Bent-Up Triangular Tab Shear Transfer (BTTST) Enhancement in Cold-Formed Steel-Concrete Composite Beams: Formulation of Design Equation

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ABSTRACT

An experimental program was conducted to study the strength and behaviour of a bent-up tabs shear transfer enhancement. Sixty eight push-out test specimens of cold-formed steel lipped channel sections (CFS) embedded in concrete plank where by usage of a new proposed shear transfer enhancement called bent-up triangular tab shear transfer (BTTST) was used in this program. This paper summarizes the results of develop an expression in order to predict the innovative shear transfer enhancement mechanism BTTST in a new type of precast composite beam comprising Cold-formed steel (CFS) embedded in precast concrete plank. The results show that the proposed equation is in good agreement with the observed test values. The average absolute difference between the test values and predicted values was found to be 8.07%. The average arithmetic mean of the test/predicted ratio (μ) of this equation was 0.9954. The standard deviation (σ) and the coefficient of variation (CV) for the proposed equation were 0.09682 and 9.7%, respectively

Keywords: *Composite beams, Cold-formed steel, Shear transfer mechanisms, Shear connector*

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1.0 INTRODUCTION

Cold-formed steel (CFS) sections, usually between 1.2 and 3.2 mm thickness [1], have been recognised as an important contributor to environmentally responsible, sustainable structures in the developed countries, and CFS framing is considered a sustainable 'green' construction material for low rise residential and commercial buildings. Their use however limited to structural roof trusses and a host of non-structural applications [2].

One limiting feature of CFS is the thinness of its section that makes it susceptible to torsional, distortional, lateral-torsional, lateral-distortional and local buckling. Resorting to a composite construction of structural CFS sections and a reinforced concrete deck slab, minimises the distance from the neutral-axis to the top of the deck and reduces the compressive bending stress in the CFS sections and arranging two CFS channel sections back-to-back restores symmetricity and suppresses lateral-torsional and to a lesser extent, lateral-distortional buckling. The two-fold advantage promised by the system promotes the use of CFS sections in a wider range of structural applications.

An efficient and innovative floor system of built-up cold-formed steel (CFS) sections acting compositely with a concrete deck slab has been developed to provide an alternative composite system for floors and roofs in buildings. The system, called Precast Cold-Formed Steel-Concrete Composite System, is designed to rely on composite action between the CFS sections and a reinforced concrete deck where shear forces between them are effectively transmitted via another innovative shear transfer enhancement mechanism called a bent-up triangular tab shear transfer (BTTST) as shown in Figure 1.

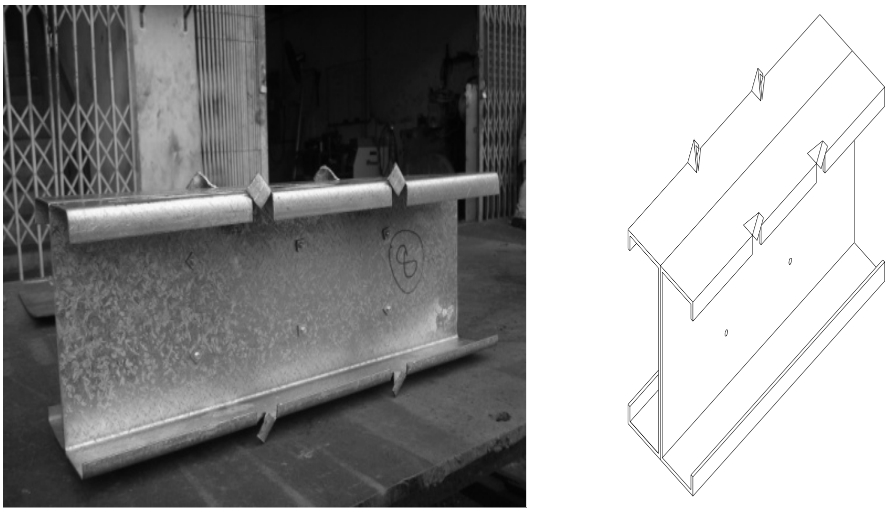

Figure 1: Bent-up triangular tab shear transfer (BTTST)

