Comparative Study of the Shear Resistance of Different Types of Shear Connectors in Steel Beam-Concrete Slab Composite Construction

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***Abstract*—The paper reviews the advantages of composite construction and the different types of shear connectors used for the same. It states important design considerations of shear connectors with the analytic expressions for determination of shear resistance of different types of shear connectors in steel-concrete composite beams. The mechanism of possible failure and shear force distribution in composite beams has been studied. The strength of the shear connectors has been reviewed in addition to a comparison between the two major types of shear connectors.**

Keywords—composite construction; shear connectors; rigid connectors; flexible connectors

I. INTRODUCTION

A. *Composite Construction*

Composite construction consists of providing a monolithic action between prefabricated steel joists and cast-in situ concrete slabs. A sufficient shear connection is provided between the two component construction units so that the two units act as one unit and resist the load by composite action where most of the compression is taken by concrete and the tension by the joist.

In these composite sections, the greatest shear stress occurs at the neutral axis which is always near the top flange of the joist. In Figure 1, a steel joist supporting a concrete slab is shown along with the related stress diagram.

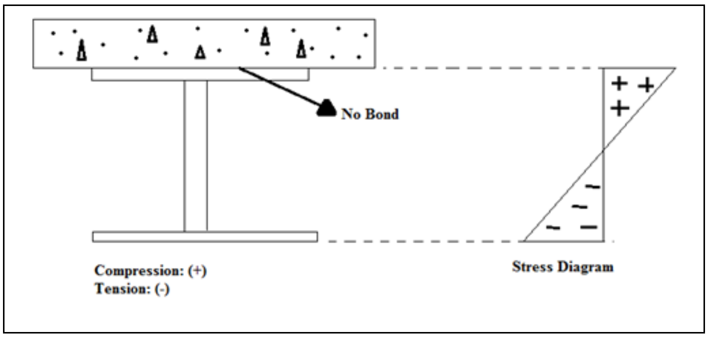

Fig. 1. Steel Joist supporting Concrete Slab

Composite Construction technique is an upcoming solution to achieve structures with high initial stiffness, bearing capacity and ductility.

B. *Advantages of Steel-Concrete Composite Construction*

Composite Construction will have the advantages of both prefabricated and cast-in situ construction. Firstly, prefabricated units can be used to serve as form work for cast-in situ work.

Secondly, prefabricated concrete flanges (i) stabilize girders during transportation and construction (ii) do not require stiffeners because of high centre of gravity (iii) avoid the use of braces for concreting of residual in-situ plates (iv) make the task of scaffolding of concrete plated un-required.

Thirdly, this method leads to the invention of new and economic constructions with high degree prefabrication so that the quality of structure increases substantially.

Fourthly, light weight cranes instead of heavy ones are required for hauling and lifting of light steel girders.

Last but not the least, new slender dimensions become superfluous as 1 bay frames can be used to easily substitute 2 bay continuous beams with the same total span but without the provision of any support in the middle.

II. SHEAR CONNECTORS

A. *Basics*

There are three essential elements used in composite construction. These are:

- Reinforced concrete slab
- Steel beam
- Shear connector

The shear connector is basically used to tie the concrete slab to the steel beam in order to transfer the horizontal shear between the slab and the beam without slip and at the same time to prevent the vertical separation of the slab from the structural steel member at the inner face. The horizontal shear at the plane of contact shall be computed from the following equation.

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$$S_h = Vm_s \quad (1)$$

In equation (1), the symbols notify the following.
S_h = horizontal shear per linear cm at the plane of contact of the in-situ concrete slab and the prefabricated beam at the cross-section of the composite beam under consideration.
V = total external vertical shear due to the superimposed load acting on the composite section.
I = moment of inertia of the transformed composite section.
m_s = static moment of the transformed area on the slab side of the contact surface about the neutral axis of the composite section or the statical moment of area of reinforcement embedded in the concrete slab for negative moment.

B. Design Considerations

The Indian Standard Code of Practice for Composite Construction (IS:3935) has made the following recommendations.

1) The shear connectors should permit a thorough compaction of concrete such that their entire surfaces are in contact with concrete.
2) The shear connectors shall be of weldable steel and shall be end welded to the structural members.
3) The capacity of the welds at permissible stress shall not be less than the shear resistance of the connectors.
4) Studs and channel shear connectors shall not be spaced further apart than 600 mm.
5) The clear distance between the edge of a beam flange and the edge of the connectors shall not be less than 25 mm.
6) The concrete cover over the shear connectors in all the directions shall not be less than 25 mm.
7) In order to ensure that the concrete slab is sufficiently tied down to the steel flange, the overall height of the shear connectors should not be less than 50 mm nor project less than 25 mm into the compression zone of the concrete slab.

C. Types of Shear Connectors

There are many types of shear connectors which are mainly divided into two categories according to the functional dependency between strength and deformations and the distribution of shear forces. Refer to Figure 2.

