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Fatigue Strength of Structural Concrete Girders

Résistance à la fatigue des poutres en béton

Ermüdungsfestigkeit von Betonträgern

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SUMMARY

This paper presents a general approach to fatigue design in structural concrete. A consistent approach can be used for both non-prestressed and prestressed concrete girders if the effective prestress force is treated as an external load. The paper reviews a series of studies on the fatigue performance of prestressing strand, when subjected to cyclic loading in air, in pretensioned girders, and in post-tensioned girders.

RÉSUMÉ

Une approche générale du calcul à la fatigue est présentée; c'est ainsi qu'une prise en compte cohérente du problème peut s'appliquer de façon égale aux poutres non-précontraintes et précontraintes, si la force de précompression est considérée comme une charge extérieure. Une série d'études est présentée au sujet des effets de fatigue sur les câbles de précontrainte soumis à des charges cycliques, et ceci pour les cas de poutres précontraintes et postcontraintes.

ZUSAMMENFASSUNG

In dieser Veröffentlichung wird ein allgemeines Bemessungsverfahren von Trägern aus Konstruktionsbeton gegen Ermüdungsversagen präsentiert. Spannbetonträger und nicht vorgespannte Träger können einheitlich behandelt werden, wenn die Vorspannkraft als äussere Kraft betrachtet wird. In der Veröffentlichung werden eine Reihe von Studien über das Ermüdungsverhalten von Spannstahllitzen zusammengefasst. Diese Studien umfassten Versuche an freien Litzen, an Spannbetonträgern mit sofortigem Verbund und an Trägern mit nachträglichem Verbund.

1. INTRODUCTION

With the trend towards ultimate load design, materials are better used and generally experience higher stresses at service load levels. Consequently fatigue has become a concern in the design of structural concrete.

In non-prestressed concrete bridges, fatigue is generally only a problem of the fatigue strength of the tensile reinforcement. The stress range in such reinforcement can be readily determined for service load conditions using a fully cracked, transformed section analysis. Based on extensive tests of deformed reinforcement, the AASHTO Bridge Specifications [1] present the following expression for the allowable stress range in deformed bars:

$$f_f = 145 - 0.33f_{min} + 55(r/h)$$

where f_f = stress range in MPa;
f_{min} = minimum stress level in MPa;
r/h = ratio of base radius to height of rolled-on transverse deformations, equal to 0.3, when the actual value is unknown.

For prestressed concrete girders fatigue is generally not a problem if the girder remains uncracked. However, with the tendency to increase allowable tensile stresses in the precompressed concrete tensile zone and the possibility of larger prestress losses than anticipated in design, prestressed concrete has become more susceptible to cracking and subsequently to fatigue of the prestressing tendon. This paper presents a survey of several studies investigating the behavior of prestressing strand when subjected to fatigue loading in air, in pretensioned girders, and in post-tensioned girders.

2. PERFORMANCE REQUIREMENTS AND DESIGN APPROACH

To preclude fatigue failure, the stress range under service loads in the various components of the structure must be controlled and must be kept below a certain limit, depending on the number of load cycles the structure has to sustain during its lifetime.

In current U.S. practice tendon fatigue in prestressed concrete girders is addressed indirectly by assuming an uncracked section and then by limiting the nominal tensile stresses computed in the concrete tensile zone. This method does not account for the possibility of cracks in the girder due to modest overloads, fatigue of concrete in tension, or other unforeseen effects. A more logical approach would be to treat the prestressing force as an external load on the cross section, as suggested by Bruggeling [2], and to determine the tendon stress range from a cracked section analysis, ignoring any concrete tensile strength contribution. With this approach all levels of prestress including no prestress can be readily handled, without imposing any artificial limits on the allowable concrete tensile stresses.

3. STRAND-IN-AIR TESTS

Paulson, Frank, and Breen conducted a study of the fatigue characteristics of prestressing strand tested in air [8]. Previously reported data and additional strand-in-air test results were used to compile a database comprising over 700 prestressing strand samples from different manufacturers. Based on statistical analysis of this database a lower bound design equation for strand-in-air was developed (Figure 1).

