Josef Rötzer

Design and Construction of LNG Storage Tanks

- **international regulations are considered**
- **author with international expertise**

Tanks are required for the transport, temporary storage and use of liquefied natural gas (LNG). This book introduces the complex requirements, calculations and design considerations for such tanks. The principal European and American standards are taken into account.

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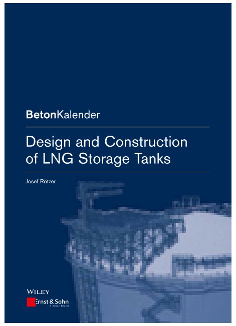

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Design and Construction of LNG Storage Tanks

Josef Rötzer

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2019 · 136 pages · 83 figures · 17 tables

Softcover
ISBN 978-3-433-03277-0 € 59*

eBundle (Print + ePDF)
ISBN 978-3-433-30000-8 € 89*

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ABOUT THE BOOK

Worldwide, the use of natural gas as a primary energy source will remain vital for decades to come. This applies to industrialized, emerging countries and developing countries. Owing to the low level of impurities, natural gas is considered to be a climate-friendly fossil fuel because of the low CO2 emissions, but is at the same time an affordable source of energy.
In order to enable transport over long distances and oceans (and hence create an economic and political alternative to pipelines) , the gas is liquefied, which is accompanied by a considerable reduction in volume, and then transported by ship. Thus, at international ports, many LNG tanks are required for temporary storage and further use. The trend towards smaller liquefaction and regasification plants with associated storage tanks for marine fuel applications has attracted new players in this market who often do not yet have the necessary experience and technical expertise. It is not sufficient to refer to all existing technical standards when defining consistent state-of-the-art specifications and requirements.
The switch to European standardisation has made it necessary to revise and adapt existing national codes to match European standards. Technical committees at national and international level have begun their work of updating and completing the EN 14620 series.
In the USA, too, the corresponding regulations are also being updated. The revision of American Concrete Institute standard ACI 376 Requirements for Design and Construction of Concrete Structures for the Containment of Refrigerated Liquefied Gases, first published in 2011, will be completed in the spring of 2019, and the final version, published in autumn 2019.
This book provides an overview of the state of the art in the design and construction of liquefied natural gas (LNG) tanks. Since the topic is very extensive and complex, an introduction to all aspects is provided, e.g. requirements and design for operating conditions, thermal design, hydrostatic and pneumatic tests, soil surveys and permissible settlement, modelling of and calculations for the concrete structure, and the actions due to fire, explosion and impact. Dynamic analysis and the theory of sloshing liquid are also presented.

BESTELLUNG

Anzahl	ISBN / Bestell-Nr.	Titel	Preis
	978-3-433-03277-0	Design and Construction of LNG Storage Tanks	€ 59*
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Editorial

The *Concrete Yearbook* is a very important source of information for engineers involved in the planning, design, analysis and construction of concrete structures. It is published on a yearly basis and offers chapters devoted to various, highly topical subjects. Every chapter provides extensive, up-to-date information written by renowned experts in the areas concerned. The subjects change every year and may return in later years for an updated treatment. This publication strategy guarantees that not only is the latest knowledge presented, but that the choice of topics itself meets readers' demands for up-to-date news.

For decades, the themes chosen have been treated in such a way that, on the one hand, the reader gets background information and, on the other, becomes familiar with the practical experience, methods and rules needed to put this knowledge into practice. For practising engineers, this is an optimum combination. In order to find adequate solutions for the wide scope of everyday or special problems, engineering practice requires knowledge of the rules and recommendations as well as an understanding of the theories or assumptions behind them.

