Zeitschrift: IABSE congress report = Rapport du congrès AIPC = IVBH Kongressbericht

Band: 12 (1984)

Artikel: Design of offshore structures, with emphasis on the Canadian challenge

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DOI: https://doi.org/10.5169/seals-12101

Design of Offshore Structures, with Emphasis on the Canadian Challenge

Projet de structures offshore, spécialement au Canada

Entwurf von Offshore-Konstruktionen für die kanadischen Verhältnisse

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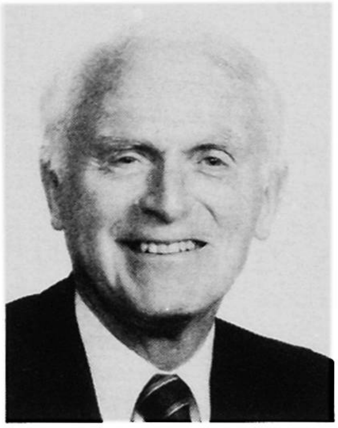

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SUMMARY
The new challenge in the design of offshore structures lies in the Arctic and sub-Arctic regions where environmental criteria include sea ice and icebergs. These considerations dominate the design of offshore oil and gas platforms for the Canadian offshore, and are applicable to other Arctic and Sub-Arctic regions of the world as well. While existing rules and recommended practices for design are generally adequate for the design of offshore structures in temperate zones, there are a number of new or intensified considerations for these regions where icebergs or multi-year sea ice floes may develop much greater lateral forces against structures than hitherto faced in the temperate zones.

RESUME
Le nouveau défi dans le projet de structures offshore provient des régions arctiques avec ses calottes de glaces et ses icebergs. Ce défi se rencontre particulièrement au Canada. De nouvelles sollicitations sont alors à considérer, en particulier l'énorme poussée horizontale de la glace.

ZUSAMMENFASSUNG
Die neue Herausforderung im Entwurf von Offshore-Bauten liegt in den arktischen und subarktischen Verhältnissen, wo die Umgebungseinflüsse auch Treibeis und Eisberge umfassen. Diese Kriterien dominieren beim Entwurf der Offshore-Plattformen für Oel und Gas im kanadischen Fördergebiet. Während bestehende Bemessungsregeln und Richtlinien im allgemeinen für wärmere Klimazonen ausgelegt sind, muss in Zonen, wo Eisberge und Treibeis vorhanden sind, mit viel grösseren Horizontalkräften gerechnet werden.

1. INTRODUCTION

It is part of the very nature of Offshore Structure Engineering that the successes in overcoming the severe wave environment of the North Sea, and the unprecedented depths in the Gulf of Mexico, have led to new challenges in even more hostile and difficult environments.

Today's new challenges lie in the Arctic and sub-Arctic, and in the deeper offshore regions. Canada is host to two of the most difficult regions in the world: Eastern Canada, with its icebergs, and the Canadian Beaufort Sea with its multi-year ice floes containing embedded pressure ridges, its weak soils, and in one area, high seismicity. Should oil ever be discovered off Canada's West Coast, it will pose another new problem, that of very long period waves.

While the design rules and practices developed for the offshore in general and the North Sea in particular give an excellent basis, many new aspects and requirements have emerged in planning for the development of the rich resources of the Canadian continental shelf.

These new considerations include:

- Global dynamic response to impact of massive ice features.
- Concentrated local loadings from ice.
- Transfer of large lateral forces to the foundation soils.
- Materials for Arctic and Sub-Arctic service.
- The appropriate design philosophy for rare events of great magnitude.

While the development of the Canadian offshore presents an unprecedented challenge to engineers, the present state of knowledge and current level of effort indicate that safe, functional and relatively economical structures can be attained to serve the relentless advance of man's offshore resource development.

2. ENVIRONMENTAL FACTORS

We are now confronted with a major new factor, ice. Eastern Canada, offshore Newfoundland and Labrador, present the rather terrifying phenomena of icebergs, ranging in size up to many millions of tons and moving in summer open water with speeds of 1 knot or greater. The resultant kinetic energy is enormous. Impact with a fixed structure can develop forces twice or more than the 100,000 tons environmental design load which is the maximum yet faced in the North Sea, in that case due to storm waves.