The design equation is recommended for checking fatigue stress ranges in uncracked pretensioned concrete girders and in stay cables. The authors point out that stress concentrations in cracked girders and at anchorages or gripping systems may reduce the fatigue life significantly. These effects were not considered in the development of the fatigue model.

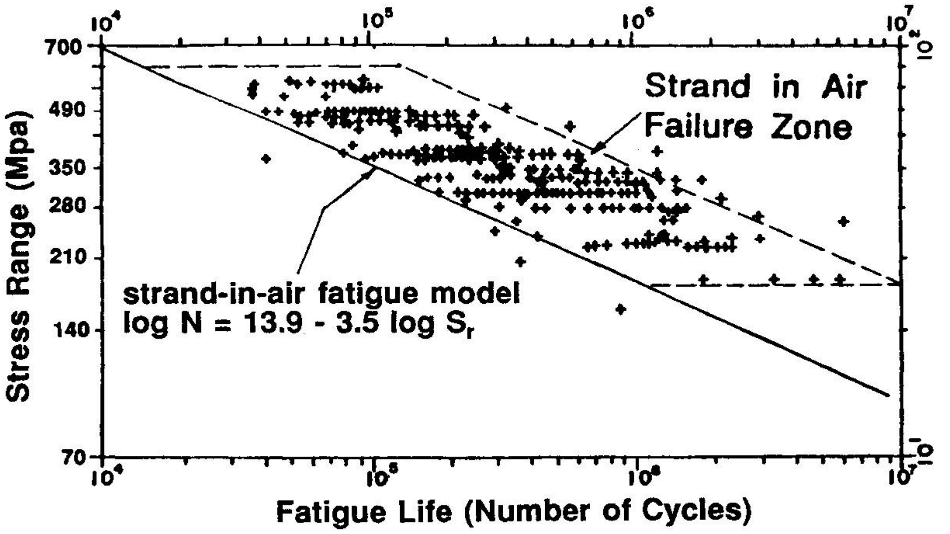


Figure 1 Strand in Air Fatigue Model (from [8])

4. TENDONS IN PRETENSIONED CONCRETE

Rabbat, Karr, Russel, and Bruce reported on a study of the fatigue strength of pretensioned concrete girders in 1978 [9]. This study was continued by Overman, Breen, and Frank and completed in 1984 [7]. The main variables included maximum nominal concrete tensile stress levels, tendon stress range, tendon layout, presence of passive reinforcement, degree of precracking, prestress losses, and presence of occasional overloads.

An important objective of the study was to evaluate current U.S. bridge specifications. In these specifications fatigue of prestressed concrete girders is addressed indirectly by limiting the nominal tensile stresses in the concrete tensile zone to $0.50\sqrt{f'_c}$ MPa, assuming an uncracked concrete section.It has been implicitly assumed that this limitation will ensure adequate fatigue performance of prestressed concrete girders. However, the results of the study indicate that this approach may be unconservative. Three out of eight girders with nominal concrete tensile stresses at approximately $0.50\sqrt{f'_c}$ MPa failed after less than three million load cycles, and one of these girders failed at less than two million load cycles. In general the maximum nominal concrete tensile stress level was not a good indicator of the fatigue performance.

The authors also point out the detrimental effect of modest overloads and excessive prestress losses. Both effects accelerate the formation of cracks in the concrete. At crack locations tendon stress concentrations occur which greatly aggravate the fatigue problem. In addition, prestress losses reduce the decompression moment of the section and subsequently cause an increased tendon stress range.

Presence of passive reinforcement was found to have a twofold beneficial effect on the fatigue performance of prestressed girders. It provides additional steel area in the tensile zone and thus reduces the tendon stress range, and it reduces prestress losses by controlling creep deformations.

The authors recommend to determine the tendon stress range from a cracked section analysis with a conservative estimate of the effective prestress level. The test results indicate that allowable fatigue stress ranges for strand-in-air are also adequate for pretensioned cracked concrete girders, provided a cracked section analysis is used (Figure 2).