During the history of the *Concrete Yearbook*, an interesting development has taken place. In the early editions, themes of interest were chosen on an ad hoc basis. Meanwhile, however, the building industry has gone through a remarkable evolution. Whereas in the past attention focused predominantly on matters concerning structural safety and serviceability, nowadays there is an increasing awareness of our responsibility with regard to society in a broader sense. This is reflected, for example, in the wish to avoid problems related to the limited durability of structures. Expensive repairs to structures have been, and unfortunately still are, necessary because in the past our awareness of the deterioration processes affecting concrete and reinforcing steel was inadequate. Therefore, structural design should now focus on building structures with sufficient reliability and serviceability for a specified period of time, without substantial maintenance costs. Moreover, we are confronted by a legacy of older structures that must be assessed with regard to their suitability to carry safely the increased loads often applied to them today. In this respect, several aspects of structural engineering have to be considered in an interrelated way, such as risk, functionality, serviceability, deterioration processes, strengthening techniques, monitoring, dismantlement, adaptability and recycling of structures and structural materials plus the introduction of modern high-performance materials. The significance of sustainability has also been recognized. This must be added to the awareness that design should focus not just on individual structures and their service lives, but on their function in a wider context as well, i.e. harmony with their environment, acceptance by society, responsible use of resources, low energy consumption and economy. Construction processes must also become cleaner, cause less environmental impact and pollution.

The editors of the *Concrete Yearbook* have clearly recognized these and other trends and now offer a selection of coherent subjects that reside under the common "umbrella" of a broader societal development of great relevance. In order to be able to cope with the corresponding challenges, the reader can find information on progress in technology, theoretical methods, new research findings, new ideas on design and construction, developments in production and assessment and conservation strategies. The current selection of topics and the way they are treated makes the *Concrete Yearbook* a splendid opportunity for engineers to find out about and stay abreast of developments in engineering knowledge, practical experience and concepts in the field of the design of concrete structures on an international level.

Prof. Dr. Ir. Dr.-Ing. h. c. *Joost Walraven*, TU Delft
Honorary president of the international concrete federation *fib*

About the author

Dr.-Ing. Josef Rötzer (born in 1959) studied civil engineering at the Technical University of Munich and later obtained his PhD at the Bundeswehr University Munich. From 1995 onwards, he worked in the engineering head office of Dyckerhoff & Widmann (DYWIDAG) AG in Munich. His area of responsibility included the detailed design of industrial and power plant structures. The DYWIDAG LNG Technology competence area, focusing on the planning and worldwide construction of liquefied gas tanks, was integrated into STRABAG International in 2005.

Josef Rötzer is a member of the Working Group for Tanks for Cryogenic Liquefied Gases of the German Standards Committee and a member of the committee for the American code ACI 376.

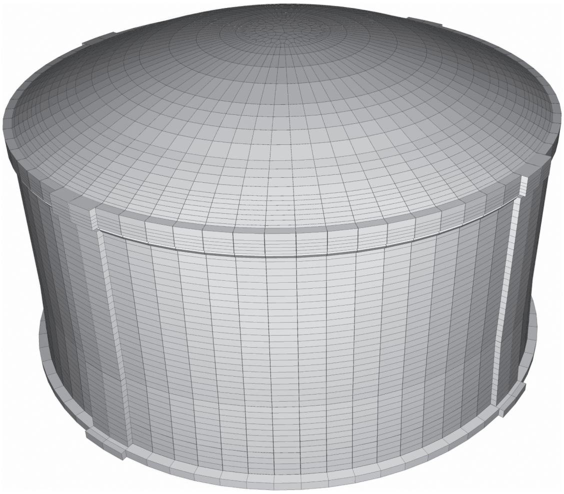


Fig. 6.1 A 3D model of a concrete outer container.

distribution around the circumference of the tank. Prestressing from both ends reduces the friction losses. As a rule, even large tanks with a diameter of 90 m require four buttresses. In Korea and Japan the design of the prestressed concrete structure assumes a higher concrete compressive stress in the tank walls. The force transfer calls for a greater distance between the anchorages and hence the need for six buttresses in many cases.

The buttresses must be rigidly connected to the base slab, and so this connection must be designed and reinforced accordingly. A few tanks have been built with a joint between the base slab and the buttresses. This means that the junction between the wall and the base slab has a constant wall cross-section over the entire circumference of the tank. The intention of this design approach is to produce more consistent forces or stresses at the slab/wall junction and reduce the influence of the buttresses. Each buttress strengthens the wall in the vertical direction like a T-beam, which decreases the compressive stress and increases the crack width in the buttress. A buttress creates a fixity effect for the wall, which increases the amount of reinforcement required at the wall/buttress junction. It is therefore necessary to include the buttresses in the model of the whole tank and carry out separate calculations to verify certain details (see section 6.3).

