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OCEAN STRUCTURES OF PRESTRESSED CONCRETE

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Floating and submerged structures rank high among the outstanding applications of prestressed concrete in past years. The caisson for the quay at Brest, La Fontaine subaqueous vehicular tunnel at Montreal, the Hyperion Outfall near Los Angeles, ocean-going cargo barges in the Philippine Islands, the dry dock caisson gate at Hamburg (Fig. 1), compressor and production barges offshore from Louisiana, the

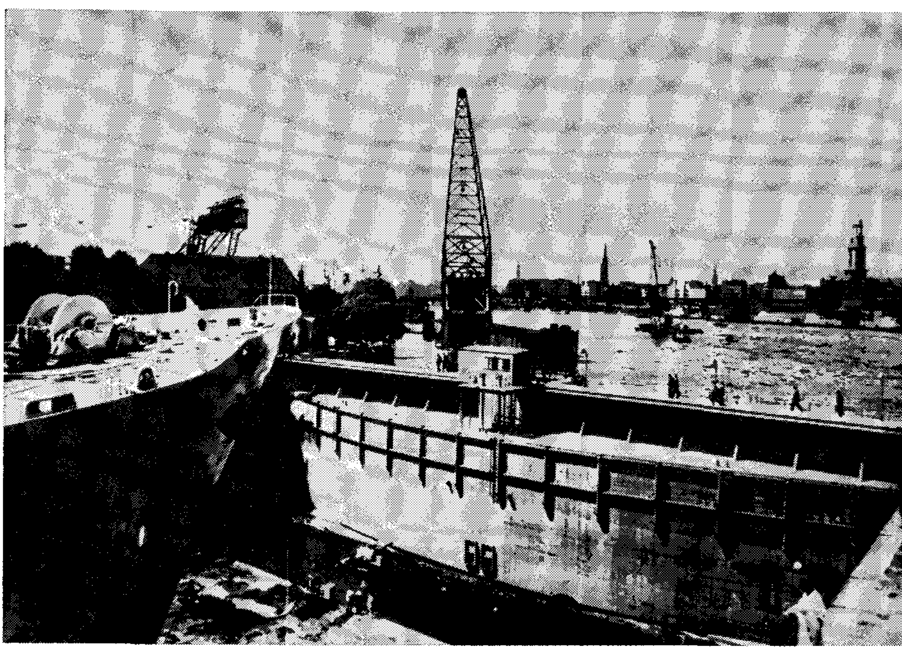

Fig. 1. Prestressed concrete dry dock caisson gate at Hamburg, Germany

Reports potential new applications of prestressed concrete for floating and submerged ocean structures such as vessels for transport and storage of cryogenic materials; petroleum storage and drilling installations; floating airports and nuclear power plants; and boats and barges of all types. Advantages and disadvantages of prestressed concrete are enumerated, and special design and construction considerations are discussed.

floating refinery towed from Belgium to Libya, floating bridges in the State of Washington (Fig. 2), offshore platforms in Lake Maracaibo, caissons for bridge piers in Denmark: these have established a magnificent record of accomplishment for prestressed concrete and give us a reservoir of experience from which to draw for the future.

There is a vast new frontier which challenges man today—the oceans.

