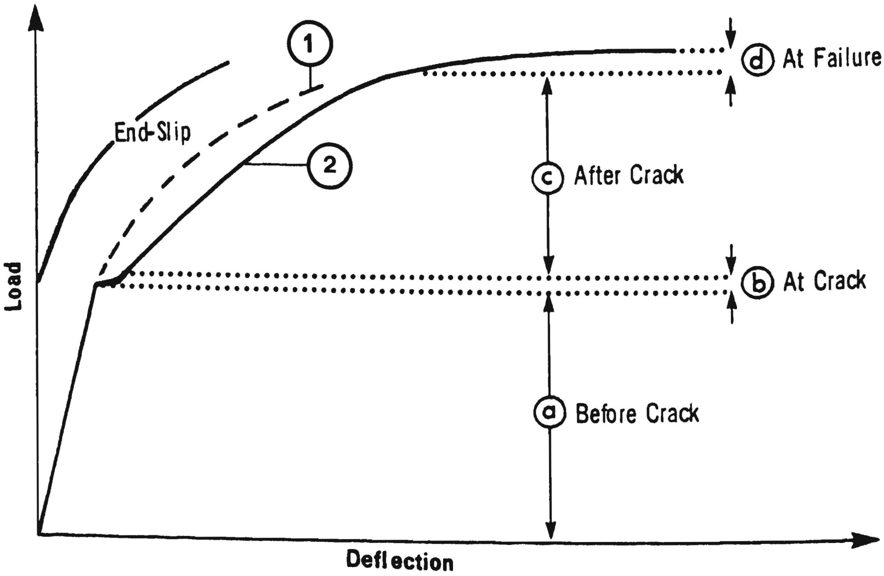


FIG. 1. TYPICAL LOAD-DEFLECTION AND END-SLIP CURVES

Where V_u is the ultimate transverse shear, b is the width of the composite slab, d is the effective depth of the concrete, f'_c is the compressive strength of the concrete, L' is the shear span, p is the percent of steel and m and k are unknown coefficients (slope and intercept of the shear-bond line, respectively) which must be determined for each steel deck thickness of each product type from laboratory performance tests. For a detailed development of Eq. 1, see Ref. (9).

Porter and Ekberg (6), (7), based on Ref. (8) and as a result of the ongoing committee work until 1977 by the "Ad 'Hoc' Task Group on Tentative Recommendations for the Design of Cold-Formed Steel Decking as Reinforcement for Concrete Floor Slabs" under the auspices of AISI, presented an ultimate shear-bond equation which is basically the expression used by ACI, (1) and CSA A23.3, (2) to compute the ultimate shear capacity of reinforced concrete members without web reinforcement as a measure of diagonal tension. In the comparison study of a number of shear-bond expressions,the ACI shear and diagonal tension expression was also investigated by replacing the constants of 1.9 and 2500 with m and k, respectively, resulting in the following equation for the ultimate transverse shear, V_u:

$$\frac{V_u}{bd} = m \frac{dp}{L'} + k\sqrt{f'_c} \quad . \tag{2}$$

As can be seen from Eq. 2, the parameters are the same as those of Eq. 1, with the exception of the arrangement. Since both Eqs. 1 and 2 give almost identical results, as concluded in Ref. (8), the percent of steel and strength of concrete do not appear to be influential parameters in the above expressions. In fact, the percent of steel seems to be redundant because m and k must be determined for every steel deck thickness anyway, meaning that the area of the steel deck, A_s, is constant for every steel deck thickness. The development of Eq. 2 was also based on the assumption that a shear-bond mode of failure is the result of excessive principal tension stresses in the concrete.

Behavioral Characteristics of Interlocking (Shear-Bond) Failure

In contrast to composite slabs failing in shear-bond with no end-slip prior to ultimate load, a number of composite slab systems recently introduced on the market are exhibiting end-slip prior to ultimate load (5), (11), (12), (14). Such end-slip, in most cases, is experienced at the time of the formation of the first potential failure crack under or near one of the concentrated line loads. The magnitude of load at initial end-slip is generally between 50-60% of ultimate.

Curve 2 of the typical load-deflection curve of Fig. 1 and Fig. 2 and used to describe the interlocking (shear-bond) behavioral characteristics of composite slabs exhibiting early end-slip during loading. The four regions of primary importance are discussed as follows:

a) Before Crack
The concrete and steel deck act as a fully effective composite section, where the tensile bending stress is carried proportionally by both the concrete and steel deck. Hence, the resisting interlocking force between the concrete and steel deck is not active during this stage.

b) At Crack
In the immediate region of the potential failure crack, the mechanical interlocking devices begin to transfer load in the horizontal direction, causing the resisting mechanical interlocking force between the concrete and steel deck to become active at that region. If there are no interlocking devices in the steel deck (smooth deck), sudden failure of the system will result. However, with interlocking devices the composite slab will only experience initial end-slip in the affected shear span portion and continue to carry additional load. Initial end-slip is identified not only by end-slip instrumentation but also by the flat plateau of the load-deflection curve.

c) After Crack
Immediately after the potential failure crack has occurred, the resisting mechanical interlocking capacity of the system in the vicinity of the crack has been exceeded, causing the curve of the assumed resisting mechanical interlocking stress of Fig. 2(a) to move to the right as shown in Fig. 2(b). Hence, at the region of crack where the resisting mechanical interlocking capacity has been exceeded, resisting frictional forces are now acting, permitting the composite slab to carry additional load. Resisting frictional forces are inherent with all interlocking-type composite slab systems after initial cracking has taken place. These frictional forces play a particularly important role when early end-slip is being experienced. The magnitude of both the resisting mechanical interlocking and the frictional forces depended greatly upon the type of interlocking device and on the geometric profile of the steel deck.

d) At Failure
The load carrying capacity of a composite slab is said to reach its ultimate load when the combined resisting mechanical interlocking and frictional forces (see Fig. 2(b)) reach their ultimate capacities within the failure shear span. Any additional load after this stage will cause the composite slab to fail, resulting in loss of composite action and large end-slip.

