Performance and stud failure in steel-concrete composite beams

Performance and Stud Failure in Steel-Concrete Composite Beams

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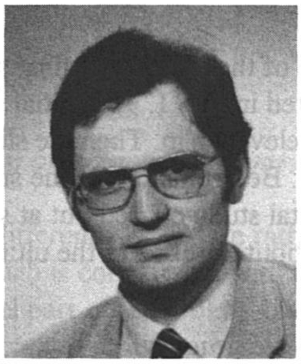

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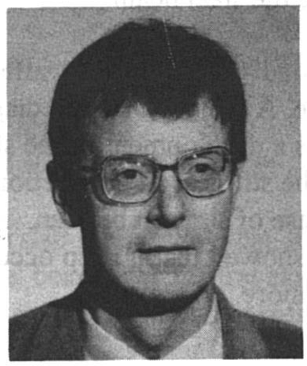

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Summary

The effect of deformability of connection in composite beams was investigated on the basis of an experimental research. The performance was studied in both ultimate and serviceability conditions. The differences in performance between bridge and flooring composite beams are shown. The use of composite construction to improve buckling resistance and to reduce shear lag effects in box girders is proposed.

1. Introduction

Concrete steel composite structures are very efficient. Concrete is effective in compression and steel in tension, compressed steel parts are stiffened against buckling by a concrete slab. In old composite structures, a very stiff connection between steel and concrete was designed. Welded studs are connectors which are used very often mainly because of the simple production. The studs are flexible to some extent and therefore only partial interaction between a steel flange and a concrete slab exists. This implies that slip occurs at the interface, and so causes a discontinuity of strains. For most connectors used in practice, failure by vertical separation is unlikely and any uplift would have only negligible effect on the behaviour of the composite structure. If the deformability is taken into account in the design, the steel concrete structures can perform satisfactorily during their whole service life.

2. Stud resistance

A series of experiments has been carried out at the CTU Prague, in order to get the load slip diagrams, which made it possible to observe the progressive failure of one stud. They were arranged so that the results were not influenced by redistribution of the load between the two studs as it is in the case of a usual push out test. The loading process was controled by slip between steel and concrete which made it possible to detect the drop of ultimate load after failure. The mode of failure depends on the length of the stud embeded in concrete slab, on the diameter of the shank of the stud and on the quality of concrete. It may be simply concluded that the short studs fail due to failure of concrete adjacent the stud and longer studs, which are well anchored in concrete usually fail by reaching the ultimate load carrying capacity of the shank in shear just above the steel beam.

The load - slip diagram is affected by the failure mode of the stud at the final stage just before its failure. A typical load-slip diagram of one stud is plotted in Fig. 1. The initial stage of the diagram shows a development of the shear force without any relevant slip. Then the slip starts to develop and the stiffness of connection is reduced significantly. Before failure of the stud a considerable increase of slip can be seen. Results of the experimental study carried out at studs of different sizes showed that no slip occurs if the shear force is about 25-30% of the ultimate shear force or even more.

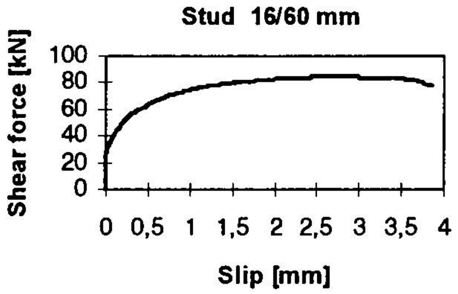

Fig. 1 Shear - slip diagram of one stud tested

3. Modelling of the stud performance in ultimate limit state

In the ultimate limit state of steel concrete composite beams, the failure may be achieved in various modes. (i) The stress in steel exceeds the yield limit, (ii) the stress in concrete exceeds strength in concrete or (iii) shear force in contact between concrete and steel exceeds the load carrying capacity of the connection. The last case need not necessarily lead to colaps of composite beams, however, a significant redistribution of internal forces can result due to failure of steel or concrete earlier than it would be expected assuming a stiff connection between steel and concrete.

To model failure of connection between steel and concrete, a simplified method has been developed [2]. The performance of studs is assumed according to a quadrilinear diagram (Fig.2). The first two lines (ascending part of the diagram) can be determined from the experimental results directly. The descending branch can be taken also from deformation controlled tests and the last horizontal line represents friction between steel and concrete after failure of studs. If no experiments are available, the descending branch can be assumed according to an empirical calculation, e.g. [1].

The behaviour of composite beams depends on the geometry of the cross-section. The beams used in buildings have rather thick and wide concrete slabs compared with the steel beam dimensions. The neutral axis usually lies in the concrete slab. Thus, a part of concrete section is under tension, which causes cracking and reduces stiffness of the slab. The studs are anchored in the tensile zone, and so their stiffness is necessarily lower than that of the studs anchored in concrete under compression. The contribution of the slab to the overall stiffness is high and the structure is sensitive to cracking, creep and shrinkage effects.

