INVESTIGATION OF PRESTRESSED REINFORCED CONCRETE FOR HIGHWAY BRIDGES

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This report provides a guide to the work accomplished in the course of an extensive research project on the use of prestressed concrete for highway bridges. The project was active over the period 1951-1969. It covered various topics related to flexural strength, shear strength, time-dependent deformations, anchorage-zone stresses, and bond characteristics of prestressed concrete beams. The scope of the analytical and experimental investigations in each area is outlined. The report also contains a list of references where complete information on different phases of the investigation can be found.

• IN October 1950, George F. Burch, then Bridge Engineer for the Illinois Division of Highways, requested the University of Illinois Civil Engineering Department to submit a proposal for research that might help to answer certain questions about the use of prestressed concrete in highway bridges, questions that had been discussed in the Committee on Bridges and Structures of the American Association of State Highway Officials. This proposal led to a comprehensive investigation of the strength and behavior of prestressed concrete bridge beams, which was conducted through the years 1951-1969 as a cooperative research project of University of Illinois, the Illinois Division of Highways, and the U. S. Department of Transportation, Federal Highway Administration, Bureau of Public Roads.

The objectives of the project, which were reviewed annually by an advisory committee with emphasis on their ultimate relation to bridge design, covered flexural strength, shear strength, time-dependent effects, anchorage-zone stresses, and bond. The resulting research produced a fund of basic information on the structural performance of prestressed concrete, which influenced directly the development of design specifications and methods in the United States and other countries. This paper provides a summary of the activities on the project.

The aims of the project as well as the research methods were formed under three influences.

1. The project was initiated only 2 years after the completion of the Walnut Lane Bridge in Philadelphia, the first prestressed concrete highway bridge in the United States. Prestressed concrete was new, full of promise, and somewhat mysterious. The claims made for its qualities in the popular professional literature were often unsubstantiated and sometimes irrelevant.
2. The basis of structural design in reinforced concrete was in the process of changing from working stresses to strength.
3. Prior to the initiation of the project on prestressed concrete, an extensive and successful investigation of concrete bridge floors had just been concluded at the University of Illinois. In that project, fundamental information was gathered and used to develop design methods by using a three-pronged approach that consisted of (a) theoretical formulation of the problem, which lead to selection of the critical variables to be investigated experimentally; (b) experimental studies, which provide tests of the

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theoretical predictions and sometimes lead to modifications of the theory and further tests of critical variables; and (c) development of simplified design methods with explicitly defined domains of applicability.

The entrepreneurial claims made for prestressed concrete on the basis of superficial evidence made it essential to establish whether prestressed concrete would have its own set of design criteria or whether the criteria for reinforced concrete would be applicable to prestressed concrete. The change in the design basis from stress to strength created a need for fundamental information. The manifest success of the methods used in the investigation of concrete bridge floors provided the confidence and the convincing evidence for planning a long-range study starting with investigations of fundamental problems.

Thus, as various different problems were considered throughout the history of the investigation, the method used was the classic experimental method of hypothesize-test-rehypothesize. The final step was that of producing design methods for use in practice. The research program was always aimed at developing information about broad and basic problems rather than specific design conditions. For example, the entire problem of the flexural strength of prestressed concrete sections was studied analytically and experimentally to develop design criteria for unbonded prestressed concrete beams. Although this approach required time to reach practical results, it eliminated backtracking and reduced the number of limitations and doubts that often surround the results of single-purpose programs designed for immediate solutions.

Various phases of the project are described in the following sections.

FLEXURAL STRENGTH

At the time of inception of the project, a general theoretical understanding of the flexural strength of reinforced concrete sections was still to be developed. Sufficient data under different conditions had not yet been obtained to provide a firm and general perspective of factors such as the limiting strain and effective strength of the concrete in a beam in relation to a test cylinder. Prestressed concrete introduced additional variables (the prestress level and reinforcement with a stress-strain curve that could not easily be idealized as elastoplastic) and brought doubts to bear on what had been one of the stable foundations of the theory of flexural strength for ordinary reinforced concrete sections (the distribution of strain over the depth of the section) because of the need for deriving comparable solutions for unbonded beams as well as beams with fully and partially bonded reinforcement.

