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Research Paper

TESTING AND ANALYSIS OF COMPOSITE STEEL-CONCRETE BEAM FLEXURAL STRENGTH

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Composite steel-concrete beams are common structural members used in floor systems and are evaluated by well known procedures. Evaluation of composite member flexural strength requires an expectation of strain transfer between the two materials, however, perfect transfer does not occur, therefore, predictions of flexural strength may not be consistent with measured. Composite beam test demonstrations conducted at the Pennsylvania State University on identically constructed members have revealed that composite beams fail before reaching predicted strength. Observations of failed composite beams include longitudinal cracking of the concrete slab and interlayer slip between the concrete slab and the steel beam. This paper presents laboratory test results and analyzes the ultimate flexural strength of the tested composite beams using currently available methods and compares to observed behavior. Additionally, simplified finite element models of the composite beam were developed with results also compared to the data obtained from the tests. Based on the results of these analyses, recommendations for design are made that allow accurate determination of composite beam flexural strength.

Keywords: Composite-beam, Shear studs, Steel-concrete

INTRODUCTION

Composite concrete slab on steel beam is a widely used construction with proven benefits of increased ultimate strength and stiffness. The predictions of both strength and stiffness have become routine on the basis of methods prescribed in the American Institute of Steel Construction *Steel Construction Manual* (2010) and American Concrete Institute 318-11 (2011). The most common composite beam consists of a W-shape steel beam made composite with a concrete slab through headed shear studs (see Figure 1). The headed studs transfer horizontal shear forces between the steel and concrete causing the two elements act as one composite member under load.

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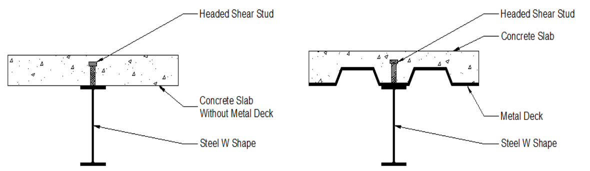
Figure 1: Typical Composite Beam Cross Sections



Two composite beam test demonstrations are conducted each academic year (one per semester) at The Pennsylvania State University for educational purposes. Composite beams are designed according to the provisions of AISC, Part 16, Chapter I for full composite action and constructed identically each semester. All composite beam tests were conducted on an A992, Gr. 50, W10 × 17 with a solid concrete slab and a single row of headed shear studs. In each test, the beam is loaded to failure with load and deflection recorded. In nearly all cases it has been observed that the predicted load carrying capacity is lower than the measured capacity. Ten complete sets of data have been recorded with the predicted flexural strength overestimated as compared to tests by an average of 7%.

Observations of the failed composite beams have commonly revealed a longitudinal crack along the center of the concrete slab directly above the headed shear studs as shown in Figure 2. In most tests, the crack was continuous and propagated the entire length of the beam. In some cases the longitudinal cracks were not continuous, and developed above and in the vicinity of the shear studs only. In addition to the longitudinal slab crack, interlayer slip between the slab and the steel beam top flange was observed.

The demonstrated and consistent over-prediction of strength reveals that current and widely accepted method of determining composite beam strength is inaccurate and the method may benefit from knowledge gained through the experimental investigation. The presence of interlayer slip indicates that the beam experiences partial composite action and assuming full composite action is incorrect. A better understanding and incorporation of a suitable level of partial interaction between the two elements and modeling of the behavior of the shear connection in the method is warranted.

The primary objective of this study is to understand and more accurately predict the behavior of a concrete slab on steel composite beam. This includes an evaluation of the longitudinal slab cracking on the behavior of a composite beam and the interface slip to better understand the degree of interaction between steel and concrete in a composite beam with headed shear studs. The concluding objective of the study is to develop a simple model and corresponding analytical method to predict flexural strength of a composite beam.

PREVIOUS STUDIES

There are many analytical studies in the published literature, however, there are very few studies based on laboratory tests. The consensus of published literature generally is that the behavior of a composite beam depends primarily on the behavior of the connection between the slab and beam. Along with theories to explain the behavior of the connection there are complex methods of exact analysis, simplified approximate analysis methods, and methods that use finite element analysis.

