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A Finite Element Analysis of Shear Connectors Impact on Shear Behavior of Concrete-Encased Composite Steel Beams

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Abstract

Advantages of joint application of two important construction materials in composite concrete-steel structures have made these structures a very popular option. Encasing steel in concrete improves its rigidity and energy absorption while reducing potential local buckling in the concrete-encased steel. Due to insufficient laboratory and analytical data on shear behavior of encased steel, the available code does not contain particular instructions that can be used to prevent fracture caused by shear failure in composite members. The present study, therefore, attempts to examine effects of application of stud shear connectors on behavior of concrete-encased composite steel beams by modeling this element in ABAQUS and analyzing the results. The findings indicate considerable impact of connectors in shear reinforcement of composite beams.

Keywords: Composite Beams, Connector, Shear Stud, Shear Failure, Finite Element Method

1. Introduction

The existing methods for designing reinforced concrete and steel structures are not adequate in terms of providing proper steel-concrete connection. Shear stress is the essential form of force - although not the only force - exerted on this connection. Shear connectors in the form of weld stud or shear bolts, complicate the analysis of the connection and therefore techniques for designing these connections have often been developed empirically using in vitro analyses. Application of shear studs plays an important role in preventing shear failure of concrete-encased composite beams, particularly when the cross section of the steel member has a larger width since in this case the span of the steel member closely matches the total width of the composite profile, leading to increased spread of shear cracks along the upper flange. Shear failure in this case can be best prevented using shear connectors often in the form of studs. In order to properly transfer concrete-steel shear stress sufficient number of studs must be used. Therefore, here we modified the spacing between rows of studs connected to the upper flange of the steel beam in composite beams and investigated the impact of this parameter in different cases.

2. Details of Finite Element Analysis

There are different techniques for modeling concrete in ABAQUS, including plastic damage model that was used here. The model assumes that the main mechanisms involved in the onset of concrete failure are cracking and compressive crushing. Both phenomena result from cracking and spread of cracks. The model largely relies on the stress-relative elongation curve under uniaxial compression as well as stress-relative elongation curve under uniaxial tensile loading both discussed below. Stress-relative elongation curve under uniaxial compression was plotted using H.G. Kwak Model [1] which has been proposed for analysis of reinforced concrete structures using finite element method (FEM).

For nonlinear analysis, steel beam was modeled using elasto-plastic model with elongation hardening often referred to as bilinear model. In addition, elasto-plastic model with strain hardening in bilinear model was used to model steel. Rebar arrangement was model using an embedded model. Separate elements were considered for modeling concrete and steel, complete continuity conditions was satisfied for steel and concrete, and finally contact conditions were applied implicitly by making changes in the structural equations governing concrete behavior. Fig. 1 illustrates a schematic of samples and their profiles.

