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Autor: Waagaard, Knut
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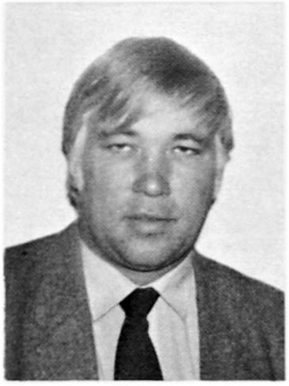
Fatigue Strength Evaluation of Offshore Concrete Structures

Dimensionnement à la fatigue des structures offshore en béton

Ermüdungsfestigkeit für Offshore-Betonkonstruktionen

Knut WAAGAARD
Principal Research Engineer
Det Norske Veritas
Oslo, Norway



Knut Waagaard, born 1946, got his B.Sc. and Ph.D in Civil Engineering at Heriot Watt University, Edinburgh, Scotland. He has since been involved in research and design application of concrete in offshore structures. Dr. Waagaard is currently employed in the research division with responsibility for special concrete analysis.

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 environment 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. The recommendations are critically assessed in relation to other design rules and recommendations and to the state of the art.

RÉSUMÉ

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 environnement, les structures offshore sont soumises à des charges qui les différencient fondamentalement des structures sur terre. 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. Les recommandations proposées sont confrontées à d'autres codes ainsi qu'aux méthodes de dimensionnement les plus communément admises.

ZUSAMMENFASSUNG

Dieser Vortrag präsentiert eine kurze Zusammenfassung der empfohlenen Berechnung der Ermüdungsfestigkeit für Offshore-Betonkonstruktionen. Offshore-Betonkonstruktionen sind anderen Umgebungsbedingungen ausgesetzt als entsprechende Konstruktionen an Land. Diese Besonderheiten werden im Zusammenhang mit den Bemessungsempfehlungen erläutert. Da die Umgebungsbelastungen und -kräfte ungewissen Charakter aufweisen, erläutert der Vortrag, wie dem in den Bauvorschriften Rechnung getragen werden kann. Im weiteren sind die Vorschriften mit anderen Baunormen und auch in bezug zum heutigen Stand der Technik verglichen.

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.

2. SUMMARY OF THE DESIGN 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 [21]. 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, γ_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.

3. RECOMMENDED DESIGN PRACTICE FOR FATIGUE STRENGTH EVALUATION

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 [16].

A complete fatigue strength evaluation using Miner's hypothesis is time consuming and often unnecessary to perform. Simplified evaluation methods may be derived in order to indicate whether fatigue is governing for the design or not. The method presented in this paper includes both a more thorough method of analysis and an example of a simplified approach. It is, however, important that the simplified approach is based upon a thorough investigation of the type of structure in question and the applied loads. Representative Wöhler curves are necessary for the successful development of such an approach.

3.1 Reinforced Concrete Members Exposed to Axial and Flexural Repeated 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

In order to take account of the difference in fatigue life of concrete members subjected to flexural and axial stressing [25], the following values of α should be used:

$$\alpha = 1.26 - 0.26\beta \leq 1.26 \qquad (2)$$

where

β equals the ratio between the simultaneous minimum and maximum edge stress in the concrete section (i.e., a value for the "flexural gradient" across the section).

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. The method provided by Veritas is as follows:

Provided one of the following requirements are fulfilled, further checks on the fatigue strength of concrete may be omitted:

- The design loading effect does not exceed half the design resistance for any load combination and no tensile stresses exists for any load combinations.

