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Volume II Final
Report/Executive Summary

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STRUCTURAL BEHAVIOR OF HIGH STRENGTH CONCRETE PRESTRESSED I-BEAMS

M.K. Kaufman and J.A. Ramirez

PURDUE UNIVERSITY

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Executive Summary

Final Report

RE-EVALUATION OF THE ULTIMATE STRENGTH AND BEHAVIOR OF HIGH STRENGTH CONCRETE PRESTRESSED I-BEAM SECTIONS

August 10, 1988

TO: H. L. Michael, Director
Joint Highway Research Program

FROM: J. A. Ramirez

PROJECT: C-36-56W

FILE: 7-4-23

Attached is a copy of the second and final volume of the Final Report of the HPR Part II study "Re-Evaluation of the Ultimate Strength and Behavior of High Strength Concrete Prestressed I-Beam Sections". I have served as the Principal Investigator on this study, directed the project and have co-authored the report.

The research results reported in this second volume include recommendations to allow the use of concrete compressive strengths up to 6500 psi in the design of precast prestressed I-Beams in the State of Indiana. No modifications of the current design equations to evaluate flexural capacity of the precast composite I bridge section are needed. The use of current IDOH Shear Design Specifications for continuous bridges with pretensioned I-beams is adequate. At simple supports of typical bridge structures the support centerline is usually between six and twelve inches from the end of the beam, and as a result, the transfer length of the strand extends into the shear span. Three tests conducted during this study, using this standard detailing, resulted in a premature strand anchorage failure as a web-shear crack penetrated into the transfer length of the strand. Although the specimens tested in this study had minimum amounts of shear reinforcement at the end regions, it is felt that the use of higher strength concrete in pretensioned beams requires an evaluation of the efficiency of the shear reinforcement in preventing this mode of failure. The effect of strand debonding in pretensioned members which was not part of the study, also needs further study.

The current AASHTO and the Zia and Mostafa methods to predict transfer length of the strand were also evaluated. The results of this study showed that the Zia and Mostafa method predicted better the transfer length of the strand. The results of this study have been recommended for implementation in the State of Indiana. The use of high strength concrete in the design

of prestressed I-Beams offers substantial benefits. The increased tensile strength of higher strength concretes is helpful in the service load design. Also, the increase in the modulus of elasticity results in better deflection control. The inherent relationship between higher strength concrete and better quality control makes high strength concrete attractive because of its improved long-term service performance. The qualities of high strength concrete are also proving themselves economically attractive in long span bridges. High strength concrete's comparatively greater compressive strength per unit weight and unit volume results in a reduction in dead load allowing lighter more slender bridges. This study also indicated the increased importance of adequate detailing in higher strength concrete members to insure proper ultimate load behavior and strength.

The results of this study and other findings should provide the necessary information so that designers can use higher concrete strengths to improve the economics and structural safety of bridges.

Sincerely,

Julio A. Ramirez

Julio A. Ramirez

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16. Abstract

The research results presented in this report include recommendations to allow the use of concrete strengths up to 6500 psi in the design of prestressed I-beams in the state of Indiana. No modifications of the current design equations to evaluate flexural and shear capacity are deemed necessary. At simple supports of typical bridge structures the support centerline is usually between six and twelve inches from the end of the beam, and as a result, the transfer length of the strand extends into the shear span. Three tests conducted during this study, using this standard detailing, resulted in a premature strand anchorage failure as a web-shear crack penetrated into the transfer length of the strand. Although the specimens tested in this study had minimum amounts of shear reinforcement at the end regions, it is felt that the use of higher strength concrete in pretensioned beams requires an evaluation of the efficiency of the shear reinforcement in preventing this mode of failure. The effect of strand debonding in pretensioned beams also needs study. The current AASHTO and the Zia and Mostafa methods to predict transfer length of the strand were also evaluated. The results of this study showed that the Zia and Mostafa method predicted better the transfer length of the strand.

