

## Reinforced concrete joints between prestressed concrete members\*

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The paper by Mr Reeves and Professor Morice provides further support for the use of reinforced concrete joints between prestressed concrete members. In their discussion of joint design, and specifically of the behaviour of this type of joint at ultimate load, the authors suggest that, at transfer of prestress, the stresses in the lower fibres of the span members at sections adjacent to the supports should be low compressive or tensile stresses. Tests of joints of the type shown in Figure 1c of the paper, recently carried out in the Structural Development Laboratory of the Portland Cement Association<sup>(1)</sup>, have shown that this requirement is not always necessary.

Pairs of precast prestressed I beams were joined together by deformed reinforcing bars placed longitudinally across the joint in a deck slab cast on top of the girders, as shown in Figure I. The space between the ends of the girders was filled by concrete forming part of a transverse diaphragm placed at the joint. The specimens were supported below the joint and loaded by equal point loads at each end. In these tests, the amount of normal reinforcing bars in the deck slab, expressed as a percentage of (depth of girder  $\times$  width of bottom flange), was 0.83, 1.66 or 2.49%. The initial precompression of the bottom flange of the precast girders was 0, 2,100 or 3,100 lb/in<sup>2</sup>. The ultimate strength of each connexion measured in the tests was compared with the calculated ultimate strength, any influence of precompression of the bottom flange of the precast member being neglected, and also with the calculated ultimate strength taking this precompression into account. From a study of these measured and calculated ultimate strengths it was concluded that, for the practical range of continuity reinforcement of from 0.5 to 1.5%, the influence of precompression of the bottom flange may be neglected in the calculation of the ultimate strength of this type of joint. These tests and the conclusions drawn from them are discussed fully in PCA Development Department Bulletin D34<sup>(1)</sup>.

Similar tests have been carried out on connexions between prestressed double-T members<sup>(2)</sup>, in which deformed bars were placed in the topping concrete

covering the top flange of the member. Equally favourable results were obtained in these tests.

The behaviour of this type of connexion has also been studied in tests of continuous composite beams<sup>(1-4)</sup>, and has been found to be most satisfactory. One of these tests is seen in progress in Figure II. The specimen consists of two 33-ft long precast prestressed I beams joined by deformed bars placed in a 39  $\times$  3 in. thick cast-in-place concrete deck slab. The beam is a half-scale model of one beam and its portion of deck slab taken from a two-span continuous highway bridge. The beam was designed for the envelope of maximum moments caused by the standard H20-S16 loading of the American Association of State Highway Officials. The test loading simulated the equivalent H20-S16 lane loading, arranged so as to cause maximum moment at the centre support.

Three tests were carried out on this beam, each successive test being carried to a higher load, the third test to destruction. The continuity behaviour of the beam is shown in Figure III, in which the ratio of the support moment to the mid-span moment is plotted against the total applied load. Also plotted on Figure III is the moment ratio corresponding to calculations based on the elastic theory, constant stiffness being moment ratio assumed along the length of the beam, and that corresponding to calculations based on limit design, full redistribution of moments at ultimate load being assumed.

For loads up to 75% of the design service load, the support moment was equal to 98% of the elastic theory moment. Slightly above this load, cracking of the deck slab occurred over the joint between the two spans and, as a result of this, the support moment dropped to 93% of the elastic theory moment at design service load. Further increase in load resulted in a progressive change in the ratio of the moments at the critical sections from that given by the theory of elasticity to that given by the theory of limit design, full redistribution of moments at ultimate load being assumed.

The continuity behaviour of the beam at service load was considered to be satisfactory. The departure from the theoretical continuity moment was no greater than that occurring in many reinforced concrete continuous beams. The behaviour at ultimate load was also considered satisfactory, since the full ultimate strength of all three critical sections was developed.

A problem not considered in the paper is the in-

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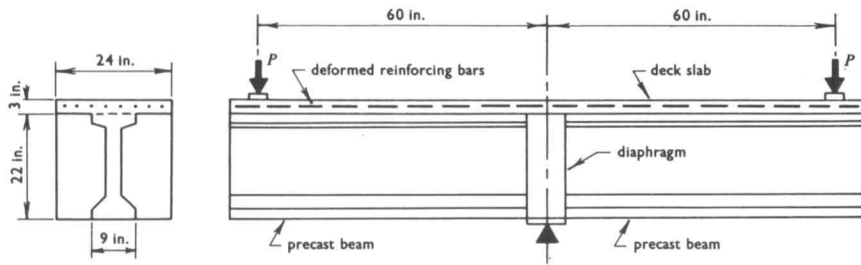


Figure I: Test of reinforced concrete joint between two precast prestressed concrete I beams.

