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New Techniques of Analysis and Design of Composite Steel-Concrete Structures

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***Abstract*— Composite steel–concrete construction has become quite popular in several countries due to significant economy through reduced material, more slender floor depths and faster construction. In composite construction, the floor slabs are cast on permanent steel formwork, which acts first as a working platform and then as bottom reinforcement for the slab. The slabs are supported on the composite steel beams. Also the columns are made either by steel or encased steel member inside the concrete, which acts as a composite member. However, incorporation of many aspects of concrete-steel behavior such as nonlinear multi axial stress-strain response, dilatancy phenomenon, cracking, stain softening, and stress transfer mechanisms between steel and concrete leads to complicated and highly nonlinear behavior. Simplifying assumptions for the interaction between the concrete slab and the steel beam has helped to establish composite construction as an easy to handle extension of the bare steel construction. This paper outlines some recent trends in the analysis and design of composite structures followed by the work carried out by the authors.**

I. INTRODUCTION

The most important and most frequently encountered combination of construction materials is that of steel and concrete, with applications in multi-storey commercial buildings and factories, as well as in bridges. These essentially different materials are completely compatible and complementary to each other; they have almost the same thermal expansion; they have an ideal combination of strengths with the concrete efficient in compression and the steel in tension. Concrete also gives corrosion protection and thermal insulation to the steel and additionally can restrain slender steel sections from local or lateral-torsional buckling. Unfortunately these two important building materials, steel and concrete, are promoted by two different industries. Since these industries are in direct competition with each other, it is sometimes difficult to promote the best use of the two materials.

It should be added that the combination of concrete cores, steel frame and composite floor construction has become the standard construction method for multi-storey commercial buildings in several countries. Much progress has been made, for example in Japan, where the structural steel/reinforced concrete frame is the standard system for tall buildings. It is best suited to resist repeated earthquake loadings, which require a high amount of resistance and ductility. In spite of wide acceptance of composite construction in the advanced countries, the method is yet to become popular in India. Exposure and experience of majority of professionals in India to steel-concrete composite design is considered to be low.

British and Eurocodes [1] specify that the design shall be done considering limit state by applying appropriate factors for the ultimate limit state and serviceability limit state. The recent relevant Indian code for steel design i.e. IS 800-2007 [2] is based on the concept of limit state analysis. To keep the pace with efficient design methodologies and optimum utilization of materials as in vogue in the advanced countries it is essential to modify the IS 11384-1985 [3] also.

Over the last few years substantial body of experimental data on the influence of the composite floor on the behavior of the beam to column joints has been developed with the aim of developing a general understanding of behavior of composite structures leading to the ability to predict performance. However, laboratory tests require a great amount of time and are very expensive. The finite element method, on the other hand, has become in recent years a powerful and useful tool for the analysis. This paper discusses some of the macro models(line elements) and micro models (2D/3D elements) proposed by some of the researcher for the analysis of steel-concrete composite structures after giving a brief overview of the design and construction aspect of the same.

II. COMPOSITE SLAB AND BEAMS

Composite deck slab comprises of profile steel decking as the permanent formwork to support the underside of the concrete slab spanning between supporting beams. The steel decking by it self supports loads applied to it before the concrete gains adequate strength. The decking can be easily handled, can be cut to the required length and openings can be formed. The steel sheeting used is normally 0.9 mm to 1.5 mm galvanized coil and is generally about 50 mm deep with pitch of corrugation between 150 mm and 350 mm. The decking usually spans 2.5 m to 3.5 m and has to support the construction loads by itself along with the weight of wet concrete. The total depth of slab is normally around 130 mm to 150 mm. Composite beams consist of steel section acting compositely with slab of reinforced concrete. The two

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materials are interconnected by means of mechanical shear connectors. The actual construction work of composite floor deck is carried on site as shown in **Fig.1.** For single span beam, sagging bending moment, due to applied vertical load, causes tensile forces in the steel section and compression in the concrete deck thereby making optimum use of each material.

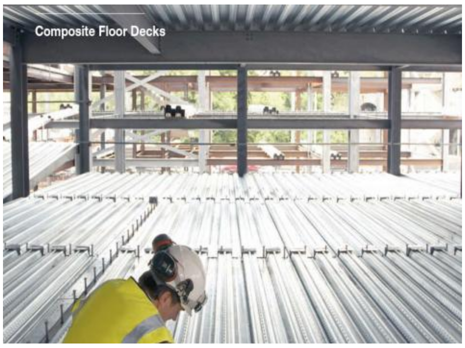
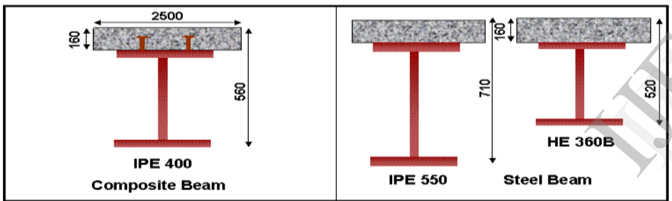


Fig.1 Construction of Composite Floor Deck

In particular, a composite beam has greater stiffness and usually a higher load resistance than its non-composite as indicated in **Fig. 2.** Instead of an in situ concrete slab, precast concrete floor or deck units can be used. The use of precast deck units reduces on-site construction operations and avoids wet trades. The units themselves are cast on steel formwork in a shop to ensure high quality.



