DESIGN AND CONSTRUCTION ASPECTS OF POST-TENSIONED LNG STORAGE TANKS IN EUROPE AND AUSTRALASIA

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INTRODUCTION

The growing world-wide use of liquefied natural gas (LNG) has seen the development of significant LNG storage tank facilities for LNG exporters and importers. These massive storage tanks are essential for receiving and safe storage of the liquid gas. The storage temperature of LNG is –162°C and is described as cryogenic conditions. The liquid occupies 600 times less space than natural gas in its gaseous state, making it practical to ship by ocean tanker. And it's stable and safe, because even though compressed in volume, the liquid remains at normal atmospheric pressure. On land, LNG is stored in specially engineered and constructed double-walled storage tanks. At these temperatures, the requirements for the containment structures are very stringent and post-tensioned concrete tanks are ideally suited to the task. The large concrete tank structures are extremely robust with significant amounts of prestressing required – all being designed and installed under tightly controlled quality conditions with hardware requiring special certifications. The design and construction techniques have been specially formulated for LNG tank construction and this paper will outline typical details as employed on various projects around the world.

BACKGROUND

LNG or Liquefied Natural Gas is natural gas that has been super cooled to a temperature around –162°C, whereby it condenses into a liquid form. The process is not a new one, having been proven in 1917 and first used in the United States over 60 years ago.

The main benefit of the cooling is that the LNG is reduced to around 1/600th of its volume as gas. It also weighs only about 45% as much as an equivalent amount of water. This has obvious benefits in terms of transportation from natural gas rich areas. LNG is a non-toxic, non-corrosive, colourless and odourless fuel.

Once the gas has passed through the LNG processing and distribution network, it can be used in conjunction with, or in place of, domestic natural gas as its properties are very similar.

The natural gas that is processed into LNG is explored for, and produced, in an identical way to natural gas. It is typically discovered in conjunction with oil exploration operations. Once extracted, the natural gas can be transported to a liquefaction plant where it is super cooled to –162°C using refrigerants. LNG tanks are usually sited in close proximity to port facilities ready for transport, and the liquefied natural gas may be stored in liquid form in preparation for shipping.

LNG is stored at atmospheric pressure in double-walled tanks: the space between the tanks being filled with insulation. The outer walls of the tank are most commonly constructed from post-tensioned concrete.

Over the past few decades, world consumption of LNG has increased more than five-fold and it is predicted that this growth will continue to be very strong. The growing demand from large markets such as China and India combined with the increasing popularity in a large number of other smaller markets has resulted in the development of many new LNG facilities throughout the world. There are significant natural gas reserves globally and exploration companies are rapidly developing facilities for exporting the natural gas with corresponding receiving facilities being planned and built in emerging markets. With a timeframe of some 5-10 years required for planning and construction, there is currently much activity underway in the LNG supply chain in preparation for current and predicted demands.

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DESIGN CONFIGURATION

Tank dimensions are typically in the order of 80-90m in diameter and 50m in height with a wall thickness in the order of 750mm (refer Figure 1). The post-tensioning tendons are very large and can run in both the vertical and horizontal directions. Vertical tendons can either be single directional tendons from the top of the tank terminating in a recess at the bottom or "U" tendons starting at the top coming vertically down through the tank curving around through 180 degrees and returning to the top.

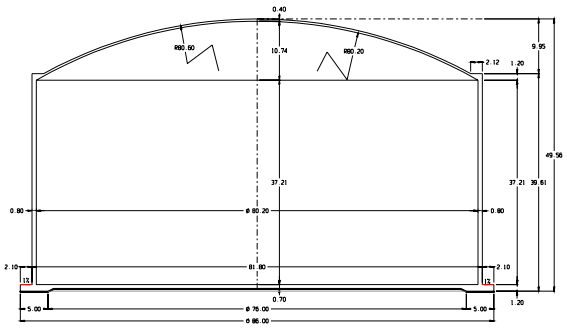

Figure 1 - Typical LNG tank cross-section

Horizontal tendons typically start at a buttress and travel half way around the tank terminating at the opposite buttress. Another tendon commences from the same buttress and travels back through the remaining half of the tank terminating at the original buttress - hence creating a complete "hoop" from the two tendons. For efficient use of post-tensioning, adjacent tendons are anchored at the alternate buttresses 90 degrees from the above noted buttress.

LNG tanks are typically constructed in a design-build fashion and the principal contractor is responsible for determining the specific design requirements for the prestressed concrete. The post-tensioning specialist will examine the required force profile and detail the spacing and tendon size of the post-tensioning.

DESIGN REGULATIONS

There is no official standard for the design of these tanks and the first guidelines published were based on the pioneering work in cryogenic applications. According to *fip* SR 88/2, testing is required to be carried out on;

- Prestressing steel (at room temperature and at cryogenic temperature)
- Tendon anchorage assembly (at room temperature and cryogenic temperature)
- Load transfer (at cryogenic temperature)

Tests according to these guidelines were completed for the BBR technology in Perth in 2005.