2.0 RESEARCH PROGRAM

Sixty eight push-out test specimens were tested to study the behaviour and capacity of BTTST [3][4][5][6]. The test parameter included the compressive strength of concrete, modulus of elasticity, CFS strength, dimension of BTTST (L_f, L_s, angles – refer Figure 2) and CFS thickness. Besides that, the objective of this study was to derive an expression for predicting the capacity of BTTST based on the results of the parametric study.

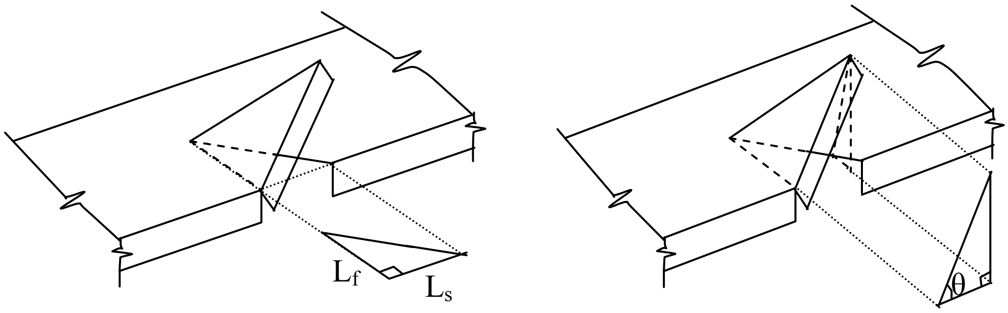

Figure 2: Dimension and angle of BTTST

3.0 DEVELOPMENT OF A NEW EQUATION: BTTST ENHANCEMENT IN CFS-CONCRETE COMPOSITE BEAMS

In order to obtain a mathematical relationship between the ultimate shear strength, P_u of a BTTST and the parameters mention in section 2, the multiple regression analysis based on the 28 results of BTTST push-out test specimens from [3][4][5][6] experimental were made. A general form of predicted ultimate load per BTTST equation, P_{tab} was developed as shown in expression 1 to expression 4. These expressions are assumed as empherical equations as development of expressions are based on observation. As a result the unit on the right side of expression does not always correspond to the unit of the left side.

3.1 General Form

First consideration in developing the equation is the contribution factor from concrete properties. According to Ollgaard et al. [7], Oguejiofor and Hosain [8] and Mujagic et al. [9], for concrete related failures, the ultimate capacity of a shear connector is proportional to $\sqrt{f_c}$. Figure 3 presents the mean ultimate loads versus $\sqrt{f_c}$ for specimens in push-out test Phase 1 in [3][4][5][6]. The increase in load with the square root of compressive strength of concrete as shown in Figure 3, is seen to be approximately linear.

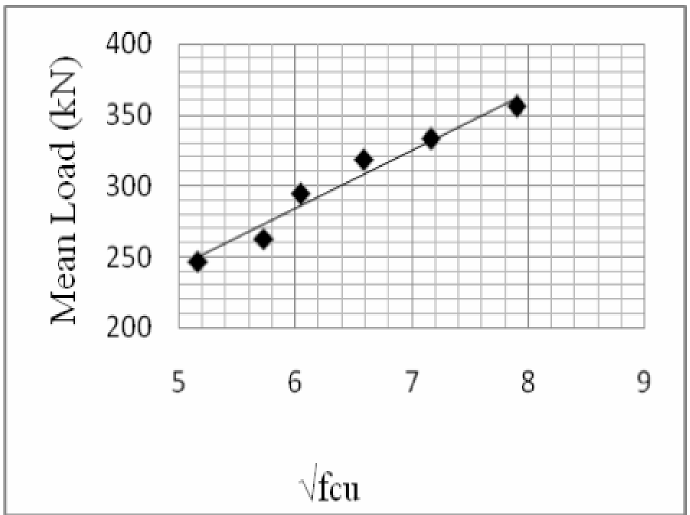

Figure 3: Load versus $\sqrt{f_c}$ curves

Meanwhile, the main properties of the concrete are the modulus of elasticity, *E*. By considering the properties of concrete, the general expression is,