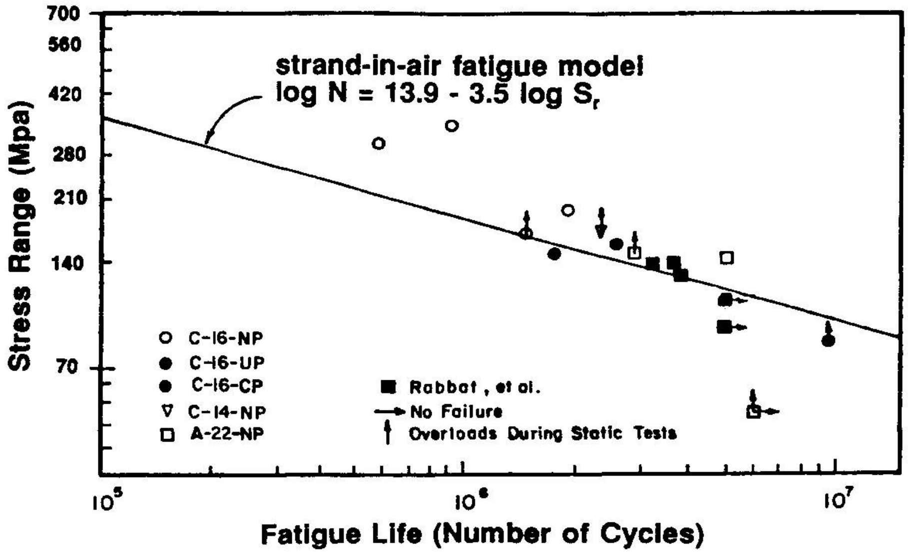


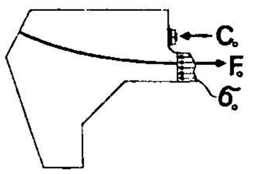
Figure 2 Fatigue of Strands in Pretensioned Girders (from [7])

5. TENDONS IN POST-TENSIONED CONCRETE

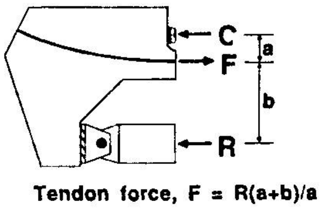
The fatigue life of prestressing strand as expected from strand-in-air and pretensioned concrete girder tests can be substantially lower in post-tensioned concrete girders with curved tendons. This observation was first reported by Magura and Hognestad in 1966 [4], but attempts to quantify it have only be made in recent years [3,5,6,10,11].

In post-tensioning tendons lateral pressure due to tendon curvature and friction stresses act on the prestressing steel, in addition to the fluctuating axial stresses. At the location of cracks stress concentrations occur, and debonding allows individual strands or wires to slip relative to each other and relative to the duct. The combined action of contact pressure, axial and friction stresses, and slip is well known in mechanical engineering as fretting. Fretting greatly accelerates the initiation of cracks in the prestressing steel and consequently reduces the fatigue performance of post-tensioning tendons.

Wollmann, Yates, Breen, and Kreger compiled data from previous post-tensioning tendon tests and conducted additional tests on girder specimens and reduced beam specimens [11]. The variables of the experimental study included tendon curvature, stress range, type of duct, and presence of strand coating. The reduced beam specimen was originally conceived by Oertle, et al., to alleviate the difficulties of determining the effective prestressing force and the tendon stress range in prestressed girders [6]. As shown in Figure 3 the reduced beam specimen allows accurate determination of tendon force and stress range from simple equilibrium conditions, provided the concrete is fully cracked.



Crack closed



Crack open

Figure 3 Reduced Beam Specimen (from [11])

The results of the study confirm that fretting fatigue can be a serious problem in cracked concrete sections at location of tendon curvature. With metal ducts rubbing between duct and strand greatly aggravates fretting. Figure 4 shows that strand-in-air test results are not adequate for the evaluation of allowable tendon stress ranges. Use of plastic duct improved the fatigue performance of single strand tendons by eliminating fretting fatigue between strand and duct. However, with multiple strands in more than one layer, fretting occurred between layers of strand, and use of plastic duct did not improve the fatigue performance significantly (Figure 5). Epoxy coating of the strands alleviated fretting and improved the fatigue performance.