TESTS

A limited number of composite beam laboratory studies have been conducted to confirm prediction models currently in use. Naithani and Gupta (1988) tested three composite beams to compare measured to predicted strength. The three beam configurations tested the effect of shear connection type and transverse reinforcement placement. One configuration failed by concrete crushing with a longitudinal crack. The ultimate strength of the beams exceeded the predicted strength by 8%, 4%, and 45%. The configuration that exceeded predicted strength by 45% utilized double, but smaller, shear studs. These tests demonstrate that the shear connection significantly affects the ultimate strength of a composite beam. Ramm and Jenisch (1997) investigated interface longitudinal shear forces and recognized that additional transverse bending in the concrete slab affects composite beam strength. Full scale beam tests were performed to study the effect of transverse bending. It was observed that negative transverse bending moments reduced the ductility of the composite beams and longitudinal cracks and transverse bending moments significantly influence capacity.

ANALYTICAL MODELS

A number of theoretical/analytical studies have been conducted. Leon and Viest (1997) conducted a review of elastic and inelastic composite beam theories based on incomplete interaction. Assumptions for inelastic analyses include no friction or bond at the interface, no uplift, and linear strain distributions. Finite element models were found to be very accurate, however, are most often used for academic purposes and special cases. Leon and Viest (1997) conclude that two concerns require development: (1) develop a refined shear connection model; and (2) simplify finite element models. Sapountzakis and Katsikadelis (2003) presented an analog equation method as a solution to the case where deformable shear studs are used. The method neglects uplift, but considers in-plane shear forces and deformation of the slab and axial forces and deflection of the steel beam. The results show that as the stiffness of the connection decreases, the interface slip increases, the shear forces at the interface decrease, and the lateral deflections of the beam increase. Liu *et al.* (2005) investigated strain differences between the steel and concrete in a composite beam using partial interaction and the theory of elasticity. Taking slip and curvature into account, it was demonstrated that the strain difference affects the displacement and load capacity of a beam. In comparing full interaction and partial interaction, the calculated deflection difference was 11% in one case, therefore, it was suggested that the full interaction assumption should not be used for design. Girhammar *et al.* (1993) proposed a complex composite beam-column analysis of partial interaction to determine internal actions and displacements. The analysis incorporates a first- and second-order analysis that accounts for interlayer slip. Girhammar *et al.* (2007) proposed a refined composite beam or beam-column static analysis with partial interaction that accounts for interlayer slip where more accurate boundary conditions are included. The methods of exact analysis presented by Girhammar *et al*. (2007) are, however, extremely long, intensive, and detailed resulting in a need to simplify.

APPROXIMATE ANALYTICAL PREDICTION METHODS

Girhammar *et al*. (2009) presents an approximate strength prediction method that is simpler and more readily applied. The approximate, simplified method incorporates an effective bending stiffness that was used for buckling in the more exact analysis. This analysis uses a differential element to define equations for moment, section shear, interface shear, deflection, and axial force for a fully composite member. For approximation of these terms for a partially composite beam, the bending stiffness for the full composite member is replaced with the effective bending stiffness for the partially composite member. While this method is much simpler than the previously proposed methods by Girhammar *et al.* it is suitable for approximation only and not for codified design. Effective stiffness:

$$EI_{eff} = \left[1 + \frac{EI_\infty / EI_0 - 1}{EI_0 + (\mu/\pi)^2(\alpha L)^2}\right]^{-1} EI_\infty \quad \text{...(1)}$$

where EI_∞ = bending stiffness of the fully composite section, EI_0 = bending stiffness of the non-composite section, K = slip modulus of shear connection, r = distance between the two centroids, L = length of composite beam, μ = buckling length coefficient (for a simply supported beam, = 1), αL = the partial composite action parameter (defined below in equation (2)) obtained from the general solution, in terms of displacement, to the differential equation for a partially composite beam loaded transversely as discussed by Girhammar *et al.*

$$\alpha L = \sqrt{\frac{Kr^2}{EI_o\left(1 - {EI_o}/{EI_\infty}\right)}}\,L \quad \text{...(2)}$$

Fabbrocino *et al*. (1999) also proposed an analysis method to predict composite beam flexural strength. Their results demonstrate that actual behavior of a composite beam differs from predictions based on a full interaction assumption. The Fabbrocino analysis recognizes that composite beam behavior depends on slip distribution and the resulting forces at the interface. In this model, slip is related to the rotation of the beam and displacement of the centroids of the two sections. By defining this relationship, the derivative of the slip is shown to be a function of the curvature and strains at the centroids of the two sections. The dependency of the relationships causes the solution to be involved and non-linear, however, the method predicted ultimate load to within 1% of experimental results.

