Further Studies of Composite Steel and Concrete Structures

Etudes ultérieures de structures mixtes acier-béton

Weitere Studien über Verbundkonstruktionen aus Stahl und Beton

J.W. RODERICK
University of Sydney
Sydney, N.S.W., Australia

Much of the work over the last twenty years on composite steel and concrete structures has been devoted to the behaviour of simple composite beams and pin-ended columns. Limited use of this knowledge has been made in the design of concrete encased rigid steel frame structures by permitting some account to be taken of the stiffening effect of the concrete in proportioning members. But full advantage of the composite form will not accrue until such frames are designed to make greater use of the concrete in transmitting moment and shear force from beam to column. When the moment rotation characteristics of these truly composite connections can be reliably forecast, it should be possible to develop plastic design methods for the rigid frame composite steel and concrete structure which could lead to significant savings.

Over the last eight years considerable progress has been made at Sydney University towards the development of analytical methods of this nature. Both experimental and theoretical studies have been undertaken and include the topics: shear force transmission in composite T-beams; the effects of slip and other variables in these beams in both the linear and non-linear loading ranges; the characteristics of the negative moment region in continuous beams; eccentrically loaded pin-ended columns bent about any centroidal axis; and the behaviour of composite beam-to-column connections. In addition repeated loading tests have been made on simple and continuous beams; creep of eccentrically loaded pin-ended columns under sustained loading is also being examined.

SIMPLE BEAMS

The initial work on shear connection was described in a paper by Rao(1) who tested a variety of connectors and concluded that welded studs are likely to be the most economical. Their flexibility does however lead to slip between slab and joist which in turn affects the distribution of forces on the studs and leads to increased deflections of the beams. The experimental work has been directed mainly to examining these effects.

In addition to studies of small-scale beams, tests were carried out on 17ft span T-beams of 10in. x 4½in. @ 25 lb. R.S.J. with 72in. x 4in. concrete slabs, connected by pairs of 3/4in. studs, 3in. long and spaced at intervals of 15in. A symmetrical two point loading acting at third points of the span was applied in increments right up to failure. While the main purpose was to observe deformations and ultimate load carrying characteristics, the opportunity was taken to examine the effects of using different stud steels and both normal and lightweight aggregate concretes. The relevant information for the first three beams (A1, A2 and A3) is given in Fig.1. Due to the predominant influence of the steel joist in flexure, the difference in concretes did not have a particularly significant effect upon the load-deflection relationship (Fig.1c) despite the low modulus of the lightweight concrete (Fig.1b). Different strengths of steel studs also had little effect; in fact the ultimate strength of the stud joist combination occurs by shearing out of the joist material below the stud.

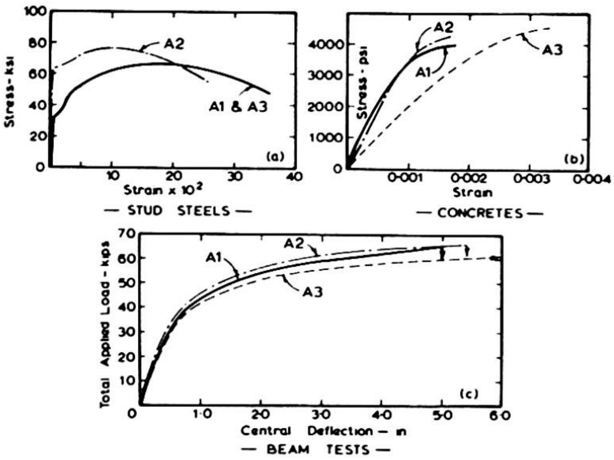


FIG. 1 LOAD DEFLECTION AND STRESS-STRAIN CURVES FOR FULL SCALE BEAM TESTS

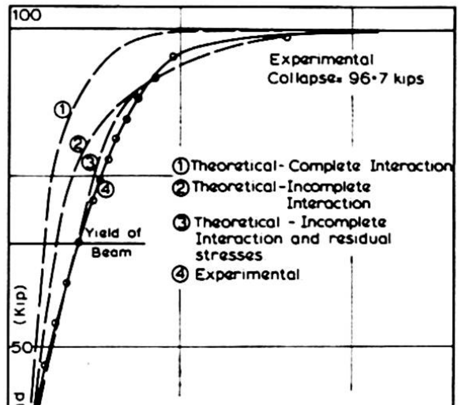


FIG 2 SIMPLY SUPPORTED T-BEAM – (UNIFORMLY DISTRIBUTED LOAD)