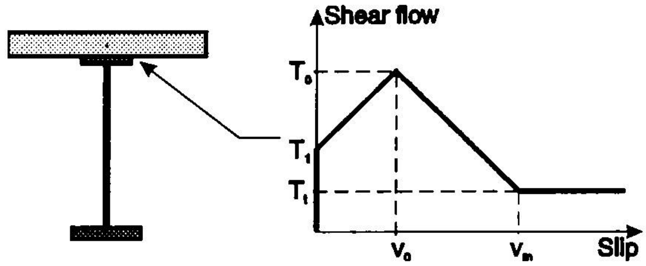

Fig. 2 The cross-section of composite beams studied and the idealized shear - slip diagram

Bridge beams behave differently. They are rather deep and the concrete slab is relatively thin. The width of the concrete slab is comparable with the dimensions of the steel beam. The neutral axis lies normally in the steel part of the cross section and thus the concrete slab is fully in compression zone. The studs are anchored in the compression zone of the slab which increases their load carrying capacity.

The distributions of the bending moments and axial forces in composite beams with deformable and stiff connectors are different. Near midspan, where the connection is stiff, the total bending moment is taken by the axial forces in steel and concrete, which form a couple. On the other hand, at the end regions of the beam, the connection can be rather weak due to partial failure of connectors, and then the total bending moment equals roughly the sum of the moments in the cross-section parts, with a reduced contribution of the couple of axial forces. Typical stress distributions in the concrete slab and in the steel beam of a bridge composite beam are plotted in Fig.3a,b together with the shear flow variation (Fig.3c) along the bridge span of the length 30 m. The stress variations are plotted in the stage when the connection partialy failed and the stress in the steel beam reached the stress limit. The sudden changes in the stress variations are due to a simplified shape of the shear force - slip diagram as shown in Fig.2. In a real structure, the changes would be smooth, but not disappear. In the central part, where no slip occurs, the stress becomes lower and in the end parts the slip develops. The extreme compression stress in concrete is in the central part, the extreme tensile stress at the bottom surface of the concrete slab develops approximately in the middle of the end parts (Fig.3a). The extreme stresses in steel are at the location where the slip starts to develop (Fig.3b). In the case of stiff connection, the stresses would correspond to those stresses plotted in Fig.3 at the central part of the beam and the stresses in steel (particularly in the top flange) would be significantly underestimated against the real arrangement with deformable connection. Tensile stresses occur at the bottom surface of the concrete slab (Fig.3a) where compression stresses in concrete would be expected in the case of stiff connection.

4. Perfomance in the serviceability limit state

The effect of variable stiffness of connection has been studied on a bridge beam of 35 m span. The depth of the steel **I** beam was 2.84 m and the thickness of the 2.125 m wide concrete slab was 0.2 m. The deformability of connection significantly affects the stress distribution and deflections of composite beams. However, its effect on stress and deflection variations is not proportional with respect to the deformability of connection. The degree of deformability varies from 0 (stiff connection) to 1 (no connection) in this study. The bridge beam with deformable connection exhibits a deflection w_{def} and the bridge beam with stiff connection has a deflection w_{stiff}. The