While the structures must thus be designed to resist high global forces and transit them into the foundation soils, they must also consider high local forces, as the ice impacts a specific region of the structure. Because of the erratic paths of icebergs under the influence of current and winds, especially in the southern regions off Newfoundland, impact can occur from any direction.

Such local forces, with intensities of 1000 Tons/m^2 and more, can be imparted not only by large bergs but also by smaller masses, such as "growlers" of a few thousand tons, hurled at speeds up to 8m/s by storm waves.

The ice conditions of the Canadian Arctic are different but no less formidable. The permanent polar pack of sea ice slowly rotating clockwise around the pole, occasionally spins off gigantic multi-year ice floes, with masses comparable to those of icebergs. These floes contain embedded multi-year ridges reaching down as deep as 50 meters. Their kinetic energy of impact must also be absorbed by the structure. Floes up to several thousand meters in diameter may be driven against the structure by the relentless forces of the Arctic ice sheet, limited only by the crushing of the ice against the full rear face of the floe.

In the Canadian Beaufort and especially off the mouth of the Mackenzie River, the soils are extremely weak and unstable. Hence soil-structure interaction tends to dominate the design concepts.

A much rarer but nevertheless critical phenomenon is that of ice islands and ice island fragments. These are tabular icebergs, spawned from glaciers on Ellesmrere Island, just west of Greenland, which are caught up in the Polar Pack. Unlike the icebergs off Newfoundland, driven only by wind, current and Coriolis force, these ice island fragments are driven by the polar pack itself.

As if the combination of ice forces and weak unstable soils were not enough, the eastern Beaufort Sea is a zone of high seismicity (zone 3). One must consider the effects of earthquake on a structure whose upper portion is embedded in an ice sheet or ice rubble pile.

Reference has been made above to the difficult Arctic seafloor soils. In many areas the upper stratum is largely silt, varying from unconsolidated silty clay having undrained shear strengths at the surface of only 5 KPa, to overconsolidated silts of high capacity, but frequently underlain by weak strata below.

The surface of the Arctic seafloor is being continuously plowed by the keels of ice ridges, with the resultant 1 to 7 meter deep furrows being refilled with loose silty deposits. While these do not represent an extreme problem for structures, they do for any pipelines leading from the offshore structures towards shore or to a shipping terminal.

At varying depths below the surface (10 to 20 meters usually), subsea permafrost may be encountered. Its upper boundary is thawing over geologic time, releasing water and gas which then may be trapped below the silty clay. This phenomenon may account for the extremely low strengths of such interbedded strata.

Fortunately, off the East Coast, where the icebergs occur, most of the area appears to have very competent seafloor soils, principally dense sands.

The eastern and western coasts of Canada are also exposed to extreme storms. In fact, a number of studies have shown that for specific cases off Newfoundland, the design storm wave may generate larger forces than the design iceberg impact. Of course, this is in large part due to the need to make a bottom-founded structure very massive in order to resist the icebergs: this in turn attracts very large wave inertial forces.

3. DESIGN ASPECTS

A number of authorities have published rules and recommended procedures for the design of offshore structures in the temperate environments, covering the design of both steel and concrete structures. Most widely used are:

API-RP2A "Recommended Practice for the Design and Construction of Offshore Fixed Platforms: (primarily addressed to steel structures)", American Petroleum Institute, 13th edition, 1981.

DNV Rules for the Design, Construction and Inspection of Fixed Offshore Structures, 1977 (revised 1981) and Appendices. Det Norske Veritas.

ACI 357-78R (currently being revised), Design and Construction of Concrete Sea Structures. American Concrete Institute.

FIP Recommended Practice for Concrete Sea Strctures, 1978 (currently under revision) Fédération International de la Précontrainte.

While these adequately address the basic principles of design for offshore structures to waves, currents, and earthquakes, additional guidelines are needed for design to resist ice loads.

The American Petroleum Institute has therefore published a tentative set of guidelines as API Bulletin 2N, "Guidelines for Design and Construction of Fixed Offshore Structures in Ice-Covered Waters."

Under the leadership of the Canadian Standards Association, a set of rules for offshore platforms in the Canadian offshore environment is currently being prepared. These presumably will include design for ice loads.

