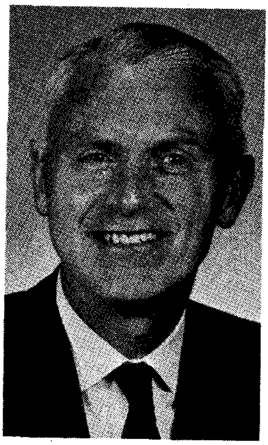
High-Amplitude Low-Cycle Fatigue in Concrete Sea Structures



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Fourteen prestressed concrete structures are now in service as oil drilling, production, and storage platforms in the North Sea. Other fixed concrete structures are in service as offshore terminals, floating docks, floating terminals, breakwaters, and floating bridges in many parts of the world. These structures will typically be subjected to 2×10^8 cycles of waves during a normal service lifetime.

At the same time, concepts are being developed for concrete structures in the Arctic regions, where they may be subjected to many extended periods of continuous crushing of sheet ice. One such structure, the Dome Petroleum's Tarsiut caisson-retained island, is currently under construction in the Canadian Beaufort Sea.

Such ice crushing may have a frequency of peak force development similar to the natural period of the structure.[1] If continuous crushing is assumed to act in one direction for 25 percent of the time over an ice regime lasting 4 months per year, such a structure could experience 10^7 cycles in a 50-year lifetime.

In the case of waves, a probable long-term history of expected loadings can be developed, from which the stress ranges versus number of cycles (S-N curves) can be computed. In the case of Arctic ice, the distribution of ridges in the sheet and the forces and stresses acting on the structure are less well determined; however, a Poisson distribution appears probable[2] with relatively few large events interspersed among a large number of moderate and low cycles (see Fig. 1).

The typical concrete sea structure, such as those in the North Sea, is so configured as to resist the cyclic forces in alternating membrane (in-plane) compression and tension. Some hydrostatic flexural bending and shears may be superimposed on these axial responses. The walls of their base caissons are subjected to cyclic membrane shears as they transmit the wave forces to the base and the underlying soil.

In the case of Arctic structures, where the continuous crushing is unidirectional over the short-term history, the local zones of the peripheral walls are subjected to a single amplitude cyclic flexural shear plus bending, while the internal walls of the supporting structure are subjected to single-amplitude cyclic membrane shear.

It has long been recognized that prestressed concrete has high endurance to cyclic loads which lie primarily in the moderate compression regime of the concrete, that is, ranging from zero to about 60 percent of the compressive strength (f'_c) of concrete.[3] Many tests have established that this range can be safely extended even to a tension of one-half the tensile strength of the concrete. At this level, cracking of the concrete does not occur even under a large number of cycles, and there apears to be little, if any, reduction in endurance. A thorough discussion of fatigue and fatigue endurance of reinforced concrete under cyclic loading at moderate levels of stress range is given in the ACI Committee 215 Report.[4]

Synopsis

During the past decade concrete structures, both conventionally reinforced and prestressed, have been used (and will continue to be utilized) for fixed and floating platforms in the world's oceans. As such, these structures are subjected during a normal service lifetime to fully-reversing loads from the waves, ranging from 2×10^8 cycles of relatively low waves to a few hundred very large waves.

More recently, prestressed concrete structures are being used in Arctic environments, where their peripheral walls are being subjected to large numbers of flexural cycles under continuous crushing of the ice, punctuated by a few extreme cases of very high local loads.

This paper addresses the special considerations for high-amplitude low-cycle fatigue which may occur in concrete structures due to repeated opening and closing of cracks in the sea environment.

The majority of concrete sea structures constructed to date have been designed so that there are relatively few cycles which extend into the tensile range; thus, the design corresponds quite well with the capabilities of prestressed concrete as given in the previous paragraph. As a result, there have been no cases, to this author's knowledge, in which fatigue has occurred in a concrete sea structure.

However, as increased use is made of concrete sea structures in even more adverse environments, it becomes necessary to develop a more thorough understanding of the fatigue characteristics of the composite material "concrete-prestressing steel-unstressed steel." In recognition of this, many tests have been and are continuing to be carried out, especially in laboratories of the United Kingdom, Norway, and The Netherlands (countries bordering the North Sea), from which a considerable body of data has been accumulated and from which it is possible to begin to