Development of Interlocking (Shear-Bond) Expression

Based on the foregoing discussion of the behavior of composite slabs experiencing early end-slip, the overall interlocking capacity can be considered to be a function of the mechanical interlocking resistance and the frictional resistance within the failure shear span of the composite slab.

The development of the ultimate interlocking (shear-bond) equation is based on the moment balancing technique commonly used in reinforced concrete, i.e., balancing the external or applied moments with the internal reacting moment at the location of failure crack. With reference to Fig. 3, the moment balancing equation is expressed at ultimate load as follows:

$$V_u L' + M_d = F(d - \frac{a}{2}) \quad , \qquad (3)$$

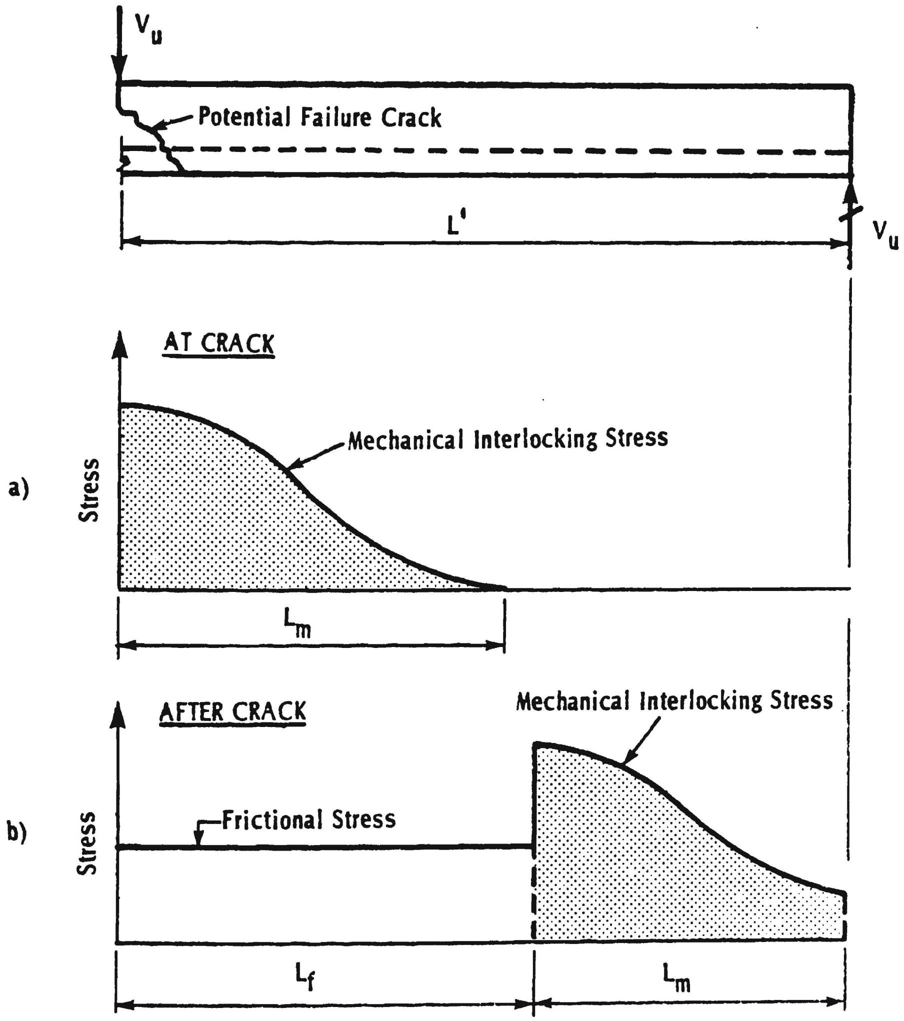


FIG. 2. ASSUMED DISTRIBUTION OF RESISTING MECHANICAL INTERLOCKING AND FRICTIONAL STRESSES.

where M_d is the bending moment at a distance L' from the support, exerted by the dead weight of the slab element. F is the force in the steel deck at the location of crack, and is equal to the sum of the resisting mechanical interlocking and frictional forces within the shear span, L'. Therefore, F can be expressed as follows:

