Concrete Offshore LNG Terminals
A Viable Solution and Technical Challenges

Dajiu Jiang, American Bureau of Shipping; Ge Wang, American Bureau of Shipping; Bret C. Montaruli, American Bureau of Shipping; Kenneth L. Richardson, American Bureau of Shipping

Abstract
This paper discusses the feasibility of concrete offshore LNG terminals with a focus on applications in the Gulf of Mexico and other coastal areas of the United States. There is an ever-growing need to import more natural gas into the United States. Yet, this need is limited by the lack of infrastructure for receiving liquefied natural gas (LNG) from LNG carriers. In the search for safe, economical and environmentally-friendly installations, concrete offshore LNG terminals are emerging as a very promising solution.

A prestressed concrete structure has many advantages over steel installations [9,10,11]:
- Large volume to accommodate LNG tanks and topside facilities,
- Durable life in marine environment,
- Low maintenance cost,
- Variety of structural configuration,
- Excellent resistance to cryogenic temperature,
- Better resistance to fatigue and buckling,
- Stronger resistance against accidents of boat/vessel impact, missile attack, fire and explosion,
- Good sea station keeping capability.

There still remain many challenges in design, construction, transportation, and installation [9 to 13]:
- Relatively less experience,
- Only a few design codes and rules specifically devoted to concrete offshore LNG terminals,
- Design of high performance concrete,
- Material deterioration,
- Difficulties in quality control of field construction.

1. Introduction
There is an ever-growing need to build offshore LNG import terminals in the Gulf of Mexico and other coastal areas of the United States. In the search for safe, economical and environmentally-friendly installations, concrete offshore LNG terminals are emerging as a very promising solution. Figure 1 shows a concept of an offshore LNG terminal. ABS has approved it in principle. This LNG terminal is a concrete gravity base structure (GBS).

Prestressed concrete structures have many advantages over steel installations [9,10,11]:
- Large volume to accommodate LNG tanks and topside facilities,
- Durable life in marine environment,
- Low maintenance cost,
- Variety of structural configuration,
- Excellent resistance to cryogenic temperature,
- Better resistance to fatigue and buckling,
- Stronger resistance against accidents of boat/vessel impact, missile attack, fire and explosion,
- Good sea station keeping capability.

Figure 1: Offshore LNG concrete GBS terminal [14]
Possible catastrophic shear failure,
Lack of design experience about various accident scenarios, i.e., accidental LNG leakage, vessel impact, fire, explosion, etc.,
Procedure of transportation and installation.

This paper intends to address major aspects of a concrete LNG terminal project from design, construction, transportation to installation. It reviews the state-of-the-art technology, and highlights successful project experiences and the latest design standards. This paper has the following sections:

1. Introduction
2. Concrete Materials
3. Design
4. Construction, Transportation and Installation
5. ABS Offshore LNG Terminal Rules
6. Conclusions

2. Concrete Materials

Reinforced concrete consists of:
- Concrete, including cement, cement replacement materials, admixture, and fine and coarse aggregates,
- Reinforcement steel, including reinforcement, prestress tendon, and mechanical connector.

Except for precast concrete structure, reinforced concrete structures are usually made in the construction field using these “raw” materials. The session focuses on:
- High performance concrete,
- Quality control for field workmanship,
- Unique concrete failure,
- Concrete behavior under cryogenic temperatures.

2.1 High Performance Concrete. Building concrete offshore LNG terminals usually requires using high performance concrete. The high performance concrete is expected to achieve:
- High strength,
- Low permeability,
- Good workability,
- Moderate hydration heat development,
- Excellent resistance to cryogenic temperature,
- Good durability in a harsh marine environment.

Making high performance concrete in a more economical way highly depends on proper material selection and mix proportion design. This can be achieved with:
- Ordinary portland cement,
- Adequate amount of pozzolan as cement replacement,
- Cementitious materials, which can minimize temperature rise due to hydration heat,
- Light weight course aggregate, which has a sealed ceramic-like surface, or limestone course aggregate,
- Air entraining admixtures (for splash zone),
- Other admixtures (i.e., workability agents, retarding agents, corrosion inhibiting agents, and non-chloride accelerator),
- Reinforcements and prestress tendons, which have adequate toughness at cryogenic temperatures,
- Mechanical reinforcement connectors instead of welds.