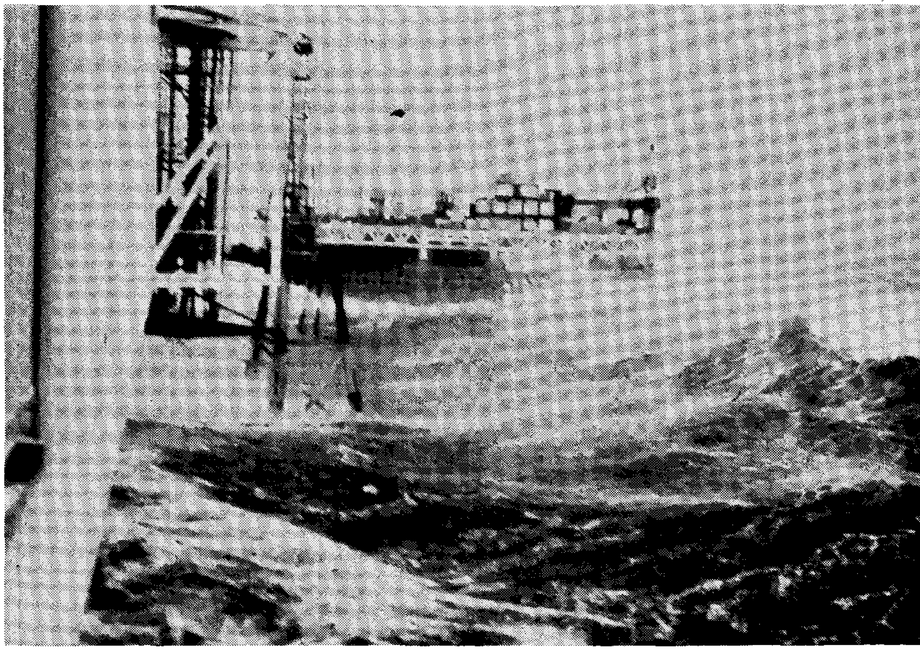

Fig. 1. Storm waves striking the Ekofisk offshore concrete storage caisson. These waves cause fully-reversing cyclic loadings and develop significant stress ranges in both the concrete and steel.

develop an understanding of the behavior of the composite material.

High amplitude load cycling, ranging into tension sufficiently to result in cracking, is shown to dramatically reduce the number of cycles which the composite material can withstand, with failure occurring either in the concete or the steel.[3] The purpose of this paper is to examine these phenomena and to develop principles for safe design of concrete sea structures.

Relevant Experience

Prestressed concrete bridges and sea structures have shown excellent endurance under service conditions, with no reported failures due to fatigue. A triaxially prestressed concrete foundation for a forge has successfully sustained more than 3×10^8 cycles of 100g acceleration.[5] Many millions of prestressed concrete piles have been successfully driven under a thousand or more repeated hammer blows which developed stress excursions from $0.6f'_c$ compression to zero or even into a small amount of tension.

Contrasting with the above are several cases of failure of concrete structural elements in other applications under relatively few cycles of high amplitude loads, extending into the tensile range sufficiently far to develop cracking. In the case of prestressed concrete piles being driven in soft soils, where high rebound tensile stresses lead to the development of cracks that open and close under repeated blows, failure has occurred under as few as 50 to 100 blows.[6] The failure consists in disruption of the aggregate-paste bond and in brittle fracture of the steel. Interestingly, significant heat develops indicating the large amount of energy which is generated in the vicinity of the crack. Preformed "cracks," as at splices, often exhibit similar behavior.

Similar high amplitude fatigue failures occur during demolition, by repeated impact, of reinforced and prestressed concrete structures.

Prestressed concrete railroad sleepers may develop fatigue cracks at the rail seat leading to progressive loss of bond and failure in 10^4 to 10^5 cycles after cracking.

Earthquakes of prolonged duration can produce failures due to cyclic membrane shear. During the Anchorage, Alaska earthquake of 1964, several buildings collapsed when shear connectors between precast elements failed in bond and shear under a few cycles of high intensity. Cyclic shear under earthquake has been intensively investigated[7] in connection with the behavior of prestressed concrete containment structures for nuclear power plants.

Recent Laboratory Tests

Several tests have been carried out by Det Norske Veritas on prestressed concrete blocks, submerged in sea water at pressures typical of offshore platforms. Waagaard[8] reports that the hydraulic fracturing effect of water trapped in the cracks as they repeatedly opened and closed, led to the splitting of the concrete along the reinforcement.

Similar reductions in fatigue life where cracks repeatedly open and close are reported by Taylor and Sharp.[9] Bannister[10] reports on the accelerating effect of corrosion in reducing the fatigue life of reinforcing steel which is exposed to seawater through large cracks. His work has been recently confirmed and extended by Arthur *et al*[11] and Roper and Hetherington.[12]

Muguruma,[13] carrying out low-cycle high-amplitude tests of prestressed concrete beams under flexural loading in air, found that failure was preceded by cracking, loss of bond, and then either compression failure of the concrete or brittle failure of the tendon.

The PCA tests[14] were conducted on precracked prestressed concrete bridge girders. When cycled with a stress range that went to the nominal tensile limit of the concrete on each cycle, $6\sqrt{f_c'}$ (based on an uncracked section), failure occurred at 3×10^6 cycles, whereas no failure occurred when the cycling did not extend beyond $3\sqrt{f_c'}$ in tension.

A series of tests on concrete spheres[15] subjected to low-cycle, high-amplitude hydrostatic loading showed an S-N pattern that is consistent with the previous data. These tests also showed the benefit of the inclusion of wire fibers in delaying the initiation of cracking and hence delaying fatigue failure.

Effect of Cracking on Fatigue Endurance

When prestressed concrete is cycled through moderate compressive ranges, there is no significant development of microcracks; therefore, the stiffness or modulus remains unchanged. The steel stress ranges of both stressed and unstressed reinforcement remain at low levels.