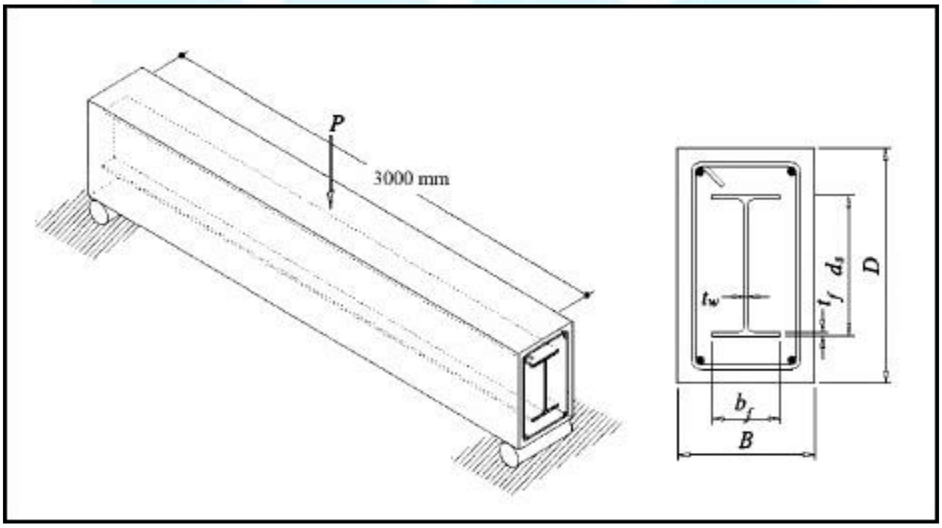

Fig. 1 A 3D view of the samples studied and their cross sections

3. Description of Samples

Application of shear studs plays an important role in preventing shear failure of concrete-encased composite beams, particularly when the cross section of the steel member has a larger width since in this case the span of the steel member closely matches the total width of the composite profile, leading to increased spread of shear cracks along the upper flange. Shear failure in this case can be best prevented using shear connectors often in the form of studs.

In order to properly transfer concrete-steel shear stress sufficient number of studs must be used. Therefore, here we modified the spacing between rows of studs connected to the upper flange of the steel beam in composite beams and investigated the impact of this parameter in different cases. In total 9 models were developed and analyzed in three groups with a large ratio of flange width which increases the probability of shear failure.

The first group includes the models E1, E2, and E3 with the stud spacing 25, 20, and15 cm, respectively. The steel profiles used in this group had a flange width to gross width ratio of 0.6.

The second group includes the models E4, E5, and E6 with the stud spacing 25, 20, and15 cm, respectively. The steel profiles used in this group had a flange width to gross width ratio of 0.7.

The third group consists of the models E7, E8, and E9 again with the stud spacing 25, 20, and15 cm, respectively. The steel profiles used in this group had a flange width to gross width ratio of 0.8.

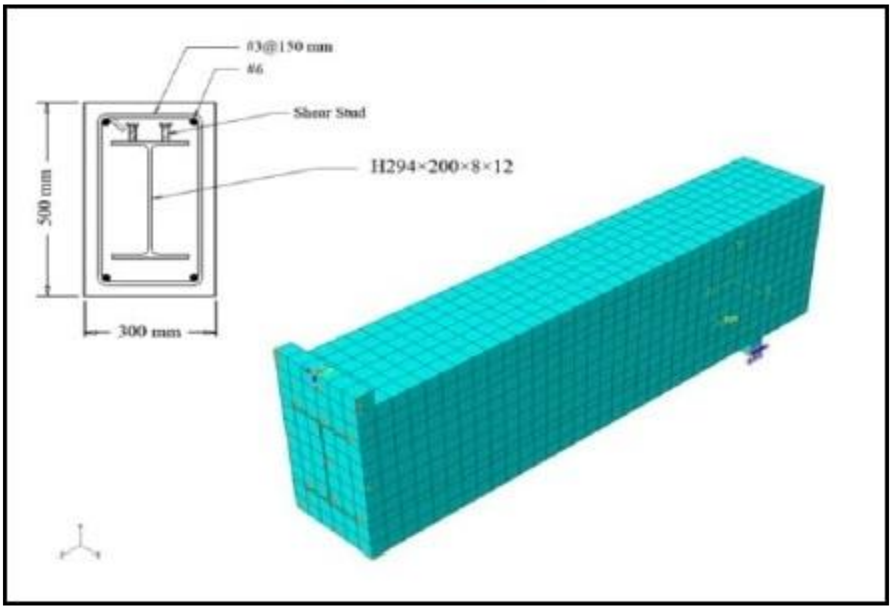

Fig. 2 A 3D view of the samples modeled in ABAQUS

In all models, the section of the whole composite beam had a dimension of 300 mm by 500 mm. The longitudinal bars were 19 mm in diameter while the stirrups, spaced at 150 mm, were 10 mm in diameter.

4. Comparison of Numerical Results

Fig. 3 shows load-deflection curves for E1, E2, and E3. A comparison of these curves indicates that smaller spacing between the studs slightly increases loading capacity of the composite beams. The loading capacity of E2 was increased by 1.26% compared to E1, and by 2.99% in E3 compared to E1.