The FIP Commission on Concrete Sea Structures is currently preparing a set of guidelines for the Arctic environment. ACI Committee 357 is also preparing a State-of-the-Art Report on Concrete Structures for the Arctic.

A number of special problems arise due to ice loading. Some of the principal ones will be addressed in more detail below.

4. GLOBAL DYNAMIC RESPONSE TO IMPACT OF MASSIVE ICE FEATURES

As noted earlier, structures may be subject to the impact of very large multi-year floes in the Beaufort Sea or icebergs off the East Coast. Moving at speeds in the range of 0.5 m/s, the kinetic energies are extremely high. Upon impact with a fixed structure, this energy is primarily dissipated by crushing of the ice and ride-up on the structure, thus changing part of the kinetic energy to potential energy. Smaller amounts of energy may be absorbed by friction of the ice against the structure, by local bending and shear, and by the hydro-dynamic forces generated in the water trapped between the impacting bodies, and by the non-linear strain in the foundation soils. Once lodged against the structure, the force is limited only by the continued crushing of the ice sheet against the rear or trailing edge of the floe, and the wind shear on the floe itself.

The crushing along the contact area with the structure is not uniform but rather develops sharp cyclic peaks (ratcheting) due to the iterative breaking of ice fragments as the floe is pushed against the structure. Thus both dynamic amplification and fatigue need to be considered, especially in slender structures. The breaking of ice occurs in discrete elements, in which the force builds up to a peak about twice the average, then falls as the cracks propagate. A force-time graph will thus show periodic peaks, the time interval being dependent on the strength and velocity of the ice and on the natural period of the structure.

In shallower waters, less than 100 meters, various configurations have been developed in an attempt to minimize the ice forces: monopods, cones, and stepped pyramids.

The aim of the monopods is to reduce the contact area. However, when large embedded ridges impact or are forced against such a monopod's column, developing high apparent crushing strengths due to confinement of the contact zone by the surrounding ice, the maxima forces developed are not fully reduced in linear proportion to waterline diameter.

Conical structures are designed to intercept the ice feature below water and force it to ride up. Ice sheets will break in flexure, but thick multi-year floes will just raise up, dissipating their kinetic energy in friction and gain in potential energy. To be effective the cone must have a relatively flat angle: thus it results in extremely large base diameters in deeper water. A full conical shape thus becomes impracticable in water depths over 60 to 80 meters.

A third configuration is the stepped pyramid, designed like the cone to intercept the ice feature at a deeper elevation, and by virtue of the relatively small contact zone, to fail the ice in horizontal shear, plus crushing, at loads well below the maximum allowable. Fig. 1.

In all cases, the greater the distance of penetration, ride up, and displacement, the lower will be the maximum force.

The ice feature may contact the structure centrically or eccentrically, and on a course parallel to a radius or obliquely. This produces a combined lateral shear plus torque, tending to rotate the structure.

The cone and the stepped pyramid both develop their initial reaction at a lower elevation and thus reduce the overturning moment. Overturning moments applied to large base structures normally cause high bearing under the far edge. With cones or stepped pyramids however, the resultant may pass near the centroid of the base, thus limiting the maxima soil bearing values imposed by the impingement of the largest features.

Resistance to lateral shear and excessive bearing may require that the base of the structure be very large, 150 to 180 m. in diameter in typical cases, in order to not exceed the allowable values in the generally weak soils.

A structure of this size will be constructed in temperate waters, outfitted, and towed to the site during the open water season. Naval architectural aspects, towing horsepower requirements, and minimum draft to permit construction and deployment must all be considered in selecting the optimum configuration for a specific location in order to reduce global ice forces and responses to acceptable levels.

