Design recommendations for offshore concrete structures

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Design Recommendations for Offshore Concrete Structures

Recommandations pour le dimensionnement des structures offshore en béton

Bemessungsempfehlungen für Offshore-Bauten aus Beton

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SUMMARY

The paper presents a short summary of recommendations for fatigue strength evaluations of offshore concrete structures. Offshore concrete structures are exposed to an environment which is different from the environmental exposure of land based structures. These special features are discussed in relation to the design recommendations. As the environmental loads are random in nature, the paper will discuss how a design recommendation can incorporate random loading.

RESUME

Cette publication présente un condensé de recommandations en vue d'évaluer la résistance à la fatigue des structures offshore en béton. Du fait de leur environment, les structures offshore sont soumises à des charges qui les différencient fondamentalement des structures onshore. Ces particularités sont détaillées en relation avec les recommandations de dimensionnement. Compte tenu que les charges dues à l'environnement sont aléatoires par nature, on s'attache à étudier comment des recommandations de dimensionnement peuvent tenir compte du caractère aléatoire du chargement.

ZUSAMMENFASSUNG

Der Beitrag präsentiert eine kurze Zusammenfassung der empfohlenen Bestimmung der Ermüdungsfestigkeit für Offshore-Betonkonstruktionen. Offshore-Bauten sind anderen Umgebungsbedingungen ausgesetzt als entsprechende Bauten an Land. Diese Besonderheiten werden im Zusammenhang mit den Bemessungsempfehlungen erörtert. Da die äusseren Lasten und Kräfte Zufallscharakter aufweisen, wird dessen Berücksichtigung in den Empfehlungen erläutert.

1. INTRODUCTION

Offshore concrete structures have been constructed and are in operation in several parts of the world. Following the first offshore concrete oil platform, which was installed nearly eight years ago, several offshore concrete structures have been constructed in several countries.

The design of the first offshore concrete structure with regard to fatigue strength was based upon an evaluation of the available knowledge regarding fatigue strength of concrete in the marine environment. The available knowledge was to some extent represented by design practice in different national codes and the current research presented by the work of ACI Committee 215 [2].

At that particular time, it was widely accepted among experts in this field that fatigue failure of reinforced/prestressed concrete structures most likely would occur in the reinforcement/tendons. The owners, designers and certifying authorities did, however, accept the risk that reversible of stresses could cause pumping [3] in crack, (see Figure 1) thus reducing the fatigue life of an offshore structure relative to a conventional land structure. The design philosophy was to limit the likelyhood of the occurrence of cracks in offshore structures exposed to fatigue loading.

The environmental loads on an offshore structure are completely random in nature with respect to frequency, magnitude and order of loading. In order to handle the above nature of the load in an analytical investigation, the general accepted method has been to devide the stress histogram into stress blocks (see Figure 2) and applying the Miner's hypothesis in its origianl form or a variant of this method.

Based upon above early evaluations of the fatugue design of offshore concrete structues, some research activities were started in different countries.

At Veritas [3] work was started on defining the fatigue strength of submerged concrete members, the area of investigation was the influence of reversible cyclic loading on the compressive fatigue strength of submerged concrete. Submerged concrete members exposed to reversible cyclic loading will crack and pumping of water in and out of the crack may occur. The conclusion [3] in the early work was that a reduction in the fatigue strength was observed when the concrete specimens were tested under hydrostatic pressure and reversible cyclic loads. The work described in [3] has been continued as a sponsored project.

At TNO in Holland, some interest was also generated on the compressive fatigue strength of concrete [4] and [6].

The main parameters in the first study [4] were:

- storage time in water
- saturated vs unsaturated concrete
- effect of frequency on saturated concrete

The conclusions from the TNO tests [4] are shortly summarized as follows.

- submerged concrete has a shorter fatigue life than air dried concrete
- the longer the storage time in water, the shorter is the fatigue lie (effect of saturation)
- the frequency affect the fatigue life, the shorter the frequency the shorter is the fatigue life

In its second study [6], TNO studied the influence of cumulative damage of concrete in compression with the use of Miner's rule. Van Leeuwen and Siemes [6] conclude that the Miner number proved to have a logarithmic - normal distribution with a mean value which is less than one. This conclusion was similar to the results obtained in Sweden by Tepfers et al [5] and by Holmen [7] in Norway.