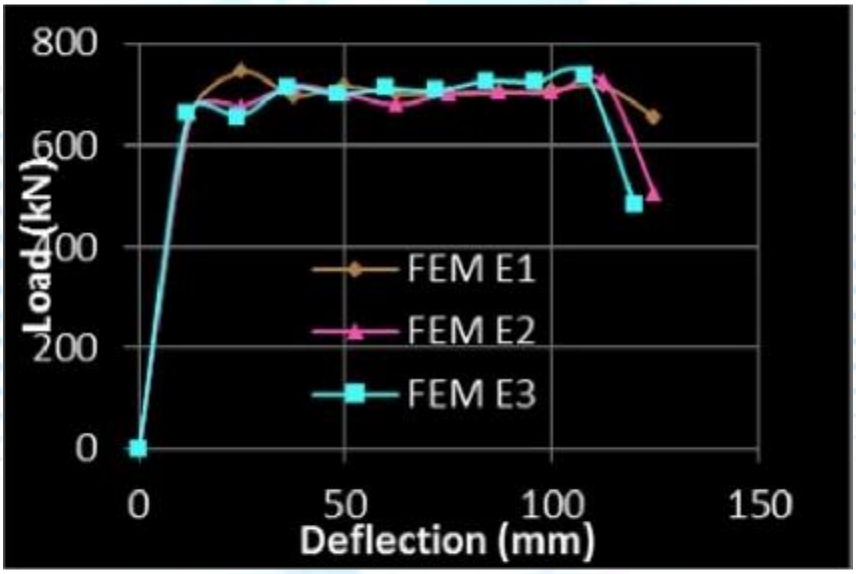

Fig. 3 Load-deflection curves for E1, E2, and E3

Fig. 4 shows load-deflection curves for E2, E3, and E4. As seen in this figure, loading capacity of beams increases as the spacing between the studs is reduced. The loading capacity of E5 was increased by 1.48% compared to E4, and by 2.99% in E6 compared to E4.

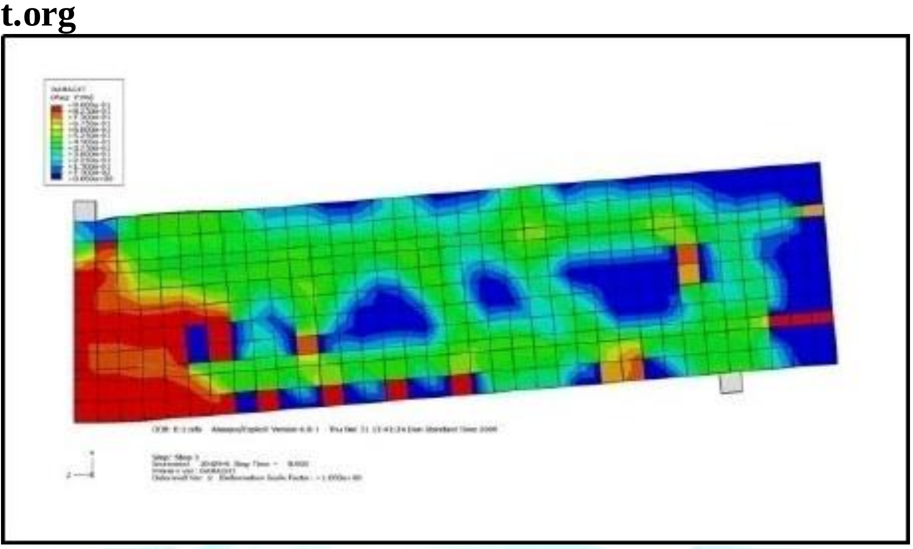

Fig. 4 Load-deflection curves for E4, E5, and E6

Fig. 5 shows load-deflection curves for E7, E8, and E9. Again, loading capacity of beams increases as the spacing between the studs is reduced. The loading capacity of E8 was increased by 1.50% compared to E7, and by 2.89% in E9 compared to E7.