$$P_{tab} = \beta_1 \sqrt{f_{cu} E} \quad \text{---------------------------- (1)}$$

where P_{tab} is predicted ultimate load per BTTST (N), f_{cu} is compressive strength of concrete (N/mm^2), E is modulus of elasticity of concrete (N/mm^2) and $\beta_1$is constant to be refer to Table 1.

The bearing area, A_b of the connector is also as one of the important factor contributing the shear capacity of the connector. Bearing area functions as the resistance to prevent concrete slip and the schematic diagram of A_b is shown in Figure 4. A_b is affected by its size and the angle of BTTST. The increment of the angle and size of BTTST will increase the A_b and achieved a higher P_{tab}. Thus, A_b is applied by multiplying with expression 1 to produce the following expression,

$$P_{tab} = \beta_1 A_b \sqrt{f_{cu} E} \quad \text{-------------------------- (2)}$$

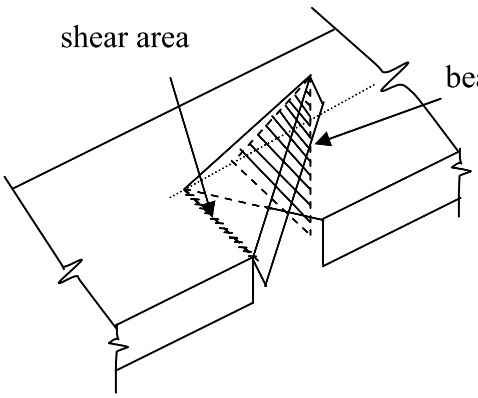

Figure 4: Diagram of bearing and shear area of BTTST.

The following factors that affect the P_{tab} is the shear area, A_s of BTTST (refer Fifure 4). Shear area acts as the resistance for the triangular tabs from bent. The bent capacity of the BTTST increases with the increase of shear area. Shear area, A_s of BTTST as shown in Figure 4 is multiplying between the collar length, L_f (refer to Figure 2) and thickness of CFS, t. Meanwhile, result from [3][4][5][6] showed that the increment of CFS thickness increase the shear capacity of BTTST. Therefore, it is appropriate to include this variable into the expression of 2 to produce the following expression,

$$P_{tab} = \beta_1 A_b \sqrt{f_{cu} E} + \beta_2 A_s \quad \text{----------------- (3)}$$

where β_2 is constant to be refer to Table 1.

Another factor to be considered is the strength of CFS, f_y. It has to be applied by multiplying with its shear area, A_s. Thus, the following form of the expression is obtained,

$$P_{tab} = \beta_1 A_b \sqrt{f_{cu} E} + \beta_2 A_s f_y \quad \text{-------------- (4)}$$

Therefore, there are 3 model of regression which have been tried to obtain the most accurate equation for predicting the P_{tab} of BTTST. Referring to Table 1, Model 1 is depending on the factor from concrete properties. Model 2 is depending on the factor from properties of CFS, and Model 3 is the combination of Model 1 and Model 2.

