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Fatigue Strength and Behavior of Prestressed Concrete Bridge Girders
Résistance et comportement à la fatigue des poutres de pont en béton précontraint
Ermüdungsfestigkeit und Verhalten von Spannbetonbrückenträgern

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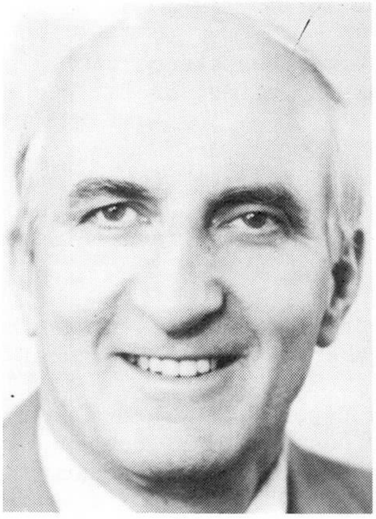

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SUMMARY

This paper constitutes a summary of selected research investigations related to the strength and behavior of prestressed concrete bridge girders. The investigations selected were inter-related and continuous over a twenty-year period. The investigations address aspects of strength and behavior related to flexure and fatigue, with fatigue emphasized in the paper.

RÉSUMÉ

Cet article présente un résumé des travaux de recherche ayant rapport à la résistance et au comportement des poutres de pont en béton. Les études choisies sont liées les unes aux autres et représentent un effort continu sur une période de vingt ans. Elles traitent certains aspects de la résistance et du comportement des gaines de précontrainte, du comportement en flexion et de la résistance à la fatigue.

ZUSAMMENFASSUNG

Dieser Artikel ist eine Zusammenfassung ausgesuchter Forschungsberichte, die sich mit der Baustoffestigkeit und dem Verhalten von Spannbetonbrückenträgern befassen. Die inhaltlich zusammenhängenden Beiträge behandeln einen Zeitraum von zwanzig Jahren. Sie behandeln Aspekte der Baustoffestigkeit und des Verhaltens bezüglich Biegewiderstand und vor allem Ermüdungsfestigkeit.

1. INTRODUCTION

This paper is a summary of selected research investigations related to the strength and behavior of pretensioned concrete bridge girders. The investigations selected were all inter-related and continuous over a twenty year time span. The investigations address strength and behavior related to strand blanketing, shear behavior under static load, flexural behavior and fatigue strength and behavior. The main focus of the paper is on fatigue strength and behavior.

Emphasis is placed on recent tests at the University of Texas. The overall objectives of the Texas project were:

1) To re-examine the fatigue resistance of typical pretensioned concrete girders with emphasis on the effect of fatigue on the strength of the girders.

2) To determine the effect of level of tension stress in the precompressed tensile zone on the capability of pretensioned girders to withstand traffic loading without strand fatigue during their design life.

3) To re-examine the approximate stress range to be used in design of prestressed concrete members to avoid fatigue failure in strands.

The main objective of this paper is to re-evaluate the recent research relative to its contribution and continuity of research previously conducted under sponsorship of the Louisiana Department of Transportation and Development.

The research and tests which are reviewed in this paper are:

1) Portland Cement Association tests reported in 1965 related to strand blanketing on half scale girders.

2) Tulane University tests reported in 1975 related to strand blanketing of half scale and full size girders.

3) Portland Cement Association tests reported in 1980 related to strand blanketing and fatigue tests of full size girders.

4) University of Texas tests reported in 1984 related to fatigue strength and behavior of full size girders.

The paper indicates that the Texas research provided continuity and served to expand previous research: particularly in those areas including the influence of stress losses, strand stress ranges, nominal tensile stresses, overloads and passive reinforcement.

2. EVALUATION OF RESEARCH EFFORT

2.1 Introductory Remarks

The main objective of this paper is to integrate the results of research conducted by the University of Texas for the Texas Department of Highways and Public Transportation and the Federal Highway Administration, with related research previously conducted under Louisiana Department of Transportation and

Development sponsorship. The evaluation is concerned mainly with the strength and behavior of full-size pretensioned prestressed concrete girders tested under conditions of static and cyclic flexural loading.