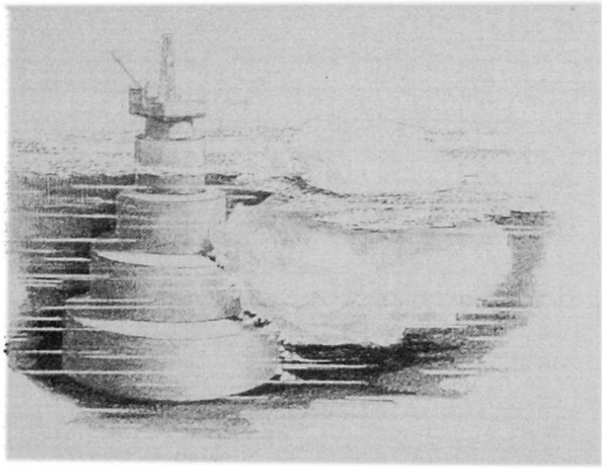

Figure 1 - Stepped Pyramid Concept.

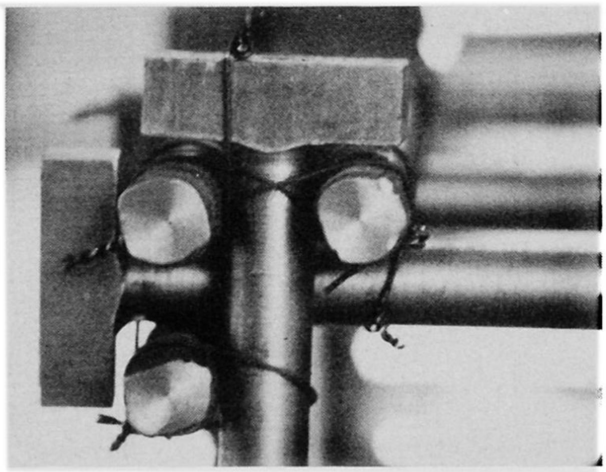

Figure 2 - T-Headed Bars for Shear and Confinement.

5. CONCENTRATED LOCAL LOADS

A moving ice feature will make initial contact with the structure on a discrete area. As the structure penetrates the ice, the contact area progressively increases. The unit pressure over the initial small contact area may be quite high, due to the triaxial confinement of the ice contact area by the surrounding ice giving an indentation factor as much as 3 to be applied to the uniaxial unconfined compressive strength. Small areas, perhaps 2m x 4m in size, may see pressures as great as 14 N/mm^2.

These high local loads tend to punch through the shell or slab of the peripheral ice wall. Actually, the response phenomenon is often one of combined flexure and shear.

For steel external walls, experience with icebreakers shows that the hull plate tends to deform, transferring the load to the scantlings and thence to the frames. Since there is little load distribution in the typical framing design, these internal members are subjected to high compression and shear, tending to fail in web or flange buckling modes.

Special systems of steel framing have been proposed, utilizing offset inclined frames to absorb the energy of extreme concentrated loads in local plastic deformations, so as to distribute the load to adjoining members. [1]

Concrete shell walls, on the other hand, do distribute the concentrated load well, but are subject to initial cracking in flexure, opposite the load, with moments subsequently redistributed to the supports. Eventual failure comes either in punching shear or in concrete compression. Appropriate reinforcement therefore be provided on all three axes, in order to prevent shear failure and to confine the compression zones so as to ensure a ductile mode of failure. [2]

Both tests and analyses show the important role played by the supports in their resistance to rotation and displacement.

Rational designs for peripheral ice walls indicate the need for a high reinforcement ratio, typically 1-1/2% to 2% on all three axes. This can be met for the two axes in the plane of the wall by bundled bars of large diameters, augmented by post-tensioning in the vertical plane. Splices of such bars may be by lapped or mechanical splices. Lapped splices should be 50 to 100% greater than those provided in the ACI code for static loads, and should be tied at both ends of the lap.

Mechanical splices should develop the full strength in compression and tension.

The difficult axis is that through the wall, which is needed to provide confinement of the compression zone of concrete, restrain buckling of compressive reinforcement, and resist through-wall tension due to shear. Conventional stirrups are very difficult to place through the congested longitudinal and vertical steel. Their size is limited by bend radii requirements. Two or more stirrups of 10 or 12mm. dia. can be bundled and tied together, then placed as a single unit. Nevertheless, it is almost impossible to anchor both tails inside the confined core. Tests show that even well-anchored stirrups fail to develop full yield strength under high transverse tension, due to crushing under the bends and pop-out of the tails.