In Fig.2 load deflection data is given for beam A6 similar to A2 but subjected to simulated uniformly distributed loading. Curve 1 was obtained by using the Newmark(2) solution in the linear range after allowing for shear deflection; thereafter the curve depends upon an iterative plastic analysis assuming no slip and taking the stress-strain relationship for both steel and concrete to be of the form shown at (a) in Fig.3. For curve 2 the effect of slip as measured in a push-out test has been introduced into the analysis. For curve 3 a uniform distribution of residual stress of 20 kips/in.^{2} over the flange section has been assumed and taken into account in the analysis. This last solution gives better agreement with the test results.

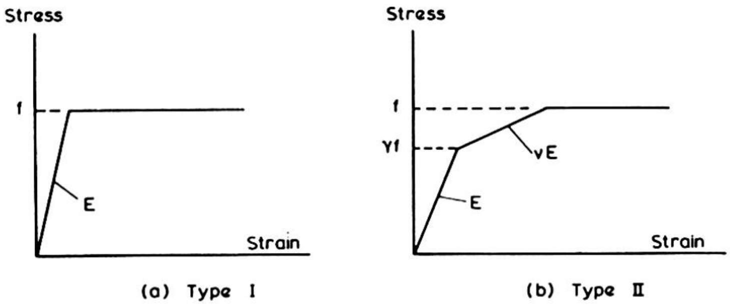


FIG. 3 ASSUMED STRESS-STRAIN RELATIONSHIPS

Repeated Loading. In order to gain understanding of the behaviour of composite beams under abnormally high repeated loading two tests were carried out on full-scale beams R1 and R2 respectively similar to A1 and A2 above. They were subjected to a programme of loading designed to produce the same maximum stress levels on the most highly loaded pair of studs as occurred in the respective push-out tests PR5 and KR2. All loads were applied at a frequency of 30 cycles/minute and were varied from nominal zero to maximum value.

Table 1. Forces on Critical Studs for Beams R1 and R2

Max. value of repeated load on beam including selfweight (kips)	Computed force on pair of studs (kips) (a) assuming rigid studs	(b) allowing for slip
8.02	11.2	10.0
10.14	14.0	12.5
12.30	17.1	15.0
14.52	20.2	17.5
16.87	23.5	20.0

Table 2. Comparison of Failure of Critical Studs - Beams R1 and R2

Condition of Stud	No. of Cycles of Load Applied x 10^{-6}							
	Beam BR1				Beam BR2			
	Stud No.				Stud No.			
	3*	4	25	26	3	4	25	26
Initial Weakening	2.33	2.33	2.33	2.33	2.45	2.45	2.35	2.24
Only Minor Stud Response	2.40	2.40	2.41	2.41	2.82	2.82	2.82	2.45
Complete Stud Failure	2.58	2.41	2.48	2.48	3.15	2.90	2.99	2.99

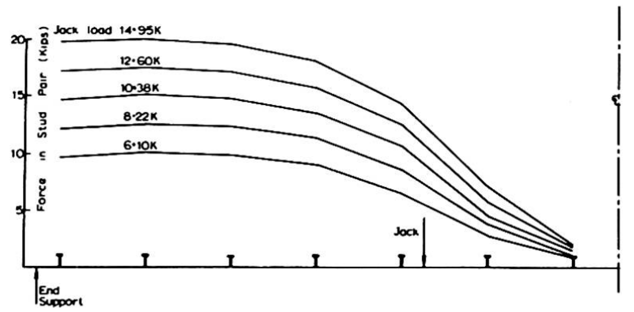
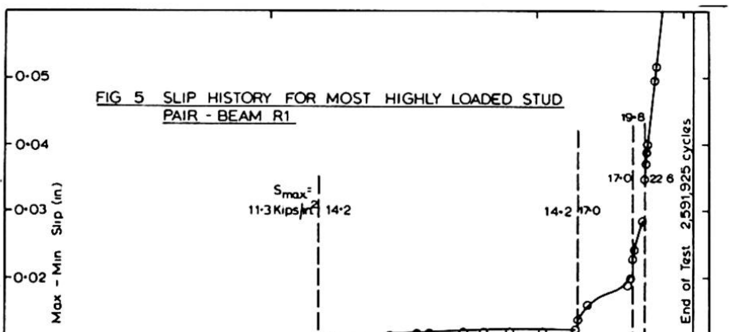