- The number of load cycles does not exceed 10000

- The design stress range, S_r, at 10000 cycles is less than the fatigue strength range, f_r , at $2 \cdot 10^6$ cycles. The fatigue strength may be obtained

IF CRACKING IS ALLOWED

— PUMPING OF WATER IN CRACKS IMPORTANT ON STRESS REVERSAL

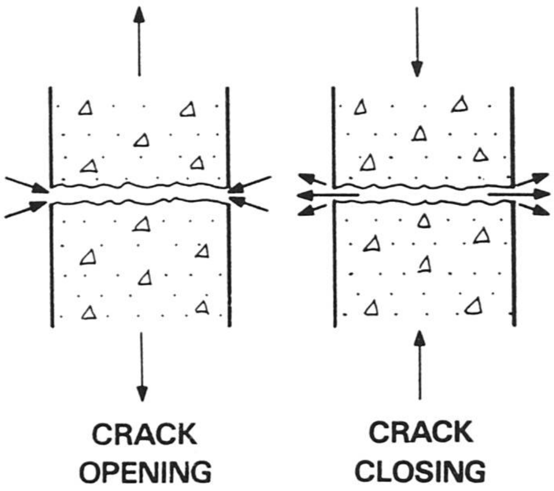


FIG. 1 PUMPING OF WATER IN A CRACK ON STRESS REVERSAL

CUMULATIVE DAMAGE CONCRETE

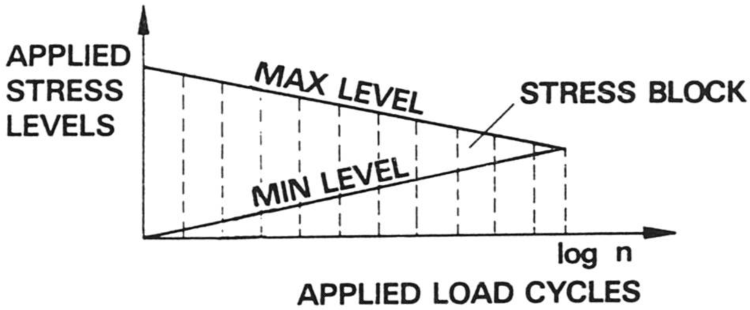


FIG. 2 STRESS HISTOGRAM FOR USE WHEN ANALYING
CUMULATIVE DAMAGE OF CONRETE

from the following equation:

$$f_r = 0.6 \left(1.0 - \frac{S_{max}}{\alpha \frac{f_k}{\gamma_m}}\right) \frac{f_k}{\gamma_m} \leqslant 0.37 \quad \alpha \frac{f_k}{\gamma_m} \tag{3}$$

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

$$\sum_{i=1}^{m} \frac{n_i}{N_i} \leqslant 0.2$$

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:

$$\log_{10} N = 6.5 - 2.3 \frac{S_r}{\frac{f_{sy}}{\gamma_m}} - 0.002 \; S_{min} \tag{4}$$

where

S_{min} = minimum stress (tension positive) (MPa)

S_r = stress range = $S_{max} - S_{min}$ (MPa)

S_{max} = maximum stress (tension positive) (MPa)

f_{sy} = yield strength (MPa)

γ_m = 1.15

The endurance limit, f_r, is taken as

$$f_r = \frac{165}{\gamma_m} - 0.33\, S_{min} \qquad (5)$$

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 may be taken as

$$\log_{10}N = 5.5 - 2.3\,\frac{S_r}{\frac{f_{sy}}{\gamma_m}} - 0.002\, S_{min} \qquad (6)$$

The endurance limit, f_r, may in this case be taken as:

$$f_r = \frac{85}{\gamma_m} - 0.33\, S_{min} \qquad (7)$$

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.

3.2 Reinforcement Concrete Members Exposed to Repeated 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:

$$\log_{10} N = 10.0 \frac{1.0 - \frac{V_{f_{max}}}{V_r}}{1.0 - \frac{V_{f_{min}}}{V_r}} \tag{8}$$

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

$= V_{cr} + V_{pr} + V_{sr}$

V_{cr} is the shear resistance caused by to the concrete and the longitudinal reinforcement

V_{pr} is the shear resistance due to prestress or axial force

V_{sr} is the shear resistance provided by shear reinforcement

The total shear resistance is not to be taken greater than

$$V_{rmax} = 0.25 \cdot f_{cr} \cdot b \cdot d \tag{9}$$

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.