Mechanically-headed bars have been used in heavy industrial buildings but would be impracticable to place in the typical ice-wall. Therefore, a T-headed stirrup has been developed which can be inserted through the previously placed circumferential bars, then turned 90 degrees to lock its heads behind those bars.

Tests show that such bars develop their full yield strength in tension. By restraining the in-plane bars from buckling and confining the core of the concrete, the compressive ductility is enhanced substantially.

These bars can be forged or can be flame-cut from plate, giving an economical use of steel comparable to that of a stirrup with tails. They permit steel percentages of 1-1/2% or more to be practicably installed through the wall. Fig. 2.

A structural concept of high potential for the peripheral ice wall is that of the hybrid or sandwich-design, in which a steel shell is filled with concrete. The inside and outside steel plates must be tied together, either with transverse plates or by overlapping welded studs. A similar hybrid concept was used by Dome Petroleum for the ice wall of the SSDC-1, an exploratory drilling vessel now operating in the Beaufort Sea.

Local concentrated loads spread over one or two bays of the peripheral ice wall generate very large total forces which must be transferred into the structure through its internal framing to the base slab and thence into the foundation. The role of the internal structural members supporting the peripheral ice wall has often been underestimated. Very high compression and shear will occur in those diaphragm walls or frames behind the load.

Horizontal diaphragms or decks are extremely useful in spreading this load, as is truss action of the vertical walls behind the ice wall.

The ice wall and its immediate supporting structure will inherently be thick, rigid, and strong. Many 2-D and 3-D finite element analyses of different framing systems all show a tendency for the local loads to run around the circumference. Because of relative stiffnesses, comparatively little load is transmitted to internal radial and "egg-crate" bulkheads. Since the vertical walls and frames usually constitute the largest proportion of the total concrete, here is an obvious opportunity to achieve economies by purposefully using a combination of truss action and horizontal plates to spread the load around the circumference, and thence downward through the side walls in membrane shear.

6. TRANSFER OF LATERAL FORCES TO THE FOUNDATION SOILS

In granular soils, such as the sands off Eastern Canada, the shear transfer to the soil may usually be attained by friction alone, under the high dead weight of the ballasted structure. However, full contact under the base or at least under the full annular ring around the outside edge of the base is essential. In the North Sea production platforms, this is accomplished by the use of skirts and underbase grout.

The total ice force must be transferred into the foundation. Sliding is a dominant mode of failure, usually controlling the design in water depths up to 40 to 50 meters. In deeper water, the ice loads, if they impact near the waterline, produce high overturning moments which in turn cause excessive bearing stresses and may lead to tilting. Hence the cone and stepped-pyramid configurations are designed to lower the point of contact, so that the resultant will run as nearly through the centroid of the base as possible.

In the Canadian Beaufort Sea, where the soils are weak and variable, additional shear transfer mechanisms are required. Skirts can be used: however, in shallow water, there may not be enough weight available by ballasting the structure to penetrate the skirts fully into the overconsolidated silts.

Another method proposed is the use of multiple large-diameter steel spuds, installed after founding by a combination of jacking, jetting, and driving. [3] These spuds would not be fixed vertically to the structure, hence would allow it to exert full contact on the soil as settlement occurs. Fig. 3, 4.

Finally, piles may be considered. Similar to typical offshore piles, they will need to carry both axial and lateral loads into the soil. They must be fixed to the structure: this requires a relatively long sleeve for grout bond transfer.

Geotechnical studies must consider cyclic strain phenomena, the non-linear strains in the soil under extreme loads, and settlement over time, especially when production of hot oil may cause thawing subsidence of the permafrost.

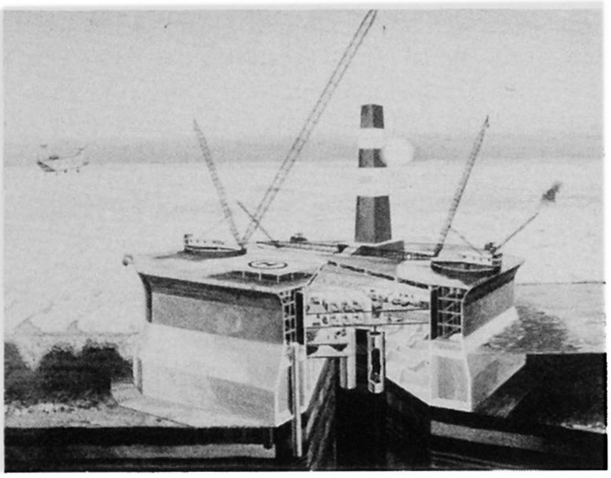

Figure 3 - Sohio Arctic Mobile Drilling Structure (SAMS).