Offshore concrete structures are located in a very corrosive environment and it is natural that corrosion fatigue of the reinforcement has been important research topics in the later years. The studies have been carried out in Britain [9], [10], [11] and in France [12]. The general conclusion from these works are:

- The fatigue life of rebars is only slightly lowered due to corrosion fatigue.
- Cracks which are constantly kept open will heal when submerged in sea-water even under dynamic loading.

The experimental data has been obtained for the test condition which is considered most severe for corrosion fatigue, namely tension-tension cycling. In submerged parts of offshore concrete structures which is exposed to cyclic loading, it is unlikely that above stress condition will be allowed. These structures will remain predominately in compression and effect of tension-compression and mean stress levels, which are compressive, will have significant interest as test parameter. Normally tensile stresses and cracks will not be accepted for offshore concrete structures for members exposed to fatigue loading.

Ben Gerwick [1] has additionally reviewed the design of offshore concrete structures with respect to fatigue strength. His paper will make useful reading in respect to general design criteria.

SUMMARY OF VERITAS REQUIREMENTS

The general requirements for the design against fatigue failure of offshore concrete structures are described in Chapter 7.7 of the Veritas Rules for the Design, Construction and Inspection of Offshore Structures [13]. The requirements are here expressed in general terms. More detailed recommendations on how to satisfy these general requirements are given in Appendix D8 to above rules. It should be noted that above recommendations are non-mandatory. The engineer is free to use other methods and procedure than those recommended, provided an equivalent standard of quality and safety is obtained.

The Veritas Rules require the characteristic S-Log N curve to be determined from the 5th percentile of the test results. The S values should additionally be divided by the appropriate material coefficient, $_{m}$. The material coefficient is to be agreed upon with the Society. The Rules require that cumulative damage to the structure caused by different fatigue loading is to be included in the analysis.

The structural aspect is considered to be of great importance for fatigue evaluations and the following points are stressed in the Rules.

- Geometric layout of structural elements and reinforcement should be such as to minimize the possibility of fatigue failure. Ductility should be assured by confinement of the concrete by appropriate reinforcement.

Submerged concrete members that are essential for the integrity of the structure and are subjected to loadings that may cause fatigue failure are to be designed without membrane tension for any load combinations. Edge stresses due to bending is to be limited so that no cracking occurs. Where creep effects may cause transfer of compressive stress from the concrete to the reinforcement such effects are to be accounted for in the determination of the concrete stresses.

RECOMMENDED PRACTICE

In the recommended practice in Appendix D8, it is accepted that offshore concrete structures are exposed to more dynamic and complex loading than most other types of structures This makes it difficult to extrapolate earlier experience on land based structures. With respect to the special influence of the marine environment, the recommendations have been based on the pilot study [3]. The criteria for the reinforcement have been based on the work by Helgason [8].

Reinforced Concrete Exposed to Axial and Flexural Dynamic Loads

For submerged concrete members exposed to axial and flexural load, the following combined Goodman and Wöhler curves are specified:

$$\log_{10} N = 10.0 \; \frac{1.0 - \dfrac{S_{max}}{\alpha \dfrac{f_k}{\gamma_m}}}{1.0 - \dfrac{S_{min}}{\alpha \dfrac{f_k}{\gamma_m}}} \qquad (1)$$

where

S_{max}	maximum average outer fibre stress in stress block i, calculated on the basis of linear elastic theory assuming cracked section
S_{min}	minimum average stress in the same outer fibre calculated on the basis of linear elastic theory assuming cracked section
f_k	characteristic compressive strength measured on concrete cylinders
γ_m	material factor = 1.25
α	takes account of the flexural gradient across the section [14]

Since the evaluation of fatigue strength is monotonous, it is of importance to derive at a method of making a quick assessment on the need to carry out futher fatigue calculations. Veritas recommends such a method.

Should a detailed fatigue check be necessary, then the cumulative fatigue life may be investigated according to a modified Miner's hypothesis.

$$\sum_{i=1}^{m} \frac{n_i}{N_i} \leq 0.2 \qquad (2)$$

where

m = number of stress blocks (minimum 8)
n_i = number of stress cycles in stress block, i
N_i = number of cycles to fatigue failure for average stress in stress block, i.

The number of applied cycles, n_i, within stress block, i, is obtained from an investigation of the sea states, wind direction, and static and dynamic response of the structure expected within the design life, which is normally not to be taken less than twenty years.

The number of cycles to fatigue failure at constant amplitude, N_i, within stress block, i, may be obtained from test results or from equation 1.