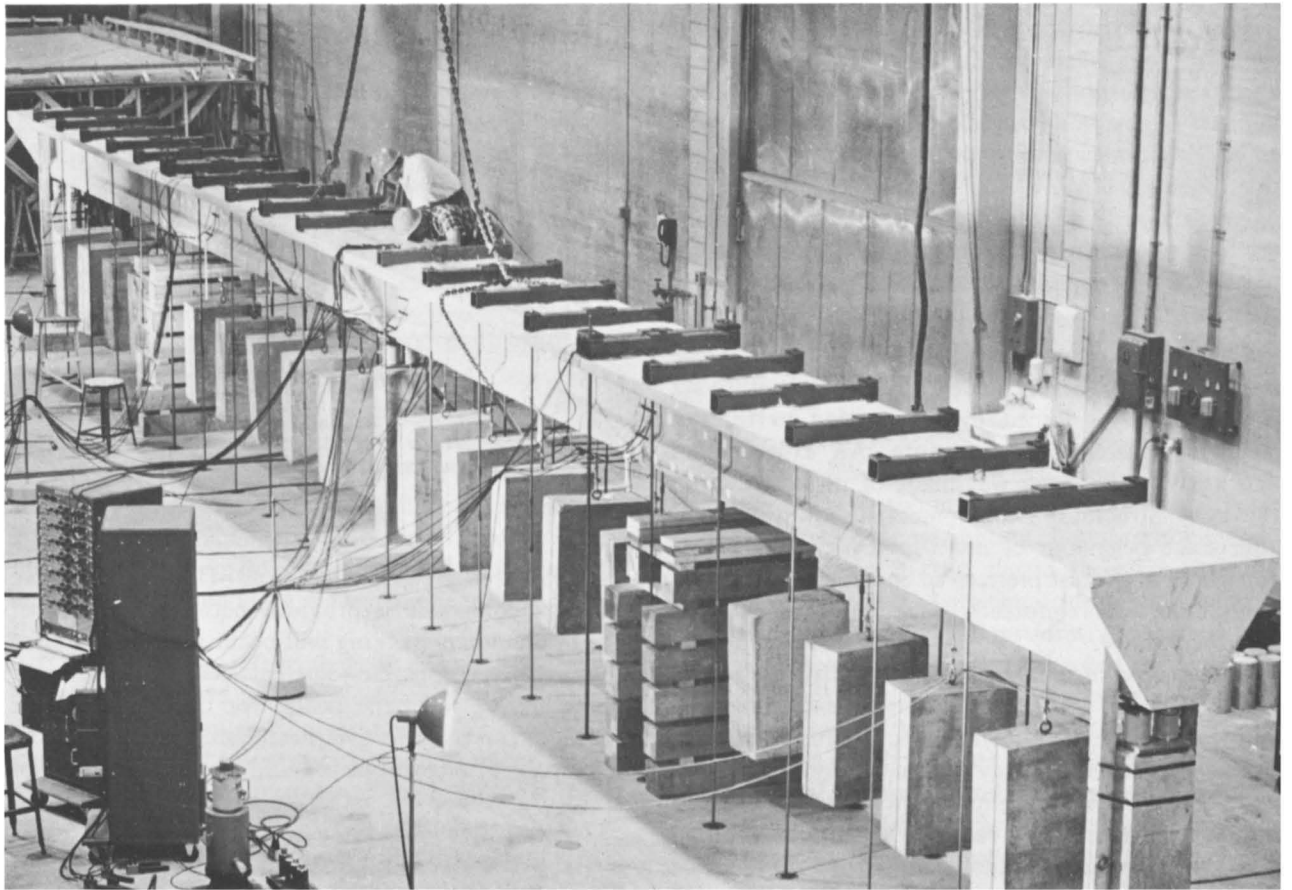


Figure II: Test on a half-size precast prestressed concrete bridge beam.

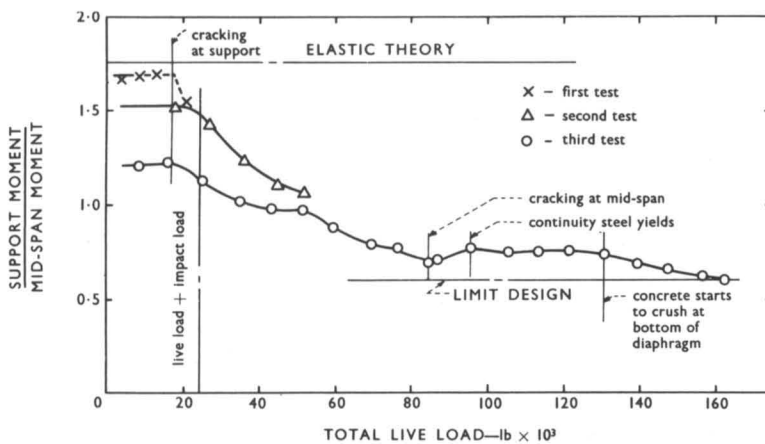


Figure III: Variation with increase in total load of the ratio of centre support bending moment to mid-span bending moment due to applied loads.

