Effect of Partial Shear Interaction in Steel Concrete Composite Girders

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Abstract. Steel concrete composite (SCC) structural system has been commonly used both in the buildings and in the bridges because of the advantages it associates when compared to its counterparts such as RC and steel structures. A typical SCC girder consists of a concrete element placed over a steel element. The effectiveness of this composite system is characterized by the type of connection that exists between the two connecting elements. More commonly shear stud connectors are used to connect the two elements. If the shear studs are infinitely rigid, then it brings about full composite action, on the contrary there is no composite action if the studs are not used, between the two connecting elements. It has been observed that generally the composite action exists somewhere between the full composite action and the no composite action, and is called the partial composite action or the partial interaction. More often the partial composite action is overlooked during the design of SCC girders, and the girder is designed assuming that there exists full composite action, because of the complexities in the analysis incorporating the partial composite action. This might lead to the serviceability issues in the SCC girders. Keeping this in mind the present work has been carried out to understand the significance of the partial interaction in SCC girders. In the present work, a comparative study has been made between the available analytical model and the numerical model. Numerical modeling is performed by using commercially available tool such as SAP2000. The main objective of this work is to bring out the relative significance of the partial interaction with respect to the full composite action, with the help of parametric study. Here, the parametric study has been carried by considering various design parameters, such as, span length, degree of shear connection, cross section geometry of steel girder and concrete slab. It is observed that there is significant increase in deformations of the SCC girder, on account of the partial interaction. The results of the numerical model and the analytical model are in good agreement.

1. Introduction
SCC girders have been extensively used both in the buildings and the bridges owing to its advantages when compared to its counterparts such as RC and steel bridges. A typical SCC girder consists of a concrete element placed over the steel element. Stud shear connectors are used to connect, which bring about the composite action, between the two connecting elements. The effectiveness of this composite action is characterised by the type of composite action brought about by the shear connector. If the shear studs are infinitely rigid, then it brings about full composite action, on the contrary there is no composite action if the studs are not used, between the two connecting elements. In practice the composite action exists somewhere between the full composite action and the no composite action, and is called partial composite action. More often, the partial composite action is overlooked during the design of SCC girders, and are designed assuming full composite action, because of the
complexity in the analysis incorporating the partial composite action. This will underestimate the deflection prediction.

The study considering partial composite action was first carried out by Newmark et al. [1] which is a highly cited work. Since then different researchers have proposed different analytical models for the prediction of deflection of SCC beams considering the partial composite action [2-5]. But, use of these analytical models in routine design may become cumbersome. Therefore, in this study a numerical study has been carried out (which is simple and easy to use in routine design of SCC girder) and is compared with available analytical models proposed by various researchers [2-4]. The objective of this work is to understand the significance of partial composite action on the deflection of SCC girders with the help of numerical study. For this purpose, a parametric study has been carried out considering various design parameters such as, span length, degree of shear connection, cross section geometry of steel girder and concrete slab.

2. Description of Analytical Models

Figure 1 shows a typical cross section of a SCC girder. The analytical models given in literature [2-4] for the prediction of deflection considering partial composite action discussed here in brief. Notations used in the calculations of geometric properties of various models considered here are defined with reference to figure 1. The assumptions made in analytical models are as follows.

1. The distribution of the shear connectors is uniform along the length of the beam.
2. There is no vertical separation between the concrete component and the steel component, i.e., the curvature is same for both the components.
3. Bernoulli's beam theory is assumed for both the concrete and the steel component.
4. The behavior of the concrete component and the steel component is elastic. The load-slip behavior of the shear connector is also elastic.
5. The friction between the two components at the interface is ignored.

2.1. Bradford's Model

The equation for the deflection of the SCC beam considering partial composite action as proposed in [2] is as follows

$$\Delta_p = \Delta_f + CF_{sh}$$

where:

- $\Delta_p$ = Deflection due to partial composite action
- $\Delta_f$ = Deflection due to full composite action
- $C = \frac{L_s}{K_s} \left( h_c + h_s \right) \frac{EI}{k_l} \sum E I = E_c I_c + E_s I_s; \frac{1}{E A_c} + \frac{1}{E A_s} \frac{EI}{k_l} = \sum E I + \frac{E A}{(h_c + h_s)^2}$

, where: $L_s$ is spacing of the connectors and $K_s$ is the initial modulus of the connector $F_{sh}$ = Total shear force on the shear connector in shear span, and is given by
\[ F_{sh} = \frac{EA}{EI} (h_c + h_s) w L^2 \left[ \frac{x (L - x)}{2L^2} + C_1^2 \left( \frac{1 - \cosh \frac{\pi x}{C_1 L}}{\sinh \frac{\pi x}{C_1 L}} + \cosh \left( \frac{\pi x}{C_1 L} \right) - 1 \right) \right] \]

where: \( L \) is the length of the beam, 
\( x \) is the distance from the support at which deflection is calculated 
and \( C_1 = \frac{\pi}{L} \left[ \frac{h_c + h_s}{E \sum \frac{1}{EI}} \right] \).