Table 1: Results of Regression Analysis Using SPSS

Model	General Equation	β_1	β_2	Correlation
1	$P_{tab} = \beta_1 A_b \sqrt{f_{cu} E}$	0.052	-	0.981
2	$P_{tab} = \beta_2 A_s f_y$	-	0.605	0.994
3	$P_{tab} = \beta_1 A_b \sqrt{f_{cu} E} + \beta_2 A_s f_y$	0.012	0.466	0.995

3.2 Regression Analysis

This study used the Multiple Linear Regression technique in order to develop model to calculate the ultimate shear strength of BTTST. Regression analysis is a statistical tool used to investigation the relationship between variables. Multiple Linear Regression is a technique that allows additional factors, be it quantitative, to enter the analysis separately so that the effect of each factor can be estimated. Outliers analysis using Statistical Package for Social Science (SPSS) was first executed, before regression analysis was performed. In this case, 37 data of push-out test with BTTST of Phase 1 and 2 in experimental testing [3][4][5][6] were used in the evaluation. The results from the outliers analysis indicated that nine out of 37 data need to be omitted. Thus, the remaining 28 data was used in regression analysis. The test results of the 22 BTTST push-out test specimens which were tested in Phase 1 and 6 from Phase 2 were used for the regression analysis and shown in Table 2.

Table 2: Push-out Test Data used in Regression Analysis

Spec. No	**P_{tab} (kN)**	**A_b**	**A_s**	**f_{cu}**	**E**	**f_y**
		(mm^2)		**(N/mm^2)**		
1	14.3	389.7	57	26.67	24720	529
2	15.3	389.7	57	26.67	24720	529
3	15.5	389.7	57	26.67	24720	529
4	16.9	389.7	72	26.67	24720	533
5	15.3	389.7	57	32.83	25630	529
6	15.1	389.7	57	32.83	25630	529
7	17.0	389.7	57	32.83	25630	529
8	19.8	389.7	57	36.51	27160	529
9	18.4	389.7	57	36.51	27160	529
10	19.4	389.7	57	36.51	27160	529
11	20.4	389.7	72	36.51	27160	533
12	19.8	389.7	72	36.51	27160	533
13	20.1	389.7	72	36.51	27160	533
14	21.0	389.7	57	43.36	27520	529
15	21.1	389.7	57	43.36	27520	529
16	22.0	389.7	57	43.36	27520	529
17	23.9	389.7	57	51.31	27330	529
18	24.0	389.7	57	51.31	27330	529

19	22.8	389.7	57	51.31	27330	529
20	28.5	389.7	57	62.35	26980	529
21	22.8	389.7	57	62.35	26980	529
22	28.3	389.7	57	62.35	26980	529
23	15.8	220.9	60	25.54	24320	533
24	16.2	220.9	60	25.54	24320	533
25	19.7	220.9	60	36.62	26950	533
26	12.1	156.3	48	36.62	26950	529
27	16.7	156.3	60	36.62	26950	533
28	20.9	318.2	57	36.62	26950	529

In order to compare the results of push-out test specimens from different series of concrete strength, the P_{tab} values were normalised [8][10][11] to reflect the differences in concrete strength using the following expression:

$$\textit{Normalised value} = (\textit{Measured value}) \times \left(\frac{f_{cu,mean}}{f_{cu}}\right)^{0.5} \qquad \text{---------------- (5)}$$

where $f_{cu,mean}$ is the average concrete strength of all specimens and f_{cu} is the concrete strength of the specimen in question.

Regression analysis was carried out using SPSS. Regression analysis resulted in the relationship of linear correlation between three independent variables (Model 1, 2 and 3). The largest correlation was obtained with Model 3, which are all considered as independent variables. Based on this result, Model 3 was used in this study to develop an equation for predicting the P_{tab} of BTTST. Based on the result and by substituting β values in the equation, the ultimate shear capacity prediction model for BTTST takes the following equation:

$$P_{tab} = 0.012 A_b \sqrt{f_{cu} E} + 0.466 A_s f_y \qquad \text{---------------------- (6)}$$

Based on the formula for bearing area, A_b and shear area, A_s of BTTST, Equation 6 becomes

$$P_{tab} = 0.01 L_f L_s \sin\theta \sqrt{f_{cu} E} + 0.5 L_f t f_y \qquad \text{--------------------- (7)}$$

where L_f is collar length of BTTST (refer Figure 2) (mm), L_s is span length of BTTST (refer Figure 2) (mm), θ is angle of BTTST (degree) and t is thickness of CFS (mm).