A short hand method is provided in order to eliminate the monotoneous fatigue calculations in cases where fatigue problems are obviously not present. The same main procedure which has been used for the axial and flexural case is also used in this case with the exception that the fatigue strength range, f_r, is to be taken as:

$$f_r = 0.6 \left[1 - \frac{V_{f_{max}}}{V_r} \right] V_r \leq 0.37 V_r \tag{10}$$

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.

3.3 Bond Strength when exposed to repeated Loads

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.

f_{br} may be taken as

$$f_{br} = \left(1 - \frac{S_{b_{max}}}{\frac{f_b}{\gamma_m}}\right) \frac{f_b}{\gamma_m} \leq \frac{1}{2} \frac{f_b}{\gamma_m} \qquad (11)$$

where

$S_{b_{max}}$ = maximum bond stress

f_b = bond strength in accordance with recognized standard

γ_m = 1.25

3.4 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.

4. SPECIAL CONSIDERATIONS FOR DESIGN OF MARINE STRUCTURES

The special problems related to fatigue strength of marine concrete structures compared to land based structures will especially be discussed in relation to the following topics:

- S-N curves for concrete in compression
- cracking limitations
- S-N curves for reinforcement
- transverse shear capacity
- cumulative fatigue life

4.1 Wöhler Curves for Concrete exposed to Compressive Loading

The fatigue strength of plain concrete tested to 2 mill. cycles is generally accepted to be 0.6 fc where fc is the static capacity [2]. The fatigue life of concrete specimens tested under water at the same stress levels is reduced to about 100.000 cycles at a test frequency of 6 Hz [4]. If tested at a frequency of 0.7 Hz the fatigue life is close to 35.000 cycles. In addition to this parameters, the effect of the long storage in water may influence the fatigue life [4]. In [3] the current author presented some early results which indicated that reversibility of stresses, which caused cracking with pumping of water in and out of the cracks, caused deteriorating fatigue lifes in the concrete.

The fatigue strength of concrete is normally represented by a fraction of the static strength that can be supported for a given number of cycles. The fatigue strength is normally presented in the form of Wöhler curves or S-N curves (Figure 3). The stress level is plotted along the ordinate and the number of cycles to failure in a logarithmic scale along the abscisse.

The Wöhler curve can be plotted for a constant minimum stress level. The influence of the minimum stress level can be incorporated in a Goodman diagram [7]. The Goodman diagram can be combined with the Wöhler diagram in the following ways:

$$\log_{10} N = X \frac{1 - \frac{S_{max}}{S_r}}{1 - \frac{S_{min}}{S_r}} \quad \text{Goodman} \qquad (12)$$

where

x = a value for the gradient of the S-N curve

S_r = static strength

The Veritas recommendations incorporate the reduced fatigue life of submerged concrete members as described earlier. The approach is additionally based upon the assumption of a linear stress-strain relationship and of a linear strain across the section. The gradual transfer of stress into the reinforcement due to stiffness degration caused by fatigue is not incorporated in the method.

The Veritas approach is based upon the method proposed by Ople and Hulsbos [25], the difference between the Wöhler curves proposed by Veritas and Ople and Hulsbos in that the Veritas curves take account of the lower fatigue life of wet and saturated concrete.

The Norwegian Oil Directorate [24] (see Figure 5) requires a different approach which is based upon work by Aas-Jakobsen [8]. In this method the following assumptions are made:

- The Wöhler curves are developed in the phase just before failure. A non-linear stress-strain curve is used and the outer fibre strain is 3.5 °/°°.

