Analysis and Design of Floating Prestressed Concrete Structures in Shallow Waters

Jiang, D.[1], Tan, K.H.[2], Wang, C.M.[3], Ong, K.C.G[4], Bra H.[5], Jin, J.[6], and Kim, M.O.[7].

ABSTRACT

Prestressed concrete floating structures have been used for over a century with notable success in various parts of the world. However, there still exist issues related to the analysis and design, and the service performance of concrete floating structures. This paper highlights the design concepts, material behavior, analysis approaches and structural systems for floating prestressed concrete structures deployed in shallow waters. Material and design requirements related to prestressed concrete floating structures in particular are reviewed and potential technical challenges are identified. Moreover, some recommendations and suggestions are summarized as a guide for future practice.

Keywords: Analysis and Design; Floating Structures; Prestressed Concrete; Shallow Waters.

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[1] Research Fellow, Dept. of Civil & Env. Engrg., National University of Singapore, Singapore
[2] Professor, Dept. of Civil & Env. Engrg., National University of Singapore, Singapore
[3] Professor, School of Civil Engrg., The University of Queensland, St Lucia, Queensland, Australia
[4] Associate Professor, Dept. of Civil & Env. Engrg., National University of Singapore, Singapore
[5] Civil Engineer, Norconsult, Trondheim, Norway
[6] Research Scientist, SINTEF Ocean, Trondheim, Norway
[7] Research Fellow, Dept. of Civil & Env. Engrg., National University of Singapore, Singapore

1. BACKGROUND

The use of concrete in floating structures dates back to the early twentieth century. The first reinforced concrete sailing vessel, *Namsenfjord*, was built in Norway in 1917 [1]. Subsequently, hundreds of concrete ships were built in the first and second world wars due to the shortage of steel. In particular, two vessels were constructed of prestressed concrete (PC) precast cellular modules during World War II [2]. In the late 1950s, some ocean-going barges made of pre-tensioned concrete were designed and constructed in the Philippines. In 1975, the world's first large PC floating liquefied petroleum gas (LPG) storage vessel was constructed and deployed in Java Sea [3]. The vessel hull was designed and constructed as a post-tensioned concrete segmental structure to carry twelve independent steel tanks with a total capacity of 375,000 barrels. As the largest existing PC floating barge in the world, N'Kossa Oil Production Unit, was constructed in 1996 off the coast of Congo. It measures 220 m in length, 46 m in width and 16 m in depth. The N'Kossa barge has successfully operated on site without interruption for 20 years [4, 5]. In 2002, the world's largest concrete floating dike, 352 m long and 28 m wide, was installed in Monaco harbor, which serves as a breakwater as well as a cruiser terminal. It was built in a 15 m deep dry dock and towed to Monaco for installation. It is expected to fulfill its functions for 120 years [6].

For the purpose of oil exploration and production, the first major base-supported concrete offshore structure, Ekofisk tank, was installed in 1973 in the North Sea. Since then, more than 40 concrete fixed offshore platforms have been built in the North Sea, the Gulf of Mexico and West

Africa [7]. These offshore concrete platforms have performed extremely well in the seawater environment with little maintenance. In 1995, an innovative type of floating concrete platform structure, known as tension-leg platform (TLP), was first installed at the Heidrun field of the North Sea at a water depth of 345 m. In the same period, Troll Oje's floating platform, a semi-submerged concrete hull anchored by catenary moorings, was also built in the deep waters of the North Sea.

For some metropolis with coastal areas, such as Singapore, Shanghai and Tokyo, there is a need for usable space expansion to address the issue of land scarcity in an urban setting. Previous experience shows that land reclamation and the use of floating structures are two main options to increase usable space to accommodate industry facilities, habitation and infrastructure as the city grows and develops. Compared to land reclamation, floating structures are preferred because they are more environmental friendly and require less construction costs, especially when the water depth is large and the seabed is soft.

Most existing floating concrete structures have been located in deep seawater area, and may not be suitable or appropriate for shallower coastal areas. Figure 1 presents two floating concrete piers located in shallow coastal areas. According to previous engineering experiences, one major difference between floating structures in deep and shallow seawater areas is in the mooring system, whose function is to keep the structure in position and prevent it from drifting under critical sea conditions [8]. As compared to conventional mooring systems, like chain/cable, tension leg and others, the dolphin - fender system (Figure 2 (a)) is more suitable for floating structures in shallow waters because it can effectively restrict the lateral motions [9]. The dolphin

- fender mooring system was first adopted in the two floating oil storage bases at Kamigoto and Shirashima islands in Japan, and has since been used for other facilities [10, 11]. Figures 2 (b) and (c) show practical lateral and roller fenders installed at the interfaces between the dolphin and floating structure, which are able to undergo large deformations and absorb kinetic energy of floating structures [9]. When the topside is to be installed on the substructure, the intersection should be carefully designed to take account of interface shear forces. Given that floating structures often undergo relatively larger displacement than fixed structures, it is preferable that the topside structure can be de-coupled from the floating substructure's deformation. Due to the lack of documented interface configurations from existing concrete floating structures, engineering solutions from FPSO can be referred herein and they include the use of: (1) multiple snipped column supports; and (2) supporting stools fitted with roller and sliding joints or elastomeric pads [12, 13].

This paper provides a critical review of the design considerations and requirements pertaining to materials and analyses for general purpose floating concrete structures. Issues pertaining to PC floating structures deployed in shallow waters are highlighted, and some recommendations are made.

1.1 Characteristics of PC Structures in Seawater Environment

Marine structures have been built of iron-and-steel for more than a century due to historical reasons. However, engineering experience shows that, when properly designed and constructed under strict quality control, prestressed concrete may be a preferred material over steel for floating structures because of its excellent durability and corrosion resistance [3]. The advantages of prestressed concrete over steel in the seawater environment have been recognized by many researchers [14-16], among which the main ones are:

(a) the use of concrete material generally results in a lower initial construction cost;

(b) large structures can be assembled with precast components integrated by post-tensioning tendons and cast-in-place (CIP) joints, leading to easier construction;

(c) the concrete shows superior durability in seawater environment, which reduce the costs for maintenance, inspection and repair;

(d) concrete structures result in reduced damages caused by fatigue-type loadings;

(e) concrete structures have larger local and global stiffnesses, and show superior performance in withstanding accidental impact loads;

(f) with proper mix design, high-performance concrete shows excellent corrosion resistance; moreover, prestressing keeps the concrete in compression, which improves water tightness and limit crack formation in the structural members; and

(g) concrete structures have superior thermal insulating and fire resistance properties.

1.2 Special Design Considerations for Floating Structures

The application of concrete to floating structures in the seawater environment usually requires more extensive considerations than typical land-based concrete structures due to different loading conditions and environmental situations [17-19]. Some special considerations are as follows:

(a) the self-weight of floating structures are automatically balanced by the buoyancy force, and there is no need for massive and expensive supporting foundations;

(b) sizing of the floating structures depends on the function and environmental conditions, such as current, wave and wind; the design may be dominated by peak loads from permanent and variable actions or by fatigue strength due to cyclic environmental loads;

(c) possible accidental events need to be considered in design, such as vessel collision and explosion, to ensure overall safety;

(d) unlike land-based constructions with their foundations poured in place, floating structures are often constructed at shore-based sites remote from the installation site; forces during construction and towing may impose different stresses than those encountered by the structural elements when in service; and

(e) owing to the corrosive sea environment, floating structures have to be provided with a good steel corrosion protection system.

