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Shear-Stud Restrained Composite Slab Strength Prediction Model

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Abstract

The use of shear-stud in composite slab (CS) construction can significantly enhances its longitudinal shear capacity. However, the strength capacity determination of such complex construction is still marred with the capital-intensive challenge resulting from the complex laboratory procedures for establishing its longitudinal shear capacity. To address this challenge, this article develops a simplified numerical function for determining longitudinal shear capacity for CS with shear stud. This study considers slope-intercept method for the longitudinal shear estimate and the adaptation of rational approach in developing the performance function. Furthermore, limit state function was from the use of shear capacity violation that considers experimental failure load (FL) value and design load estimated form the shear contributions. The resulting outputs from the rational analysis facilitated the formulation of numerical function for the determination of FL in a more simplified form. The developed FL algorithm exhibits strong performance in determining the alternate CS failure load though there is stillroom for further improvement especially if span length would be taken into consideration. Further development that incorporates span length might give much favorable result in determining CS strength especially when considering slope-intercept method

Keywords: Composite slab, shear stud, longitudinal shear, slope-intercept, strength, failure load.

1.0 INTRODUCTION

Composite slab (CS) mainly consist of reinforced concrete cast on top of profiled steel deck and its use in the construction industry has many advantages that included the construction simplicity compared to other flooring systems. This composite method added popularity for eliminating time-consuming formwork construction [1, 2]. Additionally, the construction system offers the function of tensile resistance during its service life from the decking sheet [3-6]. Most importantly, the composite action will come in to play with effective development of longitudinal shear at the steel-concrete interface. Many studies [1, 2, 7-10] shows that the behavior of composite slab is affected by the bond failure between the decking sheet and the concrete even though number of factors are known to affect the longitudinal shear. Abdullah, et al. [3] work indicated that shear bond strength influencing factors are inclined to the shear-span-to-effective-depth ratio, and this is a key factor in characterising CS shear capacity. Furthermore, the longitudinal shear bond parameters are normally determined from the capital-intensive laboratory procedure for either of the methods; slope-intercept (m-k) or partial shear connection methods [5, 6]. The significant high laboratory cost has been a serious problem in determining CS strength coupled with the significant strength variation estimation from the two aforementioned methods.

Several frameworks were developed to improve on the longitudinal shear estimation variations between those methods [3, 11, 12]. Bai, et al. [12], conducted a test on the longitudinal shear behavior of composite slab comprising of Engineered Cementitious Composite (ECC) and profiled sheeting metal on the effect of main parameters of shear behavior that considers shear anchorage. The author's experiment yields the presentation of advance numerical model for longitudinal shear that proved the use of shear studs could significantly improve the longitudinal shear but with the use of ECC. Mohammed, et al. [8], developed a procedural algorithm leading to the development of profiled composite slab strength function for both longitudinal shear estimation methods by considering section slenderness and deck characteristics [8, 13] but for metal deck without the use of shear-studs. The study findings reveal promising results where the developed algorithm mimics well in determining strength capacity of CS, and further reduction in the estimation difference to 12% from 26%. Primarily, a typical CS construction employs the use of shear stud for bonding enhancement between the metal deck and concrete

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medium especially on high-rise buildings. This manuscript develops a rational based method that will aid in predicting the shear strength behavior for CS with embedded shear-stud.

2.0 MATERIALS AND METHODS

2.1 Shear bond

The longitudinal shear strength parameters, *m* and *k* are outputs results from experimental flexural testing on composite slab specimens where the linear relationship plots of vertical shear, V_t / bd_p against shear bond, A_p / bl_s for two groups of test values of X and Y specimens as depicted in Figure 1, and the indicated parameters were, A_p represent deck cross-sectional area with yield strength value, f_{yp} and d_p is the clear centroid distance. These vectors quantities are clearly defined in literature [14]. Considering ductile failure condition V_t is computed using the failure load w value as shown in Eq. (1).

$$V_t = w/2 \quad (1)$$

The inverted slenderness, l_s / d_p ratio plays a critical role in determining CS strength, l_s and represent the shear span length. Hence, the vertical shear stress, V_t / bd_p for CS neglecting the insignificant influence of f_{yp} as found in literature is [14].