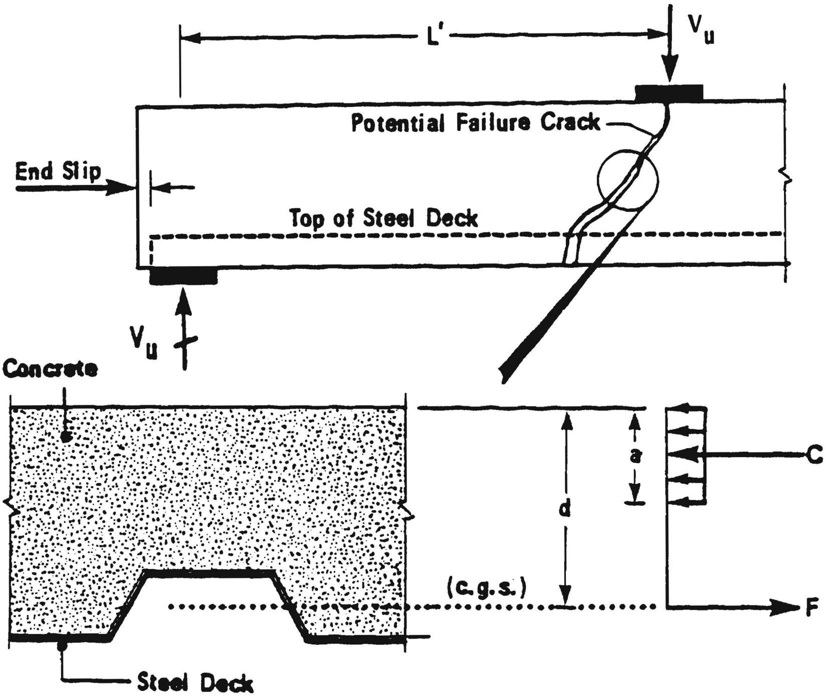


FIG. 3. INTERLOCKING (SHEAR-BOND) FAILURE MECHANISM AND ASSUMED INTERNAL RESISTING FORCES AT FAILURE.

$$F = (F_m + F_f)b \tag{4}$$

where F_m is the resisting mechanical interlocking force per width of slab and F_f is the resisting internal frictional force per width of slab, and b is the width of the composite slab. By nature of the formation of the frictional force between the concrete and steel deck shown in Fig. 2(b), the magnitude of the frictional force can be assumed to be constant throughout the length, L_f, hence, F_f can be written as follows:

$$F_f = f_f L_f \tag{5}$$

where f_f is the resisting internal frictional stress between the concrete and interlocking devices.

Substituting Eq. 5 into Eq. 4 and then substituting Eq. 4 into Eq. 3, yields

$$V_u L' + M_d = (F_m + f_f L_f) b(d - \frac{a}{2}) \quad . \tag{6}$$

Cracks may occur within the shear span, however, these cracks are near the region of loading and it is assumed that these cracks are all located within the range of L_f. One particular phenomenon that is experienced with composite slab systems is that, the failure crack at ultimate load extends very close to the top surface at the concrete. Therefore, the parameter, a/2, of Eq. 6 is relatively small in comparison to the effective depth of concrete, d, in the same equation. Thus, the term (d-a/2) of Eq. 6 can be set equal to d without causing serious error. Hence, Eq. 6 becomes

$$V_u L' + M_d = (F_m + f_f L_f)bd \quad . \tag{7}$$

Since $L_f = L' - L_m$ (see Fig. 2(b)), Eq. 7 results in

$$V_u L' + M_d = [(F_m - f_f L_m) + f_f L']bd \tag{8}$$

Setting $F_n = F_m - f_f L_m$, Eq. 8 becomes

$$V_u L' + M_d = (F_n + f_f L')bd \quad . \tag{9}$$

Eq. 9 expresses the interlocking capacity of composite slabs in terms of the ultimate transverse shear, V_u, and takes into account the variables that affect the interlocking capacity of flexural members subjected to combined shear and bending. Rewriting Eq. 9 in the format of Eqs. 1 and 2 results in

$$\frac{V_u}{bd} = F_n \frac{1}{L'} + f_f - \frac{V_d}{bd} \quad , \tag{10}$$

where V_d is the transverse dead load shear at a distance L' from the support and F_n and f_f are unknown coefficients (slope and intercept, respectively) which must be determined for each steel deck thickness of each product type from laboratory performance tests. These coefficients are similar to m and k of Eqs. 1 and 2. It is interesting to note that Eq. 10 does not contain the concrete compressive strength parameter nor the percent of steel term. As discussed earlier, these two parameters appeared not to be as influential as the shear span and depth of slab. Eq. 10 seems to support that earlier observation. Also, Eq. 10 is applicable to composite slabs failing in shear-bond without early end-slip since the failure crack is formed prior to ultimate load, regardless how invisible the crack is.

TEST DATA EVALUATION

General Remarks

Even though Eq. 9 was specifically developed for an interlocking (shear-bond) failure accompanied by early end-slip, test data without early end-slip was also used in the evaluation. This was done to show that Eq. 9 also applies to cases that do not experience early end-slip prior to reaching ultimate load. See Ref. (4) for detail.