FIG 4 THEORETICAL DISTRIBUTION OF STUD FORCES FOR BEAM R1 (INCLUDING THE EFFECT OF SLIP)



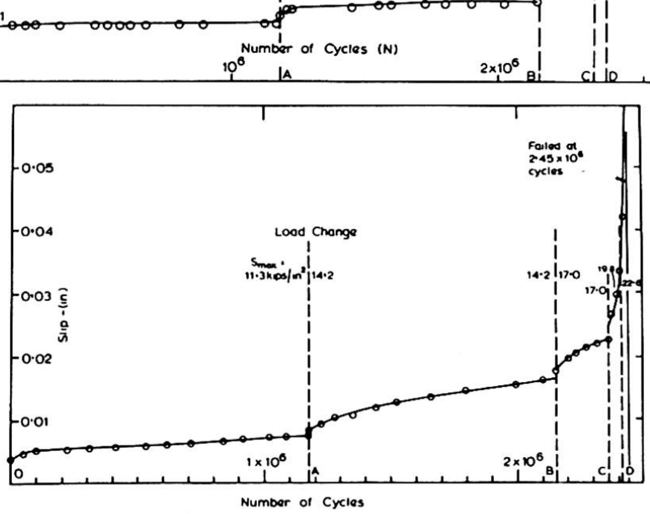


FIG 6 PUSH-OUT SPECIMEN PR5 - HISTORY OF SLIP

From accurate analysis taking account of slip, connector force distributions along the beams as shown in Fig.4 and Table 1, were evaluated. It will be seen that the maximum stud force is less than the value obtained by approximate methods assuming rigid studs. The most highly loaded pair of studs in the beams, those second from the end, were then subjected to the peak stud stresses shown in Fig.5. The slip curves for the critical studs (Fig.5) were very similar in form to those observed in the corresponding push-out tests (Fig.6). The comparison of conditions at failure for the two beams is set out in Table 2.

These tests showed that stud connected composite beams could sustain over two million applications of stresses of approximately design value, with practically no decrease in structural efficiency. Thereafter they were capable of resisting another three increments of load up to a total of twice the initial value with only a gradual deterioration of the shear connection.

CONTINUOUS BEAMS

The work on continuous beams subjected to static loading has been directed mainly to studying the behaviour in the negative moment region to provide data for use in the design of beams in rigid frame composite structures. Tests were carried out on inverted beams and small-scale continuous beams of T-section which led to the conclusion that these can confidently be designed to carry negative moments equal to the ultimate moment of resistance of the section in the positive moment region. This can be achieved by the provision of adequate reinforcement in the slab or by plating the steel section. In both cases "strain hardening" hinges of adequate rotational capacity can be developed.

Repeated Loading. A study is also being made of the behaviour of continuous beams under repeated loading of constant amplitude.

A preliminary test has been carried out on a beam of two 17ft spans and having a section composed of a 10in. x 4½in. @ 25 lb. R.S.J. and a 72in. x 4in. concrete slab with the same arrangements of studs as for beam A1. The loading consisted of central concentrated loads of 20 kips applied to each span simultaneously at 30 cycles/minute.

The elastic analysis for these tests was further refined by using three straight lines as an approximation to the observed load slip curve obtained from push-out tests. On this basis it was found from the analysis that the most heavily loaded pair of studs should carry 13.8 kips as indicated in Fig.7. A comparison of observed and theoretical deflections (Fig.8) shows good agreement.

