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New Concepts for Concrete Fatigue Design Procedures in Japan

Nouveaux concepts pour le dimensionnement à la fatigue des structures en béton, au Japon

Neue Konzepte der Ermüdungsbemessung von Stahlbeton in Japan

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SUMMARY
The "Tentative Recommendations for the Limit State Design of Concrete Structures" were published by the Concrete Committee of the Japan Society of Civil Engineers in April 1981. The present report describes the fatigue design procedures introduced in the Recommendations. Fatigue strength of concrete in compression, reinforcing bars in tension and reinforced concrete in shear are dealt with.

RESUME
Les Recommandations provisoires pour le calcul aux états-limites des structures en béton furent publiées par la commission "béton" de la Société japonaise des ingénieurs civils en avril 1981. Le présent rapport décrit les méthodes de calcul à l'état-limite de fatigue que la commission a recommandées. On traite de la résistance à la fatigue du béton en compression, des barres d'armature sous tension et du béton armé sous un effort tranchant.

ZUSAMMENFASSUNG
Die vorläufigen Empfehlungen zur Bemessung von Betonbauwerken auf Grenzzustände wurden vom Betonkomitee der Japanischen Gesellschaft der Bauingenieure im April 1981 veröffentlicht. Der vorliegende Beitrag stellt das Bemessungsverfahren auf Ermüdung gemäss den Empfehlungen vor. Dabei werden die Ermüdungsfestigkeiten von Beton unter Druckbeanspruchung, Betonstahl unter Zugbeanspruchung, und Stahlbeton unter Schubbeanspruchung behandelt.

1. INTRODUCTION

In the 1967 Standards, the Japan Society of Civil Engineers (JSCE) introduced the fatigue provisions for design of reinforced concrete structures. Through the experiences of applying the provisions to the Shinkansen railroad structures, fatigue design procedures had been developed, and new procedures were introduced in the Tentative Recommendations for the Limit States Design of Concrete Structures in 1981 [1]. This report describes the fatigue design procedures introduced in the Recommendations and their background.

2. CONCEPTS OF FATIGUE DESIGN PROCEDURES

The concepts adopted in the Recommendations for the fatigue design procedures are summarized as follows:

(1) Fatigue limit states should be considered in the design of structures when the effects of variable loads are dominant.

(2) Design fatigue strength, which is obtained by dividing the characteristic strength by the appropriate partial safety factor for strength, should be larger than applied design variable stress.

(3) Characteristic fatigue strength shall be calculated from permanent stress and equivalent cycles, N, of the applied design variable stress. The equivalent cycles may be evaluated on the assumption of a linear cumulative damage theory, such as Miner's.

(4) Characteristic fatigue strength of concrete, f'_{rck}, may be calculated as follows:

$$f'_{rck} = (0.9k\, f'_{ck} - \sigma'_{cp})(1 - \log N/15) \qquad (1)$$

where f'_{ck} denotes the characteristic static strength of concrete, σ'_{cp} permanent compressive stress, and $k(=0.85)$ coefficient considering the difference of the concrete strengths between cylinder specimens and the structural members. Principally, fatigue strength of reinforcing bars shall be determined on the basis of test results. The following values may be used for deformed bars with a diameter not larger than 32 mm:

$$f_{rsk} = (160\ \text{MPa} - \sigma_{sp}/3)\ 10^{-0.2(\log N-6)} \quad \text{for } \log N < 6$$
$$\quad = (160\ \text{MPa} - \sigma_{sp}/3)\ 10^{-0.1(\log N-6)} \quad \text{for } \log N > 6 \qquad (2)$$

where σ_{sp} is permanent tensile stress. However, fatigue strength of bars with bends or welding connections must not be taken greater than half of the values calculated from Eq.(2), unless determined by test results.

(5) Applied design stresses due to flexure may be calculated by the elastic theory of cracked section. However, the fatigue limit state for concrete in compression may be examined only for the stress at the location of compressive resultant. Applied design variable stress and permanent stress in shear reinforcement can be calculated as follows:

$$\sigma_{wrk} = \{1.15(V_{md} - 0.5\, V_{cd})s\}/\{A_w\, d(\sin\alpha + \cos\alpha)\}(V_{rd}/V_{md}) \qquad (3)$$
$$\sigma_{wrp} = \sigma_{wrk}\,(V_{pd}/V_{rd})$$

where Vmd is the design maximum shear force, Vcd design ultimate shear force resisted by concrete, Vpd applied design permanent shear force, Vrd applied design variable shear force, Aw area of shear reinforcement within a distance s, d effective depth and α angle between shear reinforcement and longitudinal axis of the member.