Concrete mix proportion design needs to strictly control the maximum water-cement ratio, minimum quantity of cementitious materials, and higher 28-day compressive strength [4].

High performance concrete is most often known for its higher compressive strength. Usually, concrete compressive strength is determined based on 28-day cylinder tests. If the loads act upon the structure earlier than 28 days after casting, the compressive strength is usually based on the test at the actual age. Meanwhile, a state-of-the-art design takes into account:
- Strength growth of concrete continues with age,
- Reduction in strength due to sustained loads and thermal cracking,
- Reduced strength resulting from low-cycle fatigue.

2.2 Workmanship and Quality Control. Compared to steel, the quality of concrete not only relies on mill certificates of multiple “raw” materials, but also depends on the quality control of field workmanship. A quality control plan (QCP) is often compiled giving guidance to all stages of construction, including [1]:
- Testing, batching and mixing,
- Conveying and placing concrete,
- Construction joints,
- Concrete curing,
- Prestressing and grouting,
- Form removal, surface repairs and finished concrete.

In addition to mill certificates from the manufacturer, samples of cementitious materials, aggregates, reinforcement and prestress tendon are usually taken from each consignment for testing. Particularly, the adequacy of prestress tendon is confirmed by satisfactory static and dynamic tests. The static test is to obtain an accurate determination of the yield strength, ultimate strength and elongation of the tendon. The dynamic test is to determine tendon fatigue characteristics.

Mixing concrete is usually performed using fully automatic stationary mixers. Samples are taken from continuous concrete batching, and cured in a lab with the same condition as that on the construction site. The lab tests include compressive strength, modulus of elasticity, coefficient of thermal expansion, shrinkage and creep, air content, unit weight, etc.
The workability of the concrete is continually assessed using a slump test on the construction site. The thermal gradients due to hydration heat are usually carefully monitored using temperature measurement to prevent thermal cracking during concrete conveying, placing, consolidation, and curing.

2.3 Concrete Shear Failure Behavior. Concrete is very strong in compression, but weak in tension. In most cases, concrete shear failure can virtually be attributed to diagonal tensile failure if shear reinforcement is not provided. Unlike steel plate, a concrete structure is more prone to shear failure. Concrete structure is less likely to fail due to buckling and fatigue. Typically, the shear failure model can be either out-of-plane (including punching shear failure), or in-plane membrane shear failure.

The out-of-plane shear failure takes place in a brittle manner. Figure 2 shows concrete plates that failed by punching shear. To prevent this type of failure, through thickness stirrups are provided, such as T-head bar [1, 3, 5].

In 1991, the “Sleipner A” platform collapsed in a Norwegian fjord. This disaster resulted from the out-of-plane shear failure in the walls of its tricells due to hydrostatic pressure during ballasting. This accident demonstrates the consequences of lacking proper shear stirrups in concrete [13]. The importance of recognizing shear failure of concrete and proper prevention design can never be overemphasized.

Figure 2: Concrete plate failed in punching shear (Jiang [3, 5])

Under membrane shear, concrete may crack in a diagonal direction as shown in Figure 3. Membrane shear capacity usually needs to be checked for all possible diagonal directions to verify that the shear transfer at any direction will not exceed the capacity in that direction [2]. The contribution to shear capacity from axial compression should not be considered.

2.4 Concrete Behavior at Cryogenic Temperatures. There has been an increasing concern over LNG loss prevention under emergency situations. If the concrete GBS or floating hull acts as a secondary containment system in any way, it is required to retain LNG release for a certain period.

If the membrane lining/barrier affixed to the inside face of concrete hull is not used, the spilled out cryogenic liquid can permeate the outer layer of concrete. When the spilled out LNG is taken out, and the temperature warms up rapidly, the liquid remaining in the concrete outer layer will generate gas, causing concrete spalling. Thus, the serviceability of the concrete hull will seriously be impeded.