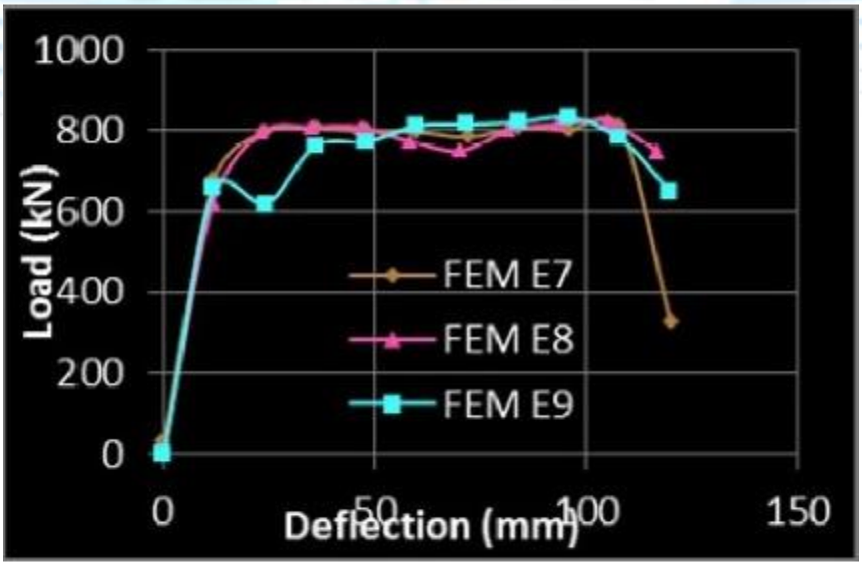

Fig. 5 Load-deflection curves for E7, E8, and E9

Figures 6 through 8 depict damage contours for E1 to E3. The ratio of flange width is 0.6 in these models.

A comparison of these contours clearly demonstrates reduced horizontal damage as a result of reduced spacing between the studs.