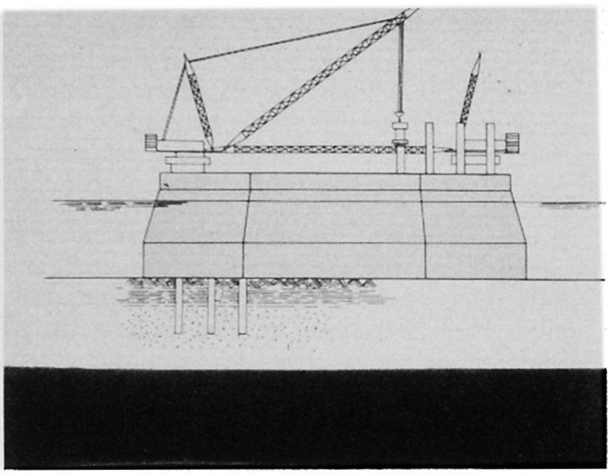

Figure 4 - Use of Steel Spuds to Transfer Shear to Soil.

7. MATERIALS FOR ARCTIC AND SUB-ARCTIC SERVICE

Special concerns about materials for these Arctic offshore projects center around freeze-thaw resistance of concrete that is periodically subject to sea water immersion and splash, the effect of low temperature on behavior under impact, corrosion of steel surfaces where abraded by ice, abrasion of concrete surfaces, use of structural lightweight aggregates and post-elastic ductility.

Extensive laboratory testing plus limited field experience have shown that highly durable concrete can be attained provided an entrained air content of 6% is provided, the aggregates are low in moisture content, and the mix is highly impermeable. The entrained air should consist of voids of proper pore size and distribution: a typical requirement is that the spacing factor not exceed 0.25mm. in the hardened concrete. Air content of the fresh concrete (e.g., 6%) is not an adequate requirement by itself because the current test procedures may include entrapped air, i.e., a few bubbles of large size, which are detrimental rather than helpful.

Figure 5 - Global Marine Super CIDS.

The aggregates should have a low moisture content (4 to 8% maximum) so as to prevent their own disruption by deep freezing. Several of the better lightweight aggregates produced in Europe, Japan, and the U.S. meet this criterion.

The concrete should be highly impermeable. This applies not only to the paste and the aggregate but also to the aggregate-matrix interface. It has been shown that it is the micro-cracking here that produces the majority of the permeability in concrete. Concrete produced with lightweight coarse aggregate may achieve a secondary pozzolanic chemical bound between cement and aggregate particles. The use of pozzolans or condensed silica fumes appears to help in achieving this secondary crystallization, thus blocking the micro-cracks. [4]

High strength lightweight concrete has been developed specifically for use on Arctic offshore structures. This new concrete was used for the Super CIDS (Fig 5) platform, recently built in Japan, for use in the Alaskan Beaufort Sea. Tests shown that when well-confined by reinforcement, this lightweight concrete has high ductility and energy absorption capabilities in the post-elastic range.

At the low temperatures typical of the eastern seaboard and Arctic, conventional steels become brittle under impact loads. Steel which may be exposed to impact should be especially selected to give adequate Charpy impact values at the lowest temperatures expected. Note that steel permanently below water will not be subjected to temperatures below -2 degrees C. These reqirements can be met with special alloy steels. New low carbon low alloy steels are now available, which combine high strength with high fracture toughness and ductility.

Welding materials and procedures must also be selected so as to preserve ductility.

Reinforcing steel embedded in concrete appears to behave satisfactorily under low temperatures because impacts are dampened by the concrete. However, it should be selected for ductile performance and the carbon equivalent should be limited.

Prestressing steels such as cold drawn wire are very suitable for low temperature services, retaining their ductility and fatigue endurance. Similarly, concrete itself becomes stronger, both in compression and tension, due to freezing of the pore water.