A total of 168 laboratory performance tests of eight different product types from four different manufacturers (see, Figs. 4 through 7) were used to

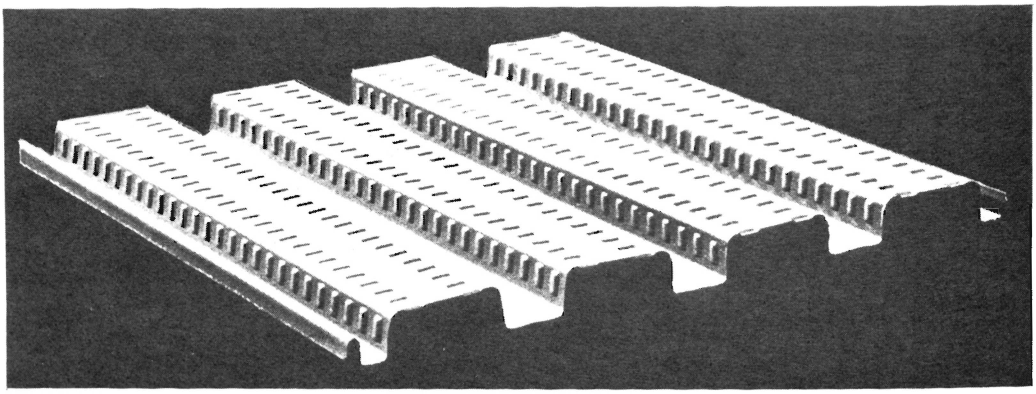


FIG. 4. DECK 200-LORLEA STEELS LIMITED, BRAMALEA, ONTARIO, CANADA.

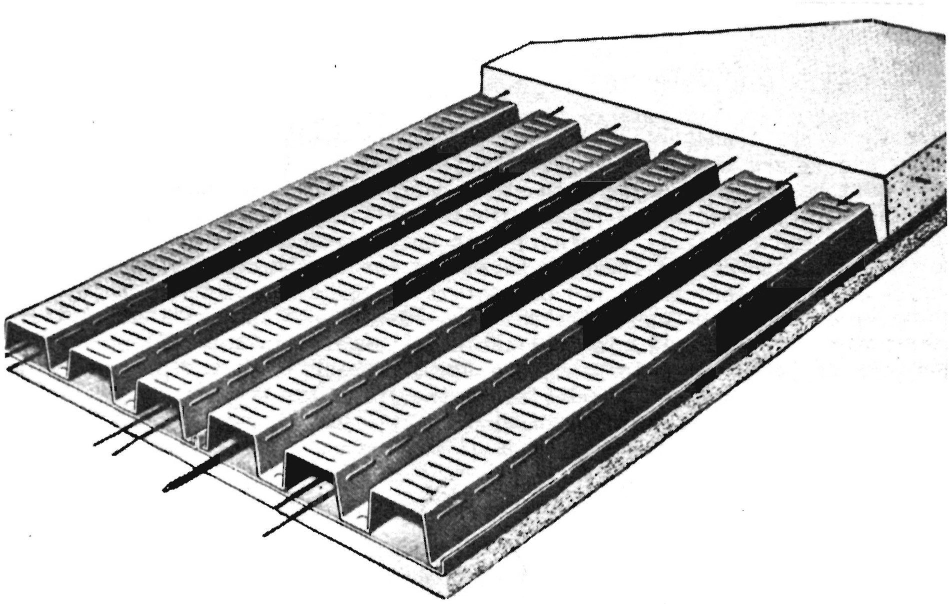
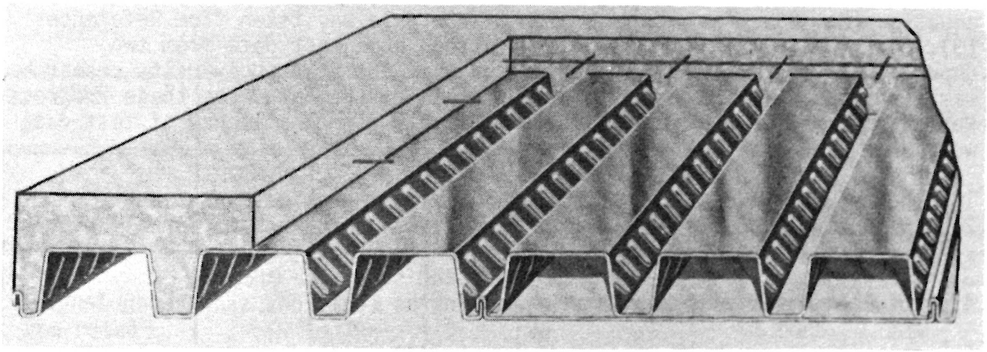


FIG. 5. DECK 300-H.H. ROBERTSON, PITTSBURGH, UNITED STATES AND ROBERTSON BUILDING SYSTEMS LIMITED, HAMILTON, ONTARIO, CANADA.



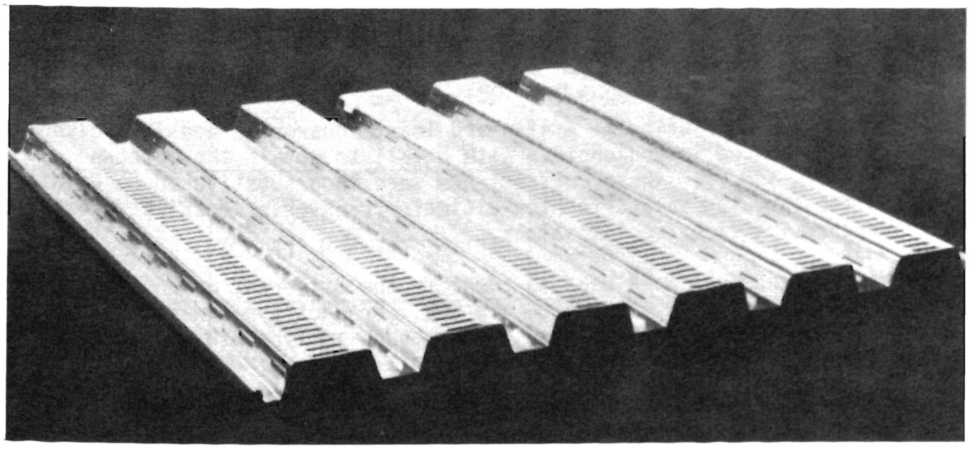


FIG. 7. DECK 500-CANADIAN METAL ROLLING MILLS LIMITED, MISSISSAUGA, ONTARIO, CANADA.