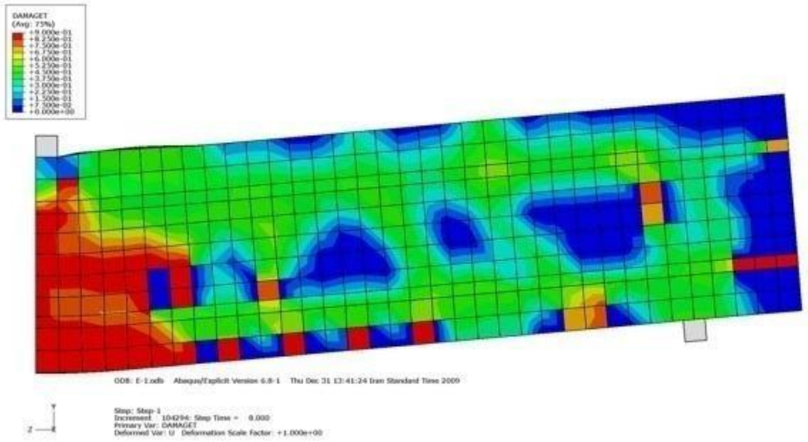

Fig. 6 Tensile damage contour for E11

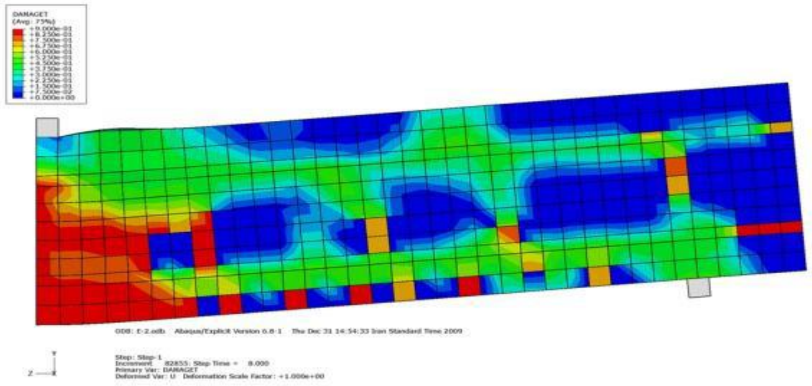

Fig. 7 Tensile damage contour for E2

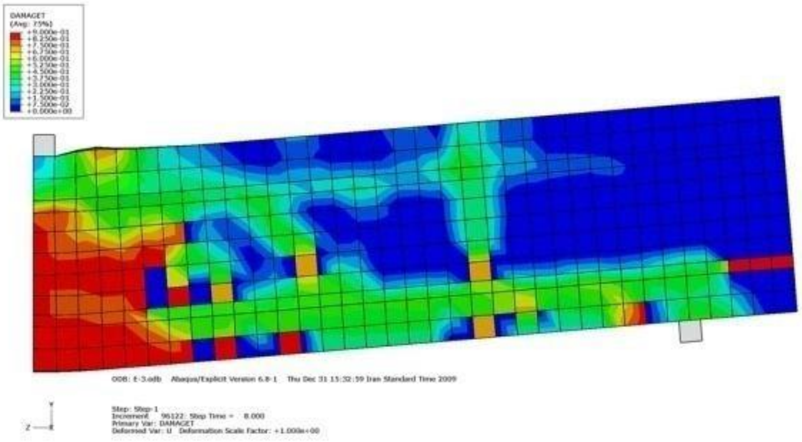

Fig. 8 Tensile damage contour for E3

Figures 9 through 11 show damage contours for E4 to E6. The ratio of flange width is 0.7 in these models. As seen in these figures, beams become less damaged as studs are placed at smaller spacing.