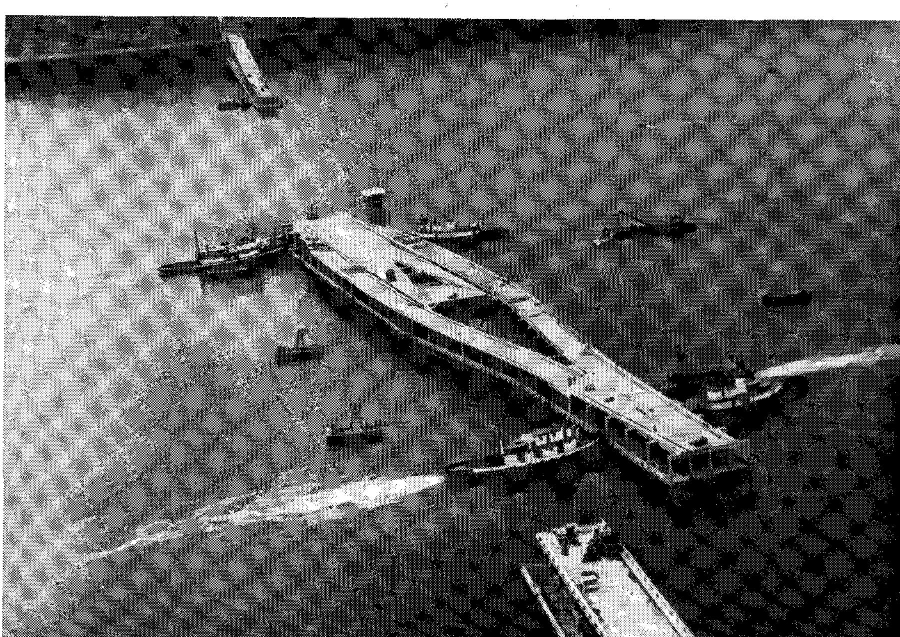

Fig. 2. Prestressed concrete floating bridge, Hood Canal, State of Washington.

The continental shelves and slopes are rich in resources awaiting exploitation for man's benefit. Unlike space, the seas can be developed by both rich and poor nations in degrees suitable to their needs and resources; they await only the development of suitable techniques and materials, and the will of men to face and survive the hostile environment of the sea. Thus, now is an appropriate time for re-examination of the past utilization and performance of prestressed concrete in the oceans in order to most effectively apply it to the needs of the future.

This is an introductory report. An FIP Symposium on the same subject is scheduled to be held in Tbilisi, USSR, in 1972 and, hopefully, an FIP Commission will undertake a more thorough and detailed study of this challenging field and report on the progress that has been made.

APPLICATIONS

In the preparation of this report, an effort was made to learn, as comprehensively as possible, the new applications of prestressed concrete which are under active design and study, as opposed to repetition of previous use or merely dreams of the future. I have been greatly assisted by formal and informal submissions from members of FIP throughout the world and I wish to express my thanks to all who contributed.

Among the new applications of prestressed concrete being actively pursued, the following are of special interest: underwater and floating oil storage vessels; floating airports and atomic power plants; offshore terminals including Arctic Ocean terminals and drilling and production platforms; and column-stabilized (floating) offshore bases. Other significant new applications include: underwater habitats such as floating cities and subsea parking structures; floating wave barriers and breakwaters; submerged floating tunnels for vehicular and rail traffic; and liquefied natural gas (LNG) storage and transport vessels as well as boats and barges of all types.

ADVANTAGES AND DISADVANTAGES

Prestressed concrete offers a number of specific advantages for ocean use. These include:

1. Durability and low maintenance
2. Moldability into any desired form, including double-curved surfaces
3. Rigidity against buckling and local deformation
4. Favorable fatigue properties under a large number of cyclic repetitions, such as those induced by waves
5. Freedom from vibration
6. Insulating qualities and freedom from condensation
7. Excellent behavior under impact at low temperature (non-brittle)
8. A desirable mode of failure (cracking rather than ripping as metals do)
9. Resistance to abrasion from ice and moving sand
10. Ease of repair of local damage
11. Resistance to fire and external explosion
12. World-wide availability of suitable materials and maximum utilization of local labor
13. Over-all economy.

As an offset to the above impressive list of advantages, concrete and prestressed concrete do have disadvantages that must be effectively met. These include:

1. Corrosion due to salt-cell formation in permeable concrete
2. Reduced durability in freeze-thaw exposure, particularly when combined with salt water
3. High unit weight
4. Spalling under local impact
5. Somewhat greater drag, that is, friction with moving water.

Salt-cell corrosion of reinforced and prestressed concrete occurs whenever salt water can penetrate the concrete's pores and evaporate, leaving minute salt deposits. These set up electrolytic action with the steel, leading to serious, progressive corrosion. An oxygen-gradient is required adjacent to the steel and this occurs with small voids which are characteristic of permeable concrete.

The above-water splash zone (cyclic wetting and drying) is notoriously susceptible to such salt-cell formation. Less well-known, due to the higher quality of concrete and the waterproofing usually employed, is that the same thing can happen in dewatered subaqueous structures such as underwater vehicular tubes or subsea habitats. Preventive measures are based on the production of dense, impermeable concrete, using a carefully designed mix, low water-cement ratio, and thorough consolidation by vibration.

