TIME-DEPENDENT BEHAVIOUR OF SIMPLY SUPPORTED STEEL-CONCRETE COMPOSITE BEAMS

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A theoretical and experimental study of the time-dependent behaviour of composite steel-concrete structural members has been undertaken at the University of New South Wales. As part of the experimental investigation, long-term static load tests were carried out on four simply-supported composite steel-concrete beams. The deformations were monitored for a period of about 250 days, as were the creep and shrinkage characteristics of concrete specimens under the same ambient conditions as the test beams. Pushout tests were also conducted on the headed studs used as shear connectors in the test specimens, and slip deformations and slip strains were recorded for two different connector densities. In this paper, transverse deflections are shown to agree well with a design proposal presented elsewhere. The experimental results presented herein provide benchmark data for the calibration of more complex theoretical treatments that incorporate creep, shrinkage and connector slip.
TIME–DEPENDENT BEHAVIOUR OF SIMPLY–SUPPORTED STEEL–CONCRETE COMPOSITE BEAMS

by

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Introduction

The time–dependent behaviour of composite steel–concrete tee–beams at service loads is governed by the creep and shrinkage induced deformations of the concrete slab. These deformations and the deformation of the beam depend on the following factors [1]:

(a) the material properties of the concrete and steel;

(b) the geometry of the beam;

(c) slip at the steel–concrete interface;

(d) the load–history and geometric distribution of the loading; and

(e) the environmental conditions.

Tests on composite beams have usually been undertaken to ascertain their ultimate strengths rather than their behaviour at service loads. Although literally hundreds of tests have been reported on the time–dependent behaviour of reinforced and prestressed concrete beams, very few test results for the time–dependent behaviour of composite beams are available in the open literature. The work most often quoted is that of Roll [2], but his results are of very limited applicability. Recently, Johnson [3] reported long–term tests on a large composite beam at the University of Warwick, but there appear to be no systematic studies available for general usage that present strains, transverse deflections and slip deflections.

In order to overcome this shortfall of data, the authors undertook a series of experiments on four simply–supported composite tee–beams at the University of New
South Wales. The tests allowed for differing loading and different slip characteristics. The results of these experiments are reported in the present paper, and the transverse deflections are compared with a simple design proposal documented elsewhere [4,5]. The results should provide benchmark data for the calibration of design procedures and more complex theoretical treatments that incorporate accurate modelling of such factors as creep, shrinkage and connector slip.

**Test Specimens and Materials**

**SPECIMENS**

Four composite tee-beams with the cross-section shown in Fig. 1b were cast and simply-supported on rollers at a spacing of 5900 mm. Two of the beams, B1 and B3, were loaded with a sustained uniformly distributed load of 7.52 kN/m applied by concrete blocks 400 mm x 400 mm x 1000 mm, while the other two beams, B2 and B4, were subjected to self-weight loading only.

All steel beams had their top flanges greased prior to casting of the concrete slab. Beams B1 and B2 had pairs of headed studs welded to the top flange at 200 mm intervals, while beams B3 and B4 had pairs of headed studs welded at 600 mm intervals in order to increase the effects of slip at the steel–concrete interface. Dimensions of the stud shear connectors are shown in Fig. 1c.

Dial gauges were used to measure the vertical deflection of the beams at quarter points, and the slip displacements of the steel and concrete at each end of the beams and at their third-points. Strains were measured using Demec gauges at midspan on the top of the slab, at the slab mid-depth on its edge, on the soffit of the slab adjacent to the steel top flange, in the steel top flange, at the web mid-depth and in the bottom flange of the steel. A photograph of the test set-up is shown in Fig. 2.

**MATERIALS**

Three cylindrical shrinkage specimens of 150 mm diameter were cast, and shrinkage strains were measured using Demec gauges placed diametrically opposite on the cylinders. Three concrete cylinders were also placed in a creep rig, as shown in Fig. 3, and total strains were measured in the same way as for the shrinkage specimens when a
sustained stress of 3 MPa was applied hydraulically. The temperature was recorded throughout the duration of the tests, as was the humidity using a wet–dry bulb hygrometer.