2.2 Tests Prior to 1980

The tests sponsored by the Louisiana Department of Transportation and Development and conducted at Tulane University were reported in 1975. They were directed at the elimination of draped strands in prestressed concrete girders through the use of strand blanketing techniques, and were based in part on previous tests at the Portland Cement Association. The results of the Tulane tests indicated that the unbonding of prestressed strands through the use of blanketing techniques was an effective method that could be used as a means of eliminating draped strands in prestressed concrete girders. This conclusion was limited to the condition of static loading in flexure. Because the tests related to the blanketing of strands had not included fatigue considerations, a new investigation was initiated at the Portland Cement Association for the Louisiana DOTD and the Federal Highway Administration.

The investigation at the Portland Cement Association reported in 1979, was to determine the effects of the elimination of draped strands in full-size prestressed concrete girders. Specifically, draped strands were eliminated by using straight strands with unbonded lengths at their ends, thus creating "blanketed strands." The effect of blanketing on the strength and behavior of prestressed concrete girders under repeated loading was the thrust of the investigation. Based on comparative fatigue tests of full-size Type II AASHTO-PCI girders, it was shown that, to control stresses in the end regions of pretensioned bridge members, straight strands having unbonded blanketed lengths at the ends of girders can be used effectively and economically as an alternative to draped strands. The PCA tests and conclusions had the effect of expanding the Tulane tests and conclusions into the range of fatigue loading, insofar as blanketed strands were the issue. However, the PCA tests also indicated that fatigue of strands may be an important consideration in prestressed girders designed according to Codes where a nominal maximum concrete tensile stress of 0.50 $\sqrt{f'c}$ MPa as calculated assuming an uncracked section is permitted under service loads. The PCA test program called for 5 million cycles of loading between dead load and dead load plus live load. These girders tested at a nominal maximum concrete tensile stress of 0.50 $\sqrt{f'c}$ MPa failed before the 5 million cycles were reached. All girders had artificial crack formers so that they were not uncracked under repeated loads. Premature fatigue fractures were responsible in part for the PCA recommendation that "further research is needed to determine the fatigue properties of prestressing strands, as well as the level of tension in the concrete at which pretensioned girders would be able to withstand traffic loading without strand fatigue during their design service life." Thus the PCA tests confirmed and extended the conclusions of the Tulane tests relative to blanketed strands. However, the PCA tests indicated that further research was needed relative to fatigue strength and behavior of prestressing strands and pretensioned girders.

The Bridge Committee of the Prestressed Concrete Institute reviewed the PCA report and commented as follows:

> "1. Results of this one series of tests should not be used as a basis for making radical changes in current design criteria that are based on numerous other tests. Consideration should be given to the large number of cycles of full load that were required to cause a strand fatigue

failure, the details of the tests which were not designed to evaluate strand fatigue properties and to artificially formed cracks at which the failures occurred.

2. Possible significance of the test results has been studied and an investigation of fatigue in prestressed concrete members designed to current criteria is being considered by the AASHTO Subcommittee on Bridges and Structures."

The Texas investigation was initiated as a result of potentially unfavorable results found in the PCA tests.

2.3 Tests After 1980

The tests conducted at the University of Texas and reported in 1984 were for the purpose of determining the fatigue strength of full-scale pretensioned concrete bridge girders. Blanketing of strands was not a consideration in the Texas investigation and was not included in the test program; the focus of the program was fatigue strength and behavior. In addition, the Texas tests provided an opportunity for response to comments offered by the Bridge Committee of the Prestressed Concrete Institute. The Texas study included a comprehensive investigation of fatigue of prestressing strands. The results of the strand study have been reported in detail, and are not addressed in this report. The Texas investigation further provided the opportunity for participation by the Louisiana DOTD through the inclusion of production AASHTO-PCI specimens fabricated in Louisiana, in addition to the Texas Type C girders; thus continuing the direct involvement of the Louisiana DOTD.