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RE-EVALUATION OF THE ULTIMATE STRENGTH AND BEHAVIOR OF HIGH STRENGTH CONCRETE PRESTRESSED I-BEAM SECTIONS

Volume II
STRUCTURAL BEHAVIOR OF HIGH STRENGTH CONCRETE PRESTRESSED I-BEAMS

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PREFACE

This is the second and final volume on the research project, "Re-Evaluation of the Ultimate Strength and Behavior of High Strength Concrete Prestressed I-Beam Sections." An evaluation of the adequacy of current design procedures for higher strength concrete AASHTO I-girders is presented in this volume. Where necessary, new recommendations are given for the design of these members. This study includes an experimental program consisting of nine tests on six full scale Type I and Type II AASHTO I-Girders with concrete strengths ranging from 8000 to 9000 psi. An evaluation of the recommendations of this research study is illustrated with the example of an existing structure containing prestressed I-girders and a cast-in-place slab.

This work was conducted as Joint Highway Research Project No. C-36-56W. The experimental study was carried out at the Purdue University Civil Engineering Structural Laboratory. The specimens were fabricated at Hydro-Conduit, Lafayette, Indiana.

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LIST OF NOMENCLATURE AND ABBREVIATIONS

A_v = area of shear reinforcement within a distance s

b_w = web width

d = distance from extreme compression fiber to centroid of tension reinforcement

f'_c = compressive strength of concrete, psi

$\sqrt{f'_c}$ = square root of compressive strength of concrete

f_{pc} = compressive stress in concrete (after allowance for all prestress losses) at centroid of cross section resisting externally applied loads or at junction of web and flange when the centroid lies within the flange. In a composite member, f_{pc} is resultant compressive stress at centroid of composite section, or at junction of web and flange when the centroid lies with in the flange, due to both prestress and moments resisted by precast member acting alone.

f_y = specified yield strength of nonprestressed reinforcement

h = overall height of member

M_{cr} = moment causing flexural cracking at section due to externally applied loads

M_{max} = maximum factored moment at section due to externally applied loads

s = spacing of shear reinforcement in direction parallel to longitudinal reinforcement

V_c = nominal shear strength provided by concrete

V_{ci} = nominal shear strength provided by concrete when diagonal cracking results from combined shear and moment

V_{cw} = nominal shear strength provided by concrete when diagonal cracking results from excessive principal tensile stress in the web

V_d = shear force at section due to unfactored dead load

V_i = factored shear force at section due to externally applied loads occurring simultaneously with M_{max}

V_n = nominal shear strength

V_s = nominal shear strength provided by shear reinforcement

ABSTRACT

This report deals with the evaluation of the ultimate behavior of AASHTO I-beams with concrete strengths up to 9000 psi. The relevant AASHTO and IDOH design specifications are thoroughly evaluated based on the results of this research. The findings of this study remark the many beneficial implications of the use of higher strength concrete in precast prestressed AASHTO I-beams. Higher strength concrete's with comparatively greater compressive strength per unit weight and unit volume would result in reductions in dead load allowing lighter more slender bridges. The increased stiffness of higher strength concrete is advantageous in the stability and control of deflections in these longer more slender structures. The larger tensile and compressive strength is also helpful in the service load design of these members. Furthermore, the inherent relationship between higher strength concrete and higher quality concrete should result in an improved long-term preformance under service loads. This study also points out the increased importance of adequate detailing of higher strength concrete members to insure ductile behavior under ultimate load. At simple supports of typical bridge structures the support centerline is usually between six and twelve inches from the end of the beam, and twelve inches from the end of the beam, and as a result, the transfer length of the strand extends into the shear span. Three tests conducted during this study, using this standard detailing, resulted in a premature strand anchorage failure as a web-shear crack penetrated into the transfer length of the strand. Although the specimens tested in this study had minimum amounts of shear reinforcement at the end

regions, it is felt that the use of higher strength concrete in pretensioned beams requires an evaluation of the efficiency of the shear reinforcement in preventing this mode of failure. The effect of strand debonding in pretensioned beams also needs further study. The current AASHTO and Zia and Mostafa methods to predict transfer length of the strand were also evaluated. The results of this study showed that the Zia and Mostafa method predicted better the transfer length of the strand.

Introduction

Higher strength concrete is being produced by precast plants manufacturing precast I-girders for the state of Indiana. In Volume I[1] of the final report it was suggested that 28 day concrete compressive design strength for these members could be increased to 6500 psi without substantial changes or additional cost to the product. Also, the study conducted on the engineering material properties for compressive strengths up to 9000 psi indicated that current empirically derived expressions could be used to determine modulus of elasticity and tensile strength. Volume II will focus on the structural behavior and current design procedures of prestressed AASHTO I-beams fabricated with the higher strength concrete.