Freeze-thaw durability requires air entrainment in addition to a well designed, properly consolidated mix. Values of air of 6 percent are usual; in Norway, it is reported that 8 percent entrained air is used successfully for prestressed concrete in freeze-thaw salt water exposures.

The high unit weight of concrete primarily affects vessels and barges, increasing their draft for the same net carrying capacity. This problem diminishes proportionately as the volume increases; thus, large vessels are not as adversely affected as small. Lightweight concrete may be used advantageously because the thickness of hull and bulkheads is usually determined by cover requirements for reinforcement and tendons and by rigidity requirements, rather than by strength.

Spalling under local impact may be minimized by using closely-spaced reinforcement near the outer face. This may be in the form of mesh. Galvanized mesh should be considered because of the reduced cover required for the steel. In the USSR, research has been conducted on the use of a mesh made of glass fibers.

The slightly greater drag coefficient of moving water over concrete reported by some observers may be minimized by casting the vessel's skin against steel or fiber glass reinforced plastic forms, and by thorough consolidation of a dense concrete mix.

DESIGN AND CONSTRUCTION OF OCEAN STRUCTURES

The design of prestressed concrete ocean structures must consider the dynamic loadings and stress reversals due to waves. Natural waves are complex, with local seas superimposed on one or more sets of swells. This usually results in less severe over-all structural demands than are indicated by the regular waves of a typical model testing basin; however, local effects may be intensified.

Storage vessels must be designed for the differential operating pressures during loading and unloading. The effect of marine growth on drag and weight must also be considered, as must the effect of ice accumulation.

Since stresses during launching

and installation usually differ from those occurring in service, and may be larger, design must be integrated with construction and must consider all phases from launching to towing to installation and final service.

Stresses in ocean vessels and structures are usually multiaxial. Many vessels and tanks behave, at least partially, as shells. Shell action may be utilized very effectively, and a symposium of the International Association of Shell Structures is to be held in Hawaii in 1971 to examine the use of polyhedrons and shells for underwater use.

To resist tensile stresses in these vessels under static, operating, and sea conditions, multiaxial prestress is usually employed. The confining effect of the sea pressure may be used for permanently submerged structures.

For deep installations, research at the Naval Civil Engineering Laboratory at Port Hueneme, California, has shown that concrete is suitable for spheres at pressures equivalent to several thousand feet of depth, that relatively small penetrations such as windows do not reduce over-all strength, and that the sphere's resistance is very sensitive to the thickness-to-diameter ratio and to variations in out-of-roundness tolerances.

High strength concrete appears to be particularly suited for deep submergence structures. It offers not only superior compressive strength but also the ability to prestress to a higher degree.

Lightweight concrete. Structural lightweight concrete made from expanded shale, slate, or clay aggregates was used extensively in building concrete ships in both World Wars I and II and gave excellent service, especially in durability and resistance to abrasion and fatigue. Structural lightweight aggregate concrete is available in strengths from 350 to 450 kg/cm^2 (5000 to 6500 psi) with densities in the range of 1600 to 1800 kg/m^3 (100 to 112 $lb./ft.^3$). Properly proportioned and placed, it is impermeable and gives full protection to tendons and reinforcement. Air entrainment should always be used with structural lightweight concrete. Its behavior under prestress and the special precautions required were presented in the report of the FIP Commission on Prestressed Lightweight Concrete at Paris in 1966.

Segmental construction. Segmental construction methods offer an opportunity to utilize high quality concrete and close tolerance elements effectively and economically in floating and submerged construction (Fig. 3). The practice follows general trends in segmental construction of bridges. Segments may be manufactured in their most advantageous position for forming and concreting, then placed in a basin or on a ways for final connection prior to floating. This permits pretensioning in one or two directions, with subsequent longitudinal post-tensioning.