The concepts involved in determining the flexural strength of prestressed reinforced concrete sections are shown in Figure 1, which shows the conditions of strain and stress at failure for a rectangular beam reinforced in tension. Notation related to the geometry of the cross section is defined in the figure. The symbols for strain and stress have the following significance:

ϵ_u = limiting strain of concrete in compression,
ϵ_{sa} = increase in the steel strain beyond the strain ($\epsilon_{se} + \epsilon_{ce}$),
ϵ_{ce} = concrete strain at level of reinforcement caused by effective prestress,
ϵ_{se} = strain in reinforcement corresponding to effective prestress,
ϵ_{su} = total strain in reinforcement at failure,
f_{cu} = average stress in beam concrete at ultimate, and
f_{su} = reinforcement stress at beam failure.

The steel strain increase, ϵ_{sa}, is related to the limiting concrete strain, ϵ_u, by the expression

$$\epsilon_{sa} = F\,\epsilon_u\left[(1/k_u) - (1)\right] \qquad (1)$$

where F is a strain compatibility factor that is influenced primarily by the bond between concrete and steel and the loading conditions. From equilibrium, it can be shown that

$$k_u = pf_{su}/f_{cu} \qquad (2)$$

which can be substituted in Eq. 1 to yield

$$\epsilon_{sa} = F \epsilon_u [(f_{su}/pf_{su}) - (1)] \tag{3}$$

The total steel strain at beam failure is

$$\epsilon_{su} = \epsilon_{se} + \epsilon_{ce} + F \epsilon_u [(f_{su}/pf_{su}) - (1)] \tag{4}$$

Equation 4 provides a direct relation between f_{su} and ϵ_{su} as represented qualitatively by curve 1 shown in Figure 2. Another relation between steel stress and strain is isolated by the inherent stress-strain curve for the steel. For a particular case, for which curve 1 may be plotted with the help of Eq. 4, the solution for f_{su} is at the intersection of the two curves shown in Figure 2. The flexural capacity of the section is almost directly proportional to f_{su}. Therefore, the relative effects of the critical variables on flexural strength can be evaluated by using Figure 2.

The stress-strain curve for prestressing reinforcement can be divided ideally into a linear and a nonlinear portion. In relation to the strength of the beam, indicated by the stress f_{su}, it follows from Figure 2 that, if curve 1 intersects the linear portion of curve 2, any factor that shifts the position of curve 1 becomes critical. If curve 1 intersects the nonlinear portion of curve 2, flexural strength of the beam is insensitive to variations in factors affecting the position of curve 1.

A series of 82 beam tests was made in the course of the investigation to establish the effects of various parameters that control the location of curve 1 as indicated by Eq. 1. The concrete strength, reflected in the term f_{cu} of Eq. 1, was varied from 1,270 to 8,320 psi. The reinforcement ratio, p, varied from 0.1 to 1.0 percent. Bond conditions, which affect the compatibility factor F, were varied by testing bonded, totally unbonded, and partially unbonded beams. The effective prestress ranged from 20,000 to 180,000 psi.

A typical example of the type of studies carried out is shown in Figure 3, which shows the variation of the failure stress in the reinforcement, f_{su}, with the ratio p/f_{cu} at different values of the effective prestress ranging from 0 ($\epsilon_{se} = 0$) to 150,000 psi ($\epsilon_{se} = 0.005$). It is evident from Figure 3 that, below $p/f_{cu} = 1.5 \times 10^{-6}$ (1/psi), the flexural strength of the beam is insensitive to the effective prestress. The curves also indicate that a reduction in prestress from 150,000 to 120,000 psi is not important for strength throughout the range of p/f_{cu} values covered and that, at prestress levels over 120,000 psi ($\epsilon_{se} = 0.004$), there is little variation in f_{su} as the abscissa changes from 1×10^{-6} to 3×10^{-6}. Large variations in concrete strength are not of significance in this range.

Analyses shown in Figure 3 not only helped to plan experimental studies (concentrating experimental work in ranges where the analytical results show little sensitivity to changes in the parameters studied may produce trivial test results) but also indicated the ranges where design simplifications are possible.