Qiongxi Lui (2011) proposed a composite beam ultimate load prediction method that accounts for reduced flexural rigidity due to cracking of the concrete and slip strain. Total slip is determined by integrating the slip strain along the beam length. In addition, as the slip is greatest at beam ends, end slip is compared to shear connector strength. The method is lengthy, but accuracy was not evaluated against experimental results.

Other researchers have proposed composite beam flexural strength prediction methods involving longitudinal shear stresses in the composite beam. Segura (1990) proposed a method to evaluate the shear stresses at the steel and concrete interface. Gara *et al.* (2010) proposed a strength prediction method based on the effects of shear lag. Along with others, these methods are long and complex, and are not practical for codified design.

FINITE ELEMENT MODELING

A number of finite element studies have been conducted in the recent several years that have investigated a number of issues relating to composite flexural members with shear studs. Mirza and Uy (2008) describe the effects of strain profiles on the headed shear stud connection in composite beams. Because shear studs are subjected to both flexure and shear, Mirza and Uy emphasize the importance of evaluating the combined effect. The presence of both moment and shear causes a nonlinear response, therefore ABAQUS was used to create a 3D solid element shear stud model. A push test analysis under different strain regimes was performed to determine the shear stud load limit. The finite element model predicted the strength of the shear studs to within 0.7% of the experimental data and concluded that strain regimes in a solid concrete slab do not significantly affect the shear stud performance. Ranzi and Zona (2011) compared three different numerical models incorporating a uniformly deformable shear connection to link the concrete slab and steel beam. Ranzi and Zona evaluated the model using two Euler-Bernoulli beams, a combination of an Euler-Bernoulli beam (concrete) and a Timoshenko beam (steel), and two Timoshenko beams. All three models predicted the ultimate load to within 2%, however, where beams were controlled by shear, none of the three models provided accurate results. In this case, the models using a Timoshenko beam provided much closer failure load predictions than the model using two Euler-Bernoulli beams. Earlier work by Ranzi and Zona (2007) presented a detailed analysis using an Euler-Bernoulli beam for the concrete and a Timoshenko beam for the steel to include shear deformation. He *et al.* (2011) used an element between the steel beam and concrete slab to represent the shear connection in a composite beam. The element was assigned a stiffness to model the average effect of the shear connectors along the beam. The results of this finite element model were compared to two different experimental tests through the ultimate load. The model prediction overestimated the ultimate load by 5.5% and 3.5%. da Silva and Sousa (2009) presented a family of interface elements to account for interlayer slip in a composite beam. Vertical, horizontal, and rotational displacement fields were considered. Different degrees of freedom were used in the different elements with some elements considering shear strain. Da Zilva and Sousa determined that a Timoshenko interface element with quadratic displacement accounting for shear strain is the most reliable.

AISC STRENGTH PREDICTION

It is presumed that the reader is familiar with AISC strength prediction of composite beams on the basis of both full and partial composite action and, therefore, the method is only described conceptually here. In general the full concrete strength and plastic yield strength of the materials is expected to develop and the internal moment is computed as M_n. In the case of partial composite action, the shear connector strength is less than the controlling internal, longitudinal shear force developed by either the steel or concrete.

LABORATORY TEST BEAM AND NUMERICAL ANALYSIS

Physical Test

The tested beam geometry and loading configuration under the present study is presented in Figure 3. Each beam was constructed with 24 identical and equally spaced, ¾ inch diameter headed shear studs. The test data sets are presented in Figure 6 and Figure 7. The AISC, Part 16, Chapter I composite beam strength prediction for a f'_c = 4,000 psi, solid concrete slab and W10×17 A992 steel beam is M_n = 158 ft-kips with a corresponding center point load of 31.7 kips.