Joints are of course of prime concern. Concreted joints, with or without mild reinforcing steel, and pressure-injected epoxy joints are alternative answers. Joint faces on adjacent units must be cast to reasonably close tolerances, cleaned of laitance, and roughened by sandblasting or bush-hammering. With concreted joints, an epoxy bonding compound is desirable. Shrinkage in the joint concrete should be prevented by use of a minimum-shrinkage mix (perhaps using shrinkage-compensating cement) and thorough curing. It is usually not practical to

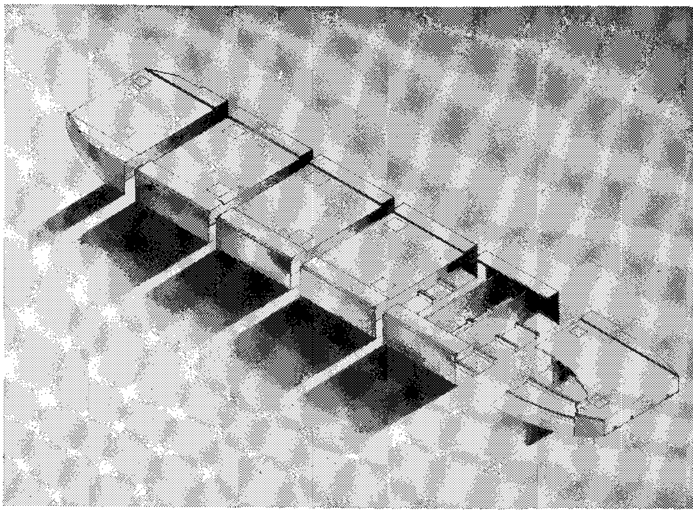

Fig. 3. Segmental construction of prestressed concrete barges (USSR)

introduce a slight degree of prestress across the joints shortly after final set; where this can be done, it will of course overcome shrinkage strains.

Larger segments—subassembled units possessing flotation in themselves—may be floated into a dry dock, positioned accurately with respect to their neighboring units, the joints concreted, and the whole post-tensioned. The same principle may be applied to the units afloat, provided a seal is established to permit evacuation of the water between the joints, and provided the units are temporarily secured relative to one another to prevent differential movement. This latter may be accomplished by external structural frames or by blocking and bolting in calm water. Such a joining-afloat procedure was recently used to weld together the two halves of a 250,000 ton steel tanker hull; it is obviously equally adaptable to concrete.

Forming afloat. For units which are concreted afloat, several methods of forming are practiced. Slip forms have been used to raise the walls of floating caissons. This procedure requires continuous slip-forming, reinforcement and duct placement, and concreting. Obviously, such a complex operation must be well organized, particularly because of the over-water transport of men and materials. Accurate and effective means must be provided for maintaining and extending the vertical axis since this will sway out of vertical due to weight imbalance, wind, and waves. Salt water must be kept off of reinforcement. The fresh concrete must be adequately cured and the surface sealed before it is submerged.

Slip forming inherently produces tensile strains in the external surface. The effect of these can be minimized by good slip forming practice, by adequate curing, and by sealing.

Panel forming has long been used successfully for concreting caissons afloat. The panels are jumped up progressively as extensions to the previously cast walls. This sequence permits the checking of alignment, and insures time for the proper placement of reinforcement and tendons in relatively rapid sequence. The external panel forms may be designed to serve as wave and splash protectors for the fresh lift of concrete.

The disadvantages of panel forming are the horizontal construction joints. A waterstop has frequently been employed. With or without a waterstop, the construction joint should be cleaned by an air-water jet while the concrete is green, or by sandblasting or bush-hammering later, then painted with an epoxy bonding compound. Special care should be taken to vibrate the bottom of each succeeding lift.

Thin precast concrete panels may be set as exterior forms which remain as part of the finished structure. These panels are highly durable and give excellent protection to the green concrete as it passes below water. Their joints can be made waterproof with an epoxy or similar jointing compound. The construction joint in the cast-in-place concrete should be at mid-height of an external panel.

Tendon protection. The ends of both pretensioned and post-tensioned tendons require protection from salt air and salt water. Ends or anchorages should be recessed, an epoxy applied to the exposed steel, an epoxy bonding compound applied to the pocket concrete, and the pocket filled with non-shrinking or low-shrinkage mortar. Epoxy mortar can also be used.