If the membrane lining/barrier is used, moisture in the form of water vapor may accumulate between the membrane lining/barrier and the inside face of the concrete hull. The water vapor may ingress the surface of concrete and form ice lenses. This tends to debond the membrane system affixed to the concrete hull [11].

Figure 3: Concrete panel failure due to membrane shear: cracks in diagonal directions [12]

3. Design

3.1 Loads. Loads include environmental, functional, accidental and deformation loads, and loads during construction, transportation and installation. Compared to steel, concrete is sensitive to the deformation load induced from:
- Prestressing forces,
- Hydration heat during concrete curing,
- Thermal gradient due to cryogenic temperatures,
- Shrinkage and creep,
- Soil differential settlement,
- Local ground pressure caused by an uneven seabed.

Loads during construction, transportation and installation include:
- Hogging and sagging moments,
- Mooring and towing loads,
- Hydrostatic pressure on external and internal surfaces,
- Wind and wave loads during towing and installation.

3.2 Structural Analysis. Structural analysis consists of global and detailed analysis. The global dynamic analysis is to obtain structural dynamic responses. The global static analysis is to obtain the distribution of
internal forces, deformations, stresses and strains.

A detailed analysis is required to investigate stress concentration areas, locations of drastic geometric change, or stress and/or strain disturbed zones.

**Global analysis.** The global analysis modeling includes the GBS, topsides, and foundation. Geometric mesh with three-dimensional element is more adequate for the GBS in order to adequately predict the out-of-plane shear stress [3]. The topside mass is usually simplified as gravity loads in the global static analysis. However, the topside mass and stiffness needs to be adequately modeled in the global dynamic analysis. The foundation can be modeled using a six degree restrained stiffness spring element.

A global analysis predicts the structural responses of the entire GBS under:
- Overturning moment,
- Base shear,
- Torsional moment in earthquake or extreme impact,
- Global squeezing or ovalization forces.

The internal forces, deformation, stress and strain are calculated from the global static analysis, based upon the principle of obtaining the maximum responses as mentioned above. The internal forces and deformation are used to calculate necessary reinforcement in concrete sectional design. Stresses and strains are used to calculate crack width and fatigue damage. In order to minimize the calculation work, a rational post process to screen out the worst load combinations needs to be developed.

**The nonlinear effects on global analyses.** Global analysis is based on a linear elastic theory while the sectional design is based on classic plasticity theory for concrete structures. In recent years, a nonlinear F. E. analysis is expected to solve this problem by taking into account [3]:
- Nonlinear stress-strain relationship,
- Different failure criteria,
- Cracking and post cracking behavior,
- Simulation of steel reinforcement,
- Interaction between steel and concrete.

However, it is difficult to carry out such a nonlinear F. E. analysis for large-scale structures with fine meshes. To improve this situation, the reduced tensile/flexural stiffness is usually considered in a global F. E. modeling to account for the nonlinear effect due to cracking. The reduced concrete modulus of elasticity is used to account for the effect of sustained loads and thermal gradients. Meanwhile, the benefit to thermal strain due to creep is also recognized. An iterative procedure of analysis may be considered. Figure 4 shows the creep effect on concrete due to sustained loading.

The redistribution between the mid span moment and end support moment is usually considered.

**Local detailed analysis.** In addition to the global analysis, a fine mesh F. E. analysis can be used for some structural regions, such as high stress concentration region or stress and strain disturbed regions. A nonlinear F. E. analysis using a general finite element package, such as ABAQUS, can be considered, if deemed needed [3].

A simplified approach, the strut-and-tie model, is attractive and can be used in lieu of running a nonlinear F. E. package for some situations. The basic concept of the strut-and-tie model is that the concrete between parallel cracks still carries compressive force. The concrete strip behaves like a strut. The reinforcement adequately arranged crossing cracks can carry tensile force. The reinforcement crossing cracks behaves like a tie. The strut-and-tie model is very effective in determining the force flow, and designing adequate reinforcement that prevents potential cracking.