Subsequent to this, a new guideline has been published to cover prestressing in cryogenic applications - ETAG 013. According to this document, testing is to be conducted as follows:

- Tendon stressed to 80% of the characteristic tensile strength
- Decrease temperature to specified cryogenic temperature of –196°C
- Test tendon in 10 load cycles between characteristic yield force and 80% level
- Finally, load tendon to failure

The testing and quality control of prestressing materials used in cryogenic applications is critical for the successful performance of the containment systems.

The BBR CONA post-tensioning system is in full compliance with the *fip* and ETAG testing regime under cryogenic conditions (-196 ºC).

PROJECT EXAMPLES

DARWIN (AUSTRALIA) LNG TANK

Background

The LNG processing plant at Darwin receives gas via an undersea pipeline from the Bayu-Undan gas field in the Timor Sea, some 500km north west of Darwin (refer to Figure 2 for an artist impression of the plant). The liquid is then pumped to the storage tank at a temperature of –162°C prior to shipment to customers in Japan.

Figure 2 – Darwin LNG tank

Japan consumes more than half of the world's LNG production. The Darwin LNG Plant is expected to supply gas to Japan over a 17 year period. Construction of the $1.5 billion Darwin

LNG plant began in June 2003 and was completed by January 2006 (refer Figure 3).

Figure 3 – Darwin LNG tank near completion

The LNG storage tank has 550mm thick post-tensioned concrete walls on the exterior. An inner tank is made of a special steel/nickel alloy to accommodate cold LNG.

Thiess and LNG Tank specialist TKK were responsible for the design and construction of the 188,000m^3 LNG storage tank - one of the largest above-ground tanks in the world at the time.

Some 47m high and approximately 94m in diameter, the LNG tank comprises an outer concrete wall and nickel alloy steel lining. Thiess is responsible for site construction, design of the secondary concrete containment tank and design management.

Specialist post-tensioning contractor Structural Systems was engaged to install, stress and grout approximately 570T of post-tensioning tendons. The stressing system is a combination of 172 vertical tendons comprising 19 No. 15.2mm EHT strands and 114 horizontal tendons comprising 19-22 No. 15.7mm Euronorm strands.

The vertical tendons are stressed to approximately 4,000kN with an ultimate capacity in the order of 5,000kN. The horizontal tendons are stressed to as much as 5,000kN with an ultimate capacity of over 6,000kN.

The horizontal tendons are anchored at four equally spaced buttresses (local wall thickenings). Each tendon is approximately 150m in length and spans half the circumference of the tank.

The vertical tendons were anchored at the top and bottom of the wall. Access to the bottom anchorage was via inverted concrete culverts measuring 750mm wide x 600mm high installed below the base slab (refer Figure 4).

The 37m long vertical tendons were prefabricated at ground level and then lowered through the top anchorage by crane as a complete tendon. Prefabrication of the tendons and site installation of the vertical tendons is illustrated in Figure 5.

Figure 4 – Bottom anchorage recess for vertical tendons

Figure 5 – Installation of prefabricated vertical tendons

Access to the horizontal tendons was via mast climbing work platforms measuring 10m long. The work platforms could be shaped to suit the geometry of the workface and allow access to any level. A typical mast climbing platform is shown in Figure 6.