2.2. Girhammar's Model

The equation for the maximum deflection of simply supported SCC beam, subjected to uniformly distributed load \( w \), considering partial composite action as proposed in [3] is as follows

\[ \Delta_{max} = \frac{5wl^4}{384EI_f} + \frac{w}{a^4EI_f} \left( \frac{EI_f}{\sum EI} - 1 \right) \left[ \frac{1}{\cosh \left( \frac{aL}{2} \right)} + \frac{1}{a^2} \right] \]  

\[ \alpha^2 = K \left[ \frac{1}{E_C A_C} + \frac{1}{E_S A_S} + \frac{(h_c + h_s)^2}{\sum EI} \right] \]  

2.3. Nie's Model

The equation for the deflection of the SCC beam considering shear connection slip effect as proposed in [4] is as follows

\[ \Delta_{max} = \frac{5wl^4}{384EI_f} + \beta w \left( \frac{L^2}{8h} + \frac{2e^{\mu L} - 1 - e^{\mu L}}{\mu h (1 + e^{\mu L})} \right) \]  

where: \( \mu = \frac{K}{A_S E_S \mu_L S} \); \( \beta = \frac{A_1 (h_c + h_s) p}{K} \); \( A_1 = \frac{A_0}{l_0 + A_0 (h_c + h_s)^2} \); \( A_0 = \frac{A_S A_C}{n A_S + A_C} \); \( I_0 = \frac{l_c}{n} + l_s \); \( n = \frac{E_S}{E_C} \).

3. Numerical Modelling

Numerical modelling has been carried out using commercially available tool such as SAP2000 [6]. In the model, both the concrete part and the steel part are modelled as beam element and the shear connectors are modelled as spring element. A linear load-slip relationship has been assumed for the shear connectors at service loads. Spring element provides connection with flexibility in two perpendicular directions. A finite stiffness value, \( K \) is provided along the span of the bridge and very high stiffness in other direction. At service load, the stress-strain relationship for structural steel and reinforcement is assumed to be linear. For concrete, the stress-strain relationship is assumed to be linear in compression, which is generally applicable at service load. A typical numerical model of a SCC girder is shown in the Figure 2.
4. Parametric Study

The parametric study carried out here, involves the analysis of SCC girders designed according to IRC:22-2008 [7]. The various design parameters along with pertinent values of parameters considered in the study are tabulated in Table 1. The grade of the steel used is $f_y=250\text{N/mm}^2$. The loading on SCC girder inclusive of live load and dead load, for the span 10m, 15m, 20m, 25m, and 30m are respectively taken as 36kN/m, 36.5kN/m, 37kN/m, 38kN/m, 39kN/m. The cross section of the steel section for different spans which is designed as per IRC22:2008 [7], is given in Table 2.

Table 1. Design parameters and their values considered in the study

| Design Parameters                              | Considered Values |
|-----------------------------------------------|-------------------|
| Span length (m)                               | 10,15,20,25,30    |
| Thickness of the slab (mm)                    | 150,175,200,225,250 |
| Ratio between bottom flange to top flange    | 1,1.5,2,2.5       |
| Degree of shear connection                    | Rigid, 1, 0.9, 0.8, 0.7, 0.6 |
| Concrete Grade(N/mm²)                         | 25, 30, 40, 50    |

a Shear connectors are assumed to be infinitely rigid and the analysis is performed by transforming the composite cross section

b Number of shear connections required for the full composite action
c Concrete grade is the characteristic compressive strength of concrete cube tested at 28days

Table 2. Steel cross section details for various spans

| Span Length (m) | Top flange width (mm) | Top flange thickness (mm) | Bottom flange width (mm) | Bottom flange thickness (mm) | Web depth (mm) | Web thickness (mm) |
|-----------------|-----------------------|---------------------------|--------------------------|------------------------------|----------------|------------------|
| 10              | 200                   | 20                        | 200                      | 20                           | 600            | 8                |
| 15              | 250                   | 25                        | 250                      | 25                           | 850            | 8                |
| 20              | 300                   | 30                        | 300                      | 30                           | 1000           | 10               |
| 25              | 350                   | 35                        | 350                      | 35                           | 1200           | 10               |
| 30              | 400                   | 40                        | 400                      | 40                           | 1300           | 12               |

5. Results and Discussion

The analysis of SCC girders considering various design parameters has been carried out using SAP2000 and the effects of various parameters are discussed here. The results thus obtained from the numerical models are compared with various analytical models discussed above.