The results of normalised ultimate shear strength of BTTST from push-out test and those predicted by Equation 7 for 28 specimens included in the above analysis are listed in Table 3. The tests over predicted values for Equation 7 are concentrated within 0.86 to 1.16. It is obvious that Equation 7 is reasonably in agreement with the observed test values. The average difference between push-out test results and those predicted by Equation 7 was found to be 8.07%. The average arithmetic mean of the test/predicted ratio (μ) of this equation was 0.9954. The standard deviation (σ) and the coefficient of variation (CV) for the proposed equation were 0.09682 and 9.7%, respectively. Figure 5 was prepared to provide a clearer observation of the performance of Equation 7. This figure plots the comparison between tested values of BTTST strength and those predicted by Equation 7 for 28 push-out test specimens.

Table 3: Test and Predicted Ultimate Shear Strength of BTTST Results

Spec. No.	**Normalized P_{tab} Test (kN)**	**P_{tab} Equation 7 (kN)**	**Ratio of Test/ Predicted**
1	16.9	18.8	0.90
2	18.1	18.8	0.96
3	18.4	18.8	0.98
4	20.0	22.9	0.87
5	16.3	18.9	0.86
6	16.2	18.9	0.86
7	18.2	18.9	0.96
8	20.0	19.0	1.05
9	18.7	19.0	0.98
10	19.7	19.0	1.03
11	20.7	23.1	0.89
12	20.0	23.1	0.87
13	20.4	23.1	0.88
14	19.6	19.0	1.03
15	19.7	19.0	1.03
16	20.5	19.0	1.08
17	20.4	19.0	1.07
18	20.5	19.0	1.08
19	19.5	19.0	1.02
20	22.1	19.0	1.16
21	17.7	19.0	0.93
22	21.9	19.0	1.15
23	19.2	18.1	1.06
24	19.6	18.1	1.09
25	19.9	18.2	1.09
26	12.3	14.1	0.87
27	16.9	17.6	0.96
28	21.2	18.3	1.16

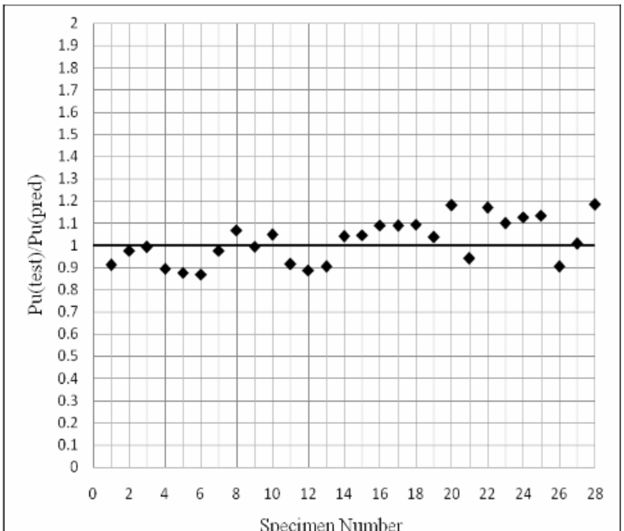

Figure 5: Comparison between tested values of BTTST strength and those predicted by Equation 7