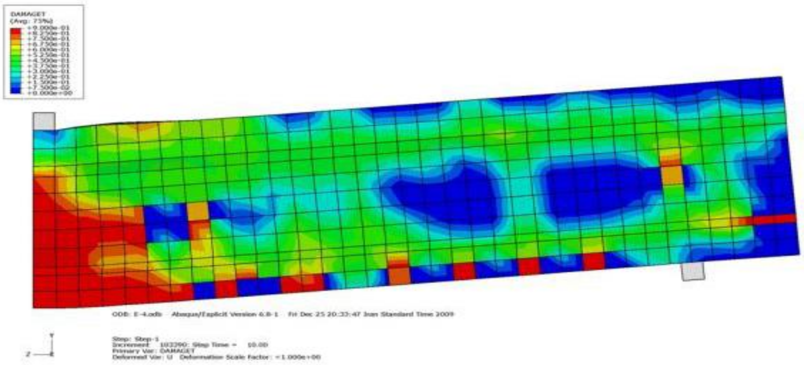

Fig. 9 Tensile damage contour for E4

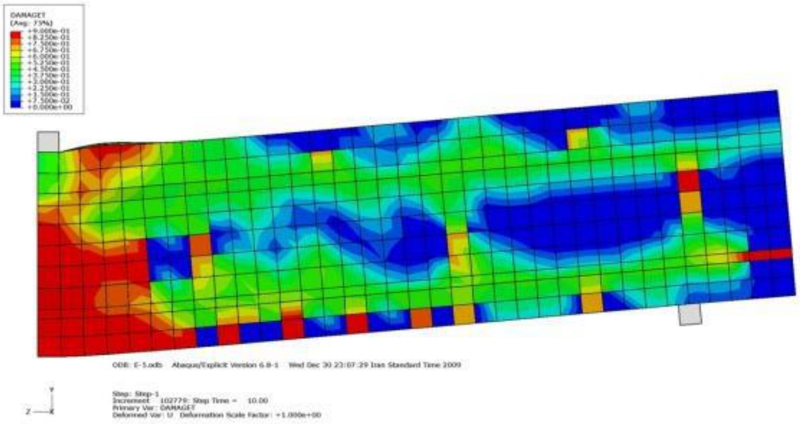

Fig. 10 Tensile damage contour for E5

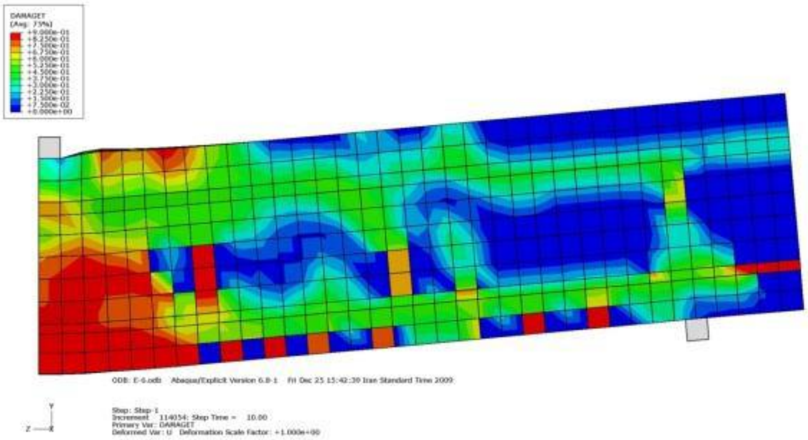

Fig. 11 Tensile damage contour for E6

Figures 12 through 14 illustrate damage contours for E7 to E9. The ratio of flange width is 0.8 in these models. Again, smaller stud spacing has led to reduced number of shear crack. However, the cracks on the concrete surface are more intense compared to the other two groups because of the large flange width ratio.

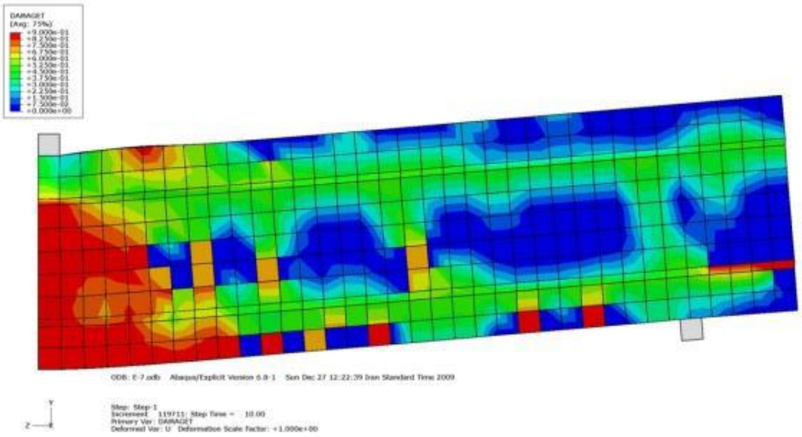

Fig. 12 Tensile damage contour for E7

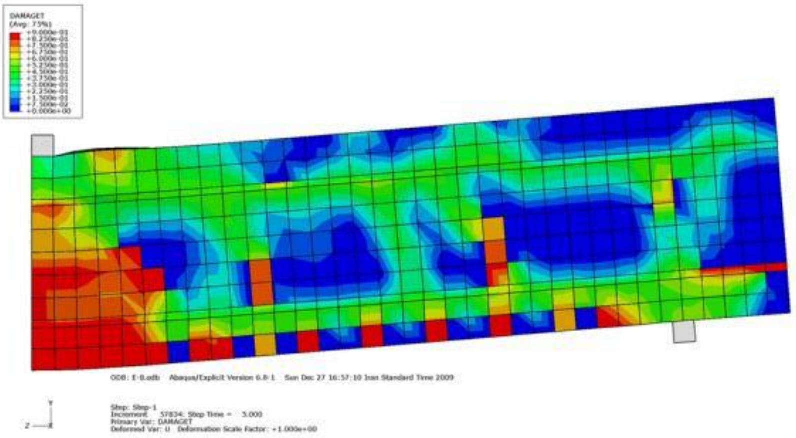

Fig. 13 Tensile damage contour for E8

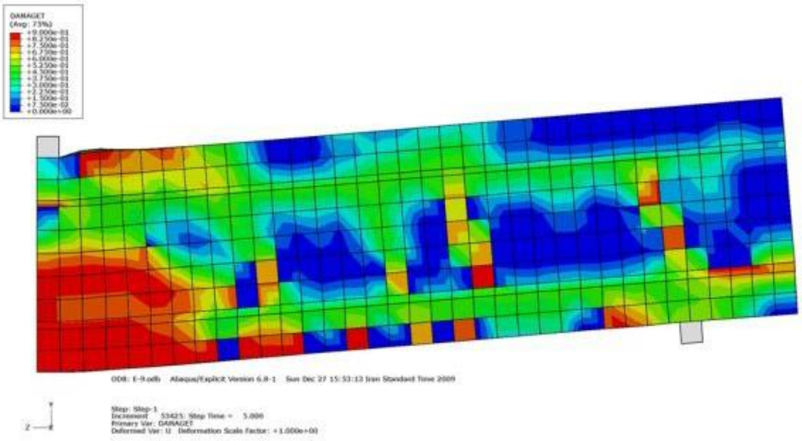

Fig. 14 Tensile damage contour for E9

Table I presents shear strength and flexural strength of the models with different stud spacing calculated by FEM. In addition, types of fractures were predicted based on the observations from the damage contours and relative plastic deformation. Iranian Code for