Finite Element Model

To better study the composite beam behavior of the tests, the tested beam was modeled numerically using a very simple, 3D, SAP2000 with shell elements for the slab and frame elements for the beam and studs (see Figure 4). To incorporate material nonlinear behavior, hinges that allow yield were assigned at discrete locations along the steel beam. Modeled concrete material is f'_c = 4000 psi on a 1" × 2" grid. To model the shear studs, frame elements were used with the cross section of the shear stud and the properties of ASTM A108 steel. Shear stud length was equal to half the thickness of the concrete slab is used, 17/16", which is less than the actual length of the shear stud, however, the shear area remained the same. The model was subjected to an incrementally increasing point load at mid-span to study the load concentrations at the shear studs, the shear lag development in the concrete slab, the longitudinal distribution of force in the shear studs, and composite beam load versus deflection relationship.

MEASURED AND SIMULATED RESULTS

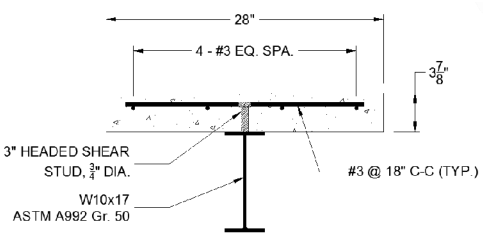
Laboratory Test Results

A number of behavior observations from both the laboratory tests and numerical results were collected. Longitudinal cracks often developed in the concrete slab of a composite beam directly above the headed shear studs as presented in Figure 2. In addition, the slab was autopsied to examine the headed stud condition after loading. The four studs at the end of the beam were examined (see Figure 5) and deflection of each of the four end studs was measured to be 1/8" toward the end of

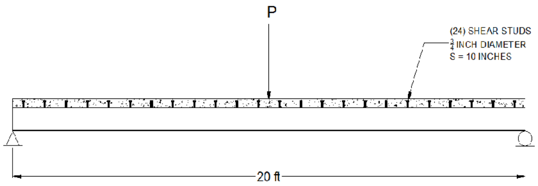
Figure 2: Observed Longitudinal Cracking of Test Beam Slab

Figure 3: Test Beam Drawings

a) Cross Section of Test Beam



b) Composite Beam Lab Test Configuration



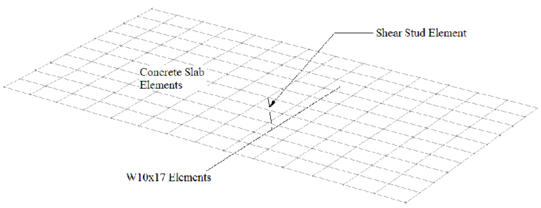
the beam—an indication that distortion of the stud and interface slip occurred during the test to failure. The relative movement between the concrete slab and steel beam flange was also measured to be 1/8", providing evidence that partial, but not full composite action, developed. After inspection of the exposed studs, a single, 20 ounce hammer impact broke the studs free from the steel beam, indicating near failure of the weld during load testing. A deformed and broken stud is shown in Figure 5.

Numerical Analysis Results

Both linear static and nonlinear analyses were conducted in the present study. To determine the load that corresponds to steel first yield (F_y = 50 ksi), the stress in the extreme tension

Figure 4: SAP2000 Finite Element Model Views of Composite Beam Numerical Model

a) SAP2000 Finite Element Model Schematic



b) SAP2000 Extruded View of Basic Elements

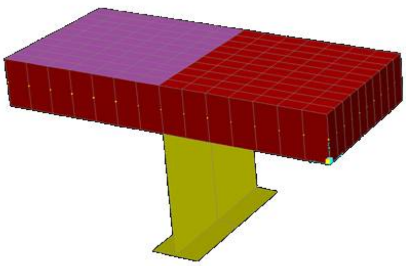
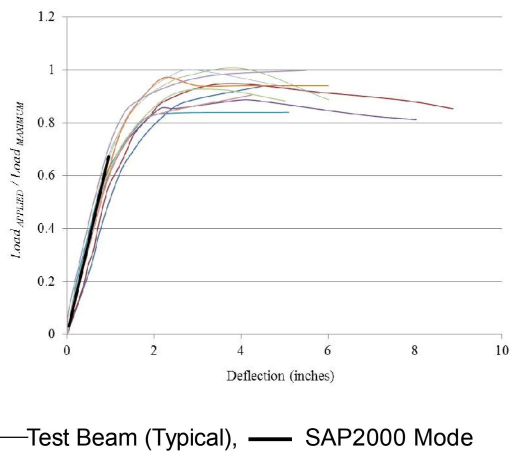


Figure 5: Shear Studs with Concrete Removed after Failure of Composite Beam

a) Shear Stud at End of Beam

b) Stud Failure after Low Impact

Figure 6: Percent Predicted Max Mid-span Load vs. Deflection – All Tests



fiber must be calculated. The analytically predicted elastic limit occurs at a concentrated load equal to 21.3 kips with f'_c = 4,000 psi. Observation of the test data load versus displacement graphs (Figures 7a through 7j) indicates the elastic limit occurs at a mid-span load between 20 kips and 25 kips, depending on the f'_c for the ten sets of test data.