For a fatigue analysis, it is necessary to obtain stress history diagrams as function of log n (see Figure 2). The stress history gives information on maximum and minimum stress in an element or member as a function of the logarithm to the number of applied cycles. The load histogram is divided into stress blocks, normally at least eight blocks.

For the reinforcement in the concrete, the number of cycles, N, causing fatigue failure of straight bars at a given stress range and minimum stress level, may be taken as:

$$\log_{10} N = 6.5 - 2.3 \frac{S_r}{\dfrac{f_{sy}}{\gamma_m}} - 0.002\, S_{min} \qquad (3)$$

where

S_{min} and S_r describe the minimum stress and the stress range.

The endurance limit, f_r, is taken as

$$f_r = \frac{165}{\gamma_m} - 0.33\, S_{min} \qquad (4)$$

If the stress range in the reinforcement at 10000 cycles is less than the endurance limit as defined above, no further checks on the fatigue strength is required.

If the stress range in the reinforcement exceeds the endurance limit, then detailed investigations are necessary. It will in this case be necessary to elongate the Wöhler curve as defined above beyond the endurance limit (see Figure 4).

For bent bars with a bend of diameter less that 25d and greater than 8d, and for welded reinforcement, the Wöhler curve defined above is modified to take account of the reduced fatigue life.

Veritas makes no recommendations for the incorporation of cumulative damage in the reinforcement. It is, however, reasonable to apply the Miner's hypothesis in its original form with a Miner sum equal to 1.0.

Reinforcement Concrete Members Exposed to Transverse Shear Loading

For reinforced and prestressed concrete members exposed to transverse shear loading of variable magnitude, the following design recommendations are made for designing against shear failure in the concrete.

The proposed Wöhler curve is similar to that used for concrete in compression and bending. In stead of formulating the Wöhler curve as a function of stress, the total shear capacity is used, which also includes the contribution from the longitudinal reinforcement and ties.

For concrete members with positive $V_{f_{max}}/V_{f_{min}}$ the V-N diagram is referred to as:

$$\log_{10}N = 10.0 \; \frac{1.0 - \dfrac{V_{f_{max}}}{V_r}}{1.0 - \dfrac{V_{f_{min}}}{V_r}} \tag{5}$$

where

$V_{f_{max}}$	maximum average shear force in stress block, i
$V_{f_{min}}$	minimum average shear force in stress block, i
V_r	design shear resistance

The total shear resistance is not to be taken greater than

$$V_{rmax} = 0.25 \cdot f_{cr} \cdot b \cdot d \tag{6}$$

where

$$f_{cr} = \frac{f_{ck}}{\gamma_m}$$

For members which are exposed to completely reversable transverse shear stress i.e. $V_{f_{max}}/V_{f_{min}}$ is negativ, the capacity part of the concrete, V_{cr}, should be ignored in the calculation of V_r.

The cumulative damage of the concrete should be investigated using the Miner's cumulative method with a summation of 0.2.

The fatigue strength of the reinforcement requires to be checked independantly. The Wöhler curves and endurance limit as described earlier should be used in the investigation. In calculation of the reinforcement stresses, realistic models in estimating the reinforcing stress should be used.

Fatigue Strength in Bond

In lack of more detailed information, it is recommended to double the anchorage length normally required for static design, if the number of load repetitions exceeds 10000 cycles and the bond stress range (S_{br}) at 10000 cycles exceeds the bond strength (f_{br}) at 2.10^6 cycles.

Fatigue Strength of Tendons

The Veritas recommendations presumes that fatigue strength data will be provided by the manufacturer as the fatigue characteristics will be dependant upon the steel qualities and other details of productions and anchorage of tendons.

The fatigue data should contain data on the total assembly of the tendons including the anchorage.