Coatings and liners. Coatings and liners such as bitumastic coatings, epoxy coatings, and mild steel liners or shells are used extensively with floating and submerged structures. The bitumastic coating has often been protected against abrasion by treated timber lagging.

Advantages of thin steel shells depend on the environment. As the liner of an oil storage vessel, they form a liquid- or gas-tight membrane, and can serve as an internal form. An external steel shell is subject to corrosion which is so serious as to render it almost impractical for service at the water line and in the splash zone. However, a steel shell may be entirely suitable for deeply submerged structures, especially if painted and given cathodic protection. In Arctic environments, corrosion is reduced, and the external steel shell may provide armor against ice abrasion.

Such steel liners and shells are ductile membranes. Various forms of glass-fiber wrapping, bitumastic, and epoxy coatings are also efficient ductile membranes.

While liners and coatings may be justified or desirable in highly important and critical structures, most floating and submerged structures rely on the impermeability and integrity of the concrete itself. When prestressed on one or more axes, cracking is inhibited. Many experts feel that it is more effective to pay attention to the concrete mix and placement, and the reinforcement details and prestressing, than to cover up potential defects with coatings and liners.

Ferro-cement. Ferro-cement has been successfully employed for many years for small boats and barges. Ferro-cement can be used with prestressing to permit thinner-walled structures, double-curvature, and to provide resistance to local impact and collision. Ferro-cement shell walls can often be effectively combined with prestressed ribs.

LAUNCHING AND INSTALLATION

Floating and submerged structures of prestressed concrete are inherently large, even mammoth in scale. The segments for La Fontaine subaqueous vehicular tube at Montreal weighed 30,000 tons and were over 100 m (330 ft.) long. It is therefore necessary that plans for launching and installation be thoroughly integrated with the design and construction aspects. A review of past practices employed with similarly-sized concrete and steel structures and vessels for ocean use may serve as a guide and also as a stimulus to even more ingenious and efficient means. Several successful assembly and launching means are listed in the following paragraphs.

Launching ways permit the structure or vessel to be assembled in the dry and slid down the ways to float in the water. The ways must be strong enough to take the concentrated loads involved and to provide necessary structural support to the unit being launched.

Tidal launching has been efficiently used for concrete barges and caissons. The unit is constructed on a tidal flat, and floated off at high tide. During construction, the fresh concrete must be protected from salt water.

Dry docks and graving docks are quite suitable for the construction of floating structures of concrete and steel, but their daily costs are very high and access for construction is usually severely restricted. These problems can be minimized if large sub-assemblies are manufactured elsewhere, and brought to the dry dock for final assembly, jointing, and post-tensioning.

Basins formed behind levees or dikes have been widely used for the manufacture of subaqueous tunnel sections. When the structure is completed, the basin is flooded, the dike breached, and the unit floated out.

Many sizeable concrete structures up to 500 tons in weight have been built on a *platform,* then lowered by jacking. Such a procedure allows re-use of the soffit base, and can be efficient and economical when multiple usage is required.

Concrete barges, caissons, and anchors have been built on *support barges,* then launched by flooding the support barge. As the deck of the support barge passes below water, stability is lost and the structure is launched sidewise, placing a concentrated load on the barge sides and on the structure. Means of controlling the support barge must be provided, either by launching in shallow water, or by columns, guides, or winches, or by pulling down under positive buoyancy.

Sand jacking consists of building a structure on sand, then jetting, washing, dredging, and air-lifting to progressively lower it to flotation depth. The structure must be strong enough to span across the variations in support conditions during lowering.

Many cylindrical caissons, bridge pier shafts, and large diameter pipelines have been launched by simply *rolling* them down a gently sloping sand or gravel beach. A positive means for simultaneous release of both ends is essential, just as in side launching, to prevent one end from getting ahead of the other.