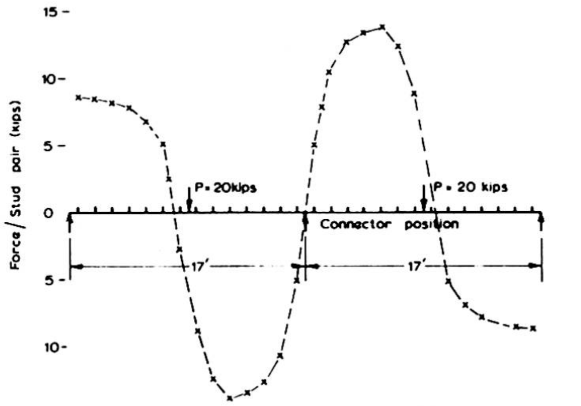


FIG. 7 DISTRIBUTION OF STUD FORCES IN CONTINUOUS BEAM USING AN ANALYTICAL METHOD ALLOWING FOR SLIP

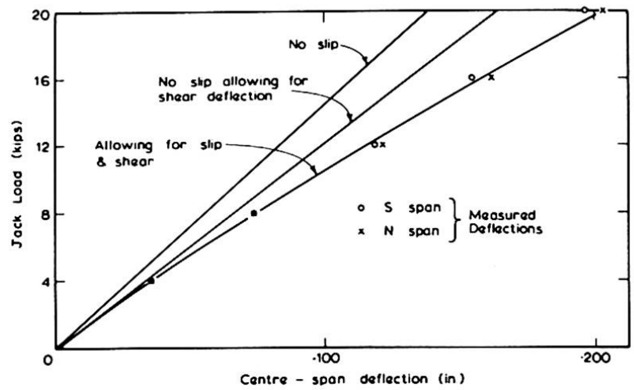


FIG 8 THEORETICAL AND EXPERIMENTAL LOAD-DEFLECTION CURVE FOR CONTINUOUS COMPOSITE BEAM

The beam loading was cycled between 0.8 and 20 kips and complete failure occurred at the first stud pair at 580,000 cycles which compared favourably with a life of 500,000 cycles as indicated by the British Code CP117(3). Sequential failure of adjacent studs then took place; at 820,000 cycles all studs had failed in one of the most heavily loaded shear spans. Final failure was brought about by the development of a fatigue crack starting at a welded bracket on the joist where the bending stress had risen to 10 kips/in.^{2}

COLUMNS

Since the completion of the early work (4) on slender pin-ended composite columns bent about their minor axes, the computerised analysis derived for the study of these columns has been applied to cases of bending about any centroidal axis. The analysis is based upon the assumption that both steel and concrete have stress-strain relationships of the form shown in Fig.3(b) and enables the deflected form of the column to be determined for any condition of equilibrium.

Typical comparisons of experimental and theoretical results for pin-ended columns of 4in. x 3in. R.S.J. with 2in. concrete cover bent about a diagonal axis are shown in Fig.9. It will be noted that theoretically "yielding" of both the steel (SY2) and the concrete (CY2) occurs before the critical load for instability. In fact in nearly all tests this critical load was attained shortly after yielding of the steel had commenced. A summary of a whole series of tests on 7ft. long columns of this section expressed in terms of collapse load (Fig.10) would suggest that the analysis is of general application for concrete encased steel columns. It further demonstrates that the assumptions that (a) torsional displacements can be neglected and (b) bending displacements occur in the plane of the applied moment, are fully justified for composite columns which are roughly square in section.

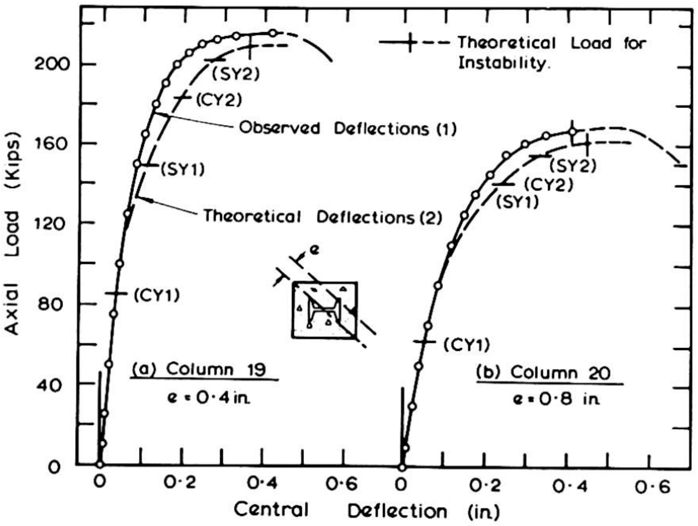


FIG. 9 LOAD - DEFLECTION RELATIONSHIPS FOR 7 FT. BENT ABOUT BOTH PRINCIPAL AXES (4"x3"RSJ(8"x7"))