(6) Fatigue limit states for reinforced concrete beams may generally be examined only for longitudinal tensile reinforcement and shear reinforcement. Fatigue limit states for reinforced concrete slabs may generally be examined only for tensile reinforcement. The examination of fatigue limit state for reinforced concrete columns may generally be omitted.

3. BACKGROUND OF THE CONCEPTS

3.1 Methods for Checking of Safety

Limit states are generally placed in two categories, the ultimate and serviceability limit states. Fatigue limit states are considered as a kind of ultimate limit states since fatigue may result in a collapse of a part or whole structure.

The characteristic fatigue strength for a certain number of stress cycles corresponding to the specified life of a structure can be determined on the basis of the same concepts as the characteristic static strength which substantially corresponds to the strength for one stress cycle. The similar concepts may be applied to the partial safety factor for the strength of materials. Namely, the values of γm for fatigue limit states can be taken to be same as for the ultimate limit states. On the other hand the loadings associated with the fatigue limit states are essentially of the same nature as those with serviceability limit states. Therefore the values of γf for the fatigue limit states may be taken as much as for serviceability limit states, that is, in general $\gamma f = 1.0$.

Criterion for fatigue failure of a material is generally expressed by a function of the permanent or the minimum cyclic stress, the range of stress or the maximum cyclic stress, and the number of stress cycles. The Recommendations define fatigue strength as the range of stress calculated from a fatigue criterion function for given permanent stress and a given number of cycles. Then the checking of safety against fatigue failure can be achieved to ensure that the design fatigue strength, frd, is larger than applied design variable stress, σrd.

$$frd > \sigma rd \quad (4)$$

where $frd > frk/\gamma m \quad , \quad \sigma rd = \sigma rk \quad (5)$

frk denotes the characteristic fatigue strength and σrk variable stress due to the characteristic loadings.

3.2 Characteristic Fatigue Strengths

The characteristic fatigue strengths adopted in the Recommendations were determined on the basis of the investigations domestic as well as overseas'. The limitation of space, however, confined to enumerate only Japanese investigations, but a little overseas' ones.

(1) Fatigue Strength of Concrete

The statistical analysis of test data led to the following equation for probable fatigue life of concrete,

$$\log N = 17 \left[1 - Sr/(1-Sp)\right] \quad (6)$$

in which Sr represents the range of stress level, defined as the ratio of variable stress to ultimate static strength, and Sp permanent stress level. Fig.1 shows a part of test data used in the analysis with the line obtained from Eq.(6). Fatigue strength calculated from Eq.(6) has an approximately 50 percent failure probability, and Eq.(1) was derived to provide characteristic fatigue strength of concrete with about 5 percent failure probability.

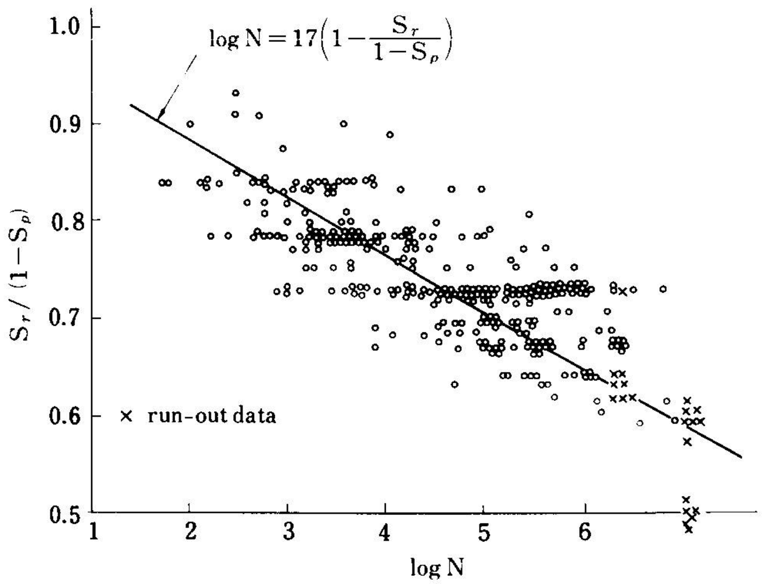
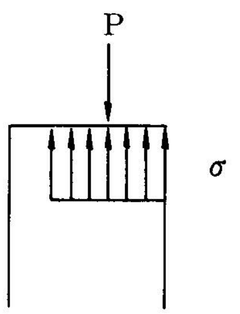


Fig.1 Fatigue strength of concrete in compression [4]-[8]



