Flexural Capacity of Composite Beams (Steel & Concrete) – A Review

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ABSTRACT: *Many researchers have been working on the flexure capacity of composite steel and concrete beams and found out various studies on the same. This work gives the review of work done by various researchers who investigated the flexural capacity of composite steel and concrete beams and the behavior of composite slabs subjected to shear and bending. The review revealed the advantages of composite construction & the most effective utilization of steel and concrete. It was seen that a more prudent and efficient steel section is adequate in composite construction as compared with the traditional non-composite construction and deflect less as compared to steel beams; keeping the span and loading unchanged. They also have improved fire and corrosion resistance.*

Keywords: *beam, bending, composite, concrete, flexural capacity, shear, steel.*

I. INTRODUCTION

Composite construction brings about paramount benefits by making concrete as well as steel work together. The advantages of composite construction as per the various literatures are:

- Get a brisk erection of the steel framework.
- Vigour to damage and satisfying performance in service.
- Weight and cost of materials are reduced to a great extent.

In contemporary composite construction, firstly the steel framing elements are hoisted, thereby making a substantial structure suited for supporting different construction loads. The composite action progresses later with the concrete or other material provides resistance to imposed loads, and more eminently, to improve the stiffness/ rigidity of the construction. Commonly, the serviceability criteria influence the modern design for which control of deflections and vibration response are equally important as load resistance. The prime intention is to explore the ingenious composite construction technology in which steel sections act compositely with in-situ concrete. This will in turn lead to escalated speed of construction, lengthy or much longer spans, more economy of materials and better efficacy in service, especially in low-rise and medium-rise buildings.

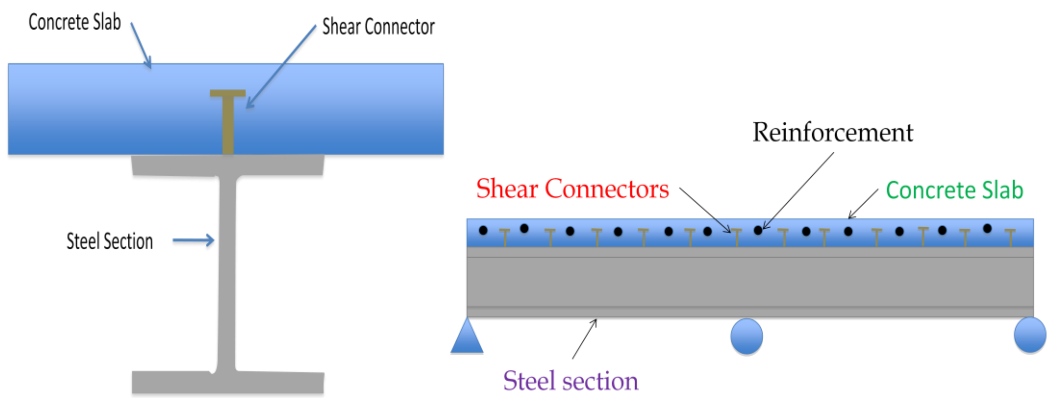
In traditional compound construction, the concrete slabs are seated over the steel beams and are bolstered by them. Under the impact of the loads, the two components act individually and a relative slip happens at the interface if there is no association between them. The slip between the beam and the concrete slab can be ignored with the assistance of an arranged, planned and proper connection provided between them. The steel beam and the slab act as a “composite beam” in such a case and their performance is comparable to that of a monolithic T-beam. Steel and concrete are the most usually used materials for composite beams; other materials like pre-stressed concrete, aluminum, foam core and timber can also be used. Concrete is much stronger in compression than in tension, and in compression, the steel is vulnerable to buckling. By the composite action between steel and concrete, we can exploit their corresponding advantages to their complete scope. Usually in steel-concrete composite beams, steel beams are elementally connected to pre-fabricated or cast in-situ RC slabs as shown in Figure 1(a) & (b).

This work gives the summary of the work of various researchers in the past who have carried out the studies on the flexural capacity of composite steel and concrete beams. Their findings have been reviewed in details and subsequent conclusions have been drawn.

II. Literature Review

In the past, most of the researches have been executed for the flexural capacity of composite steel and concrete beams. Various models have been developed to explore the behavior of composite beams subjected to different action of shear and bending. Also many numerical procedures were proposed to calculate the behavior of steel concrete composite continuous beam and had been experimentally investigated. This section gives a detailed review of the literatures studied during the work.