Successive basins were used with great success on the concrete lighthouse caisson for Kish Bank, Eire, and for the huge steel underwater oil storage dome at Dubai. The initial lifts of the structure are completed on a tidal flat or in a shallow

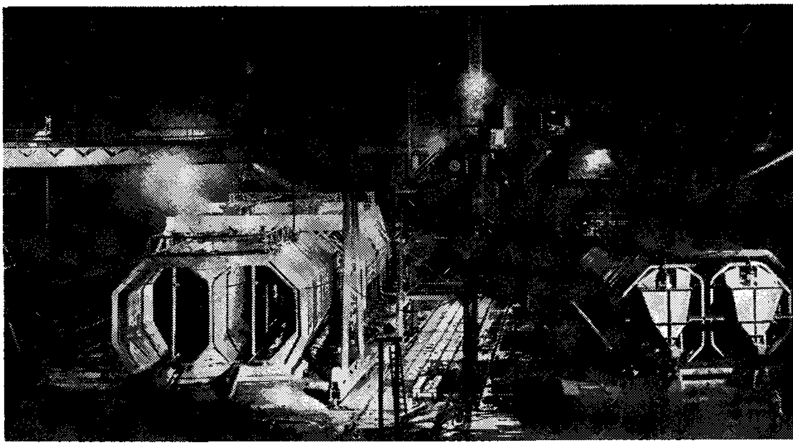

Fig. 4. Tunnel sections for Rotterdam Metro

basin, then the structure is moved and sunk in deeper water (or a deeper basin) for completion and final launching.

Collapsing timber pile platforms have been used for launching caissons in Sweden and barges in Alaska. Their collapse may be caused by side-pull or explosives. This is a highly hazardous method, for any piles which fail to break may punch a hole in the structure and cause it to sink.

Construction afloat, previously mentioned, is highly suitable for caissons and other large structures. During construction, the unit may be kept at the desired working height above water by progressive flooding. A floating or fixed enclosure may be used as a work platform and positioning pen. Once completed, the structure may be upended for towing or installation by controlled flooding.

Structural considerations. The installation of large concrete structures, whether by submerging them to the ocean floor or mooring at sea, requires thorough stability calculations for all phases of the operation. Plans for sinking must be carefully prepared in every detail, the crew trained and rehearsed, and the operation properly supervised.

Units may be assembled on the bottom or ocean floor. By means of guides and judicious location of sheaves, a second unit may be positioned in close contact with the first. Rubber bumpers, serving also as gaskets, may be used to cushion the impact and seal the joint. Dewatering of the joint space then makes available a tremendous hydrostatic force for final seating. This procedure was used on the Rotterdam Metro tunnel (Fig. 4).

Massive units such as these possess great inertia during sinking. It is best to have either a definitely positive or definitely negative buoyancy during lowering; near equilibrium, the structure may prove unmanageable. Water densities increase with depth due to salt and silt content and decrease near the bottom due to the Venturi effect of bottom currents. Actual concrete weight must be checked afloat, as even minor variations in wall thickness, for example, may increase the weight by 100 tons or more.

A number of structures, such as outfall pipelines, have been prejoined in relatively long sections by prestressing and then towed to location for final installation as a unit. In New Zealand, such ocean pipelines have been joined in lengths of 300 m (1000 ft.) or more and pulled or sunk in position like steel pipelines, utilizing the flexibility of the overall pipeline.

The assembly afloat of sub-units was discussed as a means of manufacture. It is also suitable for the assembly of large units into over-all structures, such as ocean platforms or bases or over-water airports. Since hydrostatic pressures at shallow depths are relatively ineffective for seating one unit against another, positive means of seating, such as prestressing, must be employed. Rigid joints may be filled with pumped grout or under-water-setting epoxy mortar. Articulated joints must be detailed for proper shear transfer and to prevent spalling of the concrete. The protection of tendons across such an articulated joint requires very thorough study and detailing to positively ensure against corrosion, fatigue, and pinching, during violent wave action. Failure to properly design the articulated joints led to replacement of one major floating bridge (at Hobart, Tasmania) and to the complete reconstruction of another (Hood Canal Bridge, Washington).

Pulling down against positive buoyancy is an installation method which permits excellent control. Reactions must be provided on the ocean floor; these may consist of large concrete weights, driven or drilled-in-and-grouted piles, or prestressed anchors. Pulling down also facilitates pulling into lateral position.

Up-ending of units for installation should always be checked by model tests as well as calculations. The bending moments, secondary rotations, and inertial effects are thus more readily visualized.