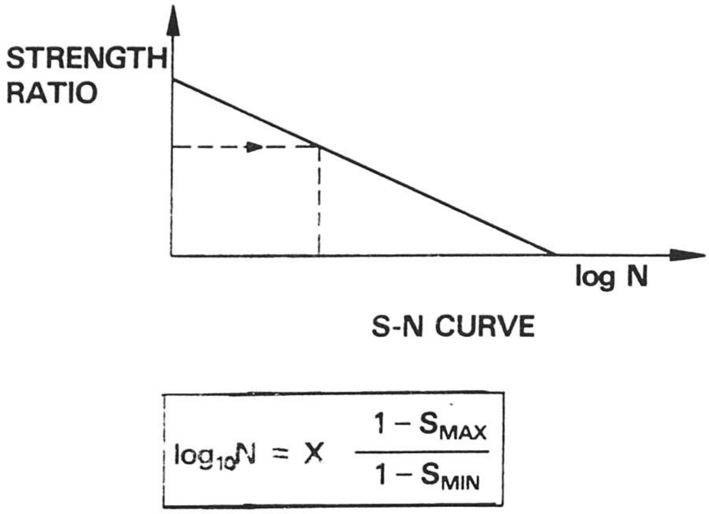


FIG. 3 EXAMPLE OF WÖHLER CURVE FOR CONCRETE

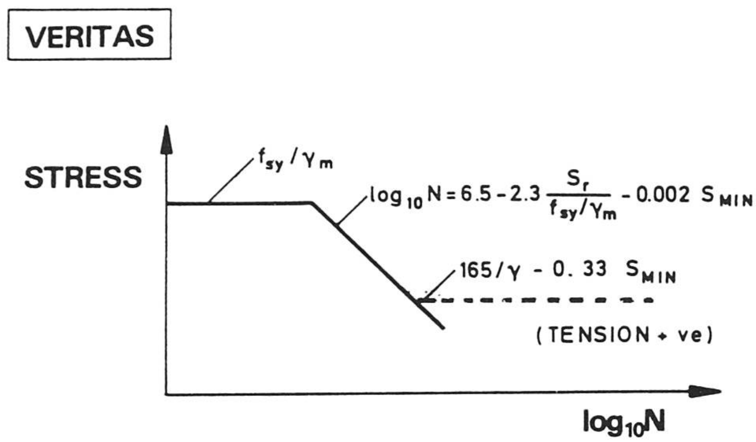


FIG. 4 WÖHLER CURVE FOR REINFORCEMENT

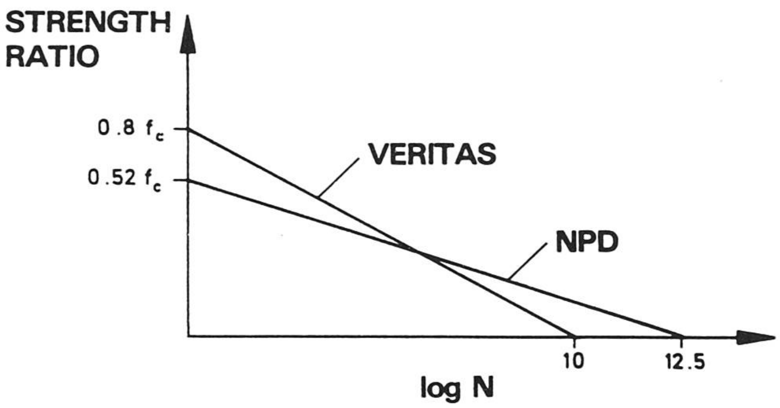


FIG. 5 DESIGN WOHLER CURVES AS SPECIFIED BY VERITAS AND NPD

- No account has been taken for the reduced fatigue life of submerged concrete. The high effective material factor which is the same as for static strength, may take account of this uncertainty at the high intensity load level, but not at the low intensity load level.
- Direct comparison of Wöhler curves between reinforced and plain concrete is difficult as Wöhler curves are method dependant.

FIP [22] states that provided the compressive stresses are no greater than those implied in R3.4 [22] for the various limit states, there is, in general, no need to check further the fatigue conditions.