Figure 5 shows the horizontal prestress tendon anchors in a buttress. The tendon anchorage force is applied at the end of the buttress, and will be passed to the concrete wall through the buttress. Figure 6 shows a strut-and-tie model, which is used to investigate the “force flow” in the buttress. A unit value is applied at anchor places to represent the tendon anchorage force. The dash lines represent the compressive force taken by...
concrete (strut). The solid lines represent tensile force causing the potential cracking in the buttress. The model indicates that reinforcement needs to be arranged in parallel with the solid line to prevent cracking.

3.3 Geotechnical Aspects. Geotechnical aspects for a concrete GBS terminal mainly refer to how to predict the following:
- Soil stability including bearing capacity and horizontal sliding resistance,
- Distribution of the soil reaction under the base slab and soil differential settlement,
- Derivation of soil stiffness and modulus of elasticity for global structural analysis,
- Penetration of the skirt wall and skirt wall design,
- Scouring and underpiping.

The concrete sectional design is mainly to determine necessary reinforcement and prestress tendon, which satisfies the needs of:
- Serviceability,
- Ultimate strength,
- Fatigue assessment,
- Ductility,
- Minimum amount of reinforcement.

The serviceability check includes cracking control, water tightness, and deflection of the structural element. The purpose of cracking control is for the corrosion resistance of reinforcement, water tightness, the adequate transfer of membrane shear force, and durability by limiting environment ingress. The ductility requirement is for preventing brittle failure or progressive failure under ductile level earthquake or accidental loads. The requirement of providing the minimum amount of reinforcement is to ensure that the tensile force on concrete can be adequately transferred to the steel before it yields.

![Figure 7: Fatigue fracture (left); tension fracture (right) [12]](image)

3.4 Concrete Sectional Design. A fundamental concept in concrete design is to have the structure fail by reinforcement yielding, rather than by concrete crushing. Concrete structures designed as such, if they fail, will fail in a ductile way, avoiding a sudden and catastrophic failure.

The concrete sectional design is mainly to determine necessary reinforcement and prestress tendon, which satisfies the needs of:
- Serviceability,
- Ultimate strength,
- Fatigue assessment,
- Ductility,
- Minimum amount of reinforcement.

Fatigue life is typically governed by reinforcement rather than concrete. Figure 7 shows fatigue and tensile fracture surfaces of prestress multi-strand tendons. The crude surfaces of fatigue fracture exhibit a different pattern.

**Simplified Fatigue analysis.** Often, design engineers perform a preliminary evaluation or simplified fatigue analysis before carrying out a very detailed fatigue analysis. The fatigue resistance can be considered as adequate if a preliminary evaluation indicates that stresses and stress ranges in concrete, reinforcement and prestress tendon are limited within certain ranges [1].

The simplified fatigue analysis focuses on extreme environmental waves. If having at least 2x10^6 cycles of fatigue resistance under the extreme wave load, a structural element is considered to have adequate fatigue strength [2].

**Detailed fatigue analysis.** The detailed fatigue analysis is based on the accumulative linear damage theory. The deterministic approach is usually considered. A minimum expected fatigue life of at least twice the design life can be considered as acceptable [1]. The wave distribution is determined based on the expected fatigue life. Multiple wave directions and enough stress blocks are considered. Utilization ratio of reinforcement fatigue damage is required to be less than 1.0, and the ratio of concrete is preferred to be less than 0.5 [2].

The detailed fatigue analysis checks both membrane fatigue and shear fatigue failure. For membrane fatigue, the concrete is checked in the direction of each principal stress and/or strain on both its faces. Special material factors need to be applied to concrete S-N curves to account for water ingress into concrete cracks in submerge and splash zone. For shear fatigue, concrete is checked according to compressive failure and tensile failure model respectively.

The fatigue life is also analyzed for each steel layer. Special material factors need to be applied to S-N curves of reinforcement and couplers to account for stress concentration on bend reinforcement and mechanical couplers [2]. The S-N curves of reinforcement and mechanical couplers are usually determined based on dynamic tests.