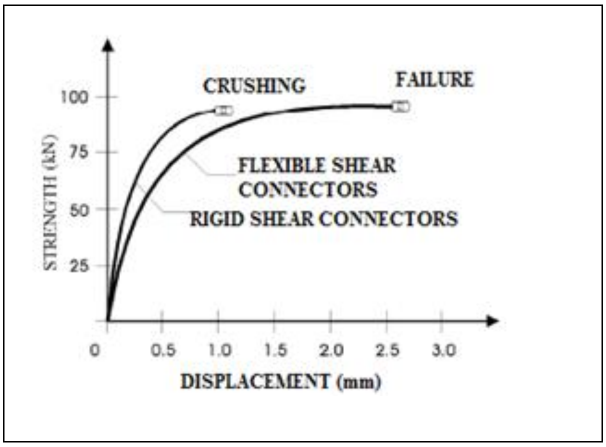

Fig. 2. Functional Dependency between Strength and Displacement

1) *Rigid Connectors*

Rigid connectors resist shear forces through the front side by shearing, and they have insignificant deformations in the proximity of ultimate strength. They produce stronger concentrated stress in the surrounding concrete that results either in failure of concrete or in failure of weld.

These consist of bars, angles, horseshoes or tees welded to the flange of the steel fabricated units. Figure 3 shows the types of rigid connectors.

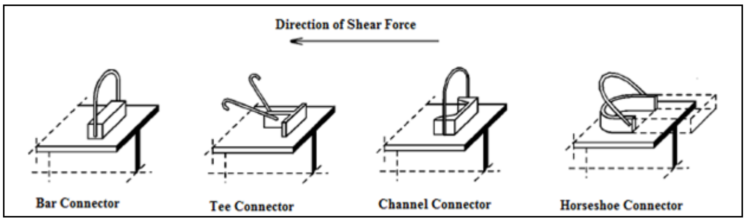

Fig. 3. Rigid Shear Connectors (with hoops)

2) *Flexible Connectors*

Flexible connectors resist shear forces by bending, tension or shearing in the root, at the connection point of steel beam, where they are subject to plastic deformations when they reach the ultimate strength values. The manner of failure of flexible shear connector is more ductile and is not prompt. They maintain the shearing strength even with a lot of movement between the concrete slab and the steel beam.

These consist of studs and channel connectors. Figure 4 illustrates the types of elastic shear connectors.

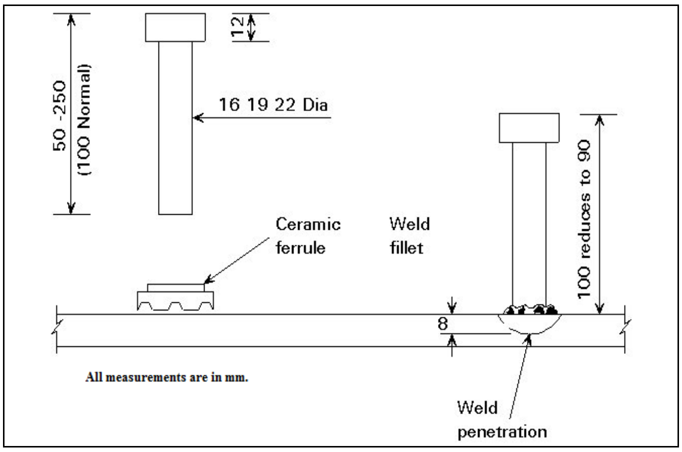

Fig. 4. Flexible Welded Shear Connector

III. Shear Force Distribution Mechanism

There is no difference in the calculation of strength in the elastic area, regardless of the type of shear connectors applied (rigid or elastic), because the cross section may be considered homogenous. However, for the calculation of the limit strength by the plasticity theory, the slim shear connectors have the advantage, because they allow certain sliding between concrete and steel, causing more favorable distribution of shearing forces.

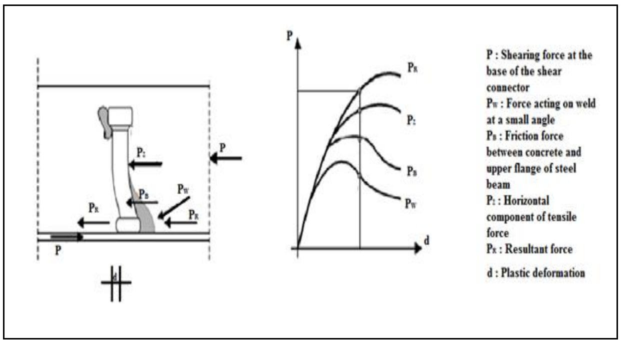

Fig. 5. The Shearing Force Distribution Mechanism at stud shear connectors in a composite beam

Refer to Figure 5. In a composite beam the shearing force P enters at the base of the shear connector into the concrete layer. Force P_w at a small angle on the weld that connects the flange and the shear connector is introduced. As we increase the pressure in concrete at the base of the shear connector, the concrete crushing occurs. Furthermore, the shearing force P_B is transferred to the shank of the shear connector. This causes the plastic deformations of the shear connector, and the occurrence of tensile forces in the shear connector, which prevents vertical lift.