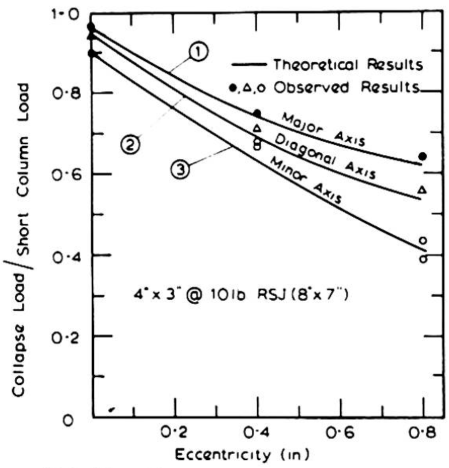


FIG. 10 RELATIONSHIP BETWEEN COLLAPSE LOAD AND ECCENTRICITY FOR 7FT COLUMNS

Consideration has also been given to eccentrically loaded pin-ended composite battened columns. As a basic study examination has been made of columns consisting of 2/3in. x $1\frac{1}{2}$in. @ 4.5 lb. channels 1 in. apart without any battens and for which reliance was placed entirely upon the plain concrete to transmit shear between the channels. Typical

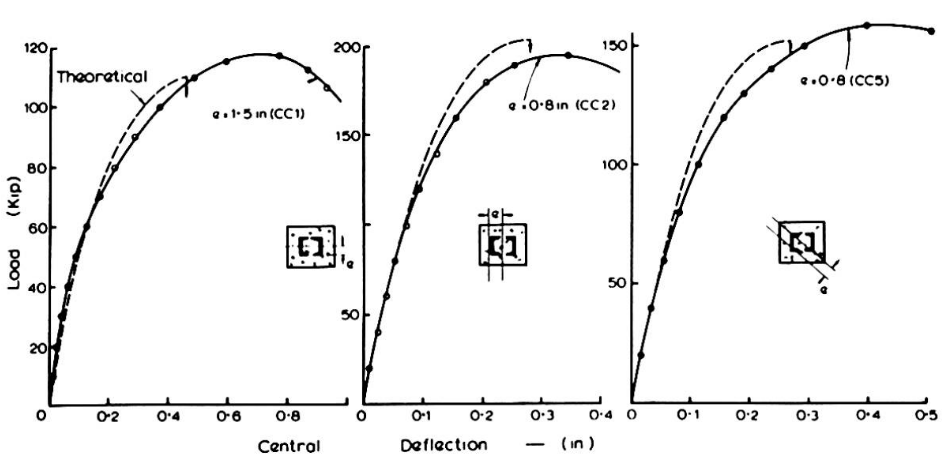


FIG 11 BATTEN COLUMNS

results together with theoretical solutions are shown in Fig.11. In all cases spalling and crushing of concrete occurred after the maximum theoretical axial load had been attained.

Pin-ended columns consisting of concrete filled tubes of 8in. x 8in. x 3/8in. section, have also been tested. Results for two specimens are given in Fig.12. Again the agreement with the theoretical solution is good.