Although considered conservative for design, the theoretical maximum deflection predicted by the AISC lower bound stiffness was in no case conservative as shown in Figures 7a through 7j. The actual stiffness of a composite section is affected by the degree of interlayer slip as well as the concrete stiffness, which is dependent on f'_c. Full composite action, which is assumed for the AISC lower bound moment of inertia calculation, was not achieved by the test beams.

In comparing the numerical model predicted deflections in the elastic range, AISC elastic deflection predictions, and measured deflections, the numerical model predictions compare more closely with measured load-deflection behavior than does AISC; however, neither provide an accurate or conservative estimate for deflection as compared to the test beams. Although a portion of the test concrete slab developed cracks, causing a loss in stiffness, this is not accounted for in the numerical analysis because the concrete slab is analyzed was a linear material in SAP2000. For analytical purposes, the concrete slab stress distribution is assumed to be uniform; however, the numerical model concrete slab stress distribution is far from uniform as presented in the results of Figure 8. The stress distribution presented reflects the composite beam nonlinear stage under the predicted maximum 31.7 kip load. It can be readily observed that a concentration of compressive stress develops around the studs and is particularly apparent at the stud near the end of the beam. The end studs experience this stress concentration because the transferred shear forces are largest at the support. In addition, longitudinal forces (in the plane of the slab) concentrate at the stud as resented in Figure 9 where the force distributions at selected studs are presented. Studs are numbered, starting at mid-span with 1 and 12 being the end stud. The numerical analysis demonstrates that the slab compressive stress is concentrated over a width of 2" to 3". In addition, tensile stresses develop directly adjacent to the end stud in the model, which are indications of the observed longitudinal slab cracks.

Uniform shear stud shear force along the beam is normally assumed, however, numerical modeling demonstrates that shear forces are concentrated at the end studs.