3.6 Design for Accidents. Designing a LNG concrete terminal may also need to consider the following accidents and the associated accidental loads:
- Boat/vessel impact,
- Dropped objects,
- Fire,
- Explosion,
- Intentioned loss of pressure difference.

Preferably, accidental loads of these scenarios are determined based on risk and reliability analysis. There is, however, very limited coverage in existing design codes. Some of the accident scenarios are yet to be defined.

**Boat/vessel impact.** Design for boat/vessel impact can be based on a calculated energy distribution...
between the boat/vessel and the concrete hull. A key issue is how to adequately determine the zone, mass and velocity of impacts. Ideally, the impact scenarios and the associated annual exceeding probability can be defined based on statistics from past accidents. When comprehensive historical data is not available, experts’ opinions gained from successful and unsuccessful experiences are regarded as valuable resources. The risk analysis approach has emerged as a very powerful tool. With this approach, significant risks can be identified [6].

The concrete capacity of impact zones is usually determined based on “lower bound” theory. The minimum thickness of impact zones and the additional amount of reinforcement are usually designed to achieve the following goals:

- The failure of an individual structural element directly exposed to an accident load does not result in a progressive failure in adjoining elements.
- The failure of a critical structural element must be in a ductile manner.
- The remaining structural system, other than the damaged or failed structural element, can continue to carry the loads that are expected before repairs are completed.

Fire. The difficulty of a fire accident analysis is the selection of fire duration and temperature elevation curve. The fire effect may be associated with:

- Operating wind, wave and current during fire,
- Design wind, wave and current after the fire and before repairs are made.

Explosion. The shock pressure depends on the enclosure volume and the ratio of easily removable surface to the total surface. The enclosing structures are assumed to transfer these imposed loads to the adjacent structures. The maximum explosion load may be limited to the ultimate strength of these adjacent structures. Figure 8 shows an explosion accident.

![Figure 8: The Piper Alpha A Platform, North Sea, 6 July 1988, 228 persons on board, 167 perished](image)

Unintended loss of pressure difference. Any compartment of a concrete GBS or floating hull subjected to hydraulic pressure during construction, installation, transportation and operation needs to be designed to resist the maximum pressure difference. As mentioned previously in this paper, “Sleipner A” platform collapsed during ballasting.

The design pressure difference is the maximum planned, but physically possible. Wherever an intended pressure difference is taken into account, the temporary loss of that differential during the operation phase or due to unintended flooding needs to be considered. The accident load needs to be in combination with the other maximum imposed loads.

3.7 Design for Severe Thermal Changes. Prevention of LNG loss requires that the concrete hull can retain any LNG release for a certain period of time if the concrete hull acts as a secondary containment system in any way. Whether or not the concrete hull acts as a secondary containment depends on the logistic, degree and mechanism of the integration between the containment system and the concrete hull.

If LNG leaks through the membrane barrier, which is affixed to the inside face of the concrete hull, and gets in contact with portions of concrete, the severe thermal changes will result in a thermal shock load to the concrete. The temperature of these portions is substantially lower than the ambient area. The coldest concrete will typically be in tension.

If the membrane barrier is not used, LNG will spill out to the space between the inside face of the concrete hull and the primary containment tank. This will result in a thermal gradient between the inside and outside faces of concrete hull. The significant global thermal shortening can cause through-thickness cracks and shear forces of significant magnitude. Typically, the maximum shear forces occur at locations where thermal deformation is highly restrained, such as the intersection between wall and base slab, or the corner of wall-to-wall connection.

The extreme thermal stresses due to severe thermal changes need to be considered for concrete hull design in combination with the maximum expected imposed loads. Attention should be paid to:

- Selecting high performance materials,
- Investigating thermal gradient and stress,
- Reducing thermal gradient using a heating system embedded in the concrete hull,
- Through thickness cracks,
- Providing prestress to control cracks,
- Ultimate strength.

Thermal properties of concrete and insulation materials are sensitive to moisture content and temperature. This phenomenon needs to be considered in thermal gradient analysis. Material properties of concrete and reinforcement can also be changed under cryogenic temperature. For example, the modulus of elasticity of concrete increases with the decrease of temperature. The influence of residual thermal strain should be considered as well.