For example, it is evident from Figure 3 that for bonded beams the variation of the steel stress with the parameter p/f_{cu} can be represented closely by a straight line. Figure 4 shows the exact solution for the steel stress with the predictions of an approximate method described by the expression

$$f_{su} = f'_s [(1) - (0.5)(pf'_s/f'_c)] \tag{5}$$

where f'_s is the strength of the reinforcement.

The work on flexural strength of prestressed concrete included studies toward the development of design specifications as well as analytical and experimental research. This phase of the project is summarized elsewhere (4).

One portion of the studies made in relation to design involved analytical studies of the interrelations among design criteria for flexure. Prestressed concrete bridge beams were designed to satisfy one set of requirements based on service load stresses, such as maximum stresses immediately after prestress and maximum stresses at design load, and another set of requirements based on minimum factors of safety. These dual sets of criteria hindered the selection of optimum sections. Consequently, a comprehensive study was made of the interrelations among design criteria for composite and noncomposite sections, leading to various aids for design as well as an explicit understanding of the effects of the design requirements. These studies are summarized elsewhere (3).

SHEAR STRENGTH

One of the early misconceptions about prestressed concrete was the belief that prestressing eliminated the need for web reinforcement. For service loads, it could be shown by calculation that the inclined principal tensile stresses were negligible or nonexistent. This is generally correct, but it does not mean that the prestressed concrete beam is not susceptible to shear failure. The first few beam tests demonstrated quite clearly that prestressed concrete beams could fail in shear with the beam developing considerably less strength and less ductility than it would have if it had failed in flexure.

Figure 5 shows the measured load-deflection curves of two prestressed concrete I-beams with similar properties except for web reinforcement. Beam 1 had no web reinforcement, and it failed in shear. Beam 2 had sufficient web reinforcement to develop a flexural failure. The undesirability of a bridge beam susceptible to a shear failure and the need for web reinforcement are clear from the comparison.

The investigation was concerned primarily with developing design methods for the determination of the optimum amount and type of web reinforcement in prestressed concrete bridge beams. Because of the lack of rational concepts related to shear failure, this task required considerably more experimental work than the investigation of flexural strength, with a substantial effort spent on understanding the behavior and modes of failure of beams without web reinforcement.

Initial tests and analyses of rectangular prestressed concrete beams resulted in the definition of shear-compression failures, which explained in an intelligible manner many features of shear failures in prestressed as well as ordinary reinforced concrete beams (5). This was followed by a study of prestressed I-beams, which related the shear-compression theory explicitly to the development of strains in the beam. It also showed that this mode of failure was only one of several possible modes and that the critical stage in the load history of a prestressed beam was the development of the inclined crack that could be initiated either in an uncracked portion of the beam or in a region influenced by flexural cracking (6). Subsequent studies showed the negative effect of draped reinforcement (i.e., that draping the strands could actually reduce the shear strength of the beam rather than increase it) and the quantitative relation between flexural cracking and inclined cracking (7, 8, 9). After a stable perspective had developed about the strength and behavior of beams without web reinforcement, work was started on beams with web reinforcement. This phase of the work (11) demonstrated that, although theoretically incorrect, the truss analogy would serve satisfactorily as a basis for the determination of web reinforcement in prestressed concrete beams and that the amount of web reinforcement was proportional to the difference between the shears corresponding to flexural failure and to initiation of inclined cracking.

During the course of this investigation of shear, a total of 250 beam tests was made. Loading conditions included simply supported beams, continuous beams, and beams subjected to simulated moving loads. Beams with rectangular cross sections as well as composite and noncomposite I-beams were tested. Concrete strength, prestress level, and amount and type of web reinforcement were major variables. The entire work is reported elsewhere (6, 10, 11).

The investigation had a strong impact on design methods for prestressed concrete. The concepts of inclined cracking, which developed during the progress of the investigation, are currently used in the ACI Building Code. As a result of the findings in this study, it has also become general practice to relate the shear capacity of the concrete to the inclined cracking load.

Figure 1. Conditions of strain and stress at failure for beams reinforced in tension only.