Many of the current design equations for pretensioned I-beams were empirically derived for concrete compressive strengths less than 6000 psi. As indicated in the state of the art report by ACI Committee 363[2], extrapolation of these design procedures to higher strength concrete members is unjustified and may be dangerous. Thus, before the multiple advantages of higher strength concrete can be utilized, it is necessary to investigate the ultimate strength and behavior of such members with careful control on the actual concrete strength.

The structural behavior of prestressed AASHTO I-beams containing higher strength concrete and the evaluation of current flexure and shear design procedures for these members are the main objective of this study. The main emphasis is focused on their shear behavior. The use of higher strength concrete in the fabrication of the precast I-sections will generally not affect the ultimate flexural strength of the composite section since the compressive force of the internal moment typically remains within the cast-in-place slab which has compressive strengths ranging from 3000 to 4000 psi.

Current Shear Specifications.

The design and analysis of a multi-span continuous structure consisting of a cast-in-place deck and prestressed I-beams can be quite difficult. Many different load cases must be evaluated throughout the fabrication and life of the structure. The evaluation of the effects of service and factored loads is conducted by developing design envelopes which represent the maximum and minimum bending moments and maximum shear force throughout the length of the structure. AASHTO specified loading conditions are used to develop these envelopes.

In the following discussion of three design specifications available for shear design of continuous composite bridges with precast I-beams, the effects of draped strand are neglected. The comparison is conducted in terms of strengths predicted.

IDOH Specifications[3]

$$V_n = \frac{4}{3} \frac{A_v f_y h}{s}$$

AASHTO 1979 Interim Specifications[4]

$$V_n = 2 \frac{A_v f_y jd}{s} + 180 b_w jd$$

AASHTO 1983 Specifications[5]

$$V_n = (V_c + A_v\, f_y\, \frac{d}{s})$$

The concrete contribution, V_c, is taken as the lesser of the two equations, V_{cw} and V_{ci}:

$$V_{cw} = (3.5\sqrt{f'_c} + 0.3\, f_{pc})\, b_w\, d$$

and

$$V_{ci} = 0.6\sqrt{f'_c}\, b_w\, d + V_d + \frac{V_i\, M_{cr}}{M_{max}} \geq 1.7\sqrt{f'_c}\, b_w\, d$$

The IDOH specifications are by far the easiest to apply. The design engineer develops the shear envelope, reflects the type and size of web reinforcement to be used in the structure, obtains the height of the section and proceeds to design the spacing of the web reinforcement. The spacing must also satisfy spacing limits and horizontal shear strength requirements.

The 1979 Interim Specifications are also very simple to apply. For concrete strengths in excess of 3000 psi, a constant value of 180 psi shear stress representing the concrete contribution is assumed. Since the critical region is located at $\frac{1}{4}$ the clear span, the formation of web shear cracks near the supports is not addressed by this equation which can result in the lack of required web reinforcement near the end region of an exterior span where shear forces are large and the web of the I-beam is relatively thin.

The 1983 Specifications recognizes two types of shear cracks. The load required to produce these shear cracks is assumed to represent the concrete contribution at ultimate strength. The specifications require a great deal of calculations and understanding. Problems arise when designing continuous structures. The equation predicting the web shear crack, V_{cw} is the simplest of the two crack predictions to apply. This equation will typically control near the end regions of exterior spans for a structure consisting of prestressed I-beams. The V_{ci} equation predicting the load required to produce a critical inclined flexure crack is the most difficult to use. Problems arise in evaluating the third term in the V_{ci} equation, $\frac{V_i M_{cr}}{M_{max}}$. M_{cr} is the moment causing flexural cracking at section due to externally applied loads. M_{max} is the maximum factored moment at section due to externally applied loads, and V_i is the factored shear force at section due to externally applied loads occurring simultaneously with M_{max}. The difficulties stem from the fact that the maximum shear force envelope can not be used in this calculation since the position of the load producing maximum moment is most likely not the position producing maximum shear. In addition, if the AASHTO truck loading is used, two values of shear exist at the section of interest. To be conservative, one would chose the algebraically lesser of the two shear values for V_i. The designer must also contend with lane loads which may control the maximum moment. Thus the evaluation of V_{ci} can present great difficulties to the design engineer and with two other design alternatives available, it is not surprising that the AASHTO 1983 Specifications are not generally used in the design of continuous structures containing prestressed I-beams and a cast-in-place deck.