Al-deen, S. et al. [1] studied the three sets (CB1, CB2, CB3) of full-scale experiments for evaluating the long-term behavior of composite steel-concrete beams. They were designed carefully and the long-term response of the composite members was administered by checking the differences in deflections, curvature, strain and slip which is happening over the time. To know the material properties of each specimen, standard tests were implemented on concrete, steel and shear connectors. Three comprehensive simply-supported composite beams with concrete (solid) slabs having indistinguishable spans and cross-sections were produced and then tested in the first set of trials.



(a) (b)

Fig.1: (a) & (b) Composite beam

At the point of pouring, the deflections for CB1 and CB2 measured were almost same and at 29 days the deflections measured for CB2 and CB3 were 15.14 mm and 22.94 mm, respectively where the change was because of the external loading. The second set of experiments (CBS1 & CBS2) two comprehensive/full-scale simply-supported composite beams with composite slab instead of a solid one were produced and then tested. At the point of pouring, the deflections measured represented the deformation due to self-weight and the wet concrete just after casting process. Due to the shrinkage in concrete, there was a rise in deflection over time in both the beams. The long-term testing of a two span continuous composite beam was involved in the 3rd set. At the internal support, a web site plate connection was fixed and the supported solid concrete slab was continuous over the connection. In view on the established applied load and the measured support reactions, the BMD of the beam was plotted. After the application of the superimposed loads, the concrete at the middle support cracked, thereby reducing the rigidity/stiffness of the member in the hogging moment zone. The results of the two mid-span spontaneous deflections were moreover akin, substantiating the symmetric behavior of both the spans. Thus, all the experiments showed appreciable rise in the beam deflection with time because of the creep and shrinkage in concrete.

AL-Latef Numan, H.A. [2] studied the linear behavior of continuous composite concrete-steel beam with partial limited connection connected by stud shear connectors. By using the forces and displacements at as the assumed elements, the equilibrium and compatibility equations were derived. While deriving the equations, it was observed that the basic equilibrium and compatibility equations of analytical model for the investigation of continuous composite beam with interlayer slip was decreased to a single 2^{nd} order differential equation in particular to the interlayer slip rather than the axial forces. The solutions of the basic equations were achieved by asserting the derivatives in finite difference form. He concluded that the numerical solution achieved showed a close understanding with the current theoretical solution, that assumed linear material and shear connector behavior and the assumption of ignoring the concrete strength at the zone of negative moment was compelling. The finite difference method (FDM) was used even at short intervals with adequate endurance as the main differential equations were of the 2^{nd} order.

Chen,S., and Jia,Y. [3] carried out a study on the composite beams which are continuous over the internal support with a homogeneous section along the beams. It was depicted that the appropriate moment redistribution for the beam raises as the ratio of negative to positive moment resistance reduces, but lessens as the span difference or the change in load in the two spans rises. They developed an approach to determine the available moment redistribution at the notional plastic hinges of a composite beam based on the rotation capacity. The likely moment redistribution was evaluated in a continuous composite beam when the available rotation capacity at the notional hinge failed to satisfy the appropriate capacity of a plastic design. It has been come to notice that to develop full plastic design for a continuous composite beam; the available moment redistribution for the beam should be either greater than or at least equal to the moment redistribution required. Thus, the full moment redistribution in the beam was adequate from the hogging zone to the sagging zone. They illustrated the approach by giving an example of a two span continuous composite beam loaded under a uniformly distributed load. It was calculated that the plastic moment resistance of a composite section reserved a post yielding strength. The conservative based on the Euro code rule was rationalized in most of the cases. The study formulated a design method to evaluate the load carrying capacity for a continuous composite beam depending upon the available moment redistribution required and the rotation capacity or the force ratio etc. rather than a fixed value of the moment redistribution proposed, so that in utmost situations an economic and efficient design was capable.

Chiewanichakorn, M. et al. [4] extensively studied the effective flange width of a composite section, made up of a concrete slab fixed to a steel girder by the means of shear connectors. The traditional effective flange width theory was formulated as an uncomplicated approach to assess the deflections as well as stresses, and not capacity or resistance. Hence, the consequences of the shear-lag phenomenon at the strength limit state were distinct from those at the serviceability level. A total Compressive force in the slab was essential to decide the effective flange width of the section. There were 2 main inferences made and held throughout the effective flange width calculations: (i) BM computed from the FEM analysis and elementary beam theory was presumed to be the identical, and (ii) the equilibrium of section forces and moment was constantly controlled. They recognized that FEM approach provide the most resourceful method of analysis for precise structural behaviour forecasting. The verification of the FEM scheme was accomplished by correlating the results/conclusions generated by the ABAQUS software to those obtained from experimental evidences.