substantiate the validity of the ultimate interlocking capacity (shear-bond) equation (Eq. 9). The major portion of the data was taken from References (3), (9), (11), (12) and (14). In addition, some test data from two unpublished Progress Reports produced by the Iowa State University researchers was also used. It was impossible to use all of the data from these Progress Reports because some of the basic requirements for consistency of test data were not satisifed, i.e.,

1. the type of steel deck was not an interlocking-embossment-type,
2. the surface condition of the steel deck was not the same for all steel deck thicknesses,
3. the widths of the specimens were not the same,
4. not enough variation in shear span lengths (only one shear span length, and
5. the type of concrete was not the same, i.e. either normal or light weight concrete for the given steel deck thickness.

Determination of Coefficients F_n and f_f

Since in most cases a number of different experimental test values were available, a statistical approach (linear regression analysis) was used in the determination of the unknown coefficients for each steel deck thickness of each product type.

For the purpose of carrying out statistical computations, Eq. 9 was rearranged as follows:

$$\frac{V_u L' + M_d}{bd} = F_n + f_f L' \quad . \qquad (11)$$

A computer program consisting of a standard least squares method for polynomial curve-fitting was used in conjunction with Eq. 11 to obtain the unknown coefficients, F_n and f_f. These coefficients were then substituted back into Eq. 11 and the computed values for the ultimate transverse shear were compared with the respective experimental values.

For convenience, numbers were used to identify the different composite deck systems, such as, Deck 200, 300, 400, and 500. Product types were identified by changing the middle digit of these numbers such as Type 310 and added to the deck identification number.

Discussion of Results

Only the final regression results (F_n and f_f) are presented in Table 1. For other detailed information leading to these results, see Ref. (4). The mean and standard deviation values given in Table 1 were computed on the basis of each deck type, i.e., N_m number of test points were used in each computation of mean and standard deviation. As can be observed from Table 1, the mean (experimental/computed), for all practical purposes is equal to 1 for the cases investigated, with the standard deviation varying from a minimum of 0.0074 to a maximum of 0.1123.

Figures 8 through 11 illustrate the comparison of experimental and computed interlocking (shear-bond) capacities for four of the composite slab systems

TABLE 1. FINAL REGRESSION RESULTS

DECK TYPE	T (in.)	N_t	N_m	F_n	f_f	M	σ
200 (Normal wt. concrete)	0.0510	4	8	1.0451	0.0736	1.0000	0.0074
	0.0330	4		0.6227	0.0485		
200 (Light wt. concrete)	0.0510	4	8	0.8860	0.0741	1.0000	0.0229
	0.0330	4		0.5305	0.0446		
200 (Type 210) (Light wt. concrete)	0.0510	4	9	0.8590	0.0481	1.0000	0.0503
	0.0310	5		0.7965	0.0165		
300 (Normal wt. concrete)	0.0583	8	16	1.5235	0.0226	1.0000	0.0946
	0.0274	8		0.6386	0.0096		
300 (Type 310) (Normal wt. concrete)	0.0595	8	29	1.2048	0.0191	0.9978	0.0611
	0.0453	9		0.9156	0.0191		
	0.0347	12		0.8144	0.0156		
400 (12 in.wide) (Normal wt. concrete)	0.0535	19	50	0.8795	0.0241	1.0136	0.0842
	0.0330	8		0.8401	0.0076		
	0.0295	23		0.9036	0.0061		
400 (24 in.wide) (Normal wt. concrete)	0.0684	10	35	1.0638	0.0354	0.9954	0.1123
	0.0539	13		1.3267	0.0197		
	0.0311	12		0.9368	0.0089		
500 (Normal wt. concrete)	0.0360	6	13	1.0798	0.0146	0.9993	0.0653
	0.0300	7		1.0342	0.0073		

N_m = Number of tests used in computing the mean and standard deviation of each deck type

N_t = Number of tests of each steel deck thickness

M = Mean value of (Experimental/Computed)

σ = Standard deviation of (Experimental/Computed)