In evaluating the Texas research effort relative to its contribution and continuity to research previously conducted under the Louisiana DOTD sponsorship, differences between the AASHTO-PCI girders and the Texas Type C girders tested should be noted. The AASHTO-PCI girders were production line girders fabricated in a prestressing plant. They were steam cured, and were not retensioned after the first full tensioning operation. Plant fabrication procedures were essentially the same for all AASHTO-PCI girders tested in the Tulane, PCA and Texas investigation. The Texas Type C girders tested were not steam cured. Before placing the concrete, however, the strands were retensioned to the desired stress in order to reduce relaxation losses which occurred during the period in which the steel was tied and the forms were set. These two effects, the retensioning and the lack of steam curing, could reduce the relaxation component of the stress losses.

In any event, the effective prestress force was not known precisely, but was closely estimated from measurements of decompression moments as well as from an analytical model. Variations in prestress losses can substantially affect strand stress ranges and hence fatigue life. Because of differences in fabrication procedures and because of other variables including geometry, the tests of the AASHTO-PCI girders and the tests of the Texas Type C girders are, to some extent, evaluated separately with respect to their contribution and continuity to previous tests.

In general, results of the Texas study indicated that present AASHTO indirect design criteria of flexural fatigue strength of pretensioned concrete girders, through limitation of the nominal tensile stress in the precompressed tensile zone, will not ensure adequate fatigue life. The Texas study further indicated that pretensioned concrete bridge girders without well distributed confined passive reinforcement, which are actually subjected to loads producing nominal tensile stresses of 0.50 $\sqrt{f'c}$ MPa can fail as a result of fatigue.

AASHTO specifications allow 0.50 $\sqrt{f'c}$ MPa tension in the extreme fibers of the precompressed tension zone of prestressed concrete flexural members. It has been implicity assumed that fatigue failure would not occur at this design level for a significant number of cycles. The three AASHTO-PCI girders loaded to a nominal concrete tensile stress of 0.50 $\sqrt{f'c}$ MPa in the PCA tests failed at 3.63, 3.78, and 3.20 million cycles, respectively. The three AASHTO-PCI girders included in the Texas tests were loaded to maximum nominal concrete tensile stresses of 0.52, 0.52, and 0.29 $\sqrt{f'c}$ MPa, respectively. The first girders failed at 2.84 million cycles, the second deteriorated rapidly after 4.50 million cycles, and the third girder (at 0.29 $\sqrt{f'c}$ MPa) did not fail.

The main variable between the two AASHTO-PCI specimens tested at 0.52 $\sqrt{f'c}$ MPa was the presence of a few modest static overloads. It was indicated that very occasional overloads (in this case 20 percent above the fatigue load) can drastically reduce fatigue life. The specimen that failed at 2.84 million cycles was subject to overload; the specimen that deteriorated rapidly at 4.5 million cycles was not subject to overload. In addition, one girder was precracked while the other was left to crack naturally under cyclic loads. It was found that an uncracked girder will crack after only about 1000 cycles of loading to a nominal tensile stress of 0.52 $\sqrt{f'c}$ MPa.

Three of the Texas Type C girders were loaded to a tensile stress range comparable to the 0.50 $\sqrt{f'c}$ MPa. One girder was loaded to a tensile stress of 0.50 $\sqrt{f'c}$ MPa and subsequently failed in fatigue at 1.91 million cycles. The second girder was loaded to a tensile stress of 0.46 $\sqrt{f'c}$ MPa and subsequently failed in fatigue at 2.29 million cycles. The third girder had 1290 sq mm of confined passive reinforcing steel in the lower flange to control cracking, was loaded to a tensile stress of 0.46 $\sqrt{f'c}$ MPa, and subsequently failed in fatigue at 9.43 million cycles. The small amount of well distributed conventional reinforcement was credited with greatly extending the fatigue life, and was very instrumental in reducing creep related prestress losses.