Design and Construction of Steel Structures contains equations required for designing shear connectors in composite beams. Results obtained from connector design based on this Code closely match those found by FEM. To design connectors using the Code, one should first calculate the total horizontal shear that must be tolerated at some point between the maximum bending moment and the point of zero bending moment. The total horizontal shear is the smaller of the two values obtained from (1) and (2) below:

$$V_h = (0.85*f_c* A_c)/2 + (f_y* A_s')/2 \quad (1)$$

$$V_h = f_y* As/ 2 \quad (2)$$

Table I Strength and type of failure in composite beams with different stud spacing

Model	**Model Strength**		**Stud spacing**	**Type of Failure**
	V(KN)	**V(KN)**		
	Models with flange width ratio = 0.6 (bf=180 mm)			
E1	**536.4**	**357.6**	**250**	**Shear**
E2	**543.2**	**362.1**	**200**	**Flexural**

E3	**552.5**	**368.3**	**150**	**Flexural**
Models with flange width ratio = 0.7 (bf=210 mm)				
E4	**576.1**	**384.1**	**250**	**Shear**
E5	**584.7**	**389.8**	**200**	**Flexural**
E6	**590.4**	**393.6**	**150**	**Flexural**
Models with flange width ratio = 0.8 (bf=240 mm)				
E7	**608.3**	**405.5**	**250**	**Shear**
E8	**617.4**	**411.6**	**200**	**Flexural**
E9	**625.9**	**417.3**	**150**	**Flexural**

According to our calculations, Equation (1) is the equation that determines horizontal shear in all models. Since the cross section area of the compressive concrete (Ac) is the same for all models, the horizontal shear obtained for all models equals 407.8 kN. Once the magnitude of the horizontal force exerted on the connectors are calculated, the maximum allowable horizontal shear force (q) is determined based on the type of connectors and using a table presented in the Code. Given the type of connectors used here, the maximum allowable horizontal shear is 28 kN for each connector. After calculating the horizontal shear and maximum resisting force, number of required connectors can be computed at either side of the maximum flexural moment. Finally, the spacing of 20.6 cm between the studs is obtainedaccording to the equations given in the Code. Results of our FEM analysis also indicated that in models with stud spacing larger than 20 cm, failure is of shear type while in models with stud spacing less than 20 cm shear damage is largely controlled.

5. Results

Based on the observations of the form of cracks in the experimental samples and closely matching values obtained from FEM modeling, it can be argued that concrete-encased composite steel beams experience two forms of failure: shear failure and flexural failure. Shear failure is caused by deep cracks along the flange of the steel profile which result in abrupt load drop before the beam achieves its ultimate capacity, although the steel in the samples allows the composite beams to stand larger loads before reaching ultimate capacity.

Evidences obtained from experiment and analysis indicate that shear studs on the surface of steel flanges can remarkably prevent fracture caused by shear failure in composite beams with large flange width ratios, although studs have also positive impacts in reducing shear cracks caused by bending.

In this analysis of the effective role of connectors in controlling shear failure, it was observed that smaller spacing between the studs reduced intensity of plastic damage along the flange of steel beams, particularly in composite beams with larger flange width ratios which experience broader spread of cracks and therefore can benefit more from the connectors. Moreover, reduced stud spacing slightly increased loading capacity in the models studied here.

6. Directions for Future Research

Shear connectors play an important role in preventing shear failure in composite beams. It is therefore suggested that future studies should focus on the impacts of different types of shear connectors on behavior of composite beams in order to enhance shear strength of these structural members.

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