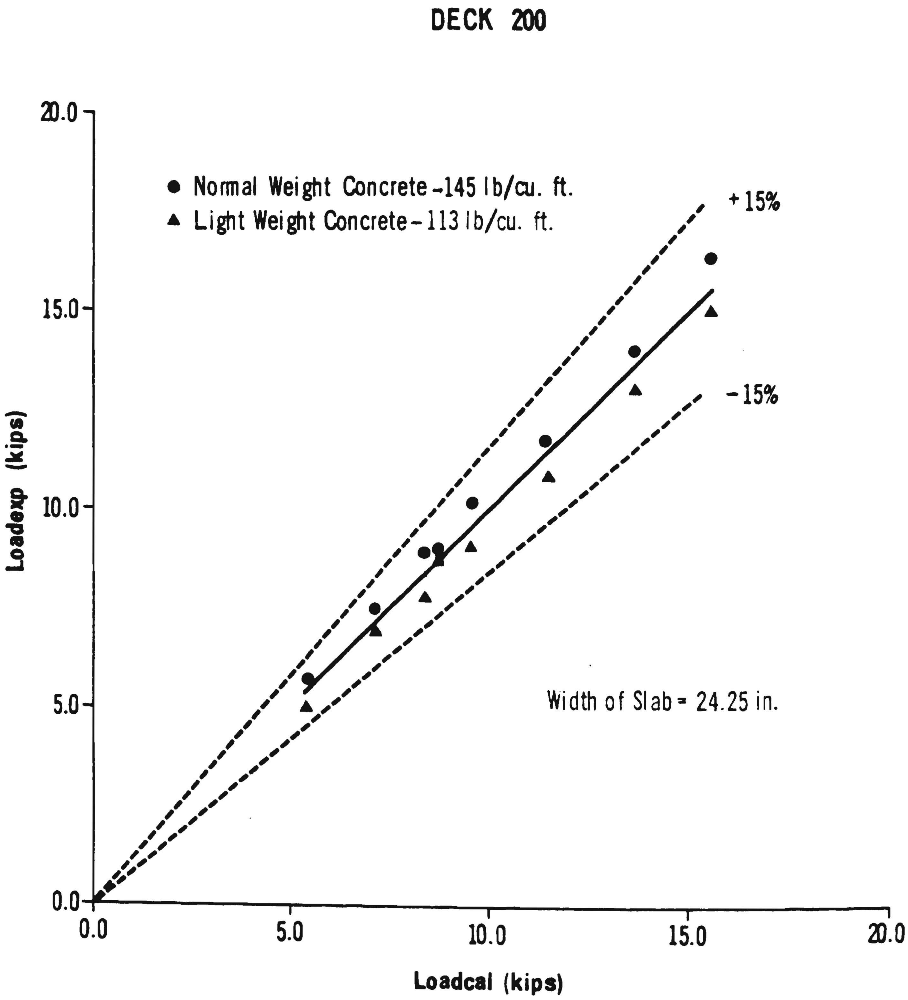


FIG. 8. COMPARISON OF EXPERIMENTAL AND COMPUTED INTERLOCKING (SHEAR-BOND) CAPACITIES OF NORMAL AND LIGHTWEIGHT CONCRETE FOR COMPOSITE SLABS CONSTRUCTED WITH DECK 200.

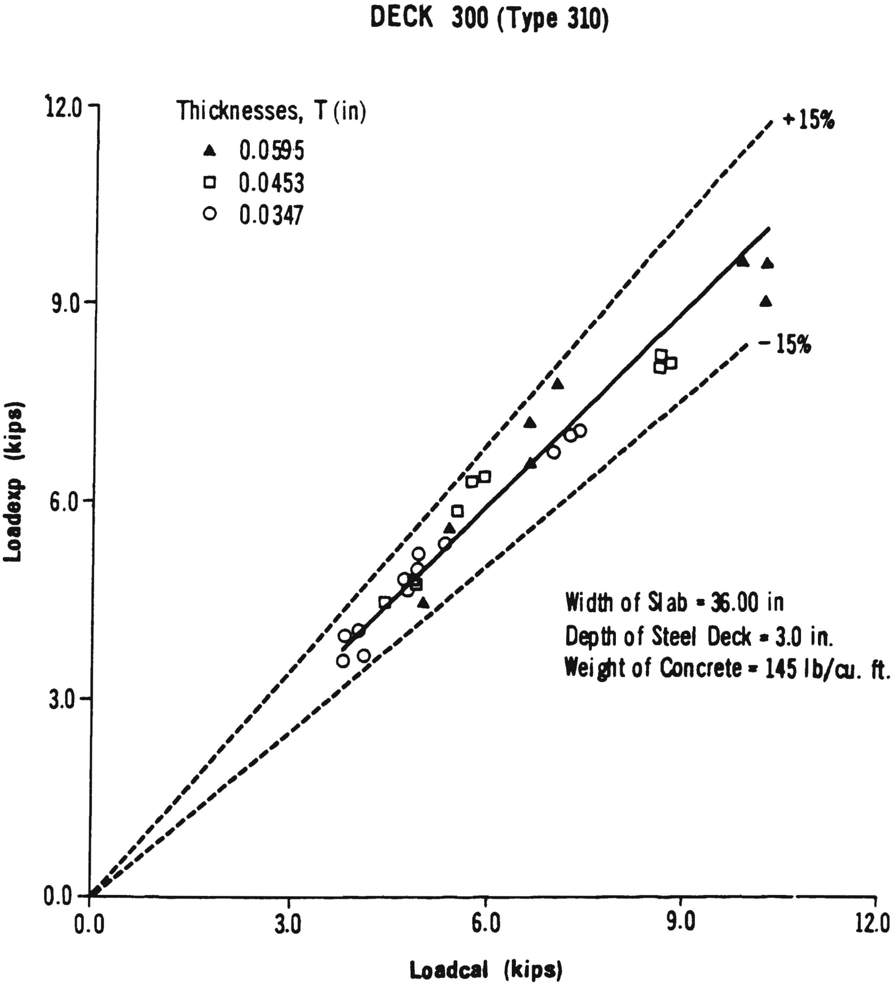


FIG. 9. COMPARISON OF EXPERIMENTAL AND COMPUTED INTERLOCKING (SHEAR-BOND) CAPACITIES FOR COMPOSITE SLABS CONSTRUCTED WITH DECK 300 (TYPE 310).