1.3 Design Guidelines

The design of floating PC structures should follow rules and regulations for general concrete structures laid down by government authorities and classification societies [20]. Although no specific design codes and standards are found for PC floating structures, relevant design philosophy and criteria for offshore concrete structures can be referred to. In particular, the American Concrete Institute (ACI) Committee 357 has published a report on floating and float-in concrete structures, which can be considered as a design guide [2]. Other guidelines such as EN 1992 Eurocode 2: Design of Concrete Structures [21], Canadian standard CSA S474 Concrete

Structures [22], DNV-OS-C502 Offshore Concrete Structures [23], DNV-OS-C503 Concrete LNG Terminal Structures and Containment Systems [24], ISO 19903 Fixed Concrete Offshore Structures [25], OTG-02 Floating Liquefied Gas Terminals [26] and Japanese Floating Bridge Design Specifications (JFBDS) [27] also provide useful information.

2. MATERIALS

Materials used in floating PC structures should provide the required performance during the construction, service and operation phases throughout the prescribed design life of the structure.

2.1 Concrete

The material requirements vary with the environmental conditions in which floating PC structures are constructed. According to EN 1992, exposure class XS3 is applicable for structural members in the tidal, splash and spray zones, and should generally be adjusted accordingly for floating concrete structures in coastal areas [21]. This exposure class requires the choice of adequately durable concrete for corrosion protection of reinforcing and prestressing steels. In general, the concrete should have adequate strength for the purpose of prestressing and installation. It should be of a sufficiently low density so as to facilitate buoyancy of the structure and to carry a higher payload. Thus, the concrete mixture proportions for general-use floating structures must be tailored to meet the specific requirements of density, strength and durability. As for floating fuel storage and production structures, special requirements of fire-resistance should also be taken into consideration. In addition, the prevention of pollution needs to be carefully handled in accordance with MARPOL Rules [28].

2.1.1 Concrete Density and Strength

Both Normal Weight Concrete (NWC) and Light Weight Aggregate Concrete (LWAC) can be used in floating PC structures. LWAC is made with lightweight aggregates having a density of 20-35% less than NWC. In order to achieve weight reduction and a shallower draft, LWAC with a density lower than 2000 kg/m^3 is recommended. In some situations, it may be beneficial to use NWC in the lower portion and LWAC in the upper portion of floating structures in order to lower the center of gravity and consequently improve the stability of the structure. Alternatively, Modified Normal Density Concrete (MNDC) produced by partly replacing the natural coarse aggregates with high-quality structural lightweight aggregates can serve as a compromised material option for floating structures. In-situ MNDC products with a reduced density of 2250 kg/m^3 and satisfactory mechanical properties equal to NWC have been successfully achieved and applied in existing engineering practices, such as in the Hibernia Concrete Platform, Troll GBS Platform and others [29, 30].

The required concrete mix and strength shall be established based on the aggressiveness of environment and the design service life as well as for the purpose of introducing prestress. The service life of floating concrete structures is generally expected to be between 50 and 100 years with preferably a low maintenance cost. Table 1 lists the minimum concrete strength classes specified in various codes and standards for PC structures in seawater environment. Specifically, EN 1992 requires a minimum concrete cylinder compressive strength, $f_c^{'}$, of 45 MPa (6,500 psi) for concrete structures with a design working life of 100 years in the seawater environment. It is worth mentioning that common values of compressive strength, $f_c^{'}$, used for PC structures in the United States are between 35 and 70 MPa [31].

Significant progress has been achieved in the development of high strength LWAC, thus placing concrete in a more competitive position as a material for floating structures. In the engineering practice, compressive strengths of 83 MPa (12,000 psi) and 62 MPa (9,000 psi) are normally achievable for NWC and LWAC [2]. High-strength LWAC can now be economically produced by ready-mix concrete suppliers, and it can therefore be supplied for the construction of floating structures.

The relationship between density and compressive strength for both NWC and LWAC has been investigated by many researchers [32-34]. Figure 3(a) shows that the compressive strength of NWC increases with density, but a relatively large variation exists in the relation. As for LWAC, the compressive strength is highly dependent on the type of lightweight coarse aggregates used. Figure 3(b) shows a positive correlation between these two properties for different types of LWAC. Because of the higher aggregate strength, expanded clay, slate, shale are commonly utilized for lightweight concrete structures. Careful selection of the lightweight aggregate is important to ensure that the desired compressive strength could be achieved.

2.1.2 Durability

As one of the key characteristics, durability is essential to ensure the functionality of floating concrete structures in expected exposure environments throughout their required service life. Although a minimum level of compressive strength is commonly required in structural design, it should be noted that compressive strength cannot be considered as a surrogate test to ensure durable concrete [35]. While there may be a general trend that both properties improve in the same direction, no evidently positive correlation was observed between compressive strength and durability [36-38]. Concrete that meets only the strength requirement may fail to develop the expected durability. Different mixture proportions, consolidation practices, curing techniques and other aspects may produce concrete with similar strengths but different durability levels. Therefore, appropriate quality control system and corresponding practices throughout the full process, including mixture design, structural layout and construction process, are essential to the production of high quality durable concrete products.

The concrete durability is influenced by various deterioration mechanisms in different environmental conditions, including chloride ingress, alkali-aggregate reaction, sulfate attack, carbonation, abrasion and others. According to existing engineering practices, for the severe sea environment, especially in the spray and tidal zones, the deterioration of floating structures arising from chloride-induced corrosion of the reinforcing and prestressing steels is a main cause of concern [39]. By proper mixture proportioning, concretes with low permeability and low seawater reactivity can be used to alleviate this problem. To achieve this, a low water to cementitious material ratio (*w*/*cm*) coupled with the addition of silica fume and/or fly ash can effectively reduce the permeability of concrete and improve chloride penetration resistance [40, 41]. For concrete made with *w*/*cm* of 0.40 and 0.50, chloride-ion permeability increases to approximately 4 to 6 times greater than that for concrete made with *w*/*cm* of 0.32 [42]. A desirable low *w*/*cm* value (0.40 maximum) is specified by ACI Committee 357 for fixed offshore concrete structures in splash zones [43]. Similarly, the Norwegian Public Roads Administration set an upper level of *w*/*cm* value of 0.38 for the most exposed parts of the bridges in marine environments [44]. ACI reported that fly ash is typically added to concrete mixture in amounts of 10 to 30% by mass of cement in large marine structures to improve the resistance against chloride-induced corrosion [42]. The use of silica fume works in several ways to reduce the risk of corrosion [45-47]. Figures 4(a) and 4(b) show a decrease in chloride penetration with silica fume replacement. Silica fume is known to enhance concrete durability by lowering the chloride diffusion coefficients, and a low level of silica fume replacement could reduce the diffusion values rapidly [48].