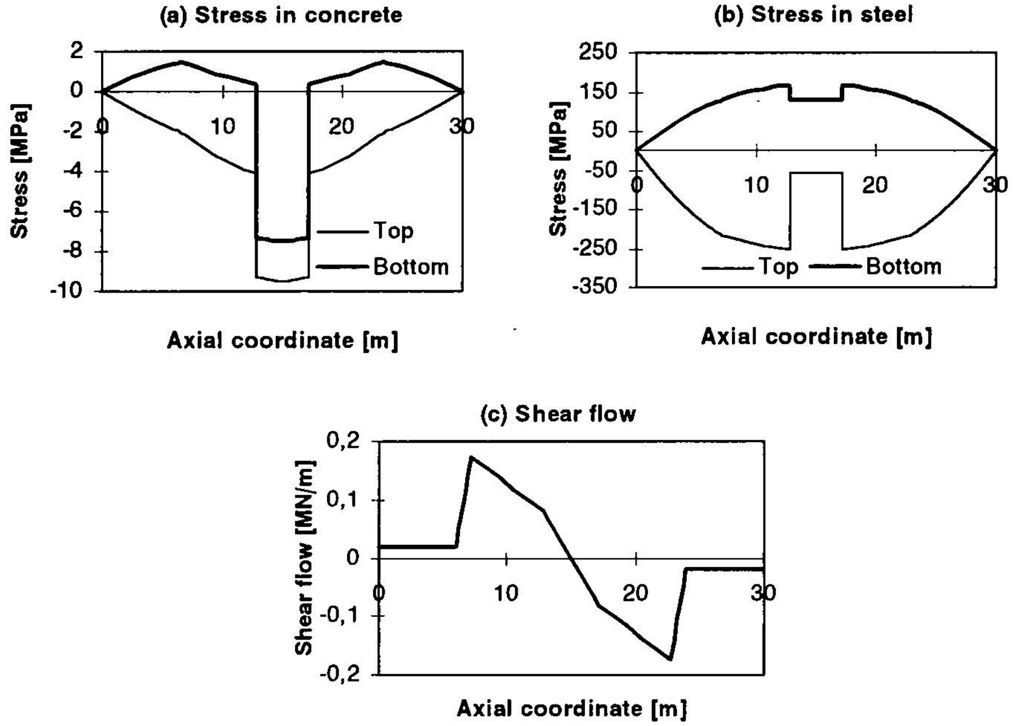

Fig. 3 Stress distributions and shear flow variation along the length of the beam

ratio w_{def}/w_{stiff} in dependence on the deformability of connection is plotted in Fig.4a. The thin line illustrates the effect of short term loading (age of concrete 28 days). It can be seen that the increasing connection deformability has initialy low effect on the deflection ratio, in the middle part of the diagram a substantial increase of deflection takes place and in the right hand side part of the diagram again very small change is seen. The thick line (10000 days after loading) shows increase of deflection ratio due to long-term loading. At the beam with stiff connection the effect of creep of concrete is significant, because of a great contribution of concrete slab to the overall bending moment, due to action of axial forces. At the beam with very deformable connection, the contribution of concrete slab to the overall bending is small, because the flexural stiffness of the concrete slab is much smaller than the stiffness of the steel beam. Therefore the creep effect is negligible. The development of stress redistribution in steel exhibits a similar trends like deflections.

The behaviour of the bridge beams was compared with the behaviour of the flooring beam. The depth of the rolled steel I beam was 312 mm, the concrete slab was 120 mm thick and 2.5 m wide. The deflection ratio similar to that of the bridge beam in dependence on the deformability of connection is plotted in Fig. 4b. The thin line (short term loading at the age of concrete 28 days) shows a similar trend as that of the bridge beam, however, the increase of deflection is higher (bridge beam 1.75, flooring beam 2.5). If the long-term load is assumed (thick line - 10000 days), the increase of deflection is even more significant. The concrete slab represents a significant part of the cross-section and its stiffness, which is reduced due to creep, influences significantly the deflection of the whole composite beam. Flooring beams are therefore more sensitive to the creep than bridge beams. The redistribution of stresses is also more significant at floor composite beams than at bridge composite beams.

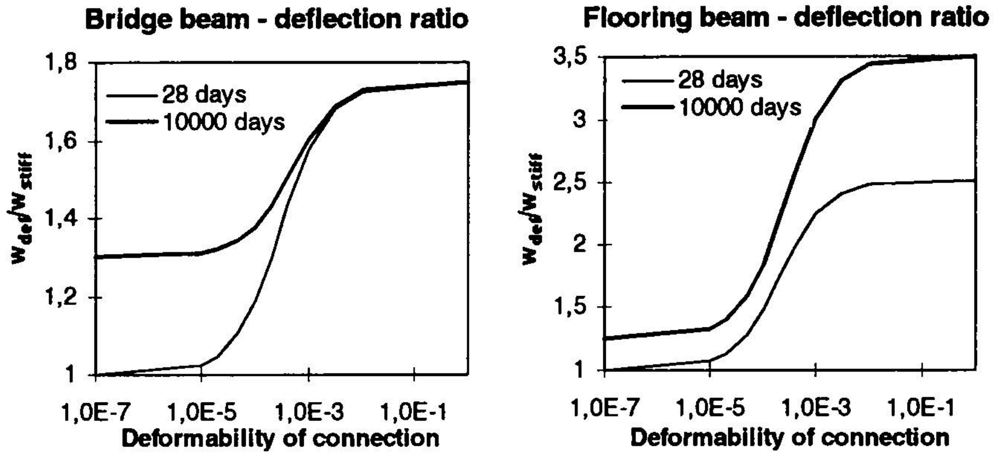

Fig. 4 Deflection ratio of the beams with deformable and stiff connection

5. Buckling resistance and controlling the effect of shear lag in box girders

The composite action may also be very effectively applied to increase the buckling resistance in the bottom flange plates in the hogging moment regions over the internal supports of continuous girders which are simultaneously very suspectible to the effect of shear lag.