Six concrete cylinders were tested in an Amsler testing machine to obtain their elastic modulus and cylinder strengths. To determine the load–slip characteristics of the headed studs, three standard pushout tests were also undertaken. The details of the pushout test specimens are given in Fig. 4, while a photograph of the pushout test set–up is shown in Fig. 5. All beam specimens, pushout test specimens, and cylinders were cast at the same time.

Experimental Material Properties

SHRINKAGE STRAINS

The average shrinkage strains \( \varepsilon_{sh} \) for each of the three cylinders are shown in Fig. 6. It can be seen that after about 220 days, the shrinkage strain is about 410 \( \mu \varepsilon \). The abnormal behaviour between 40 days and 70 days can be attributed to excessively humid conditions.

The average shrinkage strains measured on each of the shrinkage cylinders are fairly consistent, with the greatest disparity in strain being about 25 \( \mu \varepsilon \) at 120 days.

CREEP STRAINS

Figure 7 shows the averaged total strains \( \varepsilon_a \) versus time relationship measured in the creep cylinders. By noting that the total strains \( \varepsilon_a \) are the sum of the elastic strain \( \varepsilon_e \), the creep stain \( \varepsilon_c \) and the shrinkage strain \( \varepsilon_{sh} \), the creep coefficient at time \( t \) due to a stress first applied at age 10 days after casting \( \phi(t,10) \) may be obtained from

\[
\phi(t,10) = \frac{\varepsilon_e}{\varepsilon_c} = \frac{\varepsilon_a - \varepsilon_{sh}}{\varepsilon_e} - 1
\]

(1)

where the elastic strain \( \varepsilon_e \) was taken as 120 \( \mu \varepsilon \), based on a measured elastic modulus of the concrete of 25,100 MPa (see below).
By averaging the three curves in Fig. 6 to obtain $\varepsilon_{sh}$ and using Fig. 7 for $\varepsilon_c$, the value of the creep coefficient $\phi$ is given in Fig. 8. Also shown in this figure is a curve of best fit of the experimental results. The creep coefficient tends towards a value of about 2.6 at about 220 days, and is consistent with data presented in Ref. 6 for Australian concretes.

**STRENGTH AND ELASTIC MODULUS**

The load–displacement curves for the six concrete cylinders loaded to failure after 10 days were measured. The elastic modulus $E_c$ was averaged as 25,100 MPa with a coefficient of variation of 5%, while the cylinder strength $f_c$ was 31.1 MPa with a coefficient of variation of 7%.

**PUSHOUT TESTS**

The results of the pushout tests are shown in Fig. 9. Failure was generally precipitated by crushing of the concrete combined with bending of the studs, although in the specimen producing the curve with the lowest strength in Fig. 9, one of the four studs sheared off. At low values of load, typical of that experienced at service loads, the curves are fairly consistent.

**Experimental Beam Results**

**DEFLECTIONS**

The variation of midspan deflection with time are given in Fig. 10 for each of the four beams, while the deflections averaged at the two quarter points versus time are given in Fig. 11. It can be seen that the effects of slip at the steel–concrete interface result in greater deflections for beams B3 and B4 than for beams B1 and B2, respectively, although the increased deflections are not greatly marked. The time–dependent deflection increases at a decreasing rate, with much of the long–term deflection taking place in the first 100 days after first loading.

Figure 12 shows the top fibre concrete strain at midspan for each test beam. The strains are slightly greater for the beams with fewer shear connectors and hence more expected slip (B3 and B4). The same trends can be seen for the strains at the slab
mid-depth (in Fig. 13), the slab soffit (Fig. 14), the steel top flange (Fig. 15), the steel mid-depth (Fig. 16) and the steel bottom flange (Fig. 17). The measured strains in Fig. 16 are somewhat erratic, owing to their relatively small magnitude due to proximity to the neutral axis. The distributions of strain through the depth of the cross-section at midspan of each beam are shown in Fig. 18 for $t = 100$ days and $t = 200$ days. As expected, the strain distributions in both the steel joist and concrete slab are generally linear, and the slip strain at the steel–concrete interface is relatively small even for the beams with a sparse density of connectors. However, the interface slip is greater for the beams (B3 and B4) with the sparser density of connectors. In addition, the position of the neutral axis is higher for the loaded beams B1 and B3 than the unloaded beams B2 and B4, owing to the increased effects of creep in these specimens due to higher initial concrete stresses.