Also, the provision of sufficient concrete cover for reinforcing and prestressing steel would establish a barrier against the seawater environment, which helps to improve durability of the structure. Significant research studies indicated that 25 mm concrete cover is inadequate for chloride protection of steel reinforcements, even if the *w*/*cm* value is as low as 0.30. Experimental tests also show that chloride ingress reaches to a depth of 50 mm, and the chloride content can be very high in the outer 12 mm, even in high-quality concrete [49, 50]. Van Daveer and Sheret recommended that a design nominal cover of at least 65 mm over reinforcing steel be provided while Kjaer suggested that typical concrete cover should be 75 mm to reduce the likelihood of corrosion in chloride environments [51, 52].

Table 2 lists the minimum concrete cover specified by various codes and standards for PC structures in seawater environment, where, in particular, EN 1992 designates a minimum concrete cover of 45 mm and 55 mm for reinforcing and prestressing steels, respectively. According to the requirements specified in DNV-OS-C502, the concrete cover shall not be less than 70 mm for 100-year design lifetime in tidal, splash and spray zones. Moreover, ISO 19903 indicates that a minimum of 50 mm and 90 mm is adequate as concrete cover to reinforcing steels and prestressing tendons, respectively. Herein, it is recommended to adopt 50 mm and 70 mm as the minimum concrete cover for reinforcing and prestressing steels without the consideration of construction tolerances. However, when concrete with low-permeability and high chloride penetration resistance is used, a reduction in concrete cover may be allowed in design.

When it comes to the durability performance of floating concrete structures in practice, engineers should not rely solely on appropriate mixture proportion and concrete cover. Good quality control related to operation and construction phases should also be ensured, including workmanship, curing and other aspects. For instance, proper consolidation practices are vital to avoid segregation and honeycombing in concrete, which can help to secure uniform concrete with low permeability [42]. Besides, the hydration of the cement can be enhanced with good curing, which is also beneficial in reducing permeability. Acker reported that excessive early thermal stresses should be carefully handled to prevent initial crack formation [55]. ACI suggests that it is necessary to specify a minimum of 7-day uninterrupted moist-curing or membrane-curing. Furthermore, long-term inspections on in-service floating structures are useful to monitor the concrete durability performance and detect the level of deterioration, which will provide engineers with clues on the necessity of remedial works.

2.1.3 Discussion

LWAC may offer the following advantages over NWC in improving the serviceability of floating structures in seawater environment: (a) its low density helps to decrease the draft and bring extra buoyancy for imposed loads; (b) it provides a higher resistance to micro-cracking due to the reduced modulus of elasticity (MOE) of the aggregates; (c) it leads to lower stress as caused by creep and shrinkage; and (d) it is expected to have higher fire resistance because of a lower thermal conductivity and coefficient of thermal expansion [2].

Table 3 shows concrete mix designs for some existing floating structures in Norway, Japan and United States [56-58]. Note that the values for Norwegian floating concrete structures are in terms of cube compressive strength, while cylinder compressive strength are used in Japan and the United States. It is seen that either lightweight fine aggregate or coarse aggregate has been used to reduce the density of concrete. Besides, a relatively low water to cementitious material ratio (*w*/*cm*) was used to give higher compressive strength, where cementitious materials include cement, silica fume and fly ash. Silica fume or fly ash are adopted to improve resistance to chloride penetration. It would thus be challenging to develop a LWAC mix with a density less than 1800 kg/m^3 and compressive strength more than 45 MPa that have adequate durability in seawater environment.

In recent years, great efforts were devoted to exploring unconventional concrete products for use in the marine environment. Geopolymer has attracted considerable attention and is considered to be an alternative to ordinary Portland cement because of its advantageous properties, which include good chemical resistance, low permeability and excellent fire resistance behaviour [59-61]. However, it presents significant challenges to work out generalization of water-geopolymer solids ratio, bond between reinforcement and geopolymer paste, long-term durability behaviour and stable mix designs in the field [62]. Furthermore, it should be noted that no existing floating concrete structures are found to be constructed with geopolymer concrete. In view of this, there is a great need to perform further research studies on geopolymer concrete before applying it in floating structures.

2.2 Reinforcing and Prestressing Steels

The steel reinforcement and prestressing system used for general-purpose floating concrete structures are principally identical to those used in ordinary onshore structures. Reinforcing and prestressing steels should be suitable for the intended service and operation conditions, and have adequate properties and viable detailing layout to comply with the relevant standards.

2.2.1 Steel Grade

While prestressing steel may be used to eliminate most tensile stresses in PC structures, reinforcing steel are still needed as shear reinforcement or supplementary reinforcement in regions subject to high local stresses. Characteristic yield strength values of common steel reinforcement specified in the EN 1992 range from 400 MPa to 600 MPa. In the United States, ASTM standardized properties of reinforcing steel are widely used; and the yield strengths of commonly used steel grades (Grade 40, 50, 60, 75) range from 280 MPa to 520 MPa.

The most common prestressing steel used in the industry is the 7-wire strand with diameters of 12.9 mm or 15.7 mm, which is used either singly for pre-tensioning or in bundles to form multi-strand tendons. Larger post-tensioning tendons comprise 7, 12, 19, 27 or more strands. The tensile strength of the strands typically ranges from 1670 MPa to 1860 MPa, and strands are commonly stressed up to the limit of 75% of ultimate strength during the construction. High-strength bars are available in diameters ranging from 15 mm up to 75 mm, and are used in post-tensioned connection design and some temporary works. The typical minimum ultimate characteristic tensile strength is between 1000 MPa and 1080 MPa in practice [31].

2.2.2 Layout and Detailing

Reinforcing and prestressing steels shall be placed in such a way that casting of concrete will not be obstructed and sufficient bond between the concrete and steels can be achieved. This is facilitated by specifying minimum steel spacing, which are commonly controlled by aggregate size and bar/duct diameter. Table 4 lists the minimum spacing of individual prestressing tendons and ducts as specified in EN 1992 and ACI 318, where ϕ is the bar diameter and d_g is the maximum size of aggregate. Note that values specified in EN 1992 are clear spacing while those in ACI 318 are center-to-center spacing. It can be seen that the effect of concrete strength is considered in ACI 318 to determine the minimum spacing, but the critical parameter, and maximum size of aggregate, are not included. Taking a pre-tensioned concrete beam for example, with $f_c' = 45$ MPa, $d_g = 20$ mm, $d_b = 12.7$ mm, $\phi = 20$ mm, the minimum spacing values determined from EN 1992 and ACI 318 are 40 mm and 44.5 mm, respectively.