Figure 7: Load vs Deflection of the Ten Laboratory Composite Beam Tests

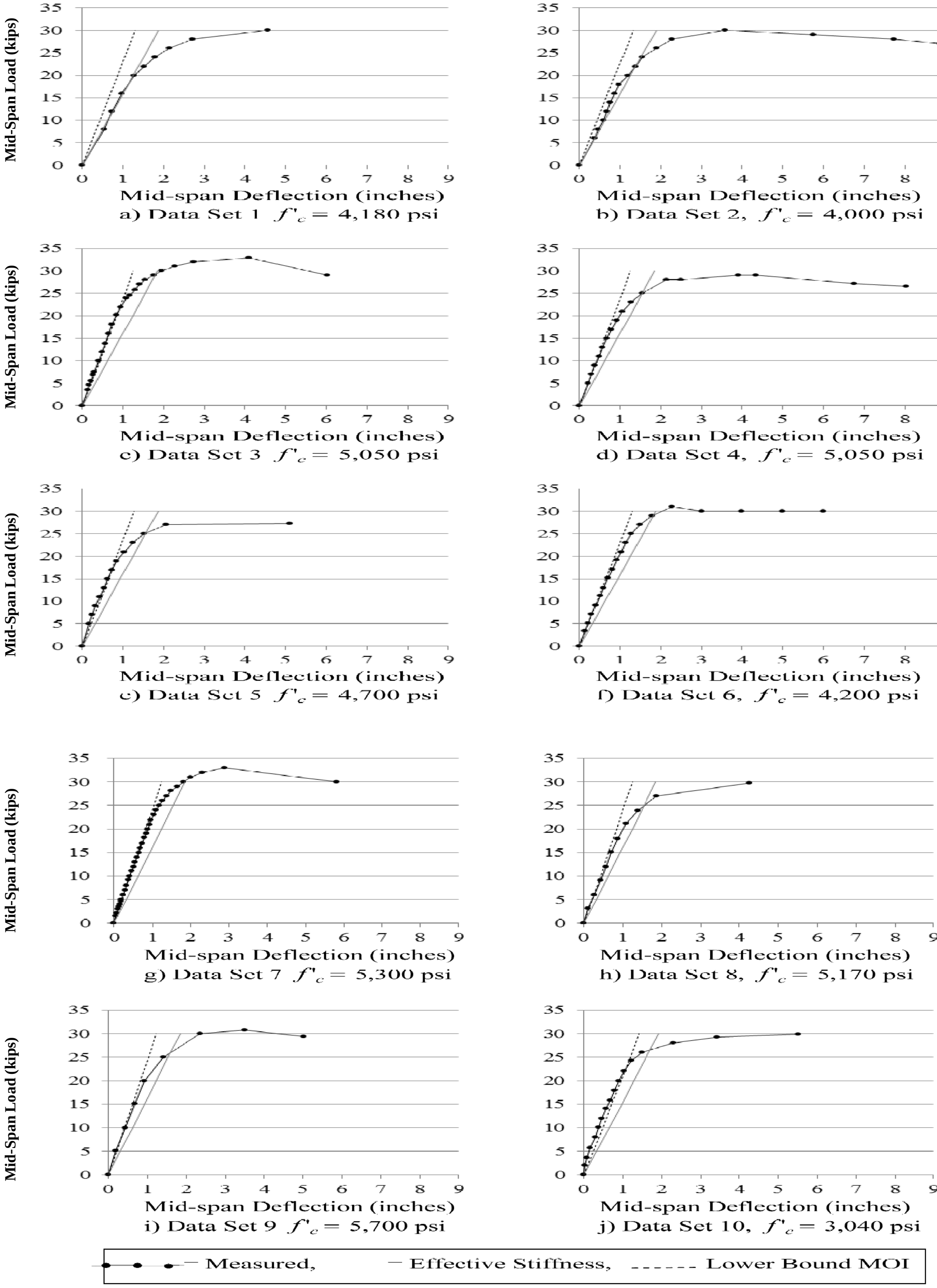


Figure 8: Numerical Analysis Results of Concrete Slab Force Stress Distribution

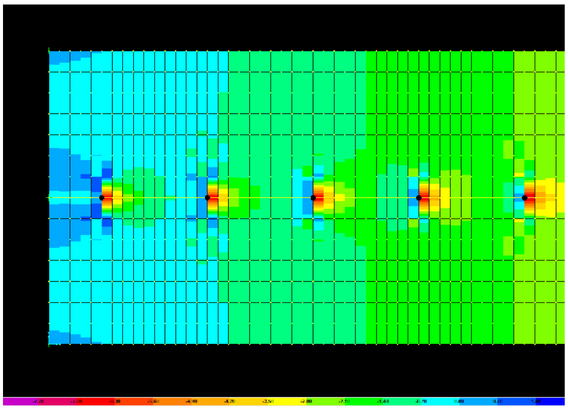


Figure 9: Force Distributions across Concrete Slab at Four Selected Stud Locations

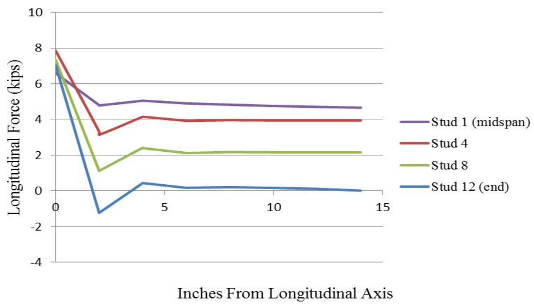
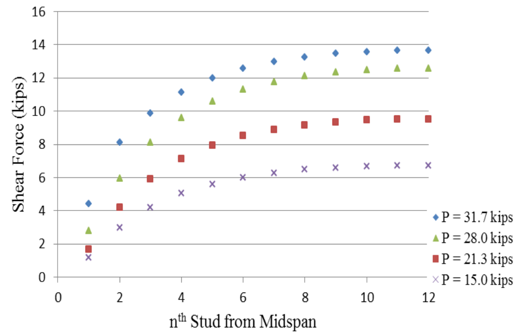