Load Resistance	100 %	100 %	100 %
Steel Weight	100 %	160 %	215 %
Overall Height	100 %	130 %	95 %
Stiffness	100 %	70 %	45 %

Fig. 2 Comparison between Composite and Steel Beams

Figure 3 depicts the possibilities to provide an interlock between steel and concrete:

- **Frictional** interlock shown in Fig. 3 (a-b) is not able to transfer large shear forces.
- **Mechanical** interlock (Fig. 3 (c-d)) is achieved by interlocking embossments of the steel decking.
- **End anchorage** like headed bolts, angle studs or end-deformations of the steel sheeting as shown in Fig. 3 (e-f) introduces concentrated load at the ends and therefore results in a sudden increase from the bare steel to the omposite resistance.

III. SHEAR CONNECTION

The shear force at the interface between concrete and steel is approximately eight times the total load carried by the beam. Therefore, shear connector are required at the interface. It is current European practice to achieve shear connection by means of headed studs, semi-automatically welded to the steel flange as shown in **Fig. 4**. Mechanical connectors are used to develop the composite action between steel beams and concrete. This connection is provided mainly to resist longitudinal shear, and is referred to as the "shear connection". Shear connectors must fulfill a number of requirements such as: (i) They must transfer direct shear at their base, (ii) They must create a tensile link into the concrete, and (iii) They must be economic to manufacture and fix.

Fig. 4 Semi-Automatically Welded Headed Studs

Composite beams are often designed under the assumption that the unpropped steel beam supports the weight of the structural steel and wet concrete plus construction loads. It may, therefore, be decided for reasons of economy to provide only sufficient connectors to develop enough composite action to support the loads applied afterwards. This approach results in less number of connectors than are required to enable the maximum bending resistance of the composite beam to be reached. The use of such partial shear connection results in reduced resistance and stiffness.