2.2.3 Discussion on Corrosion Protection

The corrosion of reinforcing and prestressing steels is a critical issue in the service of floating concrete structures in a seawater environment. An effective method to address the corrosion issue is the application of fusion-bonded epoxy coating. Where the coating adheres tightly to the steel, the epoxy prevents the steel from acting as a cathode to support corrosion at specific locations. Besides, the use of stainless reinforcement is preferred by engineers because it can tolerate chloride levels higher than ordinary carbon steels [63]. Stainless steel does not rely on concrete for its corrosion protection and is a straightforward solution when concrete is subject to the ingress of chlorides from the marine environment, thus a relatively smaller concrete cover value is required in the engineering practice. Some alternative protection approaches, such as galvanic cathodic protection system, impressed current cathodic protection system, chemical corrosion inhibitors and others, can also be utilized to resist corrosion in severe exposure conditions.

2.3 Application of Fiber-reinforced Polymer (FRP)

Fibre-reinforced polymers (FRPs) are composite materials that are made of fibers embedded in polymeric resin. FRP reinforcements have been increasingly used in various structural applications in severe environments as they do not corrode like steel reinforcement. The most common fibres used in FRP reinforcing bars and prestressing cables are glass, carbon and aramid, and more lately, basalt fibres. FRP bars normally have higher tensile strength, but lower Young's modulus, as compared to conventional steel bar and wire. All types of fibres exhibit a linear-elastic behavior under tensile loading up to failure without showing any plastic behavior. Carbon fibre-reinforced polymer (CFRP) bars have relatively higher tensile strength and modulus of elasticity compared to other types of FRP bars.

The durability of different FRP elements in seawater environment has been investigated by many researchers [64-67]. For concrete structures exposed to the seawater environment, it is difficult to distinguish the effects of chloride attack and degradation caused by moisture diffusion of the fibres. In general, CFRP and aramid fibre-reinforced polymer (AFRP) reinforcements are insensitive to chloride ions. Conversely, glass fibre-reinforced polymer (GFRP) reinforcements can be seriously damaged in a marine environment or in the presence of de-icing salts [64]. Burgoyne reported that CFRP bars show little degradation with time when exposed to combined chloride moisture attack, while up to 50% strength and stiffness losses are observed in AFRP and GFRP bars. [68]

Wolff and Miesseler [69] claimed that carbon and glass fibres do not absorb water. On the contrary, water absorption in aramid fibres results in degradation of between 15 and 25% of mechanical characteristics, which includes a reversible decrease in tensile strength and modulus of elasticity and irreversible decrease in fatigue strength [70]. Furthermore, wet/dry cycles in splash zones can cause the swelling of AFRP reinforcement and induce bond cracking. It is inferred that aramid fibres are not suitable for use in a marine environment, despite the low sensitivity to chloride.

ElSafty et al. [71] evaluated the characteristics of prestressing carbon fiber composite cables (CFCC) in severe environment and concluded that CFCC showed excellent performance, maintaining very high guaranteed tensile strength retention and elastic modulus retention after conditioning for over 7,000 hours in an alkaline solution at 60°C. Sen et al. [67] conducted experimental studies to assess the durability of carbon and aramid pretensioned elements in the marine environment. Test results indicated that AFRP is not the ideal candidate for replacing steel in pretensioned elements deployed in tidal waters. When CFRP is used to replace steel in pretensioned elements, driving stresses should be carefully monitored to prevent any damage.

Adequate bond strength between FRP bars and the concrete is required to ensure the satisfactory structural performance. Significant research studies have been performed to investigate the bond behavior between FRP bars and the concrete, and it is observed from a large amount of pullout tests that various key parameters influence the bond performance, such as concrete compressive strength, bar cross section, embedment length and others [72-78]. Okelo reported that the actual pullout of FRP rebars occurs for shorter embedement lengths with higher concrete compressive strength, while the splitting failure mode happens for longer embedment length with lower compressive strength [72]. Smaller diameter FRP bars develop relatively higher bond strengths as compared to larger diameter bars. The bond strength of FRP bars is typically 40 – 100% that of steel rebars for the pullout failure mode. No significant difference is observed between the bond strengths developed by CFRP and GFRP bars, while AFRP bars show slightly lower bond strengths [74].

In view of the above, CFRP shows more favourable behaviours in terms of mechanical characteristics, chloride resistance and anti-moisture compared to GFRP and AFPR. Therefore, CFRP is a preferable substitute for the reinforcing and prestressing steels in general-purpose concrete floating structures. However, mechanical properties, strength and stiffness in particular, of FRP is known to significantly decrease with the increase of temperature [79]. Kumahara reported that 20% reduction of tensile strength occurs in CFRP and GFRP rebars occurs at a temperature of 250°C while the tensile strength reduction of AFRP can reach 60% at the same temperature [80]. Moreover, test results indicated that the bond strength between FRP bars and the concrete decrease by 80 ~ 90% as the temperature increase from 20°C to 250°C, while only 38% reduction of bond strength occurs in ordinary deformed steel bars for the same temperature range [73]. Therefore, the use of FRP may not be suitable where high temperature is of concern, such as in floating fuel storage facilities.

3. ANALYSIS AND DESIGN CONSIDERATIONS

3.1 Design Philosophy

Currently, most codes providing design rules and guidelines for concrete structures are based on the limit state design philosophy, and they can be referred to in the design of floating concrete structures. In general, two limit states, serviceability limit state (SLS) and ultimate limit state (ULS), are specified. Various design situations are taken into consideration, that is, persistent situation in normal use, transient situation under temporary conditions, accidental situation under exceptional conditions (e.g. fire and explosion) and special situation under tsunamic action.

3.2 Action Effects

3.2.1 Actions

Table 5 lists three main categories of actions specified in EN 1990 for common structural designs: permanent (G), variable (Q) and accidental actions (A). For the design of floating concrete structures, environmental loads are predominant among various action effects. Representative actions include: buoyancy, wind loads, wave loads, hydro-dynamic loads induced by waves and currents, wave induced inertia forces and others. Note that floating structures are independent of tidal effects and storm surges. Possible approaches for calculating the environmental loads include a quasi-static procedure and a time- or frequency-domain dynamic procedure [2]. In addition, load effects at the construction and transportation stages, such as launching, towing, erection and equipment installation, also need to be checked.

3.2.2 Combination of Actions

Realistic combinations of permanent, variable and accidental actions shall be taken into account for floating concrete structures, which should be the same as that used in the design of general concrete structures. EN 1990 defines three combinations that may need to be taken into account for designs at SLS, as described by

$$\text{Characteristic Combination: } \sum_{j\geq 1} G_{k,j} \text{"+"} P \text{"+"} Q_{k,1} \text{"+"} \sum_{i>1} \psi_{0,i} Q_{k,i} \tag{1}$$

$$\text{Frequent Combination: } \sum_{j\geq 1} G_{k,j} \text{"+"} P \text{"+"} \psi_{1,1} Q_{k,1} \text{"+"} \sum_{i>1} \psi_{2,i} Q_{k,i} \tag{2}$$

$$\text{Quasi-permanent Combination: } \sum_{j\geq 1} G_{k,j} \text{"+"} P \text{"+"} \sum_{i\geq 1} \psi_{2,i} Q_{k,i} \tag{3}$$

where $G_{k,j}$ is the characteristic value of permanent action j; P is the relevant representative value of prestressing action; $Q_{k,1}$ and $Q_{k,i}$ are the characteristic values of the leading variable action *1* and the accompanying variable action i; ψ_0 ψ_1 and ψ_2 are factors for combination value, frequent value and quasi-permanent value of variable actions.