As the maximum compression level reaches about $0.70\,f_c'$, microcracking is initiated and the stiffness decreases, leading to possible increased dynamic amplification under cyclic phenomena such as waves and ice crushing. Creep of the concrete is increased, which reduces the effective prestress, and hence may lead to excursions into the tensile range. There is evidence that Poisson's ratio also is increased.

A number of studies such as those by Hawkins[16] have reported the beneficial effects of rest periods; the effect of moisture condition (reduction in tensile and fatigue strength) and the effect of age (increase in fatigue strength from

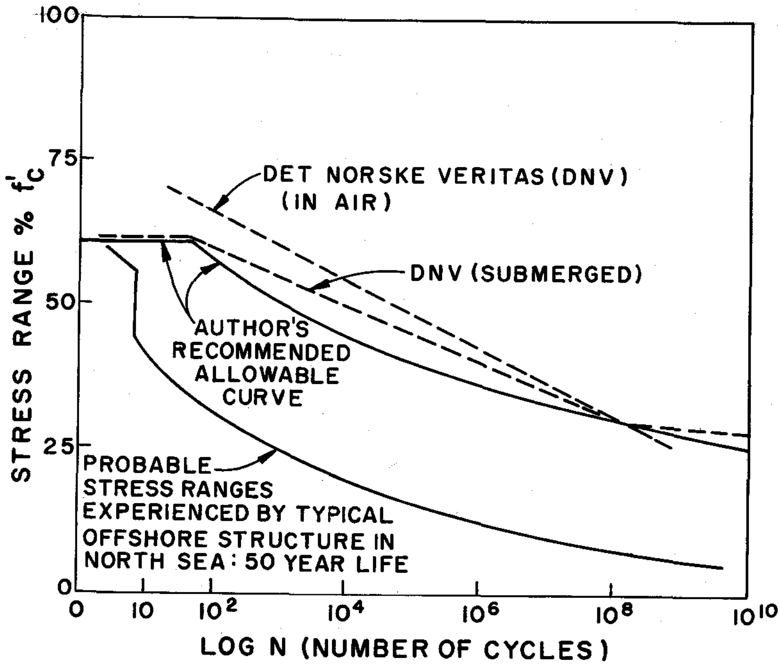

Fig. 2. Wöhler curves for concrete in compression.

28 days to 1 year by 20 percent). The effect of randomly varying loads is not yet fully established; however, recent tests by TNO[17] indicate a reduction in endurance capacity.

Cracking is initiated when the tensile strength of the concrete is exceeded, either by excessive stress excursions into the tensile range which overcome both the prestress and the static strength of the concrete, or by repeated cycling far enough into the tensile range to lead to tensile fatigue of the concrete. The reduction in prestress due to creep can contribute to this.[16]

On the other end of the range, under high compression, the increase in Poisson's ratio leads to transverse cracking. In fact, compressive fatigue failure may well be a case of tension failure due to Poisson's effect. The benefits of lateral confining steel and fibers which have been reported are presumably due to their effectiveness in restricting such transverse cracking and thus "stiffening" of the concrete transversely.

When cracks repeatedly open and close, several adverse phenomena occur. The reinforcing steel stress increases rapidly, offset to some degree by progressive loss of bond. Because of this, the "tension-stiffening effect" (the tensile force carried by the uncracked concrete between the cracks) is degraded, leading to widened cracks and increased deflections.[18] Since the prestressing steel usually has a lower effective bond than the non-stressed steel, its stress range may be somewhat less than that of the unstressed steel.

The dynamic effect of the crack closing leads to mechanical abrasion and breaking loose of the aggregate particles ("hammering").

When the structure is submerged, the water in the crack is subjected to high temporary pressures during crack closing.[8] As the water exits the crack under