Figure 10 presents the magnitude of shear force in each stud along the beam as a result of applying four load levels at mid-span: (1) the predicted ultimate load (31.7 kips); (2) the load at which yield was experienced in the nonlinear analysis (28 kips); (3) the load at which the elastic limit was observed from the linear analysis (21.3 kips); and (4) a load in the elastic range (15 kips). Within the elastic range, the ratio of maximum calculated shear to the assumed uniform shear magnitude ($V_{max}/V_{assumed}$) is constant. After the steel beam has yielded, however, the maximum stud shear force approaches the uniform force predicted

Figure 10: Shear Forces in Studs along Axis of Composite Beam (1 = mid-span, 12 = end)



value. On this basis it can be observed that the actual maximum stud shear force may be as much as 1.25 times the predicted, uniform force. Considering the f'_c = 4,000 psi case:

$$V'_c = 0.85 f'_c\, b_{eff}\, t_s = (0.85)(4{,}000\text{ psi})(28\text{ in})(3\tfrac{7}{8}\text{in}) = 369\text{ kips} \quad ...(3)$$

$$V'_s = A_s F_y = (4.99\text{ in}^2)(50\text{ ksi}) = 250\text{ kips} \quad ...(4)$$

$$V'_q = \sum Q_n = (12)(21.5\text{ kips}) = 258\text{ kips} \quad ...(5)$$

$$\frac{V'}{n} = \frac{250\text{ kips}}{12\text{ studs}} = \frac{20.8\text{ kips}}{\text{stud}} \quad ...(6)$$

Increasing this uniform shear force by the ratio discussed above to account for end stud effects results in an expected applied shear force of approximately:

$$\frac{V'}{n} = \frac{249.5\text{ kips}}{12\text{ studs}} = \frac{20.8\text{ kips}}{\text{stud}} \times 1.25 = \frac{26\text{ kips}}{\text{stud}} > Q_n = 21.5\text{ kips} \quad ...(7)$$

The predicted end stud shear force of 26 kips loads the stud beyond capacity. Stud shear forces of this magnitude results in stud deflection, slab to beam slip, and ultimately premature failure. Additionally, for this f'_c = 4,000 psi example, the stud shear force is only slightly below the value at which the surrounding concrete is expected to fail.

The composite beam laboratory observations of the studs after load are consistent with this analysis. However, this evaluation so far is limited to a W10×17 beam with a $3^7/_8$" concrete slab and 24 headed shear studs. To evaluate the effect of slab thickness and width on the distribution, two more models were constructed and evaluated.

The initial numerical model was modified to create two additional models: (1) W10×17 beam with a 60" wide by $3^7/_8$" concrete slab and 24 headed shear studs; and (2) W10×17 beam with a 28" wide by 2¾" concrete slab and 24 headed shear studs. The b_{eff} used for these two models is the AISC maximum allowable, taking span/8 on each side of the beam. Because $V_{max}/V_{assumed}$ was observed to decrease after first steel yield, the mid-span load corresponding to the elastic limit was used. Based on this study, it was determined that $V_{max}/V_{assumed}$ increases as the effective slab width increases. Also, a decrease in $V_{max}/V_{assumed}$ is observed with a decrease in slab thickness. In the case of a large effective slab width, increasing the expected shear by 1.25 may not provide a conservative estimate. However, $V_{max}/V_{assumed}$ for the numerical models with effective widths equal to 60" and 28" are within 2%. Also, $V_{max}/V_{assumed}$ is expected to decrease after the steel yields. For a slab thickness of 2¾", $V_{max}/V_{assumed}$ decreases, therefore, expecting a shear of 1.25 times greater than predicted by AISC remains conservative.

To compare this method to other typical composite beams, two additional models were created. The fourth and fifth numerical models were assigned the same material properties as all previous models. The models included a single row of shear studs and loaded with a concentrated load at mid-span. The fourth model consisted of a W18×35 beam and a 64" wide by $3^7/_8$" thick concrete slab with headed studs spaced at 8" and a span length of 32 ft. The fifth model consisted of a W14×26 beam and an 80" wide by 3" thick concrete slab with headed studs spaced at 10" and a span length of 30 ft. The simulation results demonstrate that these beams also experience end shear stud forces that were 20.2% and 17.7% higher than a uniform distribution would predict, respectively. It appears, based on this limited study, that larger steel beams will experience larger than predicted end shear stud forces.