The characteristic combination and frequent combination are normally used for irreversible and reversible limit states respectively, while the quasi-permanent combination is normally used for long-term effects. The combinations of action effects at ULS are defined according to various design situations and partial factors are specified for various actions. For general prestressed concrete structures, EN 1992 recommends a partial factor value of 1.0 for prestressing forces in persistent and transient design situations. For offshore concrete structures in the marine environment, DNV-OS-C502 and ISO 19903 suggest that the more conservative of 0.9 and 1.1 be used as the partial factor of prestressing forces. Specially for structures with FRP reinforcement, DNV-OS-C502 indicates that more conservative values of 0.9 and 1.2 should be used.

3.3 Analysis Approaches for Floating PC Structures

Compared with general land-based structures, floating concrete structures have no associated foundations, and they interact with the surrounding seawater during the service life. The analysis of floating concrete structures typically comprises a two-step procedure: a global response analysis followed by detailed structural analysis. In the first step, the global response of floating structures and the associated hydrostatic and hydrodynamic pressures are estimated based solely on rigid body (hydrodynamic analysis) or simplified plates (hydro-elastic analysis).

In the second step, detailed structural analysis is performed using the first-step output, and cross-sectional forces and wave forces acting on the floating structures, as input. In this step, a simplified analysis approach or 2D/3D finite element (FE) method may be utilized, and stress distributions are obtained for further design purpose. The global response analysis and detailed structural analysis can be carefully decoupled or integrated, considering different design situations and computational capabilities.

3.3.1 Global Response Analysis

3.3.1.1 Hydrodynamic analysis

For general floating structures whose horizontal dimensions are comparable to its depth, it is permissible to conduct rigid-body hydrodynamic analysis because structural deformations are seldom of a magnitude sufficient to affect the calculation of environmental loading and structural motions. In hydrodynamic pressure estimations, the fluid surrounding the floating structure is often assumed to be inviscid, incompressible and with irrotational motion. Under these assumptions, a fluid velocity potential exists and its spatial derivatives correspond to fluid velocity components. Potential flow theory works generally fine for large volume structures, where the dimension of the structure is comparable or even larger than the dominant wave length. Another condition for applying potential flow theory is that the viscous effect is small and it does not have a significant contribution to the overall hydrodynamic performance of the floating structure.

An illustration of the hydrostatic and hydrodynamic pressure (due to an incoming regular wave only) onto a 2D body at a representative time instant is presented in Figure 5. The length of the arrows represents the magnitude of the pressure. The hydrodynamic pressure due to incoming regular wave is derived based on the known velocity potential of linear regular wave. In reality, one has to consider the hydrodynamic pressure due to the scattering of incoming wave and body motion induced radiation wave, in addition to the hydrodynamic pressure due to incoming wave.

Potential flow theory has certain limitations in practice. For example in shallow waters, one has to evaluate the validity of the potential flow theory. Shallow water condition is defined when the ratio of water depth over the dominant wave length is smaller than 0.05. In shallow water conditions, the horizontal velocity of a fluid particle on the sea bottom is not zero and the horizontal fluid particle velocity on the body surface may still be relatively large as well. Viscous effects becomes important in such a scenario. For some specific tasks, one may have to apply the Navier Stokes equations to solve the fluid motion, while for other tasks, one may still be able to apply potential theory with viscous effect properly considered separately by other means like computational fluid dynamics (CFD) analysis and model tests [81, 82].

Frequency domain hydrodynamic analysis is often performed in the first place due to its relative simplicity. Hydrodynamic forces and motion of the floating structure are solved at each frequency of interest [83]. Fluid velocity potential is governed by the Laplace equation, and the fluid velocity potential on the boundary of the fluid domain can be solved by the Boundary Element Method [84], for example. Once the velocity potential on the body surface is solved, one can obtain the hydrodynamic pressure distribution and further the integrated total forces and moments. John provided the earliest solution to this boundary problem by using the Green's function within a boundary integral formulation to solve for the wave scattering from floating bodies [85, 86]. Wehausen and Laitone [87] published detailed description of the linear wave theory to give benchmark solutions for wave-structure interaction problems. By using the 3D panel code WAMIT, one can easily obtain the fluid velocity potential, hydrodynamic pressure and integrated forces on floating bodies [88]. The boundaries of the fluid domain include the free surface, sea bottom, body surface and far field surface.

The time domain approach is necessary when the transient response or the nonlinear effect is important for the floating structure. As a common approach, by applying Inverse Fourier transform, the frequency domain motion equation of the floating structure in waves is transformed into time domain [89, 90]. Nonlinear force terms can be added to this time domain motion equation directly. The radiation added mass and damping obtained from frequency domain analysis are represented as memory effect function in the time domain. Depending on the nonlinear behavior of the problem under consideration, one may also choose to solve the fluid-structure interaction problem directly in the time domain, skipping the solution in the frequency domain [91]. The approach is often applied to solve strongly nonlinear problems such as slamming and sloshing. In the coupled analysis of the floating structure and its mooring/station keeping system in shallow water condition, time domain analysis is often required due to nonlinear behavior of the coupled system.

3.3.1.2 Hydro-elastic analysis

Depending on the shape of the floating structure, it might be necessary to consider their flexibility/deformation in order to obtain a proper estimation of their response when deployed at sea. An example of this is the thin plate type of floating structure which can be a few hundred meters long and wide in the horizontal plane but only a few meters deep in the vertical direction. In this case, the flexible deformation of the floating structure has to be considered in its hydrodynamic response analysis on the one hand, while on the other hand, the deformation of the floating structure also changes the surrounding fluid motion. Hydroelastic theory needs to be applied in such a circumstance and a certain number of flexible modes in addition to the six rigid body modes have to be considered when solving the fluid velocity potential, hydrodynamic pressure, motion of the floating structures in wave and others [92]. The load effect due to this type of fluid-structure interaction is termed hydro-elastic load, which is important in design. Hydro-elastic analysis is thus necessary for the design of plate-type floating structures in order to assess the dynamic motion and stresses due to wave action. Similar to hydrodynamic analysis, hydro-elastic analysis can be performed in both frequency domain and time domain [93-96]. The frequency domain approach is often used when determining the hydro-elastic response amplitude operator of the floating structure because of its simplicity and ability to capture the pertinent response characters in a steady state condition. A uniform isotropic plate model as well as thin/thick plate theory are generally used for hydro-elastic response analysis. Such a simple structural model is effective for the determination of global stiffness parameters that fulfil the requirements for serviceability and safety.