The comparison of the three design equations between the quarter points of a span is conducted using the following assumptions: for the 1983 AASHTO Specifications V_{ci} controls and $V_{ci} = 1.7\sqrt{f'_c}\, b_w\, d$, $d = 0.9\, h$, $j = 0.9$, the web reinforcement contribution $V_s = A_v\, f_y\, \frac{d}{s}$, the concrete compressive strength of the prestressed I-beam is 5000 psi. Solving for the nominal shear strength, the three design equations reduce to,

IDOH Specifications

$$V_n = 1.48\ V_s$$

AASHTO 1979 Interim Specifications

$$V_n = 1.8\ V_s + 162\ b_w\ d\ \text{(psi)}$$

AASHTO 1983 Specifications

$$V_n = V_s + 120\ b_w\ d\ \text{(psi)}$$

The AASHTO 1979 Interim Specifications nominal shear capacity is substantially greater than the IDOH or AASHTO 1983 Specifications with the assumptions made. The IDOH and AASHTO 1983 Specifications would give very similar results.

Experimental Program

The evaluation of the ultimate behavior of higher strength concrete prestressed I-beams under flexure and shear was the main objective of this experimental program.

The experimental study consisted of nine tests on six AASHTO I-beams. Four Type II and two Type I AASHTO I-girders were tested using a symmetric loading system. The beams were designed to fail in shear as predicted by AASHTO Specifications. The beams were tested non-composite since the majority of the shear for a composite section is carried by the I-beam.

Elastic deformations calculated using the modulus of elasticity as predicted by the current AASHTO provisions and the the gross moment of inertia gave good agreement with the actual load-deflection response.

The flexural strength of two beams, Type I-1 and II-2, was exceeded and the AASHTO procedure estimated the capacity and ultimate stress in the strand for these beams very well.

The experimental study further illustrated that the formation of a web shear crack and its propagation across the transfer length of the lower prestressing strand can produce a failure due to loss of bond. This loss of bond results in the beam not being able to maintain equilibrium at the support. The use of lower flange reinforcement, consisting of straps and deformed reinforcement had no effect on this mode of failure. For the beams with minimum amount of shear reinforcement tested in this study, only the removal of the transfer length from the shear span insured adequate anchorage of the prestressing strand.

The formation of a web shear crack is an elastic problem occurring when the tensile strength of the concrete is exceeded. The AASHTO prediction of the formation of this crack was excellent.

The geometry, concrete strength, prestressing force, and amount of web reinforcement did not allow this study to evaluate the formation of a flexure shear crack as the failure mechanism as predicted by 1983 AASHTO procedure. However, the modifications made to this equation from that first proposed by the Illinois[6] study has made this provision quite conservative. This was illustrated in the beams tested where the flexure shear capacity controlled the predicted concrete contribution to the ultimate strength; however, the actual capacity of the beams was significantly greater as shown by specimens Type I-1, I-2 and II-2.

In all of the specimens tested, with the exception of those failing due to strand slippage, the current AASHTO design procedures were shown to be conservative.

The truss model approach was also used in this study as a behavioral model at ultimate of the beams under flexure and shear. The truss model gives the engineer an overall behavioral tool rather than the current section analysis conducted for flexure and shear. The effects of web reinforcement, concrete contribution and the importance of strand anchorage and development are better illustrated by this approach.

Cornell Study

In a study conducted at Cornell[7,8], the 1983 AASHTO shear specifications were evaluated for concrete compressive strengths up to 12000 psi. The findings of this study indicated that the 1983 AASHTO Recommendations for beams with web reinforcement were conservative for higher strength concrete. Further comparison conducted in Volume 2 of the Final Report of this study of the IDOH and AASHTO 1979 Interim Specifications with Cornell tests indicated that those provisions are also shown to be conservative for higher strength concrete.

Summary

This report presented a detailed evaluation of the ultimate behavior of AASHTO I-beams with concrete strengths up to 9000 psi. The findings of this research study were used to thoroughly evaluate relevant AASHTO and IDOH design specifications.

The use of higher strength concrete in the fabrication of prestressed I-girders has little effect on the ultimate flexural capacity of the composite section as long as the transfer requirements remain unchanged. However, high strength concrete produces benefits when evaluating stresses and deflections due to service loads.