DISCUSSION AND EVALUATION

Composite beam tests demonstrated that neither the steel beam nor the concrete slab attained full plastic strains despite loading to failure, indicating that full composite action, as normally assumed, did not develop. The error in predicting ultimate flexural capacity ranged from –0.30% (under prediction) to +19.2% (over prediction) with an average over prediction of 6.6%.

To evaluate the degree of composite action that did develop in the test beams, a partial composite analysis was conducted. From Equation 8, the flexural capacity of a partially composite section with the PNA in the top flange of the steel is determined.

$$M_n = T_s\left(\frac{d}{2}\right) + C_c\left(t_s - \frac{a}{2}\right) - 2(b_f F_y x)\left(\frac{x}{2}\right) \quad ...(8)$$

Because the calculated total shear stud strength has been shown to be sufficient, C_c becomes an unknown variable of interest. Equation 8 can be rearranged by making several substitutions and C_c can be calculated from the quadratic Equation 9:

$$-C_c^2\left(\frac{1}{2(0.85)f_c'b_{eff}} + \frac{1}{4F_y b_f}\right) + C_c\left(t_s + \frac{A_s}{2b_f}\right) + \left(A_s F_y \frac{d}{2} - \frac{A_s^2 F_y}{4b_f} - \frac{PL}{4}\right) = 0 \quad ...(9)$$

which is valid when the PNA is in the steel flange. For the f'_c = 4,000 psi example examined here, the actual C_c that was experienced is calculated to be 189 kips. Knowing the value of *x*, the tensile force component of the flexural moment at failure can be calculated. This evaluation demonstrates that 86% of the steel plastic tensile strength was coupled against the concrete at the time of flexural failure. Among the ten sets of measure beam response data, the developed tension ranged from 64% in one test to two tests of 100% with an average of 87%.

Load versus deflection plots are also presented for measured composite beam responses. Figure 6 presents a compilation of all data sets normalized to predicted ultimate flexural strength due to different measured concrete strengths with each test. Figures 7a through 7j present the measure composite beam response as compared to the analysis methods suggested by Girhammar *et al.* (2009) and AISC (2010). A lower bound moment of inertia (I_{LB}) is used to develop the AISC load vs. deflection relationship. I_{LB} is an AISC, theoretical minimum moment of inertia including only that portion of the concrete slab within Whitney's stress block and is therefore considered conservative. For many of the data sets, however, it can be observed that this seemingly conservative approach is actually very accurate other than for data sets 1, 2, and 3 where the measured elastic deflections were notably greater than deflections predicted using I_{LB}.

The deflections predicted utilizing Girhammar *et al.* (2009) are presented in Figures 7a though 7j. Girhammar *et al.* uses an effective bending stiffness that accounts for partial composite interaction involving an estimated slip stiffness, K. For a non-composite section, the slip stiffness is zero and increases with higher degrees of composite interaction. The slip stiffness, K, is difficult to estimate because the slip is small and concrete properties are nonlinear. It was determined that using a slip stiffness of 9 ksi for every test data set provided an accurate or somewhat conservative estimate. While the Girhammar *et al*. method is attractive and can provide accurate predictions, a reliable method to quantify the slip stiffness is not available.

SUMMARY AND CONCLUSIONS

Composite steel-concrete beams tested to failure have been observed to consistently fail before the nominal flexural strength predicted by AISC is reached, indicating a deficiency in current design standards. For the complete set of data, the numerical prediction error in accordance with AISC ranged from –0.30% to +19% with an average of a 6.6% over prediction. Several observations during these tests have highlighted problem areas. These observations include:

- The presence of interlayer slip, indicating that full interaction is not achieved.
- Longitudinal cracking of the concrete slab in the vicinity of the shear studs, indicating that stress concentrations are experienced in the slab at the shear stud locations.
- Shear forces in the end shear studs were higher than predicted, based on post-test examination.

A finite element model was developed using SAP2000 to analyze the test beam behavior. The results of the model show consistency with observations made during full-scale beam testing. The numerical model indicates high stress concentrations in the plane of the slab at the shear stud locations. As a result, tensile splitting forces in the concrete slab are experienced adjacent to the shear studs. Along the axis of the beam, shear distributions are subject to the effects of shear lag, causing the end studs to experience shear forces as much as 25% higher than predicted. On the basis of the results presented here, further research is necessary to determine the distributions of shear forces both in the concrete slab and along the beam in a larger sample of specimens.

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