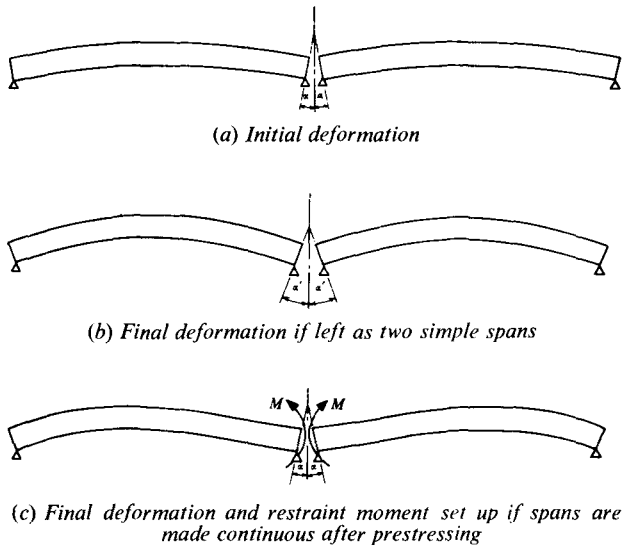


Figure IV: Deformations and restraint moments due to creep in a two-span beam (vertical scale exaggerated).

fluence of creep and shrinkage deformations on the behaviour of structures made of statically determinate precast elements joined by prestressing to form a statically indeterminate structure. An experimental and analytical study<sup>(4)</sup> was made of this problem in the PCA Structural Development Laboratory, as it affects the behaviour of multi-span highway bridges consisting of precast prestressed concrete beams made continuous with reinforced concrete joints of the type discussed above.

In this type of construction, the individual beams are prestressed while acting as simple-span beams, and they are free to deform elastically due to the prestressing force without any external restraint being set up. For an indefinite period after prestressing, creep of the concrete of the beams will cause the initial elastic deformations of the beams to increase. While the beams continue to act as simple spans, the deformations continue to occur without restraint. However, when the beams are made continuous by the casting of the joint, further increase in deformation is restrained and restraint moments are set up in the structure, as illustrated in Figure IV. If the spans are not joined together, it is seen that the relative rotation of the ends of the beams due to creep is  $(2\alpha - 2\alpha')$ . If the two beams are rigidly joined together after prestressing, to form a continuous system, then this relative rotation is prevented by the restraint moments set up in the beams. These moments are similar in character and distribution to the secondary moments which are set up in a monolithic prestressed continuous beam, prestressed by a non-concordant prestressing tendon. In this latter case, the secondary moments are caused by restraint of the initial elastic deformation of the beam at the time of prestress.

The practical consequences of the restraint mo-

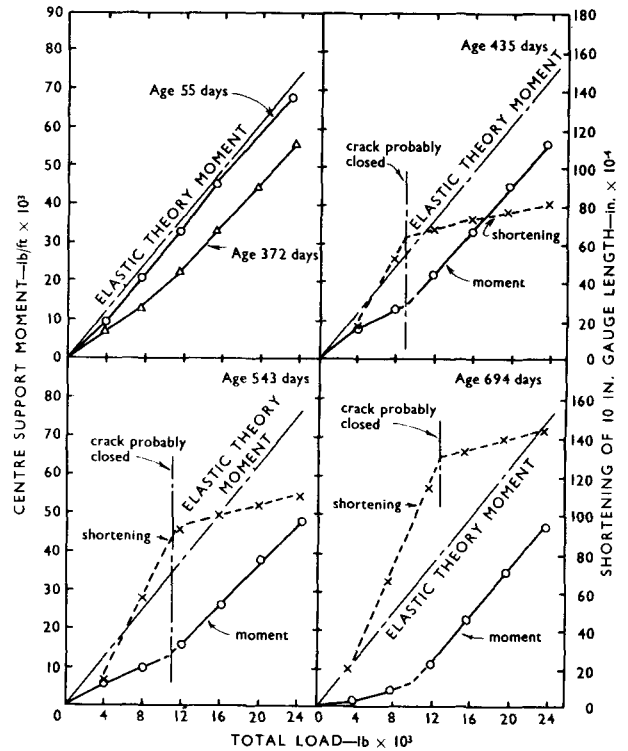


Figure V: Variation with applied load of centre support moment and shortening of 10 in. gauge length at bottom of centre support diaphragm. Beam without positive moment connexion.

ments due to creep are two-fold. (1) If no positive moment connexion is provided between the ends of the beams, then cracking will occur at the bottom of the reinforced concrete joint between the beams, and continuity between the beams for live loads will be reduced. (2) The effective prestressing moment in the mid-span regions will be reduced by the magnitude of the restraint moment acting at that section.