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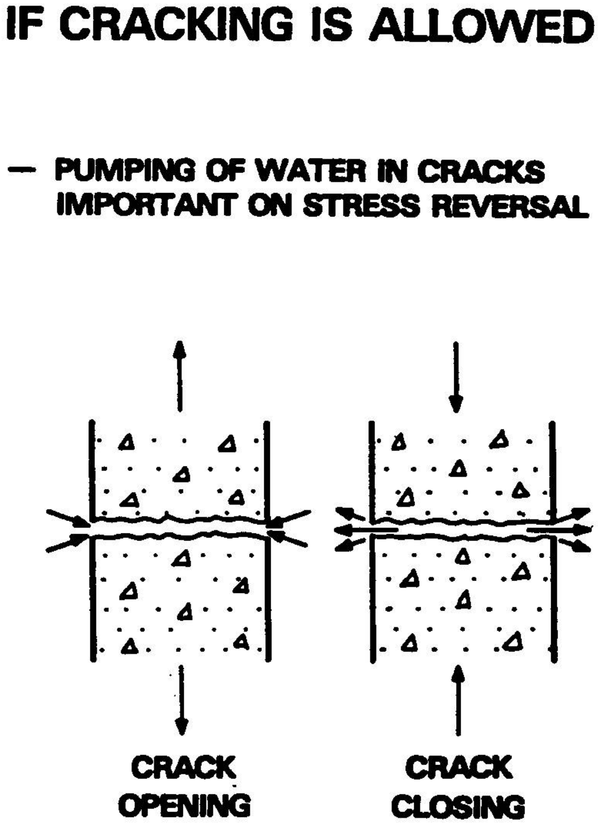

Fig. 1 Pumping of Water in a Crack on Stress Reversal

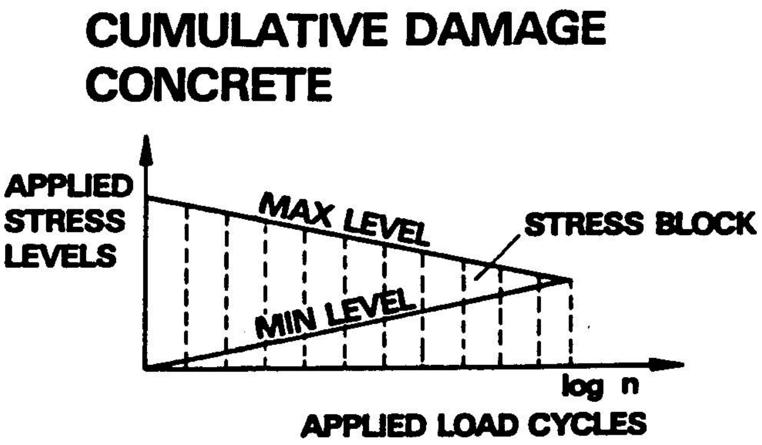

Fig. 2 Stress Histogram for use when Analysing Cumulative Damage of Concrete

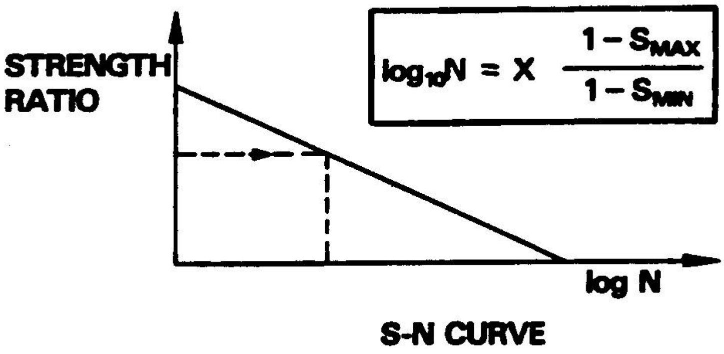

Fig. 3 Example of Wöhler Curve for Concrete

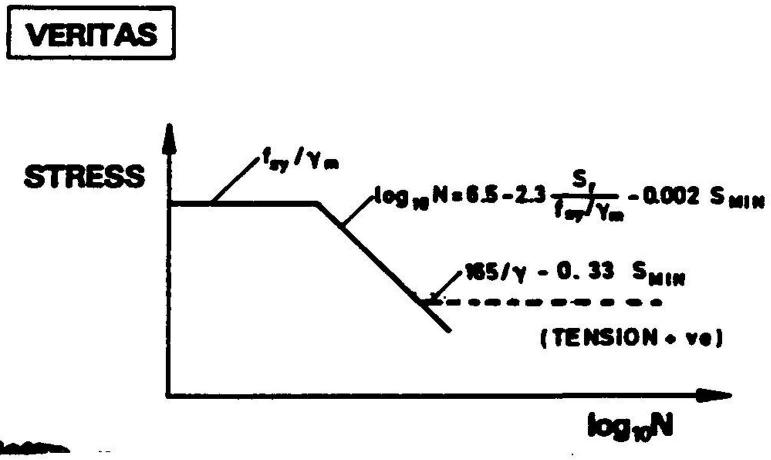

Fig. 4 Wöhler Curve for Reinforcement

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