A tabulation of the three AASHTO-PCI girders included in the Texas tests, and the three Texas Type C girders loaded to an approximate tensile stress of 0.50 $\sqrt{f'c}$ MPa is shown below. Included in the tabulation are the three AASHTO-PCI girders tested at PCA with a nominal tensile stress of 0.50 $\sqrt{f'c}$ MPa.

The extended life of specimen No. 9 has been attributed to a small amount of well distributed conventional reinforcement. Specimens No. 7 and No. 8 tend to confirm the results of specimen No. 1, No. 2, and No. 3, AASHTO-PCI girders tested at PCA. Specimen No. 6, an AASHTO-PCI girder, was loaded to a tensile stress level of 0.29 $\sqrt{f'c}$ MPa and did not fail.

Specimen	Maximum Nominal Concrete Tensile Stress During Fatigue Loading	Fatigue Life
	$\sqrt{f'c}$ MPa	millions
1. PCA G-10	0.50	3.63
2. PCA G-11	0.50	3.78
3. PCA G-13	0.50	3.20
4. A22 - 2.84	0.52	2.84
5. A22 - 5.00	0.52	4.50
6. A22 - 5.95	0.29	5.95(NF)
7. C16 - 1.91	0.50	1.91
8. C14 - 2.29	0.46	2.29
9. C16 - 9.43	0.46	9.43

The results for specimen No. 4 and specimen No. 5 (identical AASHTO-PCI specimens) differed, with the reduced life of specimen No. 4 attributed to the intentional occasional overloads.

The fatigue life of specimen No. 5 was greater than similar AASHTO-PCI girders tested at PCA under compatible levels of nominal concrete tensile stress. However, the nominal tensile stress levels used in the PCA tests were based on assumed stress losses of 20 percent, whereas the Texas study indicates that the measured stress losses for the AASHTO-PCI girders is approximately 13 percent. Stress losses less than those assumed would result in smaller nominal tensile stresses with an expected increase in fatigue life.

Specimen No. 7 and specimen No. 8 were loaded respectively to nominal tensile stress levels of 0.50 and 0.46 $\sqrt{f'c}$ MPa, and experienced corresponding lives of 1.91 and 2.29 million cycles.

Based on the above discussion, it is considered that general compatibility exists in comparing the fatigue life of the three AASHTO-PCI specimens tested at PCA, and those specimens in the Texas research loaded to the same nominal tensile stress.

3. SUMMARY

It is felt that the Texas research effort has contributed significantly and has provided continuity to the research previously conducted by the Louisiana DOTD. The Texas research effort broadened previous investigations through more detailed study of stress losses and the influence of stress losses on fatigue life; through inclusion of nominal concrete tensile stresses, during fatigue loading, that ranged from 0.29 to 0.88 $\sqrt{f'c}$ MPa; through consideration of the effect of occasional overloads; and through study of the effects of the addition of passive reinforcement as a means of extending fatigue life.

The Texas research effort directly addressed issues tabulated in the PCA report and directly related to fatigue life. The Texas report indicates that fatigue failures will occur at and below the AASHTO design limit of 0.50 $\sqrt{f'c}$ MPa and can occur at 0.50 $\sqrt{f'c}$ MPa at less than 2 million cycles.

The report also indicated that at a maximum nominal tensile stress of approximately 0.46 $\sqrt{f'c}$ MPa one specimen failed after 2.29 million cycles and another failed after 9.43 million cycles. This is approximately a fourfold difference and indicates that this design parameter is inappropriate.

In any event, the Texas report indicates that if a nominal tensile stress limit is used to implicity guard against fatigue failure, the limit should be 0.25 $\sqrt{f'c}$ MPa in the absence of adequate, well distributed and well confined passive reinforcement. The Texas report recommends that when fatigue is considered important, design for fatigue of pretensioned girders be based on the stress range determined from a cracked section analysis and the lower bound S-N curve appropriate for the strand.