ACI [23] gives the guidelines that provided the concrete stress is less than 0.5 fc' and no membrane tension or with flexural tensile stresses less than 1.4 MPa, for frequently occuring environmental loads, then fatigue resistance is considered adequate.

Neither the ACI guidelines nor the FIP recommendations attempt to give detailed guidelines or recommendations for fatigue design of the concrete. FIP states that the fatigue strength of concrete in compression is unlikely to influence the design, the normal design parameter in ULS and SLS will account for this safe assumption.

The ACI recommendations have a very similar proposal, but in contrary to FIP only allows deteriorating pumping of water in and out of cracks under flexural loading, and then to a very limited scale.

The TNO research efforts [4] and [6] were initiated after TNO provided their design procedure from 1975 [34], [35]. The latter design procedure was based upon the available knowledge at that time which also TNO accepted to be sparse for the design of offshore structures. The TNO procedure is less stringent than the procedure provided by VERITAS. It is clear that the early TNO procedure takes no account of the presence of water, pumping of water and also presume an endurance limit for the concrete.

The Veritas recommendations and the NPD rules appear to be more advanced in that both require more fundamental fatigue analysis to be carried out. Cumulative fatigue analysis is required by both methods to obtain the fatigue life of a structure.

4.2 Limitations in allowabel Cracks and Crackwidths

- Veritas Rules [21]

  The Veritas rules require that submerged 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. Only small edge tensile stresses within the tensile strength is allowed. Creep effects should be included in the analysis.

- FIP [22]

  The crackwidth should be less than 0.3 mm under extreme load conditions. For parts of the structure which are required to contain oil, the membrane stress should be less than the tensile stress necessary to cause cracking across the thickness. Edge tensile stresses are accepted within certain limits.

- NPD [24]

  No structural cracking is accepted

- ACI [23]

  Accept no membrane tension. The edge stresses should be limited to 1.4 MPa flexural tension.

It can be seen that both Veritas and ACI have very similar requirements. They accept no structural cracking, but also reduces the possibility of getting through going cracks by allowing no membrane tensile stresses. The NPD rules are not so strict in this respect. The FIP recommendations has no special restriction on cracking due to fatigue loading. For members requires tightness due to oil storage, the above limitation on through going cracks is stated.

The cracking limitation was originally included in the design of offshore concrete structures. The need for such a requirement was later partly confirmed by the pilot study [3]. It was clearly observed that cracks which opened and closed due to fatigue loading, caused pumping of water in and out of the cracks, which gradually disintegrated the concrete.

4.3 Wöhler Curves for the Reinforcement

- Veritas [21]

  Veritas has in its recommendations specified both a Wöhler curve and an endurance limit. The Wöhler curves are representative for deformed bars and are based upon results from Helgason et al. [16]. The fatigue properties of European reinforcing steel embedded in concrete in a corrosive environment, which have been tested later, are also within the above specifications [17], [18], [19] and [20].

- FIP [22]

  FIP has not specified any S-N diagram for the rebar, but it states that provided the stress range in straigth deformed high-tensile steel reinforcement is less than 140 MPa, imposed upon a minimum stress level of 0.4 f_{sy}, fatigue in the reinforcement in not likely to be critical.

- NPD [24]

  NPD states that provided no experimental data is available, the endurance limit for straight deformed rebars can be taken as 170 MPa.

- ACI [23]

  ACI states that the resistance of a structure is considered to be adequate, if the stress range in the straigh rebars is less than 140 MPa.

Only Veritas has specified a Wöhler curve and an endurance limit in its specification. None of the other three rules, regulations or guidelines give similar detailed requirements. FIP, ACI and NPD, all states that the fatigue resistance of the rebars are considered to be adequate provided the stress range is less than the endurance limit normally encountered during tensile loading. This criterium is obviously far too conservative, as the cracking limitation of offshore structures ensures a mean compressive stress level. With a mean compressive stress level, the endurance limit is increased as documented by Helgason et al. [5].