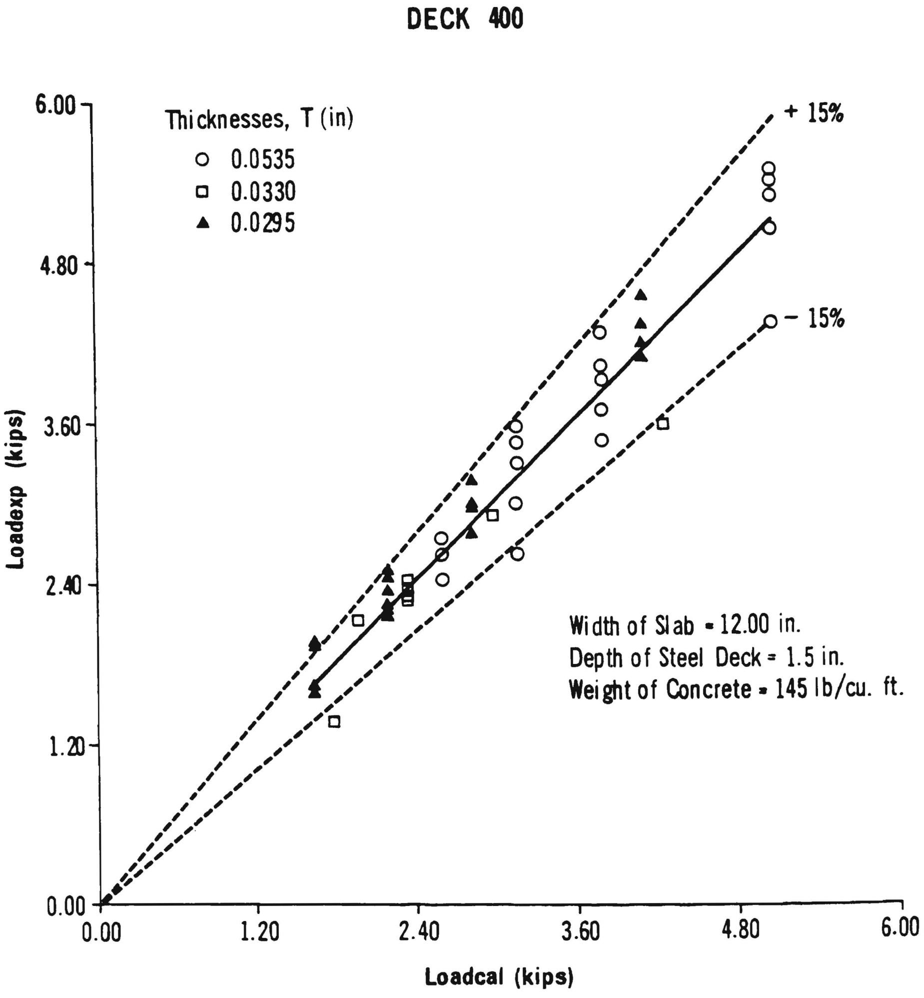


FIG. 10. COMPARISON OF EXPERIMENTAL AND COMPUTED INTERLOCKING (SHEAR-BOND) CAPACITIES FOR COMPOSITE SLABS CONSTRUCTED WITH DECK 400.