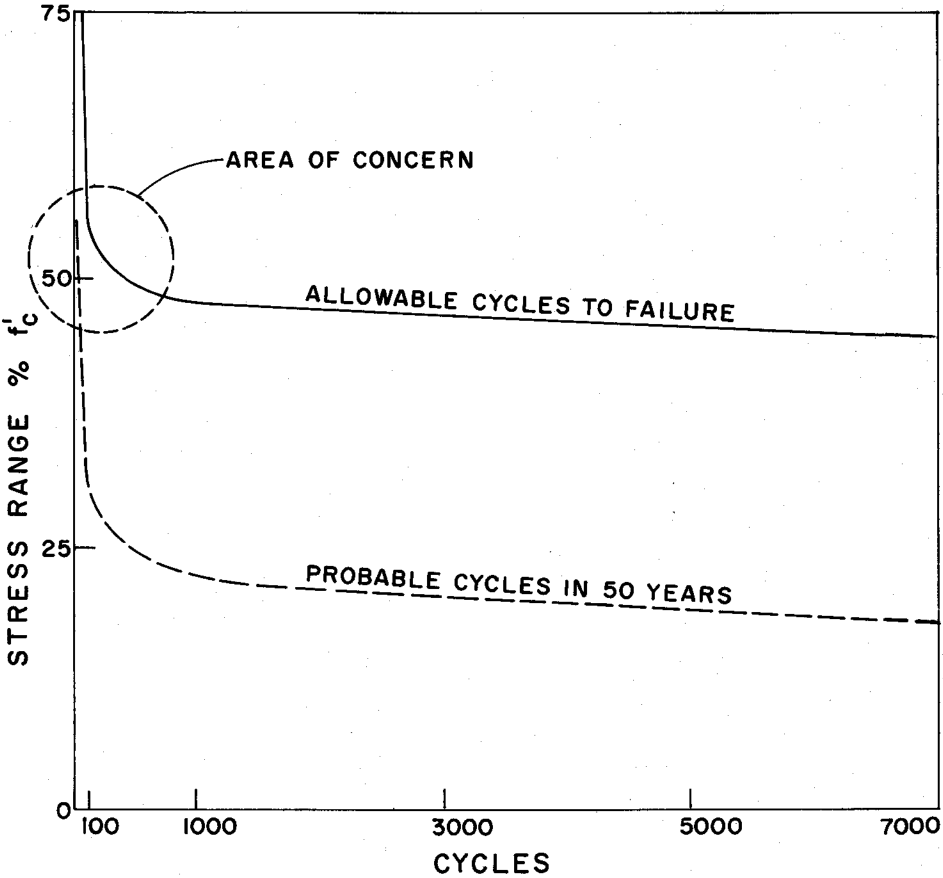

Fig. 3. S-N curves plotted to natural scale.

high local velocity, it may erode the cement paste and any loose sand grains. It also erodes any deposits which may have acted under static or unidirectional loads to "block" the cracks. More seriously, the water may be trapped in the small annulus that forms alongside a crack[19] and, under the instantaneous hydrostatic pressure peak, cause hydraulic fracturing and splitting of the concrete along the reinforcement.

These problems are magnified in the case of extreme cyclic reversing membrane shear in the walls of offshore structures and the sides and longitudinal bulkheads of floating structures. Here the reversing shear can produce a double pattern of diagonal cracks, oriented at a substantial angle to the conventional grid of horizontal and vertical bars. Crack widths are substantially increased and there may even be displacement along the crack.

Following cracking, the steel must pick up most of the force previously supplied by the tensile capacity of the concrete. Initially some of this requirement is supplied by the "tension stiffening" effect of the concrete; but as bond progressively degrades, the steel, both stressed and unstressed, must carry almost the entire amount. The effect of repeated cycling intensifies the loss of bond and the creep;[18] hence,

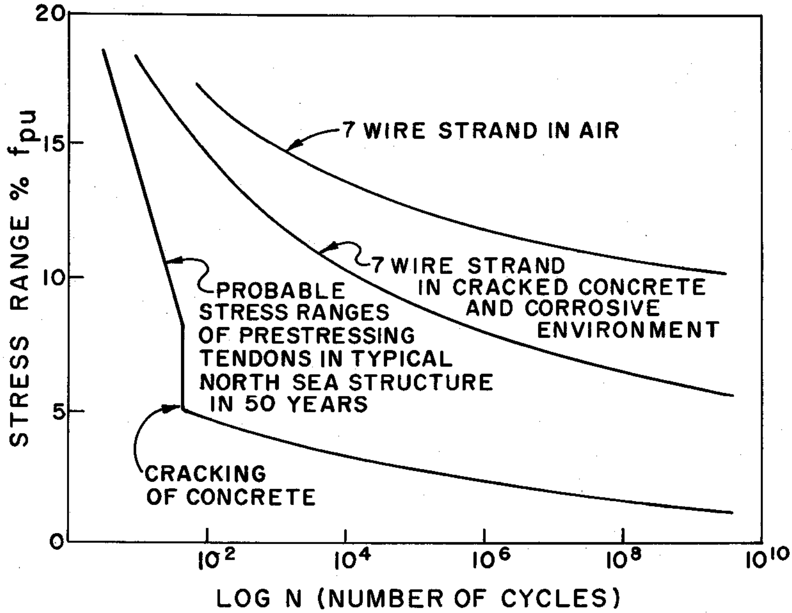

Fig. 4. Wöhler curves for prestressing steel.

the loss of effective prestress, and increases the load which must be carried by the steel.

The result, therefore, is that at cracking there is a quantum jump in the stress range of the steel, combined with a smaller but still significant jump in the maximum compression stress level in the concrete.

The steels, both unstressed and prestressed, have an endurance level of about 22,000 psi (160 MPa) or more, although Roper and Hetherington[12] report values as low as 20,000 psi (140 MPa). These levels can only be approached after significant cracking has occurred.

For concrete in the splash zone, cracking and spalling, especially that along the reinforcing bars, may lead to corrosion, which in turn, can lead to corrosion-accelerated fatigue of the steel.[10,11,20] While completely submerged structures, even when cracked are essentially free from corrosion,[21] the splash zone is vulnerable because of the ready availability of oxygen; hence, special care has to be taken in detailing these structures.