For the launching and installation of large and important structures, full employment should be made of the sophisticated instrumentation, including underwater television and position and slope indicators, which have been developed by the offshore oil industry.

SPECIFIC APPLICATIONS

It is of interest to examine a few existing and proposed projects in more detail.

For the transport of cryogenic materials, such as liquefied natural gas, prestressed concrete offers the opportunity to eliminate the double hull concept now employed with steel. If lightweight concrete is used, condensation is essentially eliminated. Bulkheads present a potential problem because they are cold on both sides; thus, despite insulation, there will be extreme thermal contraction. Prestressing is one answer. A double bulkhead with air or water space between may be better. This immediately fits into the concept of precast segmental construction.

Semi-submersible and fully submersible vessels base their stability on mass; thus the high unit weight of concrete is no detriment. Durability and freedom from maintenance assume high priority because

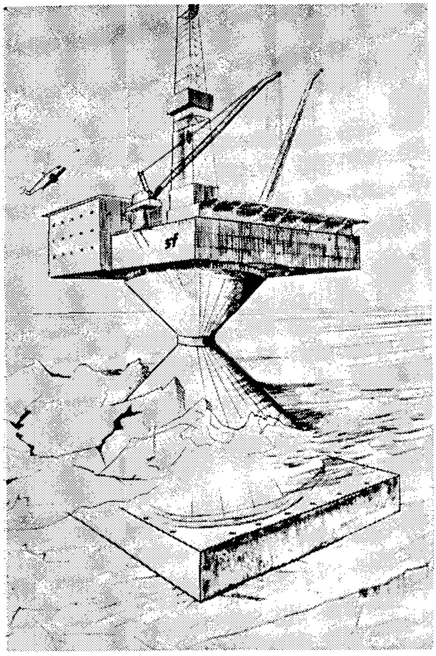

Fig. 5. Proposed deep-water drilling structure of prestressed concrete for Arctic Ocean

such vessels are usually of a size, depth, or shape that precludes docking.

The Arctic Ocean has suddenly become a forefront of exploration and development as a result of the vast petroleum and mineral reserves believed to lie beneath its perpetual ice and around its shores. Water temperatures of –2C (28F), air temperatures of –45C (–50F) and ice pressures equivalent to 22 kg/cm^2 (310 psi) for a depth of 2 to 3 m (6½ to 10 ft.) are the design criteria. The failure cycle of ice in compression approximates the natural period of structures of the size under consideration. For such service, concrete and especially prestressed concrete offer outstanding advantages. A number of important prestressed concrete structures, the first to be built of any material in the Arctic Ocean, are now under detailed design (Fig. 5). The concept is to construct them as floating structures in warm water ports, then tow them to the Arctic Ocean and sink them in location, using gravity fill or drilled-in piling to hold them in position.

Many studies have indicated that large hulled vessels and ships, such as tankers and ore-carriers, could beneficially be constructed of prestressed concrete. The current revolution in ship design favors such a development; hulls are becoming more massive and the skin surface-to-volume ratio is decreasing radically.

Underwater and floating oil storage is another field in which prestressed concrete appears to offer significant advantages. The large sizes, the need for economy and durability, the favorable behavior under accident, and the weight or mass of the vessel all tend to favor the use of prestressed concrete. A number of concepts have been designed in full detail and are now actively competing in the world market for offshore oil storage (Fig. 6).

The firm of Brown and Root has developed and successfully used prestressed concrete techniques to repair and strengthen existing offshore platforms. The steel tubular members are pumped full of very high strength grout to restore compression value, and are post-tensioned through the joints to restore tension value. This work is performed underwater. Such a technique would appear to offer potential value for new construction as well as reconstruction; since the wave forces are proportional to the member's size (virtual mass and drag), this would provide increased working strength in smaller members.

There is considerable publicity worldwide concerning offshore floating airports. Some of the concepts involve relatively shallow barge-type structures, protected from severe wave action by floating breakwaters whose width is proportioned to the wave-length. Other concepts use the column-stabilizing principle of a structural platform resting on deep floating columns, perhaps 120 m (380 ft.) deep and 7 m (23 ft.) in diameter. Prestressing is essential for joining such large area structures to make them act as a flexible whole.