Crisinel, M., and Marimon, F. [5] studied an advanced design approach for the forecasting the composite slab behaviour. This approach combined the results from standard materials tests and small-scale tests with a simple mathematical model to find out the moment–curvature relationship at the critical cross-section of a composite slab. For the same, the researchers used Euro code 4 in which two design methods for verification of composite slabs were described i.e. the shear-bond method and the partial connection method, which are based on a test program composed of at least six full-scale slab specimens and it became very expensive to conduct these tests. Since the two methods have a semi-empirical nature, neither model could result in a fair portrayal of the physical behaviour of the steel–concrete connection which led to the need of developing a design model with associated design rules based on a more physical interpretation of the connection behaviour. In the study conducted, the researchers modeled steel sheeting as an I-section with same area and moment of inertia as the original sheeting section. Correspondingly, the concrete was modeled as a rectangular section. The behaviour of the composite slab was determined at the critical cross-section i.e. at the location of the maximum sagging moment. The FEM model was validated through correlation with large-scale tests and the relationships were related at the critical cross-sections of simple span composite slabs loaded by two concentrated forces at the quarter spans. The comparative study revealed a very good correlation between the numerical simulations and the simplified method evolved and good agreement between the calculated moments and moments that were obtained from the slab bending tests (at the first slip and ultimate load levels).

Jasim,N.A., and Atalla,A. [6] investigated a elementary approach to assess the deflections at midpoints of the different spans of continuous composite beams having partial shear connection. The principle of superposition was utilized during the study so that the deflection was assessed regardless of the type of loading, the number and the length of spans of the continuous beam. The substantive continuous beam was illustrated by a series of single span beams for which the deflections were pre-determined by using a linear partial interaction theory. The composite beam was presumed to be made up of two materials (elastic) having same elastic modulus in tension and compression. The shear connectors (smeared along the beam) were equally spaced along the beam having equal moduli. The load–slip characteristic of the connectors was considered to be linear and there was no partition between the concrete slab and steel beam. In the proposed method, the inference that the redundant moments at the internal supports have same values for both the partial and full interaction cases was used. Therefore, for calculation of deflection at the midpoint of an internal span of a partially composite beam was required. The specified span was replaced by three single span beams (1 simply supported plus 2 propped cantilever beams) each with a relevant ratio of the total load, w. The fixed end moments of the propped cantilevers provided the end moments M_i and M_j of the actual span. The deflection at midpoint, y_p, of the actual span was obtained by taking the summation of deflections of the three single span beams i.e. $y_p= y_{1p}+y_{2p}+y_{3p}$. It was also pointed out that the proposed method needed two charts to calculate the deflections of partially composite continuous beams (one for the simply supported beam and other for the propped cantilever) which may be used regardless of the configuration and the type of loading. The results acquired totally concurred with those given by the precise solution of the governing differential equations.

Khatri, V. et al. [7] studied the differences in the cost between the bridge designs using conventional mild steel Fe 410, high tensile steel Fe 590 and a combination of Fe410 and Fe590. The span supported and un-supported cases during construction were considered for the study. The maximum deflection, maximum flexural stresses, weight of the specimen and cost were compared for 40m span steel-concrete composite bridge for both the unsupported and supported cases during construction. It was found that hybrid steel girders are most economical, for which there is a saving of about 34.7% in steel weight and 29.1% in steel cost in comparison to the mild steel girder bridge for the un-supported span case, while in supported span case it is 50% and 46%, respectively. However, the maximum deflection was found to rise more than two times the permissible deflection i.e. L/600 for total dead and live load, for both HPS as well as hybrid steel girder in resemblance to the mild steel girder. This clearly showed the span length has a direct effect on the deflection, stresses and the cost of the bridge.