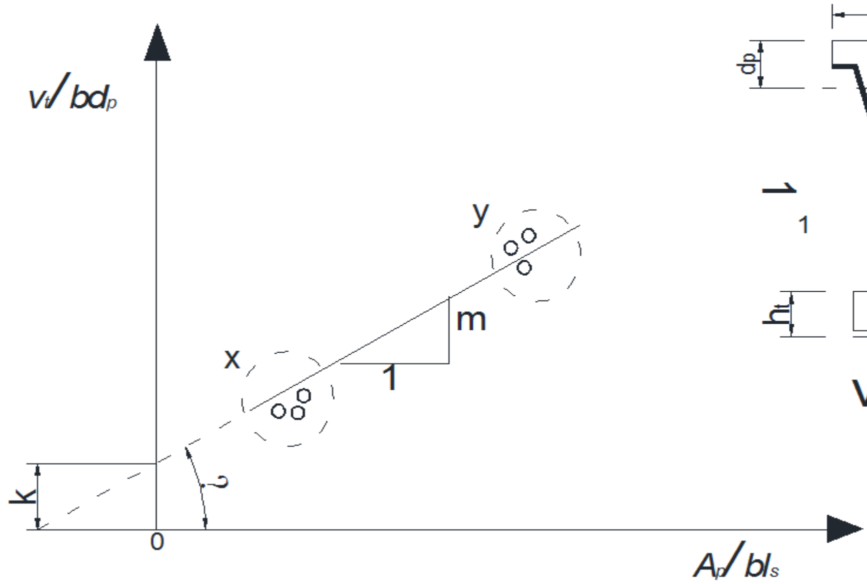


Figure 1: m-k values determination

$$\frac{V_t}{bd_p} = m\left(\frac{A_p}{bl_s}\right) + k = t_{u,rd} \quad (2)$$

Therefore, the design shear resistance function $V_{i,Rd}$ is according to the expression shown in Eq. (3) and y has a value of 1.25 [5].

$$V_{i,Rd} = \frac{bd_p}{y}\left[m\left(\frac{A_p}{bl_s}\right) + k\right] \quad (3)$$

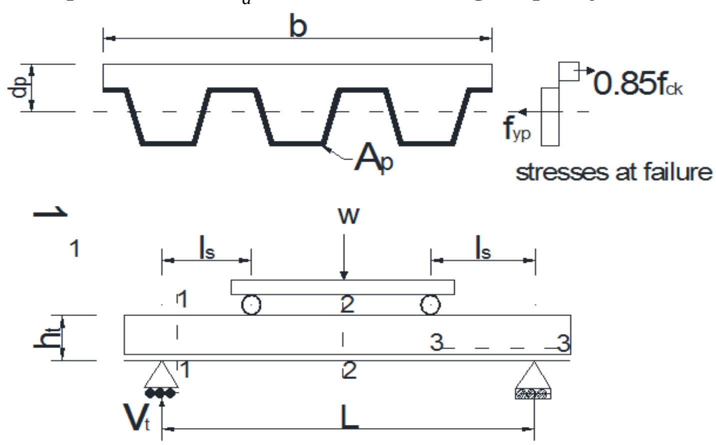
The recommended shear-bond resistance of CS with end anchorage of shear –studs is considered as found in literature [2]

$$V_u = v_s + 0.5v_a \text{ and}$$
$$v_s = \frac{2V_{i,Rd}}{l} = f \quad (4)$$

Where V_u is the total vertical shear capacity of the slab, v_s represents the CS shear-bond capacity characterised by the interaction between the metal sheet and concrete only, and v_a is the shear capacity due to the end anchorage and was evaluated from the given equation:

$$v_a = NP_a(d - x_c / 2) / l_s \quad (5)$$

where N is the number of shear connectors attached to each sheeting, x_c indicates the depth of concrete in compression and P_a is the end anchorage capacity.