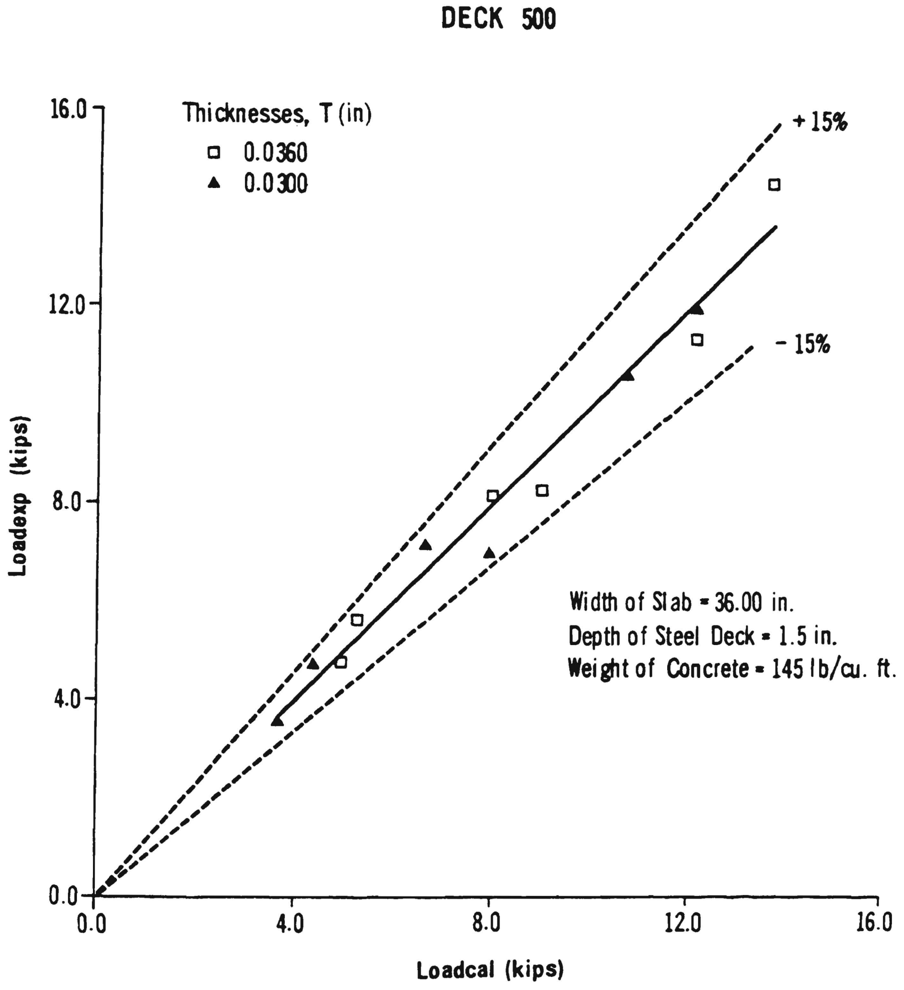


FIG. 11. COMPARISON OF EXPERIMENTAL AND COMPUTED INTERLOCKING (SHEAR-BOND) CAPACITIES FOR COMPOSITE SLABS CONSTRUCTED WITH DECK 500.

investigated. Similar comparison curves were plotted and are recorded in Ref. (4). The dashed lines represent upper and lower scatter bands of ± 15%, which is commonly used with composite slabs. It is assumed that this takes into account the possibility that adverse variations in material strengths and workmanship may exist during the preparation and testing of the laboratory specimens. As can be seen from Figs. 8 through 11, a good correlation exists within this scatter range. This same correlation also exists with all of the other investigated cases (see Ref. 4).

Eq. 9 does not contain the compressive strength of concrete, f'_c, and it was found that for the 168 tests investigated, this term had no apparent influence on the ultimate interlocking (shear-bond) capacity. The average compressive strength of all the tests was 4142 psi (28.6 MPa) with a high of 5670 psi (39.1 MPa) and a low of 2955 psi (20.4 MPa). This is by no means conclusive, but at least for the range of compressive strengths investigated, Eq. 9 gives good results, keeping in mind that the minimum concrete compressive strength usually specified by manufacturers is 3000 psi (20.7 MPa).

Fig. 8 shows a comparison of the experimental and computed ultimate interlocking (shear-bond) capacity of slabs constructed with normal and lightweight concrete, using Deck 200. It can be observed that there is a difference in the ultimate capacity of slabs constructed with lightweight concrete vis-a-vis those of normal weight concrete. However, the difference is small and well contained within the ±15% scatter bands. Based on this observation, one could test only lightweight concrete slabs and also apply the results conservatively to normal weight composite slabs.

CONCLUSIONS

An ultimate interlocking capacity (shear-bond) expression for embossment-type composite slabs has been developed. The resulting expression does not contain the concrete compressive strength term nor the percent of steel permameter which the existing shear-bond expressions do contain. The following pertinent conclusions can be made based on the 168 tests investigated to substantiate the validity of the developed expression:

1) The ultimate interlocking capacity (shear-bond) expression was found to be linear for all data used in this investigation.

2) The interlocking capacity (shear-bond) expression applies to compositie slabs exhibiting early end-slip as well as to cases where no end-slip is experienced prior to ultimate load.

3) The compressive strength of the concrete does not have an apparent effect on the ultimate interlocking (shear-bond) load carrying capacity.

4) The percent of steel parameter does not have an apparent affect on the ultimate interlocking (shear-bond) load carrying capacity.

5) In a comparison between normal and lightweight concrete of one product type, it was found that the interlocking (shear-bond) capacity was slightly greater for composite slabs made of normal weight concrete than for slabs of lightweight concrete. However, the difference between these

results was found to be well within the ± 15% scatter bands. Hence, based on this observation, one could test only lightweight concrete slab elements and also apply the results conservatively to normal weight composite slabs.

ACKNOWLEDGEMENT

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APPENDIX - NOTATION

a	Assumed height of concrete stress block
A_s	Cross-sectional area of steel deck
b	Width of composite slab
C	Compression force of assumed rectangular concrete stress block
d	Distance from extreme compression fiber to centroid of steel deck
f'_c	Concrete compressive strength
f_f	Internal frictional stress between concrete and interlocking devices, to be determined form laboratory performance tests
F	Tension force in steel deck at failure
F_f	Resisting frictional force per width of composite slab
F_m	Resisting mechanical interlocking force per width of composite slab
F_n	To be determined from laboratory performance tests
k	To be determined from laboratory performance tests
L	Length of span
L'	Length of shear span
L_f	Development length of resisting frictional force
L_m	Development length of resisting mechanical interlocking force
m	To be determined from laboratory performance tests
M	Mean value of (Experimental/Computed)
M_d	Moment at a distance L' from support resulting from dead weight of slab
N_m	Number of tests used in the computation of the mean and standard deviation
N_t	Number of tests of each steel deck thickness used in the determination of F_n and f_f
p	Percent of steel - A_s/bd
T	Steel deck thickness
V_d	Transverse shear at a distance L' from support resulting from dead weight of composite slab

V_u	Ultimate transverse shear resulting from interlocking (shear-bond) failure
σ	Standard deviation of (Experimental/Computed)

APPENDIX - REFERENCES

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