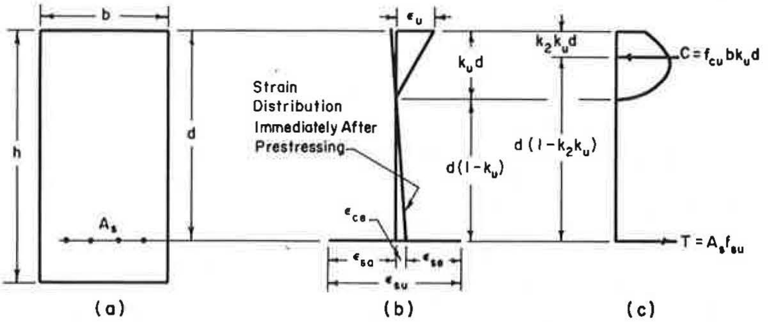


Figure 2. Graphic solution.

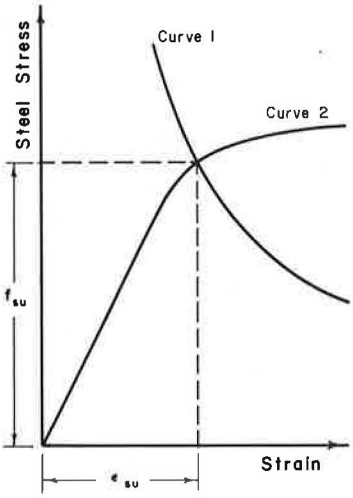


Figure 3. Effect of ϵ_{se} on reinforcement at failure.

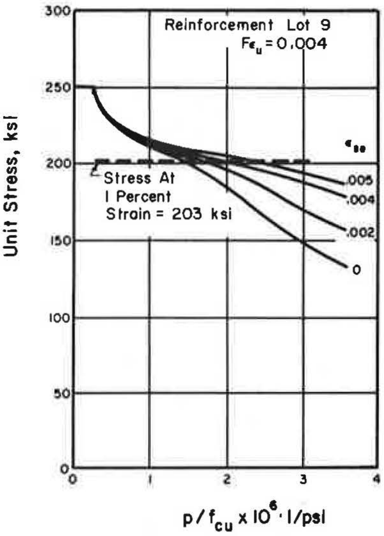


Figure 4. Comparisons of "exact" values of f_{su} with those derived from the joint committee approximate method and the proposed approximate method.

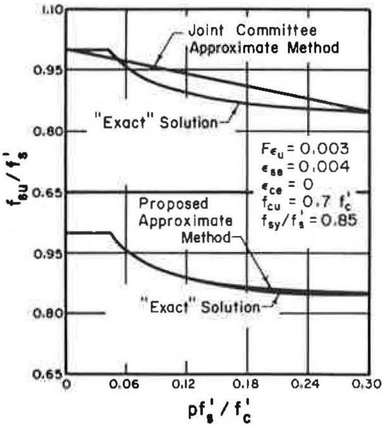
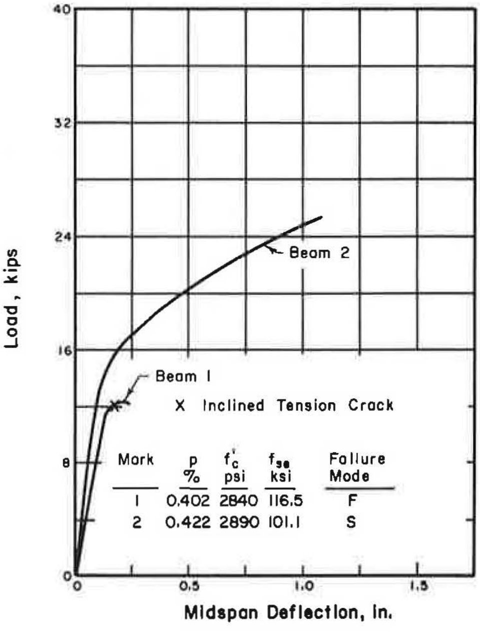


Figure 5. Load-deflection curves for beams failing in flexure and shear.



TIME-DEPENDENT EFFECTS

Stress relaxation of prestressing reinforcement and time-dependent deflections of prestressed concrete beams were studied in this phase of the investigation.