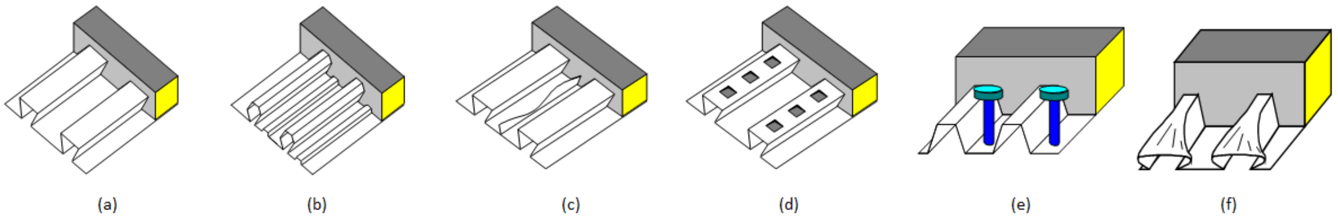


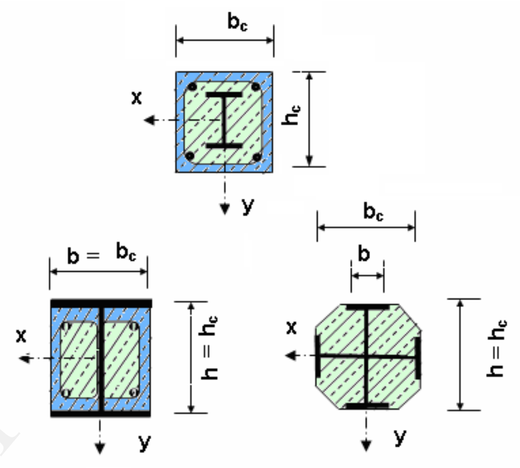
Fig. 3 Different Type of Interlocks

IV. Beam-To-Column Connection

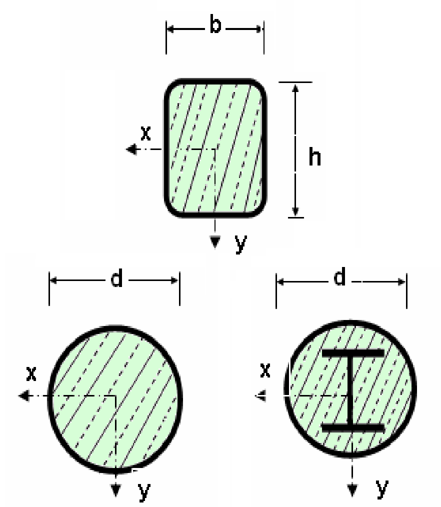
Highly developed connection techniques can be used for connecting together structural steel members. Economy requires, however, that the joints are economic to fabricate and straightforward to install on site. Studies have indicated that the cost of composite structures may be improved, if the actual degree of continuity provided by nominally simple joints is recognised in design. In composite steel-concrete structures, significant additional stiffness and resistance can be provided simply by placing continuous reinforcing bars in the slab around the columns. This effect can be augmented by a special sequence of construction and concreting, as follows: during concreting the steel section acts as a single span beam; the beam should be connected to the steel column by means of double web angles or flange cleats with or without web angles; after the concrete has hardened it is considered as a continuous beam supporting the additional applied loads. By following this construction sequence, the required bending moment redistribution is not extensive and plastic rotation can be reduced.

V. Composite Columns

Different types of composite columns in use are as shown in **Fig. 5.** In calculating the strength of such columns, full composite interaction without any slip at the steel-concrete-interface is assumed. The complete interaction must be ensured by means of mechanical connections. The connections have to be provided at least at the column ends and where loads or forces are acting. They should be distributed over the whole cross-section. Such connectors can be headed studs, top and bottom plates, suitable brackets, vertical gusset plates, shear heads or other structural means. Concrete encased columns have the advantage that they meet fire resistance requirements without any other protection. In addition, they can be easily strengthened by reinforcing bars in the concrete cover. They do not, however, present an accessible structural steel surface for later fastenings and attractive surface treatment. In the case of prefabricated encased columns, the structural steel sections are fabricated in a workshop and include all welds, connection plates and other necessary attachments. These steel columns (the longest have been up to 30 m long) can then be transported to another workshop, where concreting takes



(a) Concrete Encased Composite Column



(b) Concert Filled Tubular Sections

Fig. 5 Different Types of Composite Columns place. After curing the completed columns can be brought to the construction site.

Concrete filled steel tubes are also in use. The tubes are generally filled with high strength concrete, with minimum cube strength of 45 to 55 N/mm^2. These strengths, however, are far below those which have been developed recently in North America. If the bearing forces from the floor beams are transferred by means of vertical connection plates, these plates run through the tube and are welded on both sides. This welding ensures both parts, the steel tube as well as the concrete core, are loaded directly without excessive slip at the steel-concrete interface. In order to meet the required fire resistance rating, the concrete core must be longitudinally reinforced. It is impossible, however, to take advantage of the full column resistance in many cases.

VI. TRENDS IN ANALYSIS OF COMPOSITE SRUCTURE

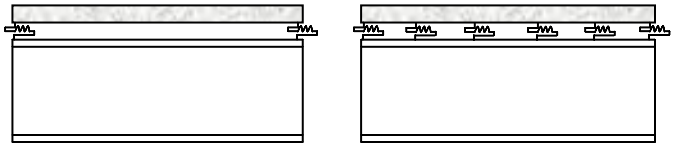
Several frame elements have been developed specifically for steel-concrete composite structures. From the formulation point of view, the element properties can be derived using lumped or distributed approaches. In elements based on the lumped approach all inelasticity is considered to be concentrated at member ends as show in **Fig 6(a)**, and thus deal with inelastic materials behavior in approximate yet computationally efficient manner. In distributed models, on the other hand, the behavior is monitored along the member length as opposed to only at the ends as shown in **Fig. 6(b).** Thus, distributed models are more accurate but are computationally more expensive.

Further, element properties can be derived with and without slip between the steel and concrete components. The simplest model of partial bond uses different elements for the concrete and steel components and uses concentrated springs to model the connection as shown in **Fig 7(a).** The spring can model either the action of the shear stud connector for example in composite slab or the friction effects in a concrete filled tube. This model is simple to use but requires a large number of elements. More efficient model is based on distributed bond as shown in **Fig 7(b)**. It assumes the bond stress and bond slip are continuous along the contact surface. In this model the steel beam and concrete slab have the same vertical displacement and curvature. Separate displacement fields on the concrete and steel components are assumed and bond slip is automatically derived from compatibility. Cubic polynomials are used for vertical deflection and quadratic functions are used for the axial displacement in the concrete slab and steel beam. These assumptions lead to a quadratic bond slip distribution.