For plate-type floating structures constructed in the coastal area, the hydro-elastic response becomes sensitive to the variation in the seabed topography, especially in shallow waters. Under such circumstances, the conventional boundary element method using infinite/finite water depth Green function becomes inappropriate. Various techniques have been developed by researchers to address this problem associated with variable water depth, such as fast multipole algorithm (FMA) [97], localized finite element method (LFEM) [98], finite element method (FEM) [99, 100], Eigen function expansions in conjunction with step-like bottom approximation [101], and local-mode series expansions using coupled-mode technique [102].

For the purpose of reducing the hydro-elastic response of floating plate-type structures, many innovative approaches were proposed for the large floating structures designed in the past decade, such as the use of bottom-founded breakwaters close to floating structures [103], anti-motion devices attached to floating structures [89, 104], pneumatic air-cushion [105, 106], gill cells [107], flexible line connectors [108], and others.

3.3.2 Detailed Structural Analysis

The hydrostatic and hydrodynamic loads derived from waves and structural motions will be used in the structural analysis to obtain detailed structural responses. Although the numerical modeling of the hydrodynamic behavior remains an open problem for both commonly used potential flow models and general CFD codes, on the structural side, the situation is slightly less complex because very efficient numerical tools based on finite element method (FEM) , such as ABAQUS and ANSYS, are available for both quasi-static and dynamic structural problems [109].

3.3.2.1 Simplified Analysis

For a floating structure, the most common loads considered in the design include self-weight, hydrostatic pressure, hydrodynamic pressure from waves, wind load, current load, imposed loads, thermal effects and loads due to towing and construction. All these loads generally have both global and local effects on the structure.

Figure 6 illustrates the simplified analysis approach, in which global and local load effects are considered and superimposed. The approach is more suitable for the analysis of rectangular-shaped floating structures. For the global response, the entire structure is loaded as a beam when it is subjected to non-uniform wave conditions and asymmetric still-water loads. The local responses include stresses and deflections of the structural parts between major support points, that is, bulkheads, side shells and others. They are commonly caused by local hydrostatic and hydrodynamic pressure distribution and cargo loads. As for the simplified analysis approach, global membrane and local bending actions are considered separately, and the corresponding responses can be determined with simple hand calculations in the early stage. The end conditions are normally approximated by engineers with assumptions of fixity, which may result in a certain degree of errors. Therefore, it is suggested that hand calculation solutions should be verified at a later stage by comparison with more accurate computer-aided structural analysis results, which are described in the next section.

3.3.2.2 Finite Element (FE) Analysis

The concrete floating structure can also be analysed by modelling the structure as a complete unit by using finite element method (FEM) computer programs to calculate the overall structural responses. Current advanced FEM tools offers engineers a wide range of analysis sophistication which can be applied to a variety of concrete structures. The analysis sophistication level varied with different design stages as well as load intensities applied on the particular concrete structure [2]. Grosch et al. [110] suggested that several types of analyses could be conducted for floating structures, such as static linear FE analyses, static nonlinear FE analyses considering material and/or geometric nonlinearities and others.

Simple estimates of general behaviour are often used by engineers in preliminary design stage to determine initial sizing. The most common modelling procedure is to assume reinforced concrete structures to behave as a linear elastic composite material; thus, a linear FE model which is a straightforward and relatively inexpensive could be used to solve the engineering problem. The typical linear FE analysis is effective and sufficient to evaluate internal forces in the global structural system at a relatively low level of loading.

When the load level becomes high and significant nonlinear behaviour exists, the results of the linear analysis would be inappropriate. Owing to the cracking of concrete and yielding of reinforcement steels, the reinforced concrete as a “composite material” behaves in an inelastic manner when subjected to actual load effects (material nonlinearity). Furthermore, large compressive forces and high slenderness ratios may cause significant second-order geometric effects. For these reasons, nonlinear structural analyses are generally adopted to assess the structural behaviour and load bearing capacity of critical members. Since such analyses are normally costly and time-consuming, they are usually introduced as further supplementary verification, confined typically to local analyses of critical sections. The use of nonlinear techniques is, in general, related to the ultimate limit state design.

Lately, significant progresses of nonlinear FE analysis have been made to achieve an efficient assessment on the global structural responses. Particularly, Dr.techn. Olav Olsen Company has developed a powerful design tool, ShellDesign, to perform nonlinear global FE analyses on large concrete structures with less time consumption by using the “consistent stiffness method” [111]. This new method makes it feasible to obtain nonlinear responses by iterative linear analyses, in which the element stiffness matrix is repeatedly updated according to the cracked shell section analysis results. The updated stiffness parameters are then applied in the linear-elastic analysis as inputs, and the repeated process will continue until a specified stiffness convergence criterion is satisfied. The consistent stiffness method as well as ShellDesign have been extensively tested and verified in the design of concrete structures, and is expected to have broader applications in more engineering practices [19]. In Demark, the consulting company Ramboll has also developed a program which is able to calculate plasticity theory on complicated constructions, and similar products are under development by Technical University of Denmark (DTU) and the Concrete Component Association[112].

3.3.3 Integrated Hydrodynamic-Structural Analysis

The two-step analysis approach, described above, is commonly adopted in general engineering practice. This approach necessitates an efficient procedure for pressure transfer from a hydrodynamic model to a structural model. If this step is not performed properly, the final loading case will not be balanced and the resultant structural response will be incorrect especially close to the artificial supports. In that situation, some researchers tried to achieve an integrated hydrodynamic-structural analysis, which enables engineers to do more realistic simulations, check the numerical accuracy of the outputs in the intermediate steps, and obtain accurate and reliable final results. However, this one-step approach places a heavy demand on computer capacity, so that its application may be limited to small floating structures [109, 113]. It is worth mentioning that the Bureau Veritas Research Department has developed a numerical software, HOMER, to cover all the aforementioned hydro-structural issues [114].

3.3.4 Physical Model Testing

Besides computer-aided engineering tools, the assistance of physical model testing is favorable for the analysis of floating concrete structures to investigate irregular environmental action effects, determine hydrodynamic behavior for complex geometries and validate numerical approaches [115]. In planning physical model tests, geometric similitude, hydrodynamic similitude (Froude, Strouhal and Reynolds) and structural similitude (Cauchy) shall be satisfied to achieve similitude between the physical model and real structure [116]. A variety of materials, including paraffin wax, wood, foam, glass reinforced plastic and others, can be utilized for manufacture of scaled models. Appropriate environmental simulation is critical for the success of model testing. For wave simulation, it is very difficult to generate high-frequency wave components at a small scale, and it was suggested that the scale factor should not be smaller than 1:70 [116]. Current is often simulated by towing. Standard instruments are necessary to measure the responses, such as linear and angular potentiometers, load cells, accelerometers, pressure gauges, and others.

In shallow waters, the water particle has a horizontal velocity on the sea bed and water flow along the structure surface may increase as well, which will induce viscous effect. It is therefore crucial to evaluate the importance of this special phenomenon and physical model testing is suggested in the detail design of such concrete floating structures. In addition, test results from specific physical models can be used to validate computational fluid dynamics (CFD) models, which is a more economic numerical procedure to evaluate environmental action effects and can be applied to similar floating structures with few additional costs.