Horizontal component of the tensile force P_Z is transferred to the shank of the shear connectors. The tensile forces in the shear connector cause pressure stress in concrete, which activates the friction force P_B at the contact between the concrete and the upper flange of the steel beams. The shear connector, in this case, fails immediately above the weld due to the action of tensile and shearing forces.

Hence, we can conclude that the flexible and rigid shear connectors act similarly, because they have an insignificant deformation that allows for the supposition that there is no moving between the concrete and the steel part of the cross-section.

IV. SHEAR RESISTANCE OF CONNECTORS

According to IS:3935, the main depending factors defining the shear resistance of connectors are stress conditions, permissible bond stress in concrete, permissible bearing pressure of concrete, structural properties of steel used and the strength of weld. Other factors may be shape and dimensions of the shear connectors, way of connecting to the steel beams, distance between the shear connectors, dimensions of the concrete slab, percentage of reinforcement.

A. Rigid Connectors

In the case of rigid connectors, the safe shear resistance capacity is given by the following formula.

$$Q = F_b A_b \quad (2)$$

F_b = permissible bearing pressure on concrete found by the expression $0.25\,\sigma_{cu}^{3}(A/A_b)^{1/2}$, this value is limited to $0.6\sigma_{cu}$.
A = area to which the bearing force is transmitted and is equal to the product of width of the top flange of steel joists at surface of contact and the depth of concrete slab including the haunch.
A_b = bearing area of the connector, that is the area of transmitting face of the connector at right angles to the joist flange.
σ_{cu} = crushing strength of 150 mm concrete cube at 28 days.

Rigid connectors are preferably associated with anchors so that shear is resisted partly by the bond of the concrete and partly by the bearing pressure of the concrete against the face of the inside connectors. In order to prevent the splitting of concrete slab, angular or wedge-shaped placing of concrete slabs should be prohibited.

B. Flexible Connectors

These can be further divided into the following three categories:

1) *Welded Steel Connectors*

Welded connectors with minimum stud head diameter of d+12 mm and stud height of 12 mm and made up of steel of ultimate strength of 4600 kg/cm^2, yield point of 3500 kg/cm^2 and an elongation of 20 percent is given by the following equation.

a) If H/d < 4.2,

$$Q = 4.8Hd(\sigma_{cu})^{1/2}\ \text{kg} \quad (3)$$

b) If H/d >or = 4.2

$$Q = 19.6d^2(\sigma_{cu})^{1/2}\ \text{kg} \quad (4)$$

d = diameter of stud connector (cm).

2) *Channel Flexible Connector*

For steel connectors with minimum ultimate strength of 4200 to 5000 kg/cm^2, yield point of 2300 kg/cm^2 and an elongation of 21 percent, safe shear resistance is given by the following equation.

$$Q = 10.7(h+0.5t)(L/(\sigma_{cu})^{1/2}) \quad (5)$$

h = maximum thickness of flange of channel connector (cm).
t = thickness of web of channel shear connector (cm).
L = length of channel shear connector.

3) *Spiral Connectors*

For all composite beams, the spirals with pitch limits of 100 mm and 400 mm, shall extend at least half way into the slab, causing shear resistance given by the following equation.

$$Q = 315(\sigma_{cu})^{1/4} \quad (6)$$

Q = safe shear resistance of one pitch of a spiral bar in kg.
d = diameter of the round bar used in spiral connectors in cm.

V. Comparison Of Shear Resistance Of Rigid And Flexible Connectors

TABLE I. COMPARATIVE STUDY

Rigid Shear Connectors	Flexible Shear Connectors
It is of rigid nature and fails suddenly if over-loaded.	It is flexible in nature and fails over a longer period of time.
Concrete surrounding the connectors separates away in case of rigid connectors.	In flexible connectors, complete separation of concrete from the connector is delayed.
It is economical and easy to use.	These require pre-fabrication in the industry and welding before installation, thereby increasing the cost.
It can be installed quickly and requires no skilled labor.	These require skilled labor for installation.
These connectors are associated with anchors to resist shear partly by bond and partly by bearing pressure of concrete.	Anchors are not necessary in case of flexible connectors.
Chances of loss of shape are high in case of rigid connectors.	No question of loss in shape concerns flexible connectors, as these can regain shape.

VI. Conclusion

The resistance of the shear connector is affected when the nature of load varies in the shear connector that connects the upper flange of the steel beam and the concrete slab.

With reference to Figure 2, it has been found experimentally that Flexible Shear Connectors fail at comparatively higher load than Rigid Shear Connectors.

Also, Rigid Connectors cannot take more than 1mm displacement for load strength between 95-100 KN while Flexible Connectors can sustain up to 3mm displacement with a maximum corresponding load of 100 KN.

Rigid connectors cause failure of concrete or that of weld because they produce high degree of concentrated stress in the surrounding concrete while flexible connectors allow movement between concrete slab and steel beam and develop the shearing resistance.

Shear is resisted by the use of anchors in case of rigid connectors while no such additional external device is necessary to resist shear in flexible connectors.

Flexible shear connector is able to sustain more strain as compared to rigid shear connector, before failure occurs.

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