a) Lumped Model

b) Distributed Model

Fig. 6 Lumped and Distributed Models



a) Concentrated Bond b) Distributed Bond

Fig. 7 Concentrated and Distributed Bond Models

Modeling the joint response is complicated by internal force-transfer mechanisms that involve composite action between steel and concrete and exhibit strength and stiffness degradation under cyclic loading. Azizinamini et al. [4] conducted detailed finite element analysis to investigate the performance of a connection between steel beams and concrete filled tubes. The three dimensional model was analysed using ANSYS software. Concrete was modeled using brick elements while the steel tube was modeled using quadrilateral shell elements. Contact elements were introduced to allow the steel and concrete elements for preventing the element from piercing one another. Gap elements were provided at selected locations to allow slip between steel and concrete components. More recently, Alemdar [5] used a multi spring model to represent the inelastic cyclic behavior of partially restrained composite connections. Each spring represents one component of connection including bolts, steel angles, steel reinforcement, concrete compression struts etc. The model was found to give reasonably good results compared to test data.

A three dimensional finite element model was developed by Liang et al [6] using ABAQUS software to simulate the geometric and material nonlinear behavior of continuous composite beams. The four-noded doubly curved general shell elements with reduced integration were used to model the concrete slab, the flanges and the web of steel beam. Discrete stud shear connectors were modeled by using 3D beam elements. A typical finite element mesh used for modeling only one half of the beam span for the analysis of continuous composite beam is shown in **fig. 8.**

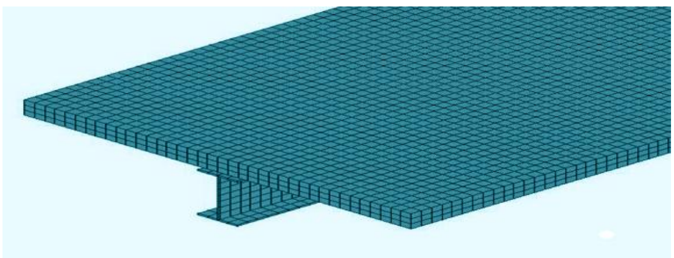


Fig. 8 Typical Finite Element-Mesh for Composite Beam

The models described above for composite beams, columns and joints can be combining and used to investigate the global behavior of composite systems. The whole systems can be represents using assembly of continuum finite elements. However this is rarely done because of not only the complications involved in modeling and analysis but also the high computational cost.

VII. Simplification Attempted

Although composite slabs are economic construction elements, the verifications that are required for their design (structural safety, serviceability) are long and complicated. This has led numerous researchers to develop methods so that engineer can do design immediately and verify the answer with number of alternatives. To simulate the behavior of the steel–concrete slab numerically, one has to include the material behavior of the sheeting, concrete, reinforcing steel, etc. as well as the characteristic mechanisms acting at the steel–concrete interface of the composite slab. A new design approach for the prediction of composite slab behavior is proposed by Panchal and Patodi [7] where Simulated and simplified moment vs. curvature relationships at the critical section for non-ductile and ductile composite slabs is used. Limit state for composite beams with solid slab or using profile sheet is considered. Based on this approach a software is developed with pre-, main- and post- processing facilities in VB.NET [8-9]. Steel table is also interfaced so that the designer can choose from the available sections directly. A program is also developed for the analysis and design of diffrent types of columns under various loading conditions [10]. Properly designed columns share significantly in the overall cost of the composite framed structures. A program developed based on

Genetic Algorithm (GA) for the optimization of steel-concrete composite columns gives cost effective composite section after checking large number of available alternatives. The use of the program is demonstrated by solving three different types of columns [11] considering total cost of column as the objective function to be minimized subject to constraints imposed by codal provisions. From the results obtained for three column examples, it is found that software selects the concrete filled tubular section as an optimum section.
For the analysis of a composite frame, a concept of the effective elastic bending stiffness of the composite section is proposed [12] and calculations are carried out by moment distribution method using Microsoft excel sheet. Results obtained are found in good agreement with those obtain using ETABS software.

VIII. Concluding Remarks

1. Composite floor construction is highly competitive if spans are increased to 12, 15 or even 20 m. There is, of course, a demand for larger column-free spans in buildings to facilitate open planning or greater flexibility in office layout. A further important consideration is that the use of rolled steel sections, profiled metal decking and/or prefabricated composite members speeds up execution. For maximum efficiency and economy the joints should be cheap to fabricate and straightforward to erect on site.
2. Continuous beams in comparison with single span beams have the advantages like greater load resistance due to the redistribution of bending moments, greater stiffness, and smaller steel section to withstand the same loading.
3. Adequately proportioned anti-crack reinforcement should be provided in the concrete slab over interior supports where joints are not present. If the reinforcing bars have enough ductility they will increase the bending resistance substantially in these hogging moment regions.
4. Despite the fact that the three-dimensional models are able to accurately provide solution for wide range of problems, a two dimensional model could be the solution for some complex structural systems due to numerical convergence aspect and processing times.

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