Corrosion processes proceed slowly in the Arctic due to the low temperature. However, where ice abrades the steel surface, removing corrosion products and exposing fresh surfaces, corrosion may be accelerated and reach 0.3mm/year or more.

Within concrete, the corrosion of embedded steels is similar to that in other environments, although slowed by the low temperature. In general, the use of the highly impermeable concrete mixes referred to earlier will also inhibit corrosion by delaying chloride penetration and limiting oxygen supply to the cathodic areas of the reinforcing steel. Epoxy-coated reinforcing should be considered for concrete decks and for the outer steel layers in the peripheral ice wall.

Concrete surfaces may be abraded by moving ice. Abrasion effects are aggravated by surface freeze-thaw attack. The addition of condensed silica fumes to the mix appears to substantially increase abrasion resistance, partly because it imparts higher strength to the matrix and partly because of better bond with the aggregate.

Thermal strains in concrete can produce cracks. Most of these occur during construction, due to the thick walls and hence high heat of hydration. Upon cooling, the resistraint induces tension.
Insulation of the forms reduces the gradient through the walls, and allows the concrete to gain strength before being subjected to tensile strains. Adequate face reinforcing must be provided in both directions, so as to ensure that if a crack occurs, the steel area will be such as to keep the steel stress below yield: then the crack will close as the thermal regime equalizes.

Cracks which do not close are subject to freeze-thaw "jacking", leading to progressive widening of the crack and spalling of the outer edges.

Internal voids and re-entrant angles should be avoided to prevent damage from freezing. Large cells can be protected by styrofoam or even wood blocks in the corners.

8. DESIGN PHILOSOPHY FOR RARE EVENTS

In the design for waves, a rational case can be made for the use of the "100-year return, most probable highest wave" in semi-probabilistic design. The same is not necessarily true for earthquakes nor for sea ice/iceberg events. It is also not adequate for accidental events.

Under extraordinary loads such as accidental loads or exceptional environmental loads such as extreme earthquake or extreme ice impact having a return period of the order of 10^{-4} years, a specific analysis of progressive collapse is necessary. This analysis starts with the identification of the threats to the structure and its possible failure modes, described in hazard scenarios which state the triggering event, such as iceberg impact, and the probable accompanying loads. For each such hazard scenario, the structure is then analyzed using load and material factors of 1.0.

Local failure is permitted provided that the damage is not disproportional to the cause, and provided progressive failure is prevented. Energy absorption and ductile behavior are required. A ductility factor of 2 is believed appropriate.

After such an event, the remaining structure should be able to survive in normal conditions. It should also be possible to effect repairs to restore the structure to use.

The above has been paraphrased from a interim report of the FIP Commission on Concrete Sea Structures and is believed by this author to present a sound philosophical basis for design of structures for the Arctic offshore areas.

9. CONCLUSION

The design of offshore structures has undergone major development over the past decade. The Arctic offshore areas present new challenges, especially those of icebergs and sea ice. The current state-of-art and level of development appear adequate, but barely so, to meet the foreseeable rate of demand. Under the limited environmental data currently available, designs necessarily have to proceed on what is believed to be a conservative basis. Some limited field observations indicate the impact forces developed by given size ice features are substantially less than currently being employed in design. On the other hand, we do not as yet have a full statistical basis of ice events (sizes, velocities, etc.), although this is rapidly being obtained in regions of immediate interest.

This paper has concentrated on structural design considerations involved in the extension of offshore structures of steel and concrete to the Arctic. However, it must be noted that there are other important aspects which the designer must consider as well:

Functional - ability to carry on operations in the severe environment.

Constructability - can it be completed within the available work "window" and under the conditions that pertain?

Ecological - can it be deployed and constructed within acceptable limits of interference with the biosphere, including the indigenous peoples of the Arctic?

Economical - can the work be done within justified limits of total cost?

The North Sea brought about a quantum jump in offshore development in the decade just past. The Arctic and sub-Arctic regions are motivating another quantum advance in man's effort to develop the resources of the seas. This area presents one of the greatest current challenges to our profession, and at the same time an opportunity for sound application of advanced engineering capabilities.

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