5. TRANSVERSE SHEAR CAPACITY UNDER REPEATED LOADINGS

Only Veritas [21] and NPD [24] gives detailed recommendations for design against fatigue failure in shear. The FIP recommendations have no guidelines at all, while ACI gives some guidelines for design.

The limited experimental evidence for the formulation of rational Wöhler curves for the shear stress or shear capacity of the concrete, has caused a noticeable differance between the NPD formulation and the Veritas formulation.

In the NPD method, an attempt is made to separate the shear contribution part for concrete, reinforcement and axial force, and checking the fatigue strength of each part independantly in a similar way as discussed for axially and flexurally loaded members.

The Veritas approach separates the investigation between the concrete and the reinforcement/ties. In considering the contribution from the concrete, a proportional distribution of the contributing parts is ensured by considering the total capacity. The effect is similar to that used for axially loaded and flexural loaded members in the Veritas method.

In the same way as the NPD method and the Veritas approach yield different results for axially loaded members, the same discrepancy is noticed for the capacity caused by fatigue shear loading.

The method proposed by Hawkins [13] has to the author's knowledge been widely accepted for the evaluation of fatigue strength of the shear reinforcement. The method proposed by Hawkins is based on the following assumptions.

- The concrete part, V_{cr}, carry no shear

- The shear is carried by the stirrups completely. Fatigue evaluation is carried out on the stirrups stresses. If the steel stresses are below the endurance limit for the steel, the strength is considered adequate in shear. Alternatively a cumulative analysis can be carried out using Miner's rule on the reinforcement stresses.

The method proposed by Hawkins [13] has also been used for axially loaded members. In doing so, one should remember that relative high normal forces are introduced and a check on the fatigue strength in shear using a compression mode of failure, may additionally be necessary.

Some parts of offshore structures are loaded with reversible transverse shear stresses. Under this load condition concrete may crack due to the shear loading to one side. At load reversal this crack will close and a pumping action similar to that described in [3] is anticipated. Veritas [21] has considered this effect by stating that for submerged members, the shear resistance component V_{cr} from concrete along should be taken as zero in the capacity evaluation under fatigue loading. The validity of such an approach is uncertain.

It should be noted that the general cracking criteria also is valid for possible cracks caused by transverse shear loading. The reinforcement stresses in vital structural parts, which are exposed to dynamic loads, will be small because of the crack limitations.

6. MEMBRANE SHEAR CAPACITY UNDER REPEATED LOADS

Structural members exposed to membrane cyclic shear stresses should be carefully analysed and designed. This is especially the case for members which can be exposed to fully reversible cyclic shear [33].

The VERITAS Rule [21] requires these members to be designed without membrane tension for any load combinations. Such a design procedure will exclude any occurance of possible pumping of water in the cracks and the resulting degradation of the concrete due to pumping. In order to avoid fatigue failure in the fully compressible member it will be applicable to check the principle compressive stress in accordance with equation 1.

Fully prestressing of the shear walls as required in the VERITAS approach is expensive and may not always be necessary. The degradation of stiffness due to pumping is, however, so serious that careful consideration and experimental evidence are necessary before relaxing on above requirements. Today, no coherent test data is available on membrane shear strength due to cyclic loading of sea structures.

Concrete ships which were made during World Wars I and II, were not prestressed. These structures did not suffer fatigue failure probably due to the heavy percentage of orthogonal reinforcement which ensures low stresses at working load. Some economy can thus be gained by relaxing on the fatigue requirements, but experimental tests are necessary in order to derive at the correct level of partial prestressing.

7. EVALUATION OF FATIGUE LIFE

The load variation on offshore structures are completely random in nature. A design method had to be derived for analyses of such, structures. The method appears more elaborate than the methods often used for reinforced concrete design. The common method is the use of the Miner's hypothesis [30]. This method has been successfully used for metals in predicting the fatigue life. The method has also to some extend been applied to materials like concrete.