2.2 Experimental Data

This study uses an experimental laboratory testing results as input variables representing failure load (*FL*) which is vital in the development of CS function. Hence, the experimental results presented in Ong and Mansurt [15] was used in this study. The author conducted the using three different lengths that included 2.4 m, 3.0 m and 3.6m and of two different thicknesses; 100mm and 120mm. The Bondek-galvanised steel plate thickness is made up of 0.75 mm thick, yield strength and modulus of elasticity values were 626 MPa and 2.02 x 10 ~ MPa, respectively. The experiment employs the use of 16 mm diameter studs as end anchorage and deck width of 610 mm. Table 1 presents the authors experimental test results and detailed explanation can be found in Ong and Mansurt [15].

Table 1: Summary of test results [15]

Slab Designation	Total Depth (mm)	Total length (m)	Span (m)	Failure load (kN)
AA1	100	2.4	2.3	26
AA2	100	2.4	2.3	26
AC1	120	3.0	2.85	35.8
AB2	120	3.0	2.86	33.8
AC1	120	3.6	3.45	27.9

Although the l_s value was not clearly defined in that experiment, for the purpose of this study analysis, the recommended value of $l / 4$ is adopted to compute the *m*-*k* parameters. Therefore with $A_p = 1259 \text{ mm}^2$, the *m* and *k* parameters from its regressed line were 40 and 0.024 N/mm^2.

2.2.1 Rational function

The formulation of Failure probability, p_f function was based on the expression in Eq. (6)

$$p_f = prob\left(R - Q < 0\right) = p\left(k < 0\right) \quad (6)$$

where *k* is the limit state function or performance function that defines the desired boundary which is a function of the material resistance, *R* and load, *Q* variables. The detailed explanation of this principle is well captured in literature for further understanding [16]. The failure load, *FL* presented in Table 3 serves as the ultimate strength resistance of the material, and the design load computation is from the shear-bond resistance as earlier shown. Thereafter, the evaluation of the performance1 function for the load capacity violation is with the use of first order reliability method (FORM). Hence, to account for the random variability, the mean resistance, Q_m estimation is from [16, 17]:

$$Q_m = Q_n(M_n.F_n.P_n) \quad (7)$$

where Q_n is the nominal resistance (the ratio of *FL* over the span length) with a bias factor of 1.0. Hence, the mean resistance coefficient of variation, V_Q is from the expression in Eq. (8).

$$V_Q = \sqrt{(v_m^2.v_f^2.v_p^2)} \quad (8)$$

The parameters, v_m, v_f and v_p are the equivalent corresponding coefficient of variation, *COV* for the factors M_n, F_n, and P_n respectively. The values for the mean *COV* for these factors are 1.10, 0.1; 1.0, 0.05 and 1.11, 0.09, and are normally distributed [4]. Consequently, this study V_Q value is therefore 0.14 from the use of the expression in Eq. (8). Similarly, based on the Ellingwood and Galambos [18] characterizations, the *COV* value and distribution type for the parameters *b* and l_s are 0.17 and log-normal distribution, and each have a unit bias factor. Furthermore, the limit state violation for the profiled deck composite slab is as shown by the expression in Eq. (9).

$$Q_m - V_u = R - Q \quad (9)$$

Transforming the expression in Eq. (9) into basic variables form, yields

$$\text{R} = \left[\left(1 - \frac{\%}{100}\right)\text{X}(1)\right]/\text{L}$$

$$Q = M(A_P.X(2).X(3) + 2.K.d_p.X92)/[(1250 + (0.64.f_{ck}E_c.\text{X}(4)^2 - 0.25X_c)]X93) \quad (10)$$

While the statistical parameters for the basic variables are shown in other quantities in the equation above are considered as deterministic variables for concrete characteristic strength, f_{ck} of 30 MPa and average elasticity modulus, E_c of 27.22 kN/mm^2.