Stress Range Histories vs. Cumulative Endurance

As long as the concrete remains without significant cracking in tension, then it is possible to plot continuous functions[3,20,22] of stress range versus the log of the number of cycles (so-called Wöhler diagrams). Both the allowable number of cycles and probable actual number of cycles at each stress range can be thus plotted for a typical concrete offshore platform in the North Sea. It will be seen (see Fig. 2) that the latter curve lies well below the allowable.

Waagaard[20] in summarizing the results of earlier research, shows that Miner sums of 0.2 to 0.5 are appropriate for describing the cumulative usage capacity of concrete. When such a

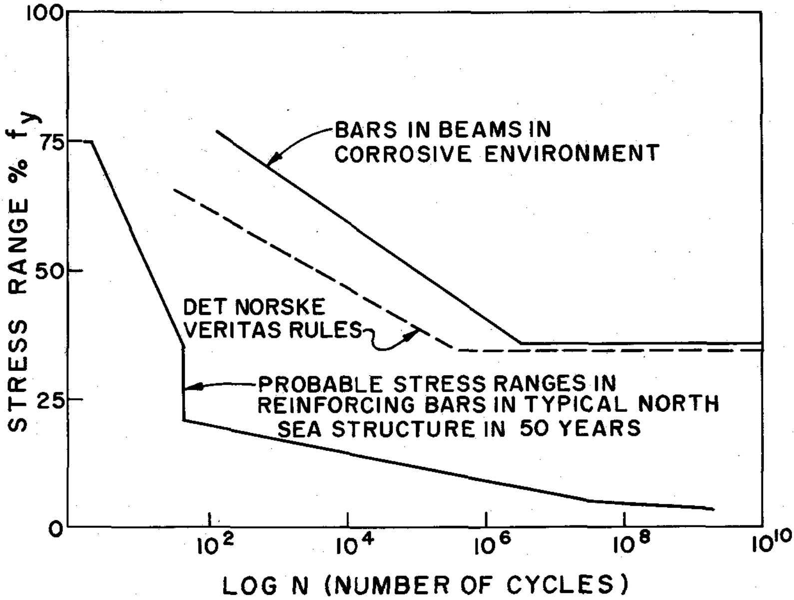

Fig. 5. Wöhler curves for conventional reinforcing steel.

Miner's summation is carried out for a typical North Sea structure, it will usually be found to be less than 0.1.

This summation, however, proves to be very sensitive to the maximum stress range, the high-amplitude low-cycle end normally contributing a major portion of the cumulative usage. This feature can be put into better perspective when the number of cycles is plotted on a natural scale (see Fig. 3). Similar plots can be made for the steels, both stressed and unstressed (see Figs. 4 and 5).

Although conventionally the safety against failure is evaluated parallel to the abscissa, by comparing the ratio of the calculated number of cycles at each stress range to the corresponding allowable number of cycles as shown by the Wöhler curve, and then summing up these ratios, there is another and very important way to address these curves and that is in regard to the ordinate, i.e., the stress range itself. A relatively modest increase in stress range or the application of a load factor can lead to a disproportionately high increase in usage (see Fig. 6).[9,20]

With excursions into the tensile range of the concrete, but still without cracking, a modified Goodman diagram can be prepared after the example of Hawkins (see Fig. 7).[22]

Once the concrete cracks, however, a significant jump takes place in the steel and concrete stresses. This jump has been indicated in Figs. 4 and 5 for the given steels.

Note also a smaller but significant jump in the probable stress range in the concrete, which is indicated in Figs. 2 and 8. This is due to the dynamic (hammering) effect on crack closing and also due to stress amplification under decreasing stiffness.

Cyclic membrane shear can be viewed as a case of cyclic diagonal tension alternating with cyclic diagonal compression. When conventionally reinforced, the concrete will crack under moderate to large shear forces; hence,

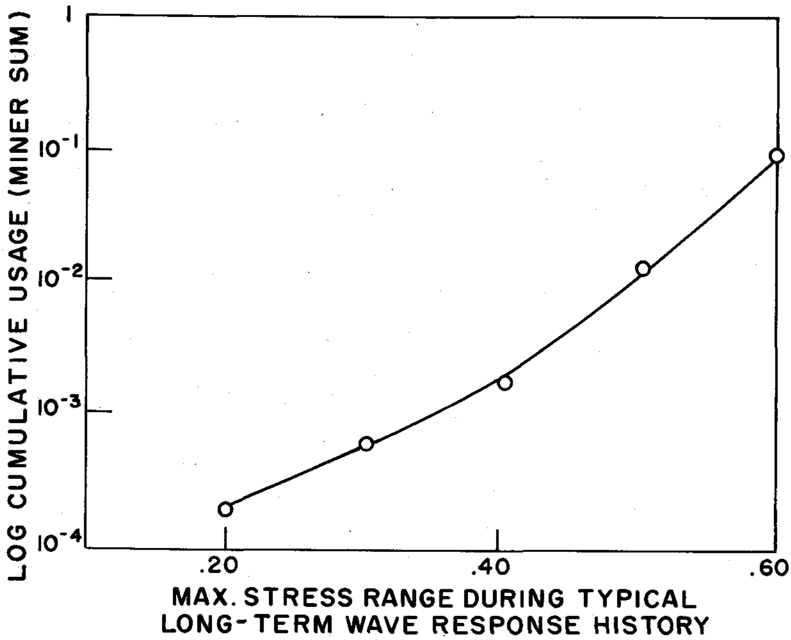

Fig. 6. Non-linear increase in usage with increasing maximum stress range.