The applicability of the Miner' hypothesis for concrete has been investigated by several research workers [31], [5], [6] and [7].

In the work carried out by van Leeuwen et al. [6], it is concluded that the value of the Miner number can be satisfactorily described with a logarithmic-normal distribution. The mean value is in general less than one. It can be concluded that program loadings and variable amplitude loadings are more damaging than can be expected from constant amplitude tests.

Earlier investigations [31] also indicated the importance of the sequence of loading on the Miner number, a high load early in the load history gave more damage than a high load later in the load sequence.

The above research works indicate different values of Miner number to be used for concrete, but a value between 0.2 and 0.5 appear to be appropriate. The deviation from unity in the Miner number does not describe a safety consideration, but purely the inadequacy of the method. The safety is included in the appropriate material factor. It should be noticed that small variation in the material factor, γ_m, has a greater influence on the safety than a small change in the Miner's summation number.

For the reinforcement, it is appropriate to use the Miner' hypothesis in its original form with a cumulative sum of 1.0.

FIP [22] gives no special advice on how to tackle random loading from environmental forces in a cumulative way. Instead FIP defines any load which may occur more than 20 000 times during the expected life of the structure as a potential fatigue load.

NPD [24] states that fatigue can be investigated according to the Miner's rule

$$\sum_{i=1}^{m} \frac{n_i}{N_i} \leq 1.0 \qquad (13)$$

ACI [23] states that the stress limitations can be satisfied for frequently recurring environmental loads at sections subjected to significant cyclic stresses. Should the stress limitation check be unsatisfactory or at locations where resistance is likely to be a serious problem, a more complete analysis based on the principle of cumulative damage should be subtituted. The analysis should also consider low-cycle, high amplitude fatigue.

8. CONCLUSION

The random nature of environmental loading on an offshore installation has made it necessary for the designer to go into great details in fatigue strength evaluations. Cumulative analyses of experimental tests with the help of Miner's hypothesis has shown that the variations in the Miner number is both a variable of concrete strength variation and of loading sequence. The Miner number for random loading when applied to concrete structures is found to be less than one.

In an actual design, the value of the material factor will have greater influence on the safety level than small variations in the Miner number. This is a result of the semi-logarithm basis of the Wöhler curve.

In converting experimantal data into design, one should ensure that the same method is used in evaluating the test data as is used in design. Wöhler curves will for example be method dependant and direct comparisons of levels on Wöhler curve will not adequately represent an evaluation of the safety in the different requirements.

It is important that the marine environment has deteriorating influence of the fatigue properties of both concrete and reinforcement. From an evaluation of actual stress and cracking conditions, the behaviour of concrete and tendons in fatigue will need the most careful consideration. In concrete both the effect of pumping of water in and out of cracks and effect of pore pressure should be included in the analysis.

Offshore structures are more complex in its load carrying nature than many comparible structures exposed to fatigue loading. It is important that the fatigue evaluation provedure has been proven also for the load condition in question. For example, the most common evaluation method for fatigue in transverse shear has to some extent been based upon a tensile mode of failure, while the high axial forces in offshore structures may make it possible for a compression mode of failure to occur.

The use of the Miner's hypothesis in design is time consuming and often unnecessary to perform. Simplified evaluation methods should be developed in order to indicate whether fatigue is governing the design or not. Such methods should be developed from a thorough investigation of the actual structures and load condition in order to ensure that all combinations of load are included in the simplification. Rough evaluation guidelines can, however, be developed in a simplier manner, but Miner hypothesis and representative Wöhler curves are necessary as background information.

It is the author's opinion that the detailed method propose by Veritas [21] gives a adequate representation for strength evaluation. Some research efforts are, however, necessary to improve and rationalise some of the parameters in the method.

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