For calculating the cracking width, the benefit from the increase of the concrete modulus of elasticity under low temperatures is usually considered. For checking
ultimate strength, the increase in concrete compressive strength and yielding strength of reinforcing steel with the decrease of temperature is usually not considered.

In order to prevent through thickness cracking, prestress is required to keep the minimum compressive stress in concrete and to retain the minimum compression zone in the section. Also, using lightweight aggregate concrete can benefit the prevention of thermal cracking. The lightweight aggregate concrete has larger strain at cracking, and thus, can sustain more thermal deformation before cracking [11]. However, if thermal deformations are highly restrained due to structural configuration, the design of the prestress concrete hull to resist severe thermal changes may be difficult or cost prohibitive [9].

4. Construction, Transportation and Installation

4.1 Dry and Wet Dock Construction. A smaller size GBS or floating hull can be entirely built in a dry dock, and directly towed to its final position. For a larger size of GBS or floating hull, the initial portion could be built in the dry dock, and then towed to a deeper water site. A drag survey is needed to verify that the structure can be safely floated across the gate area of a dry dock. During the construction phase in a deeper water site, a controlled ballast system is required to keep the GBS or concrete hull afloat perfectly vertical.

If the concrete terminal is designed as two separate units, the dry dock may be considered to accommodate the simultaneous construction of two units. Once the construction of the first unit is completed and towed to a deeper water site, the partially constructed second unit can be floated into the spot previously occupied by the first unit. This can reduce the excavation work, and optimize construction schedules.

4.2 Transportation and Installation. For ocean towing, a step-by-step procedure is required for the following:

- Towing route,
- Towing capacity,
- Damage stability.

For GBS installation at the final position, the following needs to be considered:

- Stability and control during immersion,
- Contact with the sea bed,
- Grouting procedure and requirements for filling all voids between the base slab and the seabed.

Weight control is critical for floating out and ocean towing. Due to the inherent weight of concrete structures, the clearance between the bottom of the concrete slab and the seabed during transportation has to be kept to the minimum in sometimes. The towing route needs to be planned in detail considering water depth, tide-range, currents, vertical and horizontal clearances, etc. The towing route may be surveyed by sonic profiling equipment to find shallow bars, ridges, pinnacles and other marine hazards, which may obstruct the tow. Contingency plans of buoyancy reserve need to be adequately developed for all possible accidents at all towing and installation stages.

4.3 Hibernia GBS. Hibernia Offshore Development Project was developed for the Hibernia oil field located 315 kilometers east southeast of St. John’s, Newfoundland, Canada. The completed platform was towed to the Hibernia oil field and positioned on the ocean floor in June of 1997 and began producing oil on November 17, 1997. The platform is one of the largest concrete GBS platform in the world.

Hibernia GBS constructed its base raft in a dry dock (see Figure 9). When the lower caisson walls were built, the cofferdam was removed and the dry dock was flooded.

![Figure 9: Hibernia GBS – a dry dock construction [15]](image)

Then, the partially completed GBS was towed to a deeper water site for continued construction (see Figure 10). Concrete mixing was performed using a fully automatic mixing station. A ballast system was used to keep the GBS perfectly vertical.

![Figure 10: Hibernia GBS–a deeper water site construction [15]](image)

The topside modules were assembled on the pier and matched to the GBS. Figure 11 shows the whole platform was towed to the final installation position.
5. ABS Guide for Building and Classing Offshore LNG Terminals

5.1 Applicable Design Codes/Rules. The development of offshore LNG terminals is yet another example of technical innovation by industry. Associated with such innovation is the need to accurately assess these designs to provide an acceptable level of safety for the people working on board, the unit, as well as ensuring environmental protection.

The most applicable current design codes and rules for concrete offshore LNG terminals are listed in the Appendix. Many of them, which provide the detailed concrete design requirements, are concrete building codes. Full recognition should be given to the limitations of these building codes.