Kim, H.Y. and Jeong, Y. [8] studied the ultimate behaviour of a steel concrete composite deck slab system having profiled steel sheeting and perfobond rib shear connectors. The main objectives of the study was to establish a composite deck slab for girder bridges that has the property of longer spans and less weight than the traditional RC deck slab and to experimentally substantiate the proposed deck slab system. A series of structural tests were performed; 8 deck specimens were fabricated and tested with various shear spans for assessing the horizontal shear capacity of the proposed deck system. The test results were elaborately correlated with the results of a simple mechanic equation. The other properties such as load deflection behaviour and the ultimate load carrying capacity of the proposed deck specimens was also related to the behaviour of the RC deck specimens tested. Two full-scale deck slab specimens supported by a set of steel box blocks were constructed and tested to find out the ultimate load carrying capacity under sagging and hogging bending actions. The specimen1 was subjected to a three-point load while specimen 2 was subjected to a two-point load in the loading scheme during the test. From the various results obtained, it was evident that the predicted that for the proposed deck, the horizontal shear resistance was nearly two times greater than the required horizontal shear strength. The ultimate strength and initial concrete cracking load hogging bending action was nearly 2.5 and 7.1 times greater than those of an RC deck, respectively, while the deck weighed nearly 25% less than RC deck systems. This clearly showed that there was greater horizontal shear strength and ultimate strength for a composite section as compared to conventional section.

Lloyd, R. M., and Wright, H. D. [9] studied the impact of changing the fundamental through-deck push-out test parameters so as to propose a definitive configuration for such tests and the response of the practical sheeting-joint details on the connection strength. 42 through-deck push-out tests were conducted on specimens that were made up of trapezoidal profiled steel sheets and headed shear connectors. The significant variables examined were the following: slab width, slab height, and the amount and position of reinforcement. Tests were regulated to examine the impact of applying transverse loading to the slab during the test. It was found that the resistance of through-deck welded shear-stud connectors cast in slabs with profiled steel sheeting as permanent formwork was directly depending upon the stud height as well as geometry of the sheeting. The ultimate resistance of the connection between the slabs and the steel beam were significantly less than the connection in solid slabs. It was recommended that at least three full pitches of the profile under consideration were used for a standard size of test and a width of 200 mm wider than that computed was used, which varied with the geometry of the profile and the height of the stud. Also, a traditional square slab was selected as a standard for future tests. It was concluded that variations in size and position of reinforcement had no appreciable impact but the transverse slab bending had limited effect on the ultimate connection resistance.

Nie,J., and Cai,C. S., [10] examined the impact of shear slip on the deformation of steel–concrete composite beams. The equivalent rigidity of composite beams considering three different loading types was derived found on equilibrium and curvature compatibility, through which a universal formula was then developed to justify the slip effects. Six specimens were prepared having concrete flange of 500 and 800 mm and the beams were tested with different loading conditions e.g. two point loads are placed on two beams, one point load on two beams and two continuous beams with one point load on each span. The following observations were made during the testing: (a) The maximum slips were noticed near the ends of beam, (b) the association of load and slip was reasonably linear when $P/P_u < 0.6$, where P_u is the ultimate capacity but with the gradual raise in loading, the relationship became eminently non-linear, (c) the pitches of the shear studs had compelling impact on the slip, (d) the transformed section method without taking into consideration the slip effects predict the deflection. In comparison, the formulas formulated in the study predicted very near results to the measurements. The section rigidity near the supports (0.15L of each side of the supports) for continuous beams was diminished by taking into consideration only the inputs from steel beam and reinforcement. A comparison of the study and AISC specification was extensively carried out and was observed that even for the full composite section, the study predicted a reduction up to 2% for section modulus (Z) and from 3% to 17% for moment of inertia (MOI). For 50% composite, the study forecasted up to 3% and 26% reduction in Z and MOI, respectively, compared with up to 13% and 24% for AISC specifications. Similarly, for 25% composite, the study forecasted up to 5% and 33% reduction in Z and MOI, respectively, compared with up to 23% and 41% for AISC specifications. The slip effects were overlooked in many design specifications except that AISC specifications recommended a calculation procedure in the commentary. For full composite sections, the effective Z and MOI estimated with the AISC specifications were greater than that of the study reviewed i.e. the specifications are not on the conservative side. For partial composite sections, the AISC predictions were more conservative than that in the investigation done by Nie,J., and Cai,C. S.

Nie,J. et al. [11] studied negative bending zones near the interior supports, tension in concrete being objectionable and a intricate problem. They set up a mechanics model in view of the elastic theory to examine the stiffness of composite beams in negative bending zones by taking into consideration the slips at the steel beam–concrete slab interface and concrete–reinforcement interface. In order to substantiate the approach, a test of three composite beams with profiled sheeting under negative bending and a 3-D non-linear finite element (FE) analysis was conducted to examine the normal action of the tested specimens. When compared the load deflection response at mid-span between FE analysis with/ without slip effect and experimental measurements, it clearly exhibited that the results obtained from the FE analysis were in accordance with the results obtained from the experiments in view of both the maximum load capacity as well as stiffness. Due to the lower degree of shear connection and more slip, there was an increase of reinforcement which increased the ultimate strength. Simultaneously at the working load range, it reduced more stiffness in comparison to the beams with full shear interaction. It was also concluded that higher the stiffness of the stud connectors and bond–slip stiffness at the reinforcement–concrete interface, the higher will be the flexibility stiffness of the beam in the beginning phase of loading. When the steel beam and the reinforcement began to yield, the slip had little impact on the load capacity of the beam.