the steel must be considered to carry all the shear, and the stress range must be kept low.[22,23] Under the typical patterns of diagonal cracking, crack widths are enlarged as compared with cracks normal to the reinforcement at similar levels of steel stress. Under high intensity loadings, displacement along the cracks may produce abrasion of the concrete surfaces, bending of the steel bars, and rapidly decreasing shear stiffness, leading to dynamic amplifications. Conventional orthogonal grid patterns of unstressed steel are very inefficient. Therefore, vertical post-tensioning (see Fig. 9) has proven valuable and practicable in preventing cracks, or at least, in narrowing their width and changing them to a vertical direction where they may be more efficiently resisted by the horizontal steel.[23]

For structures which are destined to serve in the Arctic, and which must therefore resist the impact and crushing forces of the moving ice, consideration must be given to the number and magnitude of cycles of loading in both flexure and shear. Peripheral walls may have been subjected to prior flexural and shear cracking by high concentrated loads such as those imposed by pressure ridges.[24] As a result, the reinforcing steel will subsequently be carrying most if not all the cyclic tensile stresses which are developed under continuous ice crushing.

The use of prestressed tendons, both in the plane of the peripheral wall, and, in critical zones, through the wall, can be used to create a favorable state of triaxial stress, as well as limit the number of excursions into the cracking range, thus preventing fatigue.

Suggested Design Principles

The design of concrete sea structures which are subjected to high amplitude cyclic loads, both unidirectional and

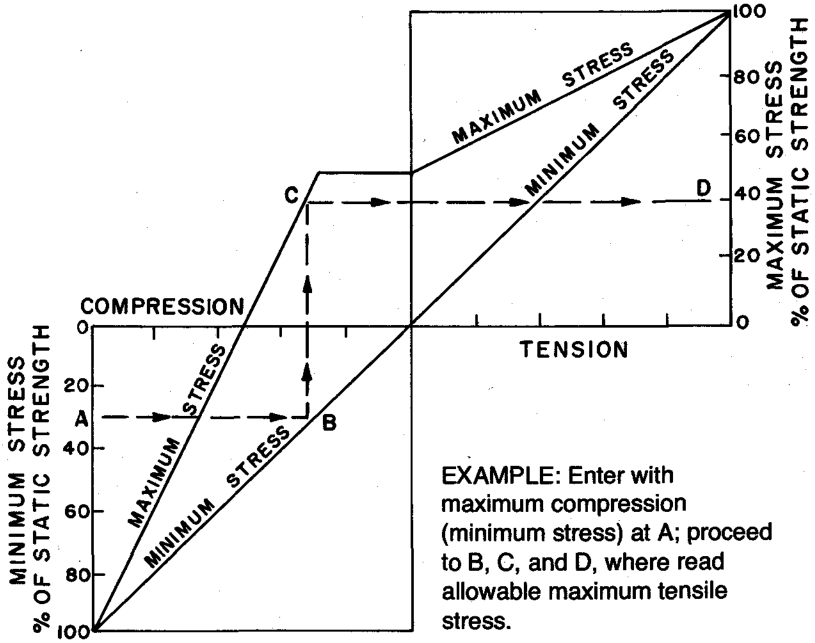

Fig. 7. Modified Goodman diagram for concrete subject to fully reversing stresses; 3×10^6 cycles, 90 percent probability of non-failure, use saturated strengths for submerged concrete.

reversing, requires the exercise of judgment as well as technical analysis. There is a significant difference in performance between reinforced and prestressed concrete which is uncracked, concrete which has been precracked by a prior extreme load, and concrete which is subject to continuous crack opening and closing. There is also a significant difference for concrete which is continually submerged as compared to that in the splash zone.

Wäagaard[20] has presented a series of formulas for determining the Wöhler curves for a number of different loading combinations and for calculating the cumulative usage. Note that additional rules are given in Appendix D of the DNV Rules.[25]

While formulas such as these are perhaps the most precise quantitative guidelines available to the analyst, they present serious problems to the practical designer because of their complexity. Further, these formulas are merely lower bounds of widely scattered empirical data and do not reflect the significant differences in behavior due to sequence of loading, random variations in stress ranges, and the effect of rest periods.

Therefore, the ACI in their "Guide for the Design of Fixed Offshore Concrete Structures"[26] followed the philosophy originally expressed in the ACI Committee 215 report[4] and sought to establish simplified guideline threshold values, below which fatigue is assumed to be a non-problem and therefore requires no further check. A similar approach has been applied to two recent large concrete platforms in the North Sea.