However, the ultimate shear carrying capacity of the composite structure is mainly carried by the precast I-beam; thus, it is directly affected by the increase in the concrete compressive strength. Three different methods are available to evaluate the shear strength. AASHTO Specifications present two possible alternatives. In addition, IDOH allows a third alternative for the design of the web reinforcement. The provision presented in the 1983 AASHTO specifications is the most detailed analysis procedure; however, the use of this approach in analysis and design is cumbersome and unclear for continuous structures. The approach in the AASHTO 1979 Interim Specifications is easier to apply, but it has shortcomings in the evaluation of composite sections. The IDOH Specifications, the simplest of the three methods, is a modification of some of the earliest recommendations for prestressed concrete members.

The experimental program in this study included nine tests on six AASHTO prestressed I-beams without a cast-in-place slab, ie. non-composite. To produce a shear failure in the beams tested a relatively short shear span to structural depth ratio was used. The behavior of these beams was controlled by the web shear cracking phenomena.

Conclusions

The findings of the experimental program indicated that in regard to the three procedures reviewed, the IDOH Specifications are the most conservative. The AASHTO 1979 Interim Specifications which do not recognize the formation of web shear cracks were found to under-estimate the shear capacity in regions were web shear cracks occur. The 1983 AASHTO Specifications, which predicts the formation of a web shear crack, is an empirical approximation to an elastic solution and is quite accurate in predicting the formation of web shear cracks. The 1983 AASHTO recommendations were found to give the best estimate of the overall shear strength.

A study conducted at the University of Cornell evaluated the 1983 AASHTO Shear Specifications for concrete compressive strengths up to 12000 psi. Test results indicated that these recommendations used to predict the concrete contribution representing web shear and inclined flexure cracks were conservative for this higher strength concrete. In the evaluation conducted in Chapter 2 of this report the IDOH and AASHTO 1979 Interim recommendations were also found to be conservative for these specimens.

In the experimental part of the research study presented in Volume II, the first two beams tested had two and three foot overhangs, respectively which were used to keep the transfer length of the prestressing strand out of the shear span. This length provided sufficient anchorage to the prestressing strand which upon the formation of a web shear crack showed an increase in the stress near the support plate. However, in a typical bridge the centerline of the exterior support is between 6 and 12 inches from the end of the beam. Hence, the transfer length of the prestressing strand usually extends past the face of the support into the span. The stress increase in the strand upon the formation of a web shear crack in three of the beams tested with the centerline of the support plate 6 inches from the end of the beam resulted in strand slip leading to a premature failure. Although the specimens tested in this study had minimum amounts of shear reinforcement at the end regions, it is felt that the use of higher strength concrete in pretensioned beams requires an evaluation of the efficiency of the shear reinforcement in preventing this mode of failure.

The current AASHTO and Zia and Mostafa methods to predict transfer length of the strand were also evaluated. The results of this study showed that the Zia and Mostafa method predicted better the transfer length of the strand.

Recommendations

The following recommendations are based on the findings of this research study:

1. The use of 28 day concrete compressive strengths up to 6500 psi in the design of pretensioned I-beams for the State of Indiana can be allowed.
2. Evaluation of deflections produced by loads, which do not exceed the cracking capacity of the member, can be adequately predicted using the gross section properties and the modulus of elasticity given by current procedures.
3. The current methods used to evaluate the flexure capacity of precast composite I-sections for bridges in positive moment regions are adequate for under-reinforced sections.
4. The use of current IDOH Shear Design Specifications for continuous bridges using pretensioned I-beams and a cast-in-place slab is adequate.

5. The transfer length of the prestressing strand must be protected from any additional increase in stress due to web shear cracks. The formation of web shear cracks is a potential problem in bridges using modified I-sections with thinner webs. In the inspection of these type of bridges, special attention should be given to the visual inspection near the end regions of exterior spans.

Future Work

Further research is needed to evaluate the efficiency of the stirrup reinforcement in preventing failure due to an improper anchorage of the strand at simple supports. The behavior of composite sections in negative moment regions of high shear and flexural stresses needs further study. Further work is also needed on the effects of strand debonding on the strength of pretensioned beams. The presence of debonded strand can possibly have detrimental effects on the shear strength of pretensioned members. A design criteria is needed for the adequate debonding of strands.

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