5.1. Effect of partial composite action

The partial composite action or degree of shear interaction is defined as the ratio of number of shear connectors provided to the number of shear connectors required for the full composite action. Here it is to be noted that, the degree of interaction is merely obtained by changing the spacing of the shear connector with respect to full composite action, without compromising the minimum spacing criteria as per IRC22:2008[7].

Figure 3, shows the effect of the degree of interaction on the deflection of SCC girders. The graph is plotted between the mid span deflection of the composite girder and the degree of interaction for a given span of 20m, grade of concrete of $40\text{N/mm}^2$ and the dimensions of concrete of 2500mm X 200mm and steel component (refer Table 2). It is observed from the figure 3, that the deflection increases with decrease in degree of interaction. It is also observed that the deflection is sensitive to the shear connector's ductility, because even for the full composite action there is an increase in the deflection with respect to rigid composite action. It is seen that the results of the numerical model closely match with the Nie's model [5], whereas the results of the Bradford's model and Girhammer's model [2-3] are on conservative side.
5.2. Effect of span length
Figure 4a, shows the plot between the mid span deflection of a SCC girder and the variation in span length for given degree of interaction of 0.8, grade of concrete of 40N/mm² and dimensions of concrete of 2500mmX200mm and steel component (refer Table2). It is seen that the deflection of the SCC girder increases with span. It is also seen from figure 4b, that the increase in deflection decreases with increase in span length. Here also it can be seen that the results of the numerical model closely match with the Nie's model [5], whereas the results of the Bradford's model and Girhammer's model [2-3] are on conservative side.

5.3. Effect of geometry of steel section
In this study the ratio of area of bottom flange to the top flange is varied from 1 to 2.5, for a given span length of 20m, degree of interaction of 0.8, grade of concrete of 40N/mm² and geometry of
concrete deck of 2500mmX250mm, to see the effect of geometry of steel section on the deflection. It is observed from the figure 5 that there is considerable increase in percentage deflection with increase in bottom flange area. This increase in deflection is because the neutral axis shifts downwards.

Figure 5. Effect of geometry of steel section on the deflection of SCC girder

5.4. Effect of concrete grade and concrete deck dimension

Figure 6 shows the effect of grade of concrete for a given span length of 20m, degree of interaction of 0.8, concrete component (2500mmX200mm) and geometry of steel (refer to Table 2), on the deflection of SCC girders. Here the grade of the concrete is varied from 25N/mm² to 50N/mm². Here the graph is plotted between the decrease in deflection (in percentage) w.r.t. to rigid shear connection and concrete grade. It is observed from the figure 6 that with the increase in concrete grade there is decrease in deflection. But this decrement in deflection is trivial. A similar observation is also made for effect of change in concrete deck dimension on the deflection. It is seen that the results of the numerical model closely match with the Nie's model [5], whereas the results of the Bradford's model and Girhammer's model [2-3] are on conservative side.

Figure 6. Effect of concrete grade on the deflection SCC girder
6. Conclusions
In this work a comparative study has been carried out between various available analytical models and numerical model. A parametric study has been carried out considering aforementioned parameters to understand the significance of partial composite action on the deflection of SCC girders. Following are the concluding remarks of the study.

1. As anticipated the deflection of the SCC girder increases with decrease in partial composite action. The increment in deflection w.r.t. rigid connection is about 12% for full composite action and is about 20% when the degree of interaction is 0.6.

2. The deflection of SCC girder is sensitive to the ductility of the shear connector, because it is observed that even for the 100% composite action (i.e., the number of shear connectors required for the full composite action) there is increase in the deflection w.r.t. rigid shear connection.

3. It is observed that there is decrease in percentage increase of deflection with increase in span length. The decrement was from 27% for 10m span to 10% for 30m span. This shows that the partial composite action is more sensitive to the composite girders of smaller spans.

4. It is also observed that there is significant increase in percentage increase of deflection w.r.t. rigid shear connection with the increase in the ratio of bottom flange area to the top flange area of the steel section. The increase in percentage deflection was from 11% when the ratio is 1 to 17% when the ratio is 2.5. This increment is attributed to shifting of neutral axis towards bottom flange.

5. The deflection of the composite girder decreases with the increase in concrete grade. This effect is not significant.

6. The results of the numerical model closely match with the results of the Nie's models [5], whereas the results of the Bradford's model and Girhammer's model [2-3] are on conservative side.

Here all the analyses have been performed assuming the uniform distribution of the shear connector. The analysis may be extended to the non-uniform distribution of the shear connector which is practically and economically more feasible.

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