RESEARCH AND DEVELOPMENT

This entire concept of the use of prestressed concrete in the oceans is expanding so rapidly that the needs for research and development are immense. We are just beginning to comprehend how much we do not know and how much of what we do know is erroneous or incomplete.

Perhaps the most exciting area for research and development is in the use of polymers. Cured and dried concrete is saturated with a monomer such as methyl methacrylate, then subjected to irradiation by cobalt 60 or a thermal-catalytic process to polymerize it. The polymer fills the interstices between the cement grains, making the concrete more impermeable, more abrasion and freeze-thaw resistant, and stronger in both compression and tension. Current studies are directed toward an attempt to include the monomer in the concrete mix itself.

Further research is needed in the combination of ferro-cement with prestressing; in the use of glass fiber cloth to prevent localized damage and inhibit the initiation of tensile cracking; in underwater connections, including concreting materials and post-tensioning details; in the seismic response of underwater and floating concrete vessels; in the effect of shape and particularly size in relation to wave length of large underwater structures such as oil storage vessels; and of the actual behavior of concrete shapes under the triaxial loading conditions that exist in service.

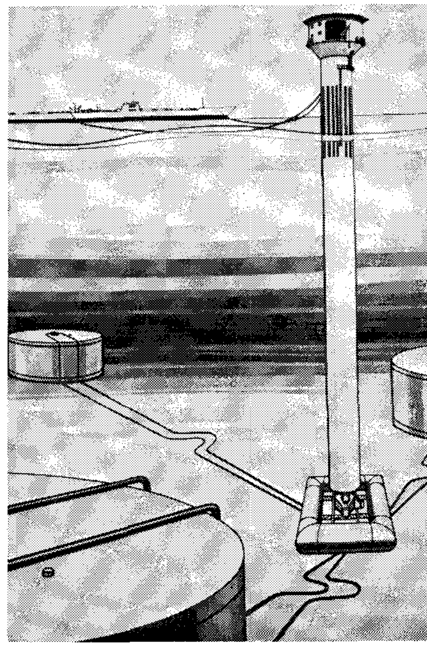

Fig. 6. Proposed prestressed concrete underwater oil storage system

CONCLUSIONS

The oceans offer to mankind a vast resource of food, minerals, power, and water. Yet the oceans are an extremely hostile environment. The practicable and economical extraction of their resources requires structural materials and techniques especially suited to the service required and the environment anticipated. Prestressed concrete and the concept of prestressing appear to be uniquely well-adapted to this need. Civil and structural engineers recognize this, but they alone cannot effect the required change in present concepts. The message must be carried to the naval architect, to the planners, and to the ultimate users. One of the principal reasons why concrete has so far failed to achieve universal acceptance for ocean usage appears to be the lack of a viable concrete shipbuilding industry. The steel shipbuilding industry has a wealth of technical, albeit mainly empirical, knowledge, and a highly refined naval engineering capability. It is our job, both as individual engineers and as the technical body of FIP, to develop a corresponding capability in this field.

The conventional ship of today evolved from man's first canoe, with changes in power from oar to sail to steam to motor, but not in basic seakeeping shape. Suddenly ships, storage vessels, and terminals are breaking through the wave-length barrier, as airplanes are breaking the sonic barrier. Dimensions are now large in relation to wave-length, and vessel response is completely changed. The submersible and semi-submersible units are utilizing mass and inertia to counter vessel response. This is a whole new world in naval architecture, and prestressed concrete has matured technically at just the right time to meet the opportunity and the need.

As early as 1954, Monsieur Freyssinet, the first president of FIP, predicted just such a development. He said: "Transport by water will, like the others, also be transformed by the employment of prestressed structures. Locks, quays, cofferdams will utilize prestressing in both its forms. But it is our ships and our ports which will experience the most astonishing evolution. It will enable us to build ships of such dimensions that the longest waves will only be a choppy sea to them. . . . Floating islands will thus be made, carrying prodigious machinery for extracting precious minerals from the depths of the sea."

What Freyssinet foresaw is today on the verge of reality. The awakening interest in the oceans and their riches has presented the need. Prestressed concrete is available to meet the challenge, provided that we adequately develop the necessary technical and industrial capabilities.

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