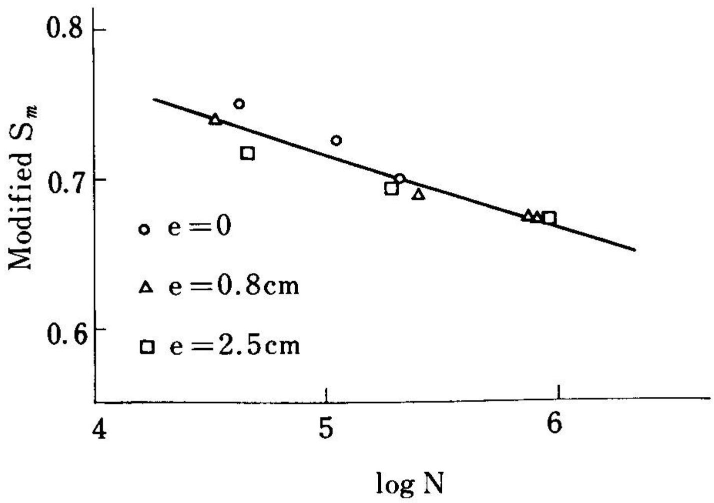


Fig.2 Stress calculation by rectangular stress distribution

Fig.3 Ople and Hulsbos' data with modified ordinate by [11]

It has been found that stress gradient has a significant effect on the fatigue strength of concrete in compression [8]-[10], in which the stress level is defined as the ratio of the extreme fiber stress to static strength in axial compression. On the other hand Matsushita and Makizumi [11] have pointed out that it is rather rational to define the stress level as the ratio of applied load to the ultimate load and proposed a method for calculating the stress of concrete by using a rectangular stress distribution, as seen in Fig.2, so that the effect of stress gradient diminishes as shown in Fig.3. The article in 2.(5) is based on their proposal.

The examination by numerical examples of the design of reinforced concrete members has shown that the checking of safety against fatigue failure of concrete can generally be omitted for the structures designed with γmc = 1.5 and γf = 1.5 for the ultimate limit states. However, it must be noted that the logarithm of fatigue life of lightweight aggregate concrete is about 70 percent of that of normal concrete, as seen in Fig.4 [5][9][10], and that logarithm of fatigue life of concrete in the water is only about two thirds or less of that in the air [15][16].

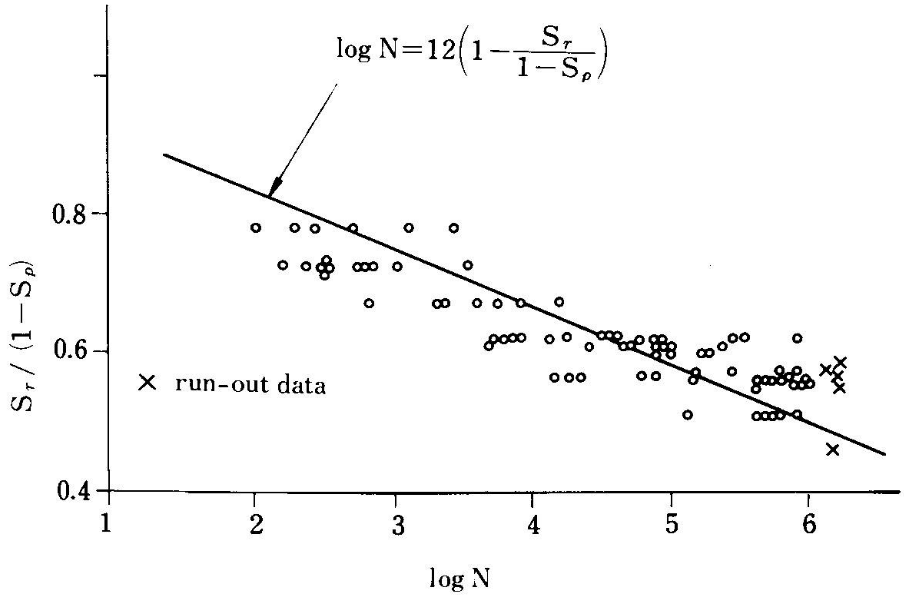


Fig.4 Fatigue strength of lightweight aggregate concrete in compression [5][9]

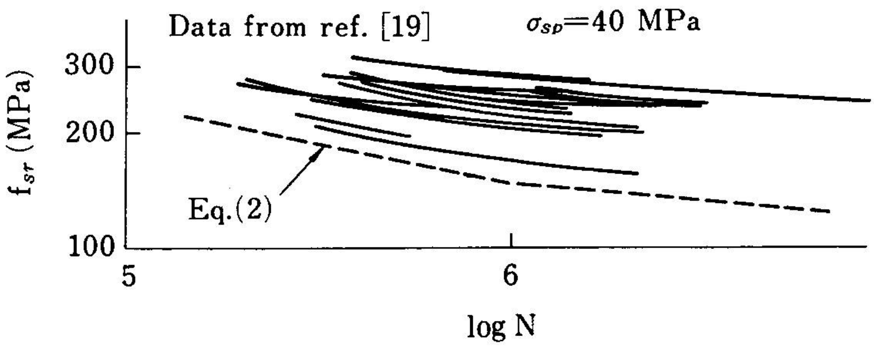
It has been found that the fatigue strengths of concrete in tension or flexure are about the same as that in compression when expressed by a percentage of the corresponding static strength [3][6]. Therefore, if necessary, Eq.(1) may be applied to determine characteristic fatigue strengths of concrete in tension or flexure.