Figure 6 – Access platform at pilaster

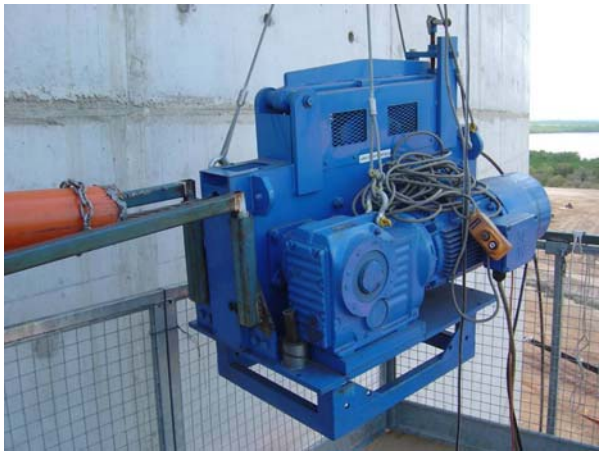

Figure 7 – High capacity strand pusher

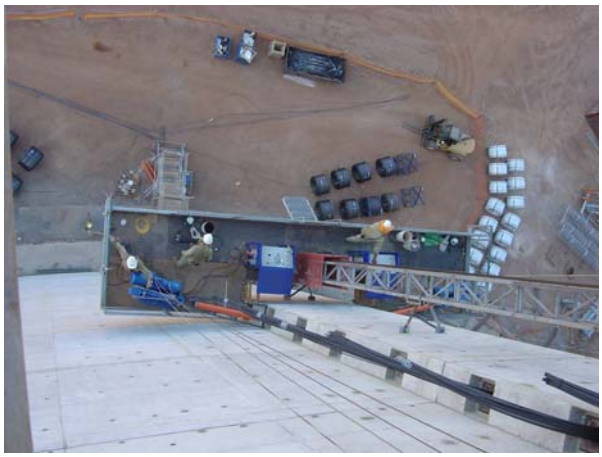

Figure 8 – Strand pusher operating on the access platform

The horizontal tendons were installed one strand at a time using specially designed high capacity strand pushers. The strand pushers are electronically controlled and can be set to automatically stop at any desired distance. Figures 7 and 8 illustrate the strand pusher equipment and pushing operation.

The post-tensioning configuration involves some large tendons which require high capacity jacking equipment. The 6,000kN capacity stressing jacks, weighing about 2.5 tonne, were supported by a winch mounted on steel framework that cantilevered over the top of the tank wall (refer Figure 9). The winch system was mounted on a rail so that the jack could easily slide over the protruding strands. The winches are controlled at the work platform level to provide the operators with complete control.

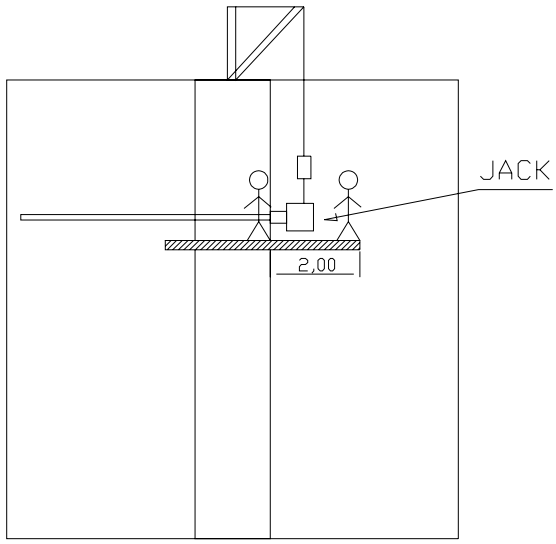

Figure 9 – Schematic showing handling of 2.5 tonne stressing jack.

Grouting of the tendons for these tanks is a critical operation. To ensure that there are no voids around the tendons, a vacuum pump grouting process is used.

5th & 6th LNG TANKS
BARCELONA (SPAIN)

The construction of the 5th and the 6th LNG tanks in Barcelona (Spain) started in 2003 for the project owner Repsol YPF / ENAGAS. The two tanks have an inner diameter of approximately 80m and an inner height of 37m (49.5m total overall height of the structure). The outer containment walls are 800 mm thick, post-tensioned vertically and horizontally with the cryogenically proven and tested BBR CONA post-tensioning system (refer to Figure 10).

Figure 10 – 5th LNG Tank in Barcelona

An approximate total of 600 tons of prestressing steel is required in each tank. There are 140 No. horizontal tendons each containing 15 No. 15.2mm strands. The 140 No. vertical tendons are of a loop configuration containing 19 No. 15.2mm strands. In addition, there are 12 horizontal tendons in the external ring of the foundation slab each with 24 No. 15.2mm strands. To ensure corrosion protection of the tendons, grouting has been carried out using a specially developed vacuum grouting technique with special high-turbulence mixers.

All post-tensioning work on these tanks is being conducted by BBR Network member, BBR PTE (Spain). The 5th tank was finished in 2004 and the post-tensioning works on the 6th tank will be completed in the fall of 2006.

Another 150,000m³ LNG tank is currently under construction in Cartagena (Spain) with an outside diameter of 81m and an inner height of 40m. The containment walls are 800 mm thick, post-tensioned vertically and horizontally. As with the 5th and 6th Barcelona tanks, the work is being undertaken with the BBR CONA post-tensioning system by the Spanish BBR Network Member, BBR PTE. The construction is expected to be completed by the end of 2006.