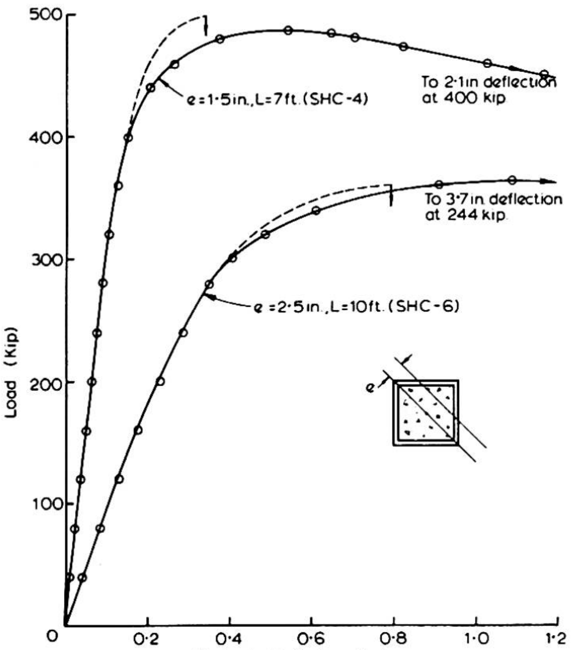


FIG 12 LOAD-CENTRAL DEFLECTION CURVES FOR COLUMNS SHC-4 AND SHC-6

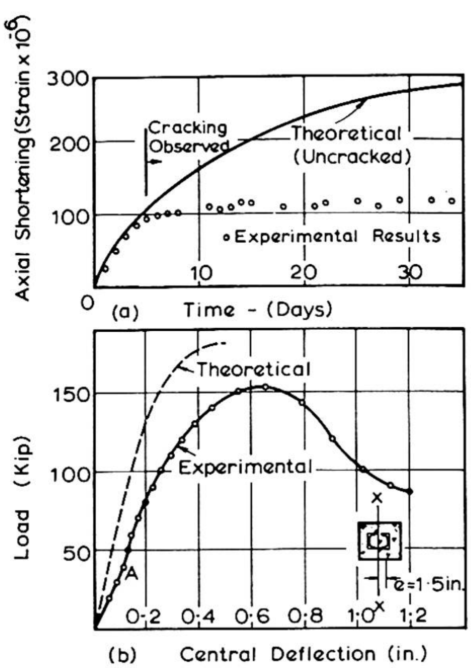


FIG.13 STRAIN DATA AND LOAD-DEFLECTION CURVES FOR COLUMN CC12.

Shrinkage and Creep of Concrete. Several aspects of the effects of shrinkage and creep of concrete on the load carrying capacity of pin-ended columns are being investigated. The test columns were all of the double channel type (Fig.11) and were 7ft. long.

Of particular interest is the case of a column subjected to large initial shrinkage stresses. For column CC12 containing an aggregate known for its high shrinkage properties, cracking commenced after 4 days drying and after some 35 days the cracking was extensive (Fig.13a). The comparison (Fig.13b) of the experimental deflections with the theoretical values assuming an uncracked section, demonstrates the effect. The portion OA of the experi mental curve indicates the region where cracks on the compressive side were closing up; once point A had been reached the column acted as a normal uncracked member with somewhat higher steel stress and an increased column deflection. This extensive cracking does in fact act as a large initial imperfection which increases the central deflections and lowers the ultimate load of the column.

Column CC7 was used to examine the effect of sustained axial load applied at an eccentricity of 1.6in. about the major axis. The short term strength of this column was estimated to be 160 kips. Curves showing central deflection against time were calculated from a creep rate analysis based on control tests, and are shown in

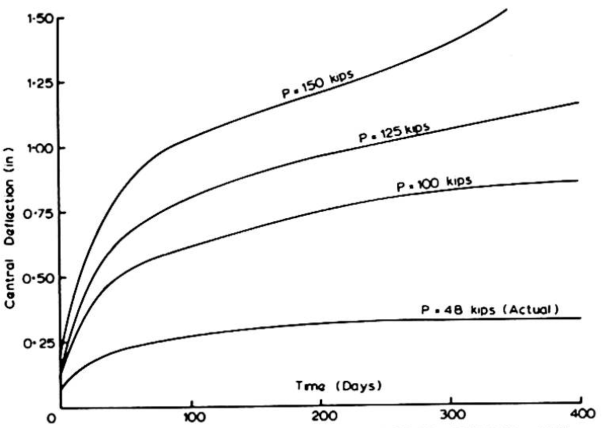


FIG 14 THEORETICAL BEHAVIOUR OF COMPOSITE COLUMN CC7 UNDER INCREASED SUSTAINED LOADS.

Fig.14. For a load of 150 kips applied for 200 days it was found that the deflection rate was still increasing with time. For 100 kips the deflection rate was always decreasing with time. It could therefore be argued that the critical load was of the order of 125 kips and less than the short term strength of 160 kips. It is of interest to note that the bare channels are themselves theoretically capable of carrying 48 kips before collapse occurs assuming provision is made for shear transmission.