Referring to Table 4, second term of Equation 7 (factor of BTTST material properties) in this study gives the significant contribution to the P_{tab}. It has contributed 79% to 91% of the BTTST strength. The CFS shear strength is linearly proportional to its shear area (L_f *x* t) and the strength of CFS (f_y). Meanwhile, the contribution of first term (concrete) in P_{tab} is around 9% to21% of the BTTST strength. The shear strength of the concrete in this study is proportional to $\sqrt{f_c}$ that made the effect of concrete strength, f_{cu} in P_{tab} is lower. Based on that, the concrete shear strength is in ranging from 12% to 20% of its compressive strength for concrete grade 25 to 60. For example, concrete grade 30 was contributing 5.5 N/mm^2 in P_{tab}. It is around 18% of the concrete compressive strength. The shearing strength of the concrete is approximately 20% of the compressive strength of concrete [12]. The above discussions reveal that, the contribution of each term in P_{tab} can be balanced by increasing the strength of the concrete and reduced the strength of the CFS. On the other hand, the ductility of BTTST can be increased by using lower grade of CFS.

Table 4. Contribution of the 1st and 2nd Terms of Equation 5.8 to the Calculated P_{tab}

No	**1st term of Eq. 7 (kN)**	**2nd term of Eq. 7 (kN)**	**P_{tab} Equation 7 (kN)**	**Contribution to P_{tab} (%)**	
	$0.01 L_f L_s \sin\theta \sqrt{f_{cu} E_c}$	$0.5 L_f t f_y$		**1st term**	**2nd term**
1	3.8	15.1	18.8	20	80
2	3.8	15.1	18.8	20	80
3	3.8	15.1	18.8	20	80
4	3.8	19.2	22.9	16	84
5	3.8	15.1	18.9	20	80
6	3.8	15.1	18.9	20	80
7	3.8	15.1	18.9	20	80
8	3.9	15.1	19.0	21	79
9	3.9	15.1	19.0	21	79
10	3.9	15.1	19.0	21	79
11	3.9	19.2	23.1	17	83
12	3.9	19.2	23.1	17	83
13	3.9	19.2	23.1	17	83
14	4.0	15.1	19.0	21	79
15	4.0	15.1	19.0	21	79
16	4.0	15.1	19.0	21	79
17	4.0	15.1	19.0	21	79
18	4.0	15.1	19.0	21	79
19	4.0	15.1	19.0	21	79
20	3.9	15.1	19.0	21	79
21	3.9	15.1	19.0	21	79
22	3.9	15.1	19.0	21	79
23	2.1	16.0	18.1	12	88
24	2.1	16.0	18.1	12	88
25	2.2	16.0	18.2	12	88
26	1.6	12.6	14.1	11	89

27	1.6	16.0	17.6	9	91
28	3.2	15.1	18.3	18	82

4.0 CONCLUSION

Bent-up triangular tabs shear transfer (BTTST) as shear connectors have been studied under static loads, and their resistance and stiffness have been shown to influence not only the load-bearing behaviour of the composite beam but also its economic performance [3][4][5][6]. BTTST provides an alternative connector system unique to CFS where CFS sections are usually thinner than hot-rolled sections and welding of headed-stud shear connectors is inapplicable. Coupled with the back-to-back arrangement of two CFS channels where symmetricity of the built-up section is restored, the resulting composite floor system has been proven to possess adequate strengthd properties under static loads. An expression for computing the shear capacity of BTTST is proposed. A regression analysis, which is based on a model that takes into account the contributions of BTTST dimension, bearing area, shear area, concrete strength and CFS strength, was used in the derivision. The results and discussions can be summarized as follows:

1. New equation (Equation 7) has been developed for the design of shear capacity of BTTST in precast CFS-concrete composite beams. These equation include all important parameter, i.e., compressive strength of concrete, modulus of elasticity, CFS strength, dimension of BTTST (L_f, L_s, angle) and CFS thickness.
2. The proposed equation is in good agreement with the observed test values. The average absolute difference between the test values and predicted values was found to be 8.07%. The average arithmetic mean of the test/predicted ratio (μ) of this equation was 0.9954. The standard deviation (σ) and the coefficient of variation (CV) for the proposed equation were 0.09682 and 9.7%, respectively.
3. Equation 7 is recommended for the design of bent-up triangular tab shear transfer (BTTST) enhancement in CFS-concrete composite beams.

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