3.4 Design Approaches and Detailing of Floating PC Structures

3.4.1 General

Durability requirements are critical for floating concrete structures to fulfil their function throughout the service lifespan. It is generally recommended that major structural components be designed such that tension stresses are eliminated or limited to very low values throughout the member thickness under normal service conditions [117]. In addition, the crack widths and corresponding reinforcing steel stresses should be controlled for all types of service loading [118].

EN 1992 specifies two criteria to control concrete cracking: decompression and crack width limitation. The decompression requires that all parts of the tendon or duct should lie at least 25 mm within the concrete in compression. Cracking checks for prestressed concrete are carried out under frequent or quasi-permanent load combinations. For the control of cracking, EN1992 tabulates bar size and spacing criteria to limit crack widths within appropriate values. Alternatively, formulae are provided for designers to calculate crack width. It is worth mentioning that ACI Committee [2] indicates that a common approach to prevent through-cracking is to require that a portion of the member remain in compression at all times.

Throughout the specified service life, floating concrete structures are subjected to repeated loading conditions due to the cyclic nature of environmental loads, which may result in serious fatigue problems. Two distinctive design methods, stress limitation control and comprehensive fatigue analysis, are used in practice to evaluate the structural members against fatigue failure. The stress limitation control method assumes that structural members are safe against fatigue failure if allowable stress criteria for both concrete and reinforcing and prestresing steels are satisfied. If the specified stress range is exceed, or the serious fatigue problem is likely to occur in specific structural members, a comprehensive fatigue analysis based on the cumulative damage theory becomes necessary in the design. The theory of cumulative damage uses a stress histogram compromising several constant stress range blocks to represent the long-term distribution of stress range: $\sum_{i=1}^{k}\frac{n_i}{N_i} \le \eta$, where k is the number of load blocks, n_i is the actual load cycle number for block i; N_i is the load cycle number causing failure if load block i acts alone, η is the cumulative damage ratio, which is taken as 0.5 for structural members below or in the splash zone [23].

Extensive research studies have been performed on the fatigue issues of concrete structures. Internal microcracking is considered as the main cause of fatigue failure of concrete structures, and the microcracking initiates when the concrete compressive reaches $0.7f_c'$[119]. For floating concrete structures, low-cycles of high-amplitude load effects can result in significant damages, like cracking and spalling, which should be handled with caution in design. In practice, cracks can open and close under subsequent cyclic loads at moderate magnitudes if there is no effective prestressing. Lately, a comprehensive R&D project “Innovation and Networking for Fatigue and Reliability Analysis of Structures (INFRASTAR)” has been initiated to predict the concrete infrastructure behaviour under fatigue load. Some research outcome has been achieved on damage detection, long-term cyclic effects and other aspects, and more significant achievements on fatigue behaviour of concrete structures are expected [120-122].

3.4.2 Design for Prestressing

PC structures are to a large extent designed to be uncracked under service load conditions. The use of high strength prestressing steel in place of a large quantity of ordinary steel reinforcement will decrease the weight of the structure, which would be advantageous in highly weight-sensitive floating structures [20].

The degree of prestressing of offshore concrete structures is often determined by counteracting the load effect of dominant actions such that no tensile stresses exist in the critical section, similar to the load balancing design philosophy proposed by Lin and Burns [123]. The prestressing effect is usually considered as a basic load in the global analysis. The time dependent losses of prestressing is taken into account by determination of an approximate single loss factor.

3.4.3 Connector System

Floating concrete can be built in drydocks in whole. However, some specific applications may also be assembled with modular units to facilitate the re-configurations if necessary. In this situation, mega-connector system is a critical component in the entire structure and should be carefully designed. A variety of connector designs have been developed in the past decades [124-126]. Figure 7 presents two typical rigid connector systems, termed as male-female connector and frictional locking connector. Armin's connector design (Figure 6 (a)) consists of two male and female coupling members, which are placed diagonally on the floating module's sides adjacent to another module in order to align two modules. Vertical-oriented detachable pins are used to lock upper male and female coupling members after engagement. Similar devices have been developed and adopted in the engineering practice, which utilize male and female coupling pairs, fitting and locking members to secure floating modules to each other. Hann-Ocean developed frictional locking connector to provide complete secured rigid connection between two floating modules, as shown in Figure 7 (b). The connector has two coupling parts, one each on one of the two adjacent floating modules. One part includes a downward directed receiving recess and the bearing surface increases in distance away from the abutment plane from top to bottom. The relative movement of two floating modules together causes the locking bars to drop down, resulting in a rigid connection.

In very large floating structures (VLFS), Fu et al. [127, 128] and Wang et al. [127, 128] proposed the use of hinge or semi-rigid connectors because they are found to be more effective in reducing the hydro-elastic responses. Riyansyah et al. [129] studied the effectiveness of semi-rigid joints in reducing the hydro-elastic response of a large floating structure modeled by interconnected beams. Gao et al. [130] further extended this idea and investigated the effect of flexible connectors by modeling VLFS with Mindlin plate theory. The response of VLFS connected by multiple hinge connectors were experimentally and numerically studied by Yoon [131]. Prestressing tendons are also utilized by practitioners in developing connector systems to achieve desired rigidity and meet design requirements. Figure 8 shows two adjacent floating modules connected with prestressing cables. When the modules is only connected at upper deck level, this connector system does not provide moment transformation between two modules. When prestressing tendons are arranged at both upper and lower deck levels, some amount of flexural bending resistance can be provided, which forms a semi-rigid connection.

3.4.4 Structural Detailing

In addition to concerns for accurate assessment of design loads and stresses imposed on floating structures exposed to a highly variable set of service conditions, one should pay close attention to structural detailing as a mean of enhancing the service performance. The structural serviceability and, in some cases, the ultimate strength performance of a floating concrete structure will be greatly affected by details such as:

(a) Reinforcing steel lap splice and bond lengths in fatigue critical areas of the structure. For example, the lap length of prestressing development length should be increased by 50% if lap splices of reinforcement or pretensioning anchorage are subjected to cyclic tensile stresses greater than 50% of the allowable static stresses [119];

(b) Control of concrete crack widths and induced reinforcing steel stresses under service conditions. For the seawater exposure condition, the maximum crack width of structural members is recommended not to exceed 0.15 mm [132]. In usual practices for severe environments, the stress value in the steel reinforcement is limited to 120 – 140 MPa, which correspond to about $0.33f_{yk}$;

(c) Adequate concrete cover over reinforcing and prestressing steel to avoid chloride-penetration corrosion in the coastal and offshore environment;

(d) Concrete mixture proportions that emphasize low permeability and high cement content; and

(e) Proper grouting and bonding of post-tensioning tendons, and proper preparation of post-tensioning blockouts and anchorages.

3.5 Special Considerations

3.5.1 Fire Resistance

In general, concrete is considered to be a better fire proofing material than structural steel for offshore oil or gas platforms. Two hydrocarbon fires were reported inside North Sea concrete platforms in 1970s. This accident resulted in approximately 10 to 20 mm deep surface scaling over a height of 5 to 10 m. This marginal impact is attributed to the large heat capacity and low thermal conductivity of concrete. No repair was found to be necessary, which clearly demonstrates the excellent fire resistance performance of concrete.