If these threshold values are exceeded, which usually occurs for only a few members in a structure, then a

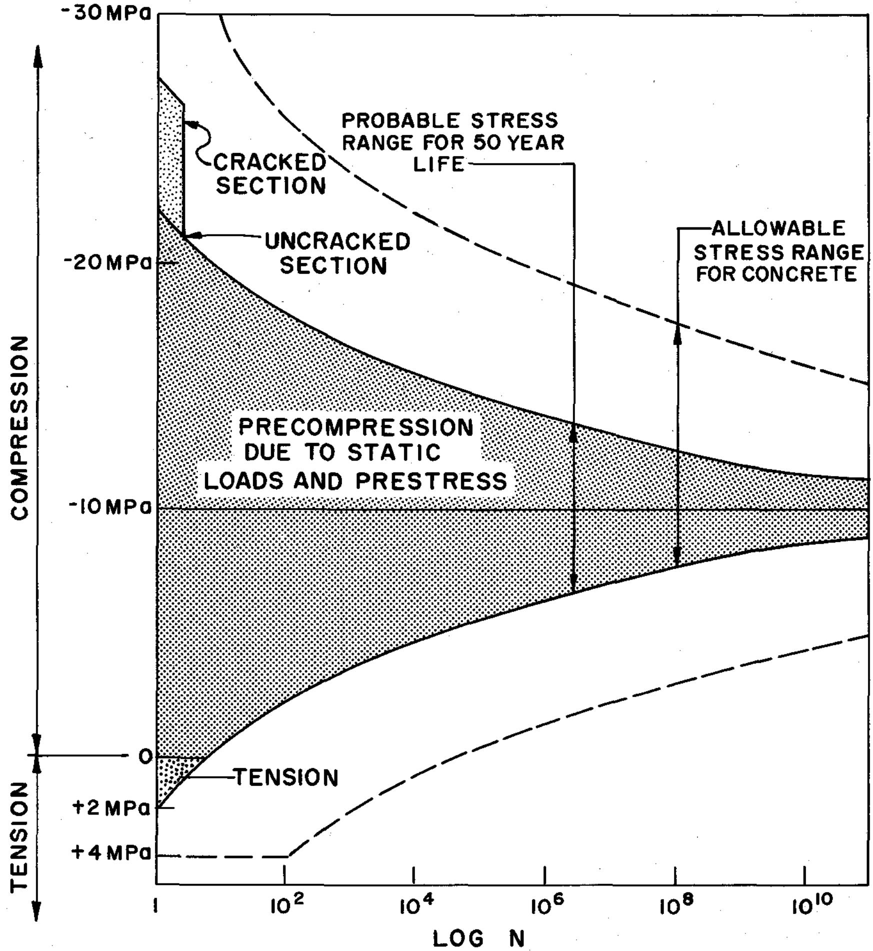

Fig. 8. Probable versus allowable stress range for prestressed concrete.

more detailed analysis must be carried out, following procedures such as those prescribed by Waagaard.[20]

Some suggested threshold values are as follows:

1. Maximum flexural tensile stress less than 100 psi (0.7 MPa) (see Item 7).

2. No tensile membrane stress (see Item 7).

3. The stress range in the concrete does not exceed 0.40 f'_c for environmental forces having a monthly return period. This can also be expressed, in the case of a wave loading, as environmental forces equal to 0.6 times those under extreme conditions.

A more exact limit, applicable especially to cases where high prestress is used, can be given as $(0.40 f'_c - 0.5\,\sigma$ min), where "σ min" is the minimum stress level during a cycle.

4. Stress range in the reinforcement less than 20,000 psi (140 MPa) for the same environmental loading as in Item 3 above. For bent or welded bars, the limit reduces to 10,000 psi (70 MPa). More exact values are given as (140 MPa $- 0.33\,s$ min), where "s min" is the