5.2 ABS LNG Terminal Rules. Classification societies are responding to the lack of existing standards for these terminals by developing new rules. The newly developed ABS LNG terminal guide [1] is the latest of the design rules devoted to the design of offshore concrete LNG terminals.

The ABS terminal guide provides comprehensive criteria for the classification of an offshore LNG terminal, including:

- Scopes and Conditions of Classification,
- Classification of Gravity-Based Offshore LNG Terminals,
- Design of Gravity-Based Offshore LNG Terminals,
- Design of Floating Offshore LNG Terminals,
- Surveys During Construction, Installation and Commissioning,
- Surveys After Construction and Maintenance of Class,
- Risk-Based Surveys for Maintenance of Class.

Detailed requirements for the design of concrete GBS and floating terminals cover:

- Plans and data to be submitted,
- Environmental loading and design basis,
- Concrete materials,
- Concrete analysis and design for serviceability, ultimate strength, fatigue, seismic and ductility, etc.

5.3 Role of Classification in the Regulatory Process [7]. International classification societies play a key role in the marine and offshore industries. They have developed a broad base of expertise that can be drawn upon in the assessment of new and developing technologies. The classification societies provide independent certification of ships and offshore installations, according to a recognized set of standards that they have developed. These standards are independent, technically authoritative, and internationally recognized. Surveillance takes place during the design, fabrication, and maintenance of the structures and systems. The primary objective of classification is the protection of life, property, and the environment.

Regulatory bodies worldwide have recognized the independent position of classification societies and have drawn upon this resource as a means for facilitating regulatory compliance. This includes referencing classification rules in regulations and, in numerous cases, authorizing classification societies to act on behalf of the regulatory body.

5.4 Class Interface with USCG. While the USCG is developing its requirements for the installation of offshore LNG terminals in U.S. waters, classification rules provide a viable means for facilitating regulatory compliance. For example, the ABS rules traditionally have been recognized by the USCG for both ship and offshore projects. This extends to numerous instances where the ABS rules form the regulatory requirements of the USCG. Discussions are underway to extend such recognition to this new Guide.

The USCG also has established the precedent of delegating its design approval and inspection responsibilities to recognized classification societies. The most relevant model is that for floating production platforms in the U.S. Outer Continental Shelf (OCS) region of the Gulf of Mexico. To date, this delegation has been limited to ABS. It may be expected that with practical experience in the installation of offshore LNG terminals and the changing role of the USCG with regards to security issues, such a model would appear to be a viable application to further streamlining offshore LNG terminal regulatory compliance.

5. Conclusions

In searching for safe, economical and environmental friendly infrastructures for receiving/exporting LNG, concrete offshore LNG terminals are emerging as a very promising solution. This paper addresses major aspects of a concrete offshore LNG terminal project, from materials, design, construction, transportation to installation. The paper reaches the following conclusions:
Concrete offshore LNG terminal is a viable solution.
High performance concrete can be achieved through proper design and quality control of workmanship.
Shear failure can be catastrophic under some situations.
LNG loss from the primary containment system poses detrimental threats (thermal shock) to the structural integrity of the concrete installation. This needs to be properly considered in design.
State-of-the-art design procedures are available for predicting loads, structural responses, and fatigue behavior.
Attention should be paid to various accident scenarios, such as vessel impact, thermal shock, un-intended pressure loss, fire, and explosion. Methodologies for analyzing these scenarios are being refined and improved.
It is important to establish a proper step-by-step procedure for construction, transportation and installation.
The latest “ABS Guide for Offshore LNG Terminal” provides very comprehensive guidance for the design, installation, and classifications of offshore LNG terminals.

Acknowledgement
The authors appreciate the valuable comments from Kuan-Tao Chang, James J. Gaughan and Rodney F. Deschamps.

Appendix: List of Applicable Design Codes
3. ACI 357R-84, Guide for the Design and Construction of Fixed Offshore Concrete Structures, American Concrete Institute, 1997.
4. ACI 318-02, Building Code Requirements for Structural Concrete, American Concrete Institute, 2002.
7. BS 8110, Structural Use of Concrete, British Standards, 1997.

References
[14] www.eagle.org