The restraint moments caused by creep due to prestress will be reduced to some extent by restraint moments of opposite sign which are developed by creep deformations of the beams caused by dead load bending moments.

The behaviour of two beams similar to that shown in Figure II was studied over a period of approximately two years. The beams were identical in all respects, except that one incorporated a positive moment connexion at the interior support whilst the other did not. The long-term variations of support reactions and deflexions due to creep and differential shrinkage deformations were measured. At intervals, the continuity behaviour of the beams was investigated by loading them within their service load range. Finally, the beams were loaded to destruction.

The two beams behaved in an almost identical manner up to an age of 337 days, at which time a crack became visible at the bottom of the diaphragm in the beam without a positive moment connexion. The positive restraint moment thereafter remained almost con-

stant in this beam, whilst it continued to increase in the beam with the positive moment connexion.

The behaviour of the beam without the positive moment connexion when subject to short-term loads at various ages is shown in Figure V. After cracking occurred at the bottom of the diaphragm, a mechanical gauge was positioned in this location to measure the shortening of a 10 in. gauge length which included the crack. Records obtained during five short-term tests are shown in Figure V. These clearly indicate the progressive growth of the crack, and its influence on the continuity behaviour of the beam.

The performance of the beam with the positive moment connexion was found to be closely predicted by calculations based both on the "effective modulus" method and on the "rate of creep" method of calculation. These calculations indicate that, if the creep strain is twice the initial elastic strain, then the restraint moments due to creep would eventually become of the order of 75% of the secondary moments which would have been set up if the beam had been prestressed as a monolithic continuous beam.

At the end of the long-term study, both beams were loaded to destruction. Apart from their reaction to small loads, the behaviour of the beams was almost identical, and their ultimate load capacities differed by less than 2%. It appears therefore that creep and shrinkage deformations do not influence the ultimate strength of a precast structure made continuous by reinforced concrete joints. A detailed report of this study will be found in PCA Development Department Bulletin D46<sup>(4)</sup>.

It is evident therefore that, if precast prestressed elements are joined to form a statically indeterminate structure after prestressing, either suitable connexions must be provided to oppose restraint moments set up due to creep, or the prestressing tendon profiles must be adjusted to minimize or eliminate relative rotations of the ends of members at joints. This last is, in effect, the same as designing concordant tendon profiles for monolithic prestressed concrete indeterminate structures.

The studies briefly described above are part of a nine-stage investigation of the behaviour of precast prestressed concrete bridges made continuous for live loads by the provision of deformed reinforcing bars longitudinally in the deck slab over the intermediate supports. These studies are reported in detail in a series of PCA Development Department Bulletins<sup>(1,3,5-7)</sup>.

### Reply by the authors

Dr Mattock's contribution adds important information to an understanding of the behaviour of composite beams under load.

The test results referring to the effect of prestress compressive stresses on the strength of the joint will, of course, give greater freedom in designing joints.

This is particularly true where the span members are prestressed by pre-tensioning, when it is not usually convenient to adopt a curved cable profile.

The results of the tests on two-span composite beams referred to by Dr Mattock are particularly interesting to us for the information they provide on behaviour in the working load range. These tests show that a joint that will not crack prematurely can be constructed, and that the formation of normal bending cracks in the joints does not lead to greater moment redistributions than those normal in continuous reinforced concrete beams.

The scope of our tests did not permit an experimental study of the effects of creep and shrinkage deformations on the continuity action of a beam. At the time the tests were planned, however, it was felt that, in the majority of composite beams, it would be desirable to use a cable profile which was swept up at the supports. This, of course, has the effect of reducing the secondary moments introduced at a joint by creep and shrinkage deformations arising from a straight cable profile. The amount of this reduction depends upon the tendon profile and it is conceivable that a negative secondary moment could be introduced at the joint.

As shown by Dr Mattock, the effect of the growth of secondary positive moment cracks on the continuity behaviour of a continuous beam is significant. Figure V of Dr Mattock's contribution shows approximately a 36% reduction in the elastic theory restraining moment at 694 days. This demonstrates the importance of a positive moment restraint when creep and shrinkage effects can proceed unchecked for such long periods. From a practical point of view, however, and for the average structure, a part or whole of the working load will be applied within a few months of the joining of the span members, thus preventing the formation of the secondary moments, and therefore the cracks, and the subsequent undesirable effects upon the continuity action.

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