SLIP DEFLECTIONS

Figure 19 shows the measured relative slip between the steel and concrete at the ends of the beams. These values are the average of the slip measured at each end of the relevant beam. It can be seen that the slip deformations under the sustained service loads considered here are not large, even for beams B3 and B4 for which substantial slip would be expected. Because the slip deformations are small, the accuracy of their measurement with a dial gauge is questionable.

Comparison with Design Proposal

In the design proposal of Refs. 4 and 5, the curvature $\rho$ is expressed as a function of the moment $M$ and is given by

$$\rho = \alpha + \beta M$$  \hspace{1cm} (2)

In the above equation, $\alpha$ is obtained from

$$\alpha = \frac{\varepsilon_{sh}}{D} \left[ 1 + 0.2 \frac{\phi}{\phi} \right]$$  \hspace{1cm} (3)

where $D$ is the overall depth of the section, $\phi$ is the creep coefficient and $\varepsilon_{sh}$ is the shrinkage strain at the relevant time. The coefficient $\beta$ is the reciprocal of the
transformed flexural rigidity relative to the concrete $\frac{1}{E_c I^*}$, where $I^*$ is the second moment of area of the transformed section relative to the concrete, using a value of $1/(1 + \phi)$ for the modular ratio of the slab and $E_s /E_c$ for the steel, where $E_s$ is the Young’s modulus of the joist. The design proposal above was based on parametric studies of a theoretical model presented in Ref. 7 that assumes negligible slip strain at the steel—concrete interface, and allows for a reasonable amount of reinforcement in the slab.

The curvatures in Eq. 2 may be integrated twice to obtain the deflections for a given bending moment distribution $M$. This was done in the present study to obtain the midspan and quarter point transverse deflections, and these are plotted in Figs. 10 and 11 respectively using the measured material properties. The comparison in Figs. 10 and 11 shows that the design proposal is a comparatively good prediction of the test results for the beams exhibiting minimum slip.

Conclusions

Long-term sustained load tests were carried out on four simply-supported composite steel—concrete beams in order to supplement a scarcity of experimental results. The shrinkage and creep strains were monitored, and three pushout tests were performed to obtain the load-slip characteristics of the connectors.

Deflections and strains were measured in the beams, the results providing benchmark data for future detailed calibration studies. The deflections and strains were not greatly sensitive to the number of shear connectors, although there was a definite correlation between density of connectors and deflection.

A design proposal documented elsewhere was compared with the test results for deflection calculations. The design proposal, which neglects the slip strain at the concrete—steel interface, was shown to predict the test results fairly satisfactorily, especially for the beams with the higher density of shear connectors.
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References


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FIG. 1 COMPOSITE BEAM TESTED
FIG. 2  DETAILS OF TEST SET-UP
FIG. 3 CYLINDERS IN CREEP RIG
FIG. 4  PUSHPULL TEST SPECIMEN
FIG. 5  DETAILS OF PUSHOUT TEST
FIG. 7 AVERAGE STRAINS FOR CREEP CALCULATIONS

- $\varepsilon_a$ (av.)
- $\varepsilon_{sh}$ (av.)
FIG. 9 RESULTS OF PUSHOUT TESTS
FIG. 11  QUARTER POINT DEFLECTIONS
FIG. 13 MID-DEPTH CONCRETE STRAINS
FIG. 18 CROSS-SECTION STRAINS AT MIDSPAN
FIG. 19  RELATIVE END SLIP DEFORMATIONS