Tests on concrete with compressive strength of 80 to 100 MPa [13][14] have shown that the fatigue strength of high strength concrete expressed by a percentage of its static strength is not less than that of normal concrete.

(2) Fatigue Strength of Reinforcing Bars

It is known that the fatigue strength of reinforcing bars depends on many factors, such as geometry of surface deformations, bar diameter, yield and tensile strength, bending, and welding [3][17][18]. However, the test results regarding the effect of these factors reported quantitatively differ considerably each other. Accordingly, it must be difficult to establish fatigue strength equation which can be applied widely. The Recommendations, therefore, state that principally, the characteristic fatigue strength of reinforcing bars, frsk, shall be determined on the test results.

Many investigations have shown that frs - N curves exhibit transition of a steeper slope to a flatter one in the vicinity of one million cycles. This may imply that reinforcing bars have an endurance limit, however, the evidence is still insufficient because of the lack of data in the region of a sufficient number of cycles. As far as the tests conducted in Japan are concerned, the average slope of log frs - log N curves of the deformed bars is about -0.2 in the finite life region as seen in Fig.5, and Eq.(2) was derived to cover all the data on the safe side.



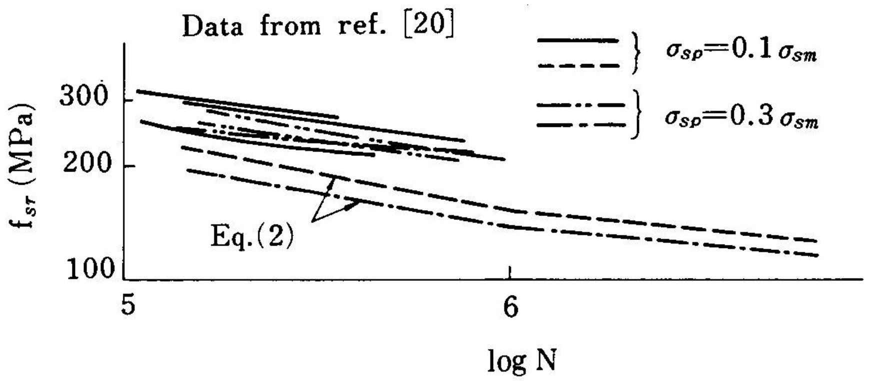


Fig.5 Fatigue strengths of reinforcing bars in tension

It is noted that most of the deformed bars made in Japan today have considerably higher fatigue strength than the value obtained from Eq.(2) owing to the efforts which have been made to improve the geometry of the deformed bars, particularly on the base radii of deformations [19]-[26]. It is, therefore, profitable to determine the characteristic fatigue strength of reinforcing bars by tests in most cases.

It has been found that the fatigue strength of bent bars, such as stirrups and bent-up bars, is considerably lower than that of straight bars [18][27]-[29].

The tests with bars bent around a pin radius conforming to the Japanese Code Requirements have shown that the fatigue strength of bent bars is 1/2 to 2/3 of that of the straight bars [28][29]. It has also been recognized that welding may considerably reduce the fatigue strength of reinforcing bars [30]-[32]. The tests [32] have shown that the fatigue strength of bars with stirrups attached by welding is about half of those attached by wire ties.

(3) Fatigue Strength of Reinforced Concrete in Shear

The investigations [33]-[36] have handled the fatigue shear strength of reinforced concrete beams without web reinforcement. Most of the data reported in these references have the fatigue lives longer than those predicted by Eq.(1), which was originally derived for the fatigue strength of concrete in compression. Furthermore, most of the data in the reference [37], in which the fatigue strength of reinforced concrete slabs in punching shear is dealt with, have longer lives predicted by Eq.(1). Therefore, if necessary, Eq.(1) may be used to determine the characteristic fatigue strength in shear of reinforced concrete beams or slabs without shear reinforcement, unless more rational procedures are available.

It is important to establish rational fatigue design procedures for shear reinforcement because the fatigue strength of bent bars is very low. The investigation [38] has proposed that the applied stress range of stirrups may be calculated by truss theory and has compared it with the fatigue strength of bent bars. A more rational method has been proposed by the recent investigations [39][40], in which the behavior of stirrups in strain is examined in detail. Eq.(3) is based on these investigations.

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