In the early 1950s, there were limited data on long-time stress-relaxation characteristics of prestressing reinforcement in general and virtually no data on prestressing steel manufactured in the United States. Consequently, a series of tests was initiated using the vibration technique (12) and continued for a 10-year period. The final paper (14) on this project reports data from 57 tests made at the University of Illinois and 444 tests made in other laboratories. On the basis of these data, design expressions were developed for estimating stress-relaxation losses as a function of time and the initial prestress level.

Prestressed concrete beams develop time-dependent deflections because of stress relaxation of the steel and creep and shrinkage of the concrete. Because the prestressing force varies with time, concrete creep occurs under varying stress. Furthermore, the prestressed bridge beam is typically subjected to sudden changes in its loading conditions in the early part of its life history, such as applications of prestress and casting of a deck, which complicate the process for calculating time-dependent deflections. An analytical investigation was initiated, complemented by laboratory tests, to study the feasibility of various methods of calculating time-dependent deflections. The main difference between the methods used was the manner of treating creep under varying stress. It was found that a simple procedure, the rate-of-creep method, was adequate for most practical cases (13). The study was extended to discuss the time-dependent deflection problem in typical composite highway bridges.

DESIGN OF ANCHORAGE-ZONE REINFORCEMENT

Longitudinal cracks have been observed in the anchorage zones of both post-tensioned and pretensioned prestressed concrete bridge girders. On some occasions, these cracks have led to collapse of the girder. A program of tests and analyses was initiated to investigate this phenomenon and to develop design methods for the proportioning of transverse reinforcement to restrain anchorage-zone cracking.

The experimental program included 66 tests of simulated anchorage zones. The results of these tests were studied in conjunction with data from 111 tests reported by other investigators. The experimental data covered a wide range of variables critical to the behavior of the anchorage zone: (a) size and shape of cross section; (b) eccentricity of the prestressing force; (c) ratio of the loaded area to the cross-sectional area; (d) distribution of the prestressing force; (e) type of prestressing (post-tension or pretension); (f) concrete quality; (g) amount, type, and location of transverse reinforcement; and (h) time-dependent effects.

Theoretical studies of the stress distributions in the anchorage zone resulted in a simplified analytical solution to the problem, which permitted the analysis of the critical cracking stresses in beams of all cross sections. More importantly, this analysis provided an intelligible basis for the design of transverse reinforcement to restrain anchorage-zone cracking. The entire study is summarized in a paper by Welsh and Sozen (17), which discusses the fundamental aspects of the anchorage-zone problem, describes the method of design, and presents an illustrative example.

BOND CHARACTERISTICS OF PRESTRESSING STRAND

In the early applications of prestressed concrete, a firm knowledge of bond was not considered to be critical because most of the bridge members were long and slender and some elements were post-tensioned and anchored mechanically. However, research on anchorage-zone stresses and shear strength indicated that the development length of the strand was critical in determining the susceptibility of the prestressed element to the development of longitudinal and inclined cracks near the anchorage zone. Consequently, an extensive investigation of the bond characteristics of prestressing wire and strand was initiated as one phase of the investigation.

The experimental program included 486 pullout tests and 5 beam tests to investigate the following parameters.

1. Strand diameter: seven-wire strands varying from $\frac{1}{4}$ to $\frac{1}{2}$ in. were tested.
2. Concrete strength: compressive strength of the concrete ranged from 2,400 to 7,600 psi.
3. Settlement of concrete: depth of concrete beneath strand was varied from 2 to 30 in.
4. Consistency of concrete: tests were made with concretes having slumps from 0.2 to 7.5 in.
5. Curing conditions: tests were made with moist-cured and dry-cured concrete, primarily to vary shrinkage.
6. Lateral pressure: a special test setup made it possible to make pullout tests with the concrete subjected to lateral pressure ranging up to 2,500 psi.
7. Age of concrete: specimens were tested from 1 to 64 weeks after casting.
8. Sustained load: pullout tests were made with the strand subjected to a constant load for periods up to 15 months.

The results of the entire investigation are reported elsewhere (18), which, in addition to presenting a hypothesis for the nature of bond between strand and concrete, contains recommendations for use in practice of the information developed.

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