If fire is allowed to continue and concrete structures are exposed to extremely high temperature for a long time, it would suffer loss of strength and the steel reinforcement within the concrete may experience reduced capacity [19]. Lotfy et al. [133] carried out unstressed residual strength tests on LWAC mixtures made of three types of lightweight aggregates (furnace slag (FS), expanded clay (EC), and expanded shale (ES)) to assess their effects on the resistance against elevated temperatures. It is observed from the tests that the residual compressive strength reduced as the temperature was incrementally increased from 300°C to 600°C, and then to 900°C. The reduction in residual strength could reach up to 67% at 900°C, which may result in structural failure. The highest reduction in original compressive strength was recorded for LWAC mixtures made with FS aggregates followed by those with ES aggregates.

A significant amount of research work has been conducted on the effects of concrete mixture proportions to improve the fire resistance behavior. The use of fly ash is claimed to be effective in preventing strength reduction at elevated temperatures, which may be attributed to the improved interfacial property and the reduction in thermal conductivity [134, 135]. Some researchers also proposed to add polypropylene (PP) fibers to increase resistance to spalling caused by hydrocarbon fires [136, 137]. Severe spalling, 20% of total volume, was observed in normal concrete products during laboratory tests. By adding PP fibers in the concrete made with low-absorption aggregate, up to 60% less spalling volume can be achieved. In summary, it is suggested that fly ash and PP fibers be used in the concrete mixtures to improve the fire performance.

3.5.2 Low Temperature

Concrete itself shows satisfactory performances in low temperature conditions, which makes it be a preferable construction material for structures working in arctic areas or storage facilities carrying cryogenic liquids such as LNG (Liquefied Natural Gas). Well-known engineering examples include concrete offshore platforms off Sakhalin Island and in the Hebron oil field and many concrete LNG storage tanks [138, 139]. Previous research studies indicated that the concrete compressive strength and the posttensioning steel tensile strength do not reduce, but rather increase at low temperatures [140]. Also, prestressed concrete and prestressing tendons made of cold-drawn wire remain ductile at low temperatures. However, carbon steel rebars show a more brittle behavior at low temperatures. Therefore, ACI specifies tensile strength limits for different sizes of reinforcing bars, for instance 83 MPa (12 ksi) for 10 mm (#3) and 12 mm (#4) bars and 69 MPa (10 ksi) for 16 mm (#5) to 22 mm (#7) diameter bars [141]. Also, prestressed concrete has been tested at extremely low temperatures e.g. -190°C, and proved to be a qualified material solution.

3.5.3 Ship Collisions

Concrete floating structures shall be checked against accidental impact actions from ship collisions to ensure the overall safety functions are not impaired. The design values for ship collision actions are characterized by kinetic energy, impact location, impact geometry and other relative parameters. The kinetic energy is determined on the basis of relevant masses, velocities and directions of ships. As indicated in DNV-OS-A101, the impact energy of vessels can be determined with the equation $E = 0.5(m_s + m_a)v^2$, where m_s is the ship mass, m_a is the added ship mass, normally assumed to be $0.4m_s$ for sideways collision and $0.1m_s$ for bow and stern collision, and v is the impact speed. Similar equation is also given by Norsok-004 for fixed installations, but no quantitative guidance was provided. DNVGL-OS-A101 specifies that the impact energy is normally not less than 14 MJ for sideways collision and 11 MJ for bow or stern collisions, which corresponds to a vessel of 5000 tonnes moving at a speed of 2 m/s (4.5 mph) [142]. The impact energy may be distributed between floating structures, vessel and fender system, and most energy is assumed to be dissipated by plastic deformation [143]. Two approaches can be used to determine the structural effects induced from ship collisions: sophisticated nonlinear dynamic finite element analyses and energy considerations combined with simple elastic-plastic methods [144]. The latter option is described in Norsok-004 for the design of offshore steel structures.

3.5.4 Stability Consideration

Different with base-supported structures, special consideration on stability should be given to floating structures so that they can remain floating upright in various afloat conditions, including launching, towing, operating and others. One principal approach for stability control is to include sufficient numbers of compartments for ballasting at different parts of floating structures. Depending on specified load conditions, some compartments may need to be filled with water to certain levels to achieve adequate reserves of stability. Note that the existence of ballasting water changes the center of gravity in floating structures, and affects the stability behavior due to the free surface effect. The stability performance shall be evaluated for different compartment filling scenarios. For each of the possible filling scenarios, sufficient restoring moment when the structure starts heeling and/or trimming needs to be ensured. And the restoring moment versus heel/trim angle curve needs to be checked up to the maximum allowable heel/trim angle [145, 146].

Additionally, the use of compartments is beneficial to limit the accidental flooding to a small part of a floating structure, and manholes and bulkheads in the compartments are required to be sealed watertight. Single-compartment and two-compartment damages are recommended for concrete floating structures that are intended for infrequent and frequent towing, respectively [2].

4. CONCLUDING REMARKS

A literature review on analysis and design of floating PC structures in coastal environment was presented. Potential design issues and challenges are identified, and design suggestions and recommendations are summarized as follows:

1. For concrete floating structures, the weight can be supported with sufficient ballast volumes, and it is suggested to use LWAC so as to achieve a shallower draft. The design cylindrical compressive strength is suggested to be at least 45 MPa.
2. For the LWAC mixture proportions, expanded clay, slate, shale coarse aggregates are recommended for use due to their high aggregate strength. A low water to cementitious material ratio (*w*/*cm*) coupled with the addition of silica fume can effectively reduce chloride diffusion and improve chloride penetration resistance. Moreover, fly ash and PP fibers may be used to improve fire and spalling resistance performance.
3. The minimum concrete cover for reinforcing and prestressing steel are recommended to be 50 mm and 70 mm in the concrete floating structures subjected to the seawater environment respectively. When concrete with low-permeability and high chloride penetration resistance is used, a reduction in concrete cover may be allowed.
4. FRP reinforcement can be adopted in the floating concrete structures to address corrosion issues. Among different types of polymers, CFRP shows the most favourable behavior in terms of mechanical properties, chloride resistance and anti-moisture, and can be considered as a substitute for the reinforcing and prestressing steel.
5. Both serviceability and ultimate limit state should be considered in the design and analysis of concrete floating structures. In addition, combination of accidental actions shall also be

taken into account, including boat impact, blast and fire, tsunami and others.

6. For concrete floating structures deployed in shallow waters, it is vital to evaluate and quantify the importance of special phenomenon occurred in the shallow water condition. Model test is suggested for verifying a floating concrete structure design in shallow waters. CFD technique can be applied to provide practical estimation of viscous effect, which can then be applied in the global hydrodynamic analysis.
7. Risk assessment should be performed to ensure the safety of concrete floating structures throughout their service life, specifically, fire explosion and ship collision. Compartment ballasting approach is suggested for concrete floating structures to ensure sufficient stability.

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