It is well known that the effects of shear lag are particularly severe in local regions immediately adjanced to applied concentrated loads, in flange plates that are wide in relation to their length and in flanges that are longitudinally stiffened. In the case of a continuous steel bridge girder, these three circumstances can coincide to produce an exceptionally high shear lag effect in the lower flange over an intermediate support. Bridge bearings are often positioned under girder webs and bear almost directly on to the girder. The points of contraflexure are usually close to the intermediate support so that the effective span of the girder is short and the resulting span/width ratio is well within the critical range. Within such a region of hogging moment, the lower steel flange may be heavily stiffened against buckling under longitudinal compression.

A substantial reduction in the accentuated shear lag effect due to longitudinal stiffening is possible. The flange plate within the critical region can be stiffened with a layer of concrete that is made to act compositely with the steel flange which will be easy to place on the lower flange of the box over the intermediate support.

As an example a multispan, continuous bridge girder is considered and the performance of the two types of cross-section shown in Figs 5(a) and 5(b) is compared. In the first case, both flanges of the steel girder are stiffened by longitudinal ribs in the conventional way, with the lower compression flange stiffened by nine ribs to give a ratio of stiffener/flange plate area of 0.2. At an internal support, the distance between points of contraflexure is calculated to be 15.2 m so that the flange span/width ratio is 2.2. The girder is subjected to uniform line loading of 100 kN/m above each web and the upward reaction force at the support is calculated as 3600 kN; this is distributed over a bearing length of 100 mm.The distribution of the longitudinal stress across the width of the bottom flange above the intermediate support is plotted in Fig 5(a). It shows the expected shear lag effect with the amplified edge stress reaching a maximum value of 147.2 N/mm^2. The alternative solution is shown in Fig. 5(b). In this case, the thickness of the lower flange has been reduced from 12 mm to 8 mm and the lower flange stiffeners have been removed

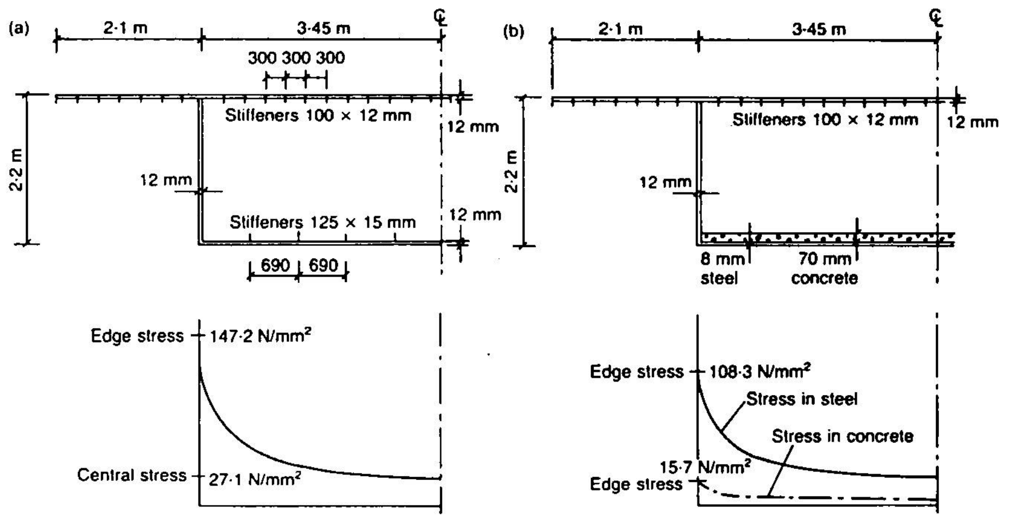

Fig. 5 Stress in an typical bridge girder. (a) Stiffened bottom flange, (b) Composite bot. flange

and replaced by a 70 mm thick layer of concrete acting compositely with the steel; other girder details remain the same. The plotted values show a significant reduction in the maximum steel stress from 147.2 N/mm^2 to 108.3N/mm^2. This reduction of about 27%, together with the amount of steel saved, shows the effectiveness of the proposed method.

Changing the number, flexibility, spacing and distribution of studs it is possible to control the distribution of axial stresses in the steel flange and in the concrete layer. It is obvious that as the stud stiffness increases the steel sheds more of its load into the concrete. On the other hand, to achieve the buckling resistance the use of a reduced number of studs can be sufficient.

6. Conclusions

1. Studs of different sizes were tested until failure and the shear force - slip diagrams were investigated. The slip has a significant effect on the distribution of internal forces, if the connection starts to fail. In those regions where slip occurs, the overall bending is transfered more by local bending of the steel beam and of the concrete slab. In the case of the simply supported beam subjected to a uniformly distributed load, the extreme stress in steel beam need not be at the midspan.
2. The effect of deformability of connection concerning the redistribution of stress and the growth of deflections, both due to short and long term loadings, is much more pronounced at flooring composite beams than that at the bridge composite beams.
3. Composite construction can be efficiently applied to achieve required buckling resistance and to control the effect of shear lag in box girders.

Acknowledgement
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