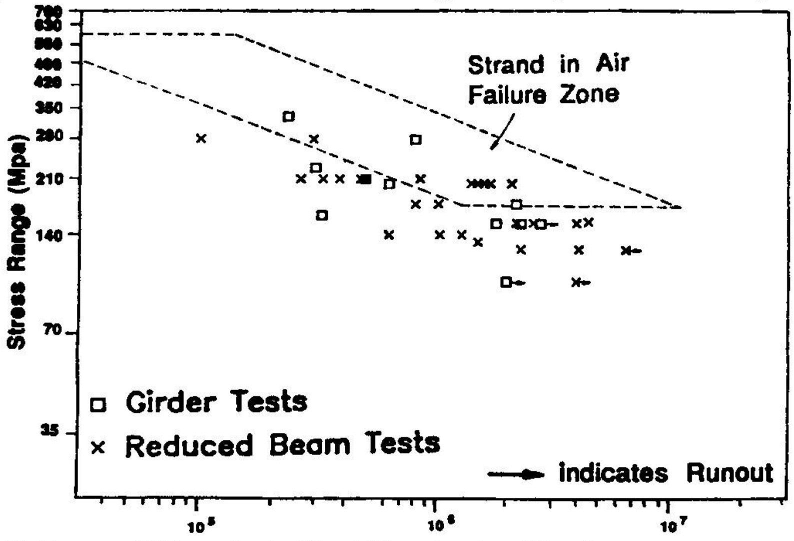


Figure 4 Fatigue of Strands in Post-Tensioning Tendons with Metal Duct (from [11])

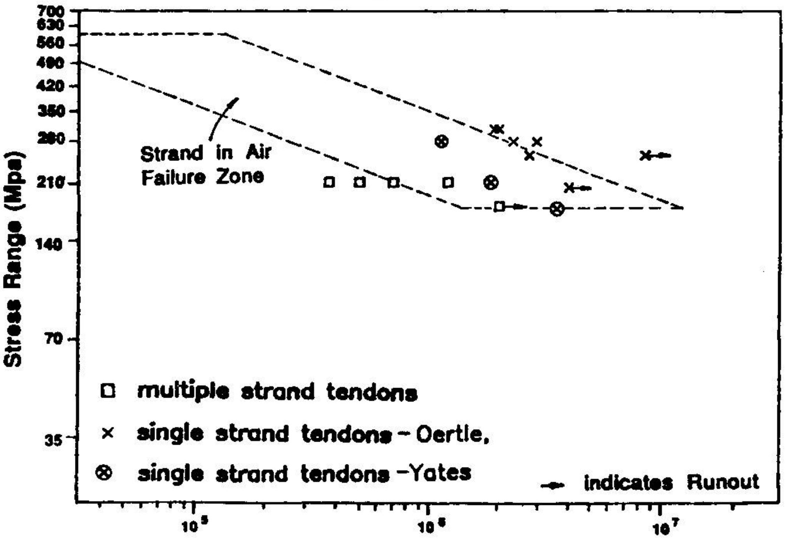


Figure 5 Fatigue of Strands in Post-Tensioning Tendons with Plastic Duct (from [11])

6. SUMMARY

A series of studies on the fatigue characteristics of prestressing strand when tested in air, in prestressing applications, and in post-tensioning applications is reviewed. Fatigue is not a problem in uncracked girders, but needs attention if the girder may become cracked. Occasional modest overloads and excessive prestress losses impair the fatigue performance of prestressed concrete girders due to accelerated crack formation in the concrete and increased tendon stress ranges. Passive reinforcement is effective in improving the fatigue performance.

A lower bound model for strand-in-air tests is also adequate for pretensioning tendons, provided the tendon stress range is determined from a cracked section analysis. In post-tensioned concrete applications fretting further impairs the fatigue performance, and lower allowable tendon stress ranges are necessary. Use of plastic duct does not significantly improve the fatigue performance of multiple strand tendons due to fretting between individual strands of the tendon.

A consistent procedure can be used for checking the fatigue strength of the structural concrete member if any long term prestressing force present is applied as a load, as suggested by Bruggeling. Subsequent analysis assumes a possible cracked section and no concrete tension contribution. Stress ranges in the reinforcing bars or prestressing tendons are compared to allowable stress ranges based on laboratory fatigue tests which must include realistic variables like duct material, cross reinforcement, and multiple strands where used.

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