Table 2: Basic variables statistical properties

Variable X	Distribution type	Nominal value	COV
Fl = X(1)	Log-normal	-	0.17
b = X(2)	Normal	610 mm	0.05
ls = X(3)	Normal	-	0.05
Stud dia. = X(4)	Log-normal	16 mm	0.17

2 RESULTS AND DISCUSSION

Figure 2 presents the safety performance index of CS in relation with the $l_r = fl/\phi$ function. The behaviour depicts a linear relationship between l_r and β value with high correlation. There is an increment in the performance index with increasing l_r value. This behaviour is in agreement with literature findings on similar work done [8].

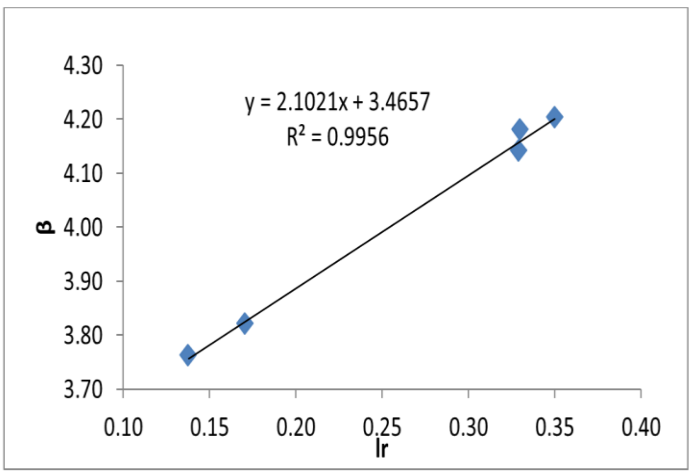


Figure 2: Performance index behaviour in relation with l_r value

Horizontal shear bond value within the acceptable limit exhibit ductile failure behaviour [11], more especially if the slip value is not greater than 0.5 mm [19]. Previous study have indicated that metal deck characteristics difference that included A_s, f_{yd} and thickness values are found to influence CS shear capacity [13]. Moreover, it is a known fact that CS shear capacity is inclined to l_s / d_p ratio, because it defines the associated failure modes [14].

Hence, this study examines the CS safety performance using the sectional inverted slenderness d_p / l_s function. This is necessary because the correct characterization of the CS performance index depends on that function [3]. In defense of this argument, the authors highlighted the importance of the characterization especially for design and numerical modeling. Further consideration is taken to account for the deck cross sections and its yield strengths. Hence, the inverted slenderness is further multiplied with the decking sheet characteristics $A_p f_{yp}$ and the product is represented by ξ.

Figure 3 presented the inverted slenderness account on the behaviour of CS because of its attached importance [3]. Although they are distinctively classified into either slender (low d_p / l_s value) or compact (higher d_p / l_s value) sections, but clear definitive boundary between these two points still posed a challenge. Nevertheless, in Figure 3, the relationship between the p_f and ξ can be modeled using a 2nd–degree polynomial which shows a good correlation with data points. This function will aid in determining rational behaviour of selected materials in the construction of CS.

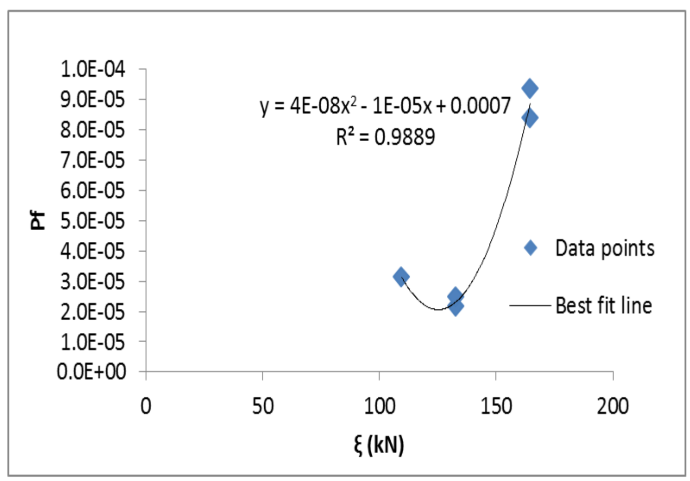


Figure 3: Section slenderness influence on CS performance index

2.2 *Rational function*

To develop a new function that will aid in determining CS failure load without the use of experimental testing is highly essential.