Seleim and Schuster [12] carried out an extensive study to find out the ultimate shear-bond equation for composite slabs failing in shear-bond. The equation was based on experimental tests that were performed on the composite slabs demonstrating the early end-slip precedent to ultimate load, and contained the steel deck thickness as a parameter that other existing equations did not, which resulted in a decline of up to 75% of the no. of laboratory performance tests that were required. The characteristic behaviour of both steel and concrete was assumed to be identical as in reinforced concrete (RC). Experimental tests on 196 one-way composite slabs (simply supported and subjected to two symmetrically placed line loads) failing in shear bond were performed. The data comprised of nine different groups from four different manufacturers given a three-digit identification number for each. For each group, steel decks with different steel deck thickness were given the same data group number. Test results were used to substantiate and correlate the results of the equation developed with other existing equations. The results also showed that the results from the equation developed ere always within +15% of the corresponding experimental results. It was also observed that the percent of steel and the concrete compressive strength did not have any apparent impact on the ultimate shear-bond capacity. The shear span is the only possible variable influencing the ultimate shear-bond capacity of composite slabs of the same product type and thickness of the steel deck.

Tesser L. and Scotta R [13] studied the flexural and shear capacity of composite steel truss and concrete beams with inferior pre-cast concrete base. In their work, the researchers presented a set of 24 lab tests on 12 composite steel truss and concrete beams. The experiments investigated the flexural as well as shear strengths of the beams with various width, depth, and transverse reinforcement inclination. The beams failure modes were studied concentrating on the crack patterns and on the interaction ‘tween concrete cast at various intervals and the gathered results were compared with analytical interpretations of common resisting mechanisms of steel-concrete composite and RC structures using updated European and American design Standards. These helped in getting the most effective utilization of steel and concrete to get fairly good flexural and shear capacity.

Thomas N. et al. [14] carried out a study to find out the flexural capacity of composite beams using Truss beams (M25 grade of concrete) under two-point loading with a span of 2m. Beam consists of top and bottom chord (8 mm dia. And Fe250 grade of steel) with cold formed light gauge steel plate (width 100 mm and thickness varying from 1.5mm to 2mm) and light gauge angle section welded at the ends of the plate were tested. A comparative study was made between truss beam and composite beam and various tests were conducted to assess the ultimate load carrying capacity, flexural strength, ultimate deflection, displacement ductility for different thickness. From the result obtained, it was observed that for truss beams as the thickness varied from 1.5mm to 2mm load carrying capacity increased by 1.08 times but when the same truss beam encased by concrete then the load carrying capacity raised by 2.26 times. When concrete was encased and thickness was increased load carrying capacity increased by 2.6 times. There was a change in displacement as well, the displacement ductility factor increased by 4.8% for truss beam but when concrete was encased displacement ductility factor increased by 76.47%. There was also a remarkable change in the flexural strength and thus, a marginal increase in load carrying capacity, flexural strength, displacement ductility occurred after encasing concrete.

III. CONCLUSION

There are various advantages related to the steel concrete composite construction which could be seen from the literatures reviewed. They are as follows:

- The most compelling utilization of steel and concrete is achieved.
- There was a marginal rise in load carrying capacity, flexural strength, displacement ductility after encasing concrete as seen by the study done by Thomas N. et al. [14].

- Keeping the span and loading unchanged; a more economical and efficient steel section in view of depth and weight is competent in composite construction in comparison to the conventional non-composite construction.
- The construction depth gets reduced as the depth of beam lowers which results in enhanced headroom. This could create more aesthetic value to the building.
- Due to its larger stiffness, there is less deflection in the composite beams than the steel beams.
- Composite construction provides efficient and productive arrangement to cover large column free space.
- Composite construction is susceptible to "fast-track" construction due to the use of rolled steel and pre-fabricated components, rather than cast-in-situ concrete.
- At the initial stage of loading, there was a greater flexibility stiffness of the beam in case of composite beams.
- Encased steel beam sections have improved fire resistance and corrosion.

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