CONNECTIONS

At first sight it might well be thought that in composite construction connections should be designed on the basis that both the shearing force and bending moment to be transmitted are carried entirely by the steelwork. Fortunately this is far from the truth in practice since the concrete when appropriately reinforced can assist the steel in several ways.

In the work at Sydney(5) both internal and external beam-to-column connections have been studied, though the latter has proved to be the more interesting in attempting to design connections in which the concrete around the steel connection will not disintegrate even after considerable permanent deformation has taken place. The successful connection eventually developed is shown diagrammatically in Fig.15. The steel beam is attached to the steel column by welding on top and bottom moment plates and a shear plate to the column below the beam. It will also be seen from the Figure that two of the reinforcing bars in the slab are carried around the column and another pair are turned down into the concrete encasement of the column. No other reinforcement was provided in the column. Tests on these units have shown that the concrete remained fully active right up to ultimate load.

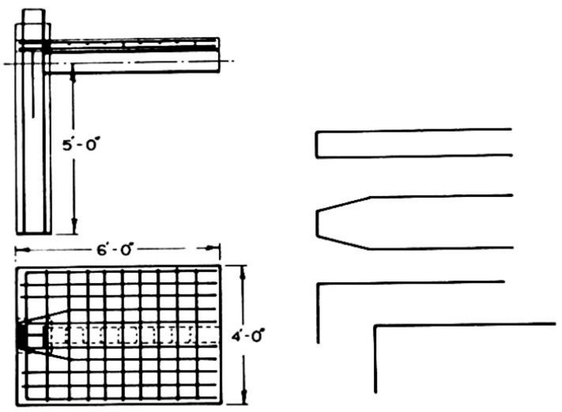


FIG 15 COMPOSITE CONNECTION REINFORCEMENT DETAILS

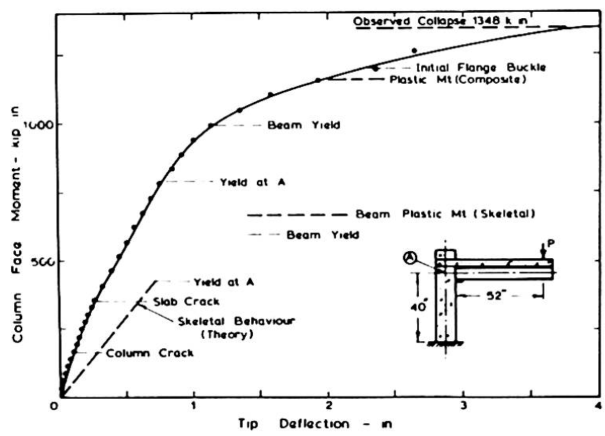


FIG 16 BEHAVIOUR OF SPECIMEN USC3

When the results of tests on bare steel units are compared with those for the corresponding composite connections, the improvment obtained with the latter is immediately obvious as may be judged from the curves in Fig.16. The upper curve relates to an 8in. x 5¼in. @ 17 lb. U.B. attached through welded studs to a 48in. x 4in. thick slab; the column consisted of an 8in. x 8in. @ 31 lb. U.C. having a 2in. cover of concrete.

The composite unit proved to be considerably stiffer than the bare steel component. The latter transmits the reactions from the beam largely by shearing action through the column web adjacent to the end of the beam. Failure occurs when the stress in this web reaches the value $1/\sqrt{3}$ times the tensile yield stress of the steel. In the composite connection the effect of the concrete between the flanges of the column is to share the shear force formerly transmitted entirely through the column web. Yielding does eventually occur in this area but again the presence of the concrete enables the connection to go on transmitting moment right up to the full plastic value of the composite T-beam.

Finally, acknowledgment is made to the present members of the Sydney group, Messrs. P.Ansourian, R.Q.Bridge and M.W.Hallam and to former members Dr. N.M.Hawkins and Dr. Y.O.Loke, all of whom contributed to the results summarised in this paper.

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SUMMARY

An account is given of the behaviour of composite steel and concrete components under the action of short and long term static loading and of repeated loading. The principal components studied were: simple and continuous composite T-beams; pin-ended composite columns made up from single and fabricated steel sections; and composite beam-to-column connections.