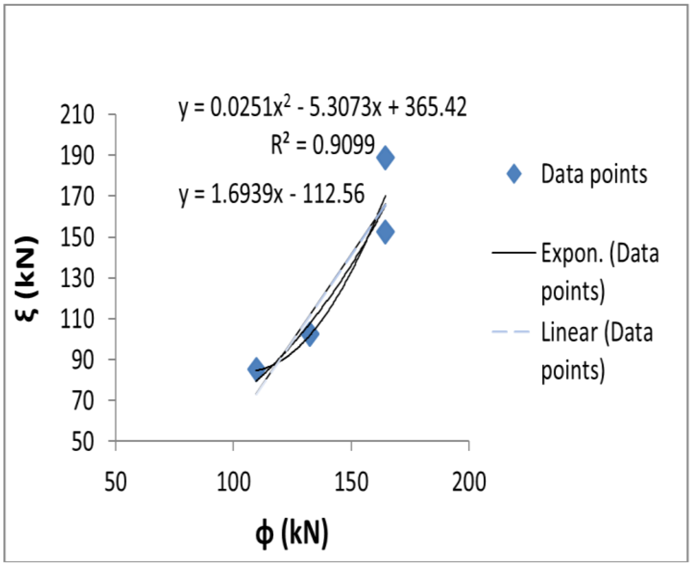


Figure 4: Deck characteristics in relation with design load

Figure 4 shows the established high correlation between deck function variables and the design load estimated and this applies to both linear and polynomial of 2nd degree best fits lines. Those best fits lines will be used for the determination of possible failure load estimation using some basic mathematical relations. Although with the available data, it is difficult to establish the previously section classification, but on the alternative, adopting a literature established delineation of slender and compact section [13] with corresponding safety margin of 2.4 for this study. Hence, from the best fit line equation in Figure 2, a corresponding l_r value of -0.5 is obtained. Therefore, the use of expression in Eq. (11) provides the projected failure load Fl_p estimate:

$$Fl_p = x * l_r \tag{11}$$

The parameter x represents design load and was given by the dependent variable expression in Figure 4. Adopting linear best fit for the projected failure load estimation and comparison was done using experimental testing data found in literature by Chen [2]. Hence, Table 3 presents the experimental test values and the corresponding projected failure load.

Table **3**

Table 3: Projected FL estimation

LABEL	A_p (mm²)	f_{yp} (MPa)	d_p (mm)	l_s (mm)	l (m)	EX.FL (kN)	Fl_p (kN)	$EX.Fl / Fl_p$
A-1	1170.8	380	55	650	2.6	52.7	35.61925	0.675887
A-3	1170.8	380	55	800	3.2	48.2	44.34898	0.920103
A-5	1170.8	380	55	650	2.6	39.8	35.61925	0.894956
A-2	1561.8	380	55	650	2.6	61.0	20.07057	0.329026
A-4	1561.8	380	55	1050	4.2	46.9	43.73047	0.932419

The projected estimation shown in Table 3 relatively performs well with overall mean value of about 80%. The associated difference could be attributed to the none-inclusion of span lengths in the formulation of the load estimation model. Certainly, new projected load model taking into consideration the testing span length is desirable despite the good performance by the developed model in this study [8]. Further study that inculcates this study limitation might yield much closure estimate to the experimental test load.

3 CONCLUSION

The simplified numerical strength determination method in this paper facilitates the failure load capacity of profiled deck composite slab (CS) with shear studs. The method that resulted from the consideration of rational-based approach exhibits strong performance in determining CS-longitudinal based strength capacity. The study findings indicate that the numerical function presented can be useful in characterizing the behavior of CS with embedded shear stud without the rigors of complex laboratory work especially when considering slope-intercept method and this will facilitate the strength verification of CS construction.

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