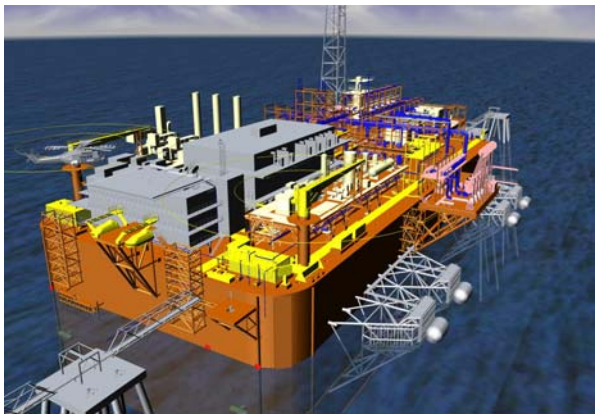

Figure 11 – Adriatic LNG Terminal

ADRIATIC LNG TERMINAL
SPAIN / ITALY

The Adriatic LNG Terminal is being constructed in a large dry-dock facility in Algeciras in the south of Spain. This same dry dock has been previously used to build a similarly large concrete structure for the Monaco Floating Dock in 2002. The Adriatic terminal is a rectangular structure, 180 m long, 88m wide and 47m high, with the capability to hold two 125,000m³ LNG tanks. It is a gravitiy-based structure, which will be tugboated to its final destination 17 km off the coast of Italy, where it will be used for receiving, storage and regasification of LNG (refer Figure 11).

Approximately 90,000m³ of concrete, 30,000 tonnes of rebar and post-tensioning steel and 350,000 tonnes of solid ballast are being used for the construction of the terminal. BBR PTE is developing the post-tensioning works in association with two other companies. This project includes both horizontal and vertical post-tensioning utilising tendon configurations of 12 and 19 No. 15.2 mm strands.

Instead of the usual corrugated flexible metal ducts, rigid steel pipes with a wall thickness of 2mm are being used to guarantee maximum durability. The pipes are factory formed to the required curvature to adapt them to the tendon geometry. The joints between the pipes are dovetailed and sealed with thermal retraction couplings.

The terminal will be put into service in April 2008.

SOUTHHOOK LNG TERMINAL
WALES, UK

This large facility commenced construction in mid 2005 by UK contractor Taylor Woodrow for project manager and specialist facility designer Chicago Bridge and Iron (CB&I). This project includes 5 No. 94m diameter x 31.2m wall height tanks (refer to Figure 12). The outer containment walls are 700mm thick, post-tensioned vertically and horizontally. This work follows on from the successful completion of the 5th LNG tank in Barcelona. In the UK, BBR Network Member Structural Systems (UK) was appointed post-tensioning subcontractor to this significant project.

The contract scope included the detailed design and specific detailing of all post-tensioning to cover the prestress force profile determined by CB&I's structural design engineers.

Working closely with the designers, Structural Systems adopted and detailed the BBR CONA tendons (19 No. 15.2mm configuration horizontally and 12 No. 15.2mm strand vertically) to closely follow the required long term post-tensioning force profile in the wall.

Figure 12 – Aerial view of the South Hook LNG tank terminal.

The post-tensioning design was carried out by Structural Systems in Melbourne and BBR CONA type tendons and anchorages were used. These anchorages were tested for compliance with *fip* recommendations for use in cryogenic conditions.

This project included 'U' type vertical tendons and wall construction was achieved by continuous slip forming.

RUWAIS LPG (Propane & Butane) TANKS. UNITED ARAB EMIRATES

The nature and form of construction of these large concrete tanks can readily be adapted to storage of other materials. Another significant storage facility designed and constructed by CB&I has recently commenced near Abu Dubai, in the UAE.

In this project, 4 No. 62.8m diameter x 34m wall height tanks with domed concrete roofs are required for storage of propane and butane.

These tanks generally have 500mm thick walls with a lower taper to 800mm thick at the base and are horizontally post tensioned only since the concrete wall here is static formed outside an inner steel liner.

Working again in partnership with C B & I, Structural Systems Ltd is the specialist post-tensioning subcontractor and has provided the design and detailing input in addition to the supply and installation site services.

NEW ZEALAND PROSPECTS

The case has been investigated for New Zealand to import LNG as an alternative fuel source to the diminishing natural gas supplies locally available. There are various studies underway to investigate the feasibility and cost of constructing an LNG storage facility and a decision will have to be made in the near future to ensure that predicted energy demands in the next 5-10 years can be satisfied. Several suitable sites have been identified and preliminary planning is underway. The future energy requirements and power generation sources for New Zealand continues to be a very political subject but there is no question that the local infrastructure, resources, international associations and capability to build such a facility are readily accessible once the decision is made to proceed.

CONCLUSION

LNG storage tanks are ideally suited to construction methods employing slip formed or climbing insitu concrete construction combined with post-tensioning. The specific design and installation techniques are very specialised and require the use of specially certified and tested materials and highly experienced contractors.

A large database of information has been developed during the construction of these massive concrete structures and many innovative techniques have streamlined the activities associated with the supply and installation of post-tensioning materials and other construction related engineering. The nature of the typical design/build project delivery method has seen the formation of some strong design and construction relationships and this has seen the rapid development and optimisation of design and installation techniques.

With the expected growth in demand of LNG storage facilities throughout the world and the rapid pace with which these facilities will need to be constructed, the specialised teams, equipment, materials and innovations developed to date are sure to add value to future customers.

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