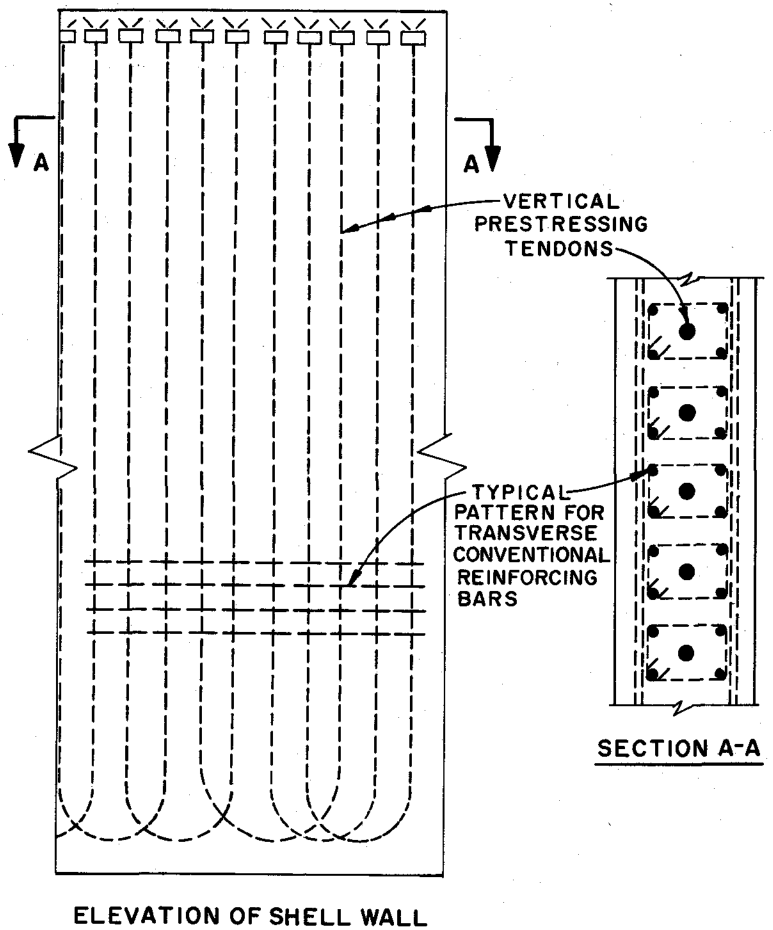

Fig. 9. Schematic layout of vertical prestressing tendons in walls of concrete offshore platforms subject to membrane shear cyclic stress ranges.

minimum stress level during the cycle.

5. If the shear force variation is greater than 25 percent of the total shear, and the total shear exceeds 50 percent of the static shear capacity of the concrete including that contributed by axial compression, then all shear is to be carried by the stirrups at the stress level determined in Item 4 above.

6. Development lengths for reinforcement at splices are to be doubled (as compared with static requirements) in the regions subject to significant cyclic loading and especially where stress reversals occur.

7. For prestressed concrete members subject to fully reversing cyclic loadings, with occasional excursions into the tensile range of the concrete greater than zero in membrane tension or 100 psi (0.7 MPa) in flexure, the steel area should be proportioned so as to be able to carry the tensile force capacity of the uncracked concrete, at a stress range in the steel appropriate to the number of cycles into tension.

The number of cycles in the tensile range that may occur during the structure's service life may be determined from the projected environmental loading history, as transformed to stress ranges, with consideration of loss of prestress through time due to stress relaxation and creep; the latter being amplified due to the cyclic nature of the loadings.[18]

From Figs. 3 and 4, the allowable stress level for the steel can be determined.

The actual cracking level of the concrete should be reduced from the static tensile strength due to submergence. A value of 80 percent of the static tensile strength of the concrete is often appropriate.

The required steel area can then be determined. In the case of cyclic fully reversing essentially axial stresses, as in the deck and bottom of a floating platform, or in the walls of shafts of offshore structures, this required steel area percentage will be the ratio of the allowable tensile stresses in the concrete and steel. A relatively high percentage, approaching 2 percent, will usually be found required, which can be contributed by both the stressed and unstressed steels.

SUMMARY AND CONCLUSIONS

1. Prestressed concrete offshore structures, both fixed and floating, have inherently great endurance for moderate amplitude high cycle loadings typical of normal sea states.

2. Under extreme high amplitude stress cycles, the concrete structure may degrade, resulting in accelerated creep, loss of bond, decrease in stiffness, increased dynamic amplification, increase in Poisson's ratio, loss of prestress, and therefore cracking.

3. When the concrete is subjected to high amplitude stress ranges, extending repeatedly into the cracking range, fatigue can occur in a relatively small number of cycles. The steel stress ranges jump *significantly* upon cracking, and may lead to fatigue of the steel. At the high compression end, the increased lateral strains may lead to disruption of bond between paste and aggregate and failure of the concrete in compression.

4. Confinement of the concrete both stiffens and contains this lateral expansion and increases the resistance of the concrete to compressive fatigue.

5. Use of adequate steel percentages, both unstressed and stressed, controls the jump in steel stress range and can be an effective means of preventing fatigue of the steel after cracking.

6. For concrete which is submerged, local hydraulic fracturing may occur with repeated opening and closing of the cracks. Hence, opening and closing of cracks in submerged concrete should be limited to a relatively few cycles during a service lifetime.

7. Cyclic membrane shear can most effectively be resisted by vertical post-tensioning combined with horizontal steel (stressed or unstressed).

8. Special care must be given in critical zones, to proper detailing and sound construction practice in order to ensure that construction joints will not act as preformed cracks and to eliminate local stress raisers such as sharp reentrant corners, embedments, etc., that will lead to early cracking. Where these cannot be avoided, additional local reinforcement should be provided to prevent crack propagation.

9. The splash zone is particularly vulnerable because of the possibility of corrosion-accelerated fatigue after significant cracking of the concrete. This cracking should be severely limited by proper design (prestress, adequate steel percentages, and confinement).

10. Adequate endurance against loss of bond can be provided in zones subject to significant stress reversals (such as the base of shafts) by using reduced bond stresses (e.g., doubling the development length as compared with that required for static loading).

11. In evaluating safety against fatigue, attention should be given to the effect of a possible increase in the stress ranges at the low-cycle high-amplitude end.

12. Through proper design and construction, prestressed concrete sea structures can be assured of long life even under the cyclic loadings accompanying the most severe environmental conditions.

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NOTE: Discussion of this paper is invited. Please submit your discussion to PCI Headquarters by May 1, 1982.