The buttresses are about twice the thickness of the wall, and the wall thickness itself can vary considerably. On a soft subsoil, the full and empty tank load cases generate larger rotations and larger moments with changing signs, which means the wall thickness has to be increased at the junction with the base slab. The transition is achieved with two or three battered wall sections. At the top, the wall can be thinner. When employing horizontal and vertical prestressing, a wall at least 60 cm thick will be necessary in order to guarantee good conditions for installing the reinforcement and ducts and placing the concrete.

The second important loadbearing member is the ring beam, which forms the transition between roof and wall. The inside of the roof is spherical, and the radius chosen is often the same as the tank diameter. That results in an angle of 30° at the wall/roof junction. The main job of the ring beam is to resist the thrust of

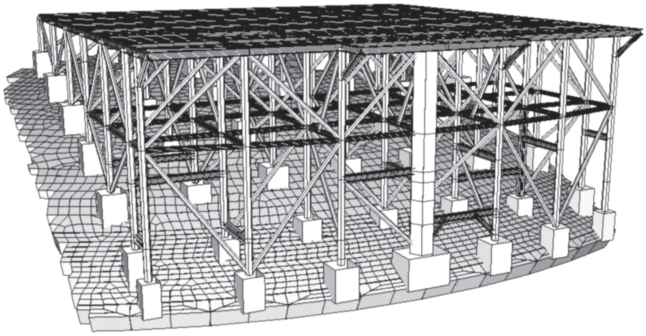


Fig. 6.2 The roof platform.

the dome roof, and that requires several tendons. Further tendons are needed to keep the ring beam and adjoining tank wall in compression over the entire cross-section.

If in addition to the structural aspects described above we also take into account the intended method of construction, primarily the concrete pours for the wall and the roof, then the result is not so many options for generating our FEM mesh. Devising a way to model the tank also includes checking the sensitivity of the mesh with respect to the ensuing internal forces. The reader is advised to consult the example of patch loads on silos by Rombach [2].

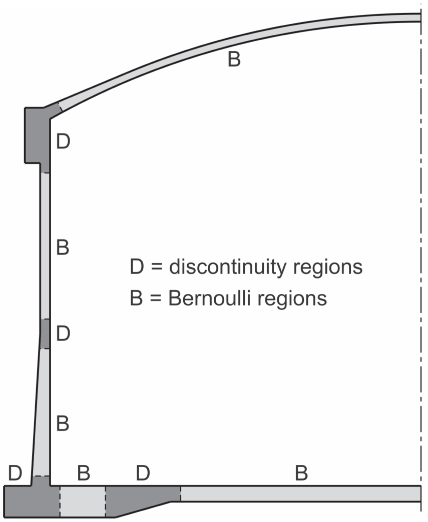
Care should be exercised when generating the mesh automatically. There are so many geometric restraint points where a load is transferred or where the amount, bar size, position or direction of reinforcement changes. Automatic mesh generation is advisable for the central area of the base slab and the irregular area of the roof platform (Fig. 6.2).

6.3 Strut-and-Tie Models for Discontinuity Regions

In certain areas, determining the internal forces and designing with FEM does not supply sufficiently accurate results. The design methods for reinforced concrete structures are generally intended for components and cross-sections with a regular stress distribution where the Bernoulli hypothesis applies (B-regions). Other areas are known as discontinuity regions (D-regions) because the form (geometric discontinuity) or loading (static discontinuity) changes. For these areas, an analysis using strut-and-tie models supplies more accurate results regarding the flow of the forces, and hence the positions and sizes of the reinforcement required, than an FEM analysis of the whole system. D-regions in LNG tanks are the ring beam with its connections to roof and wall, the buttresses, owing to the change in cross-section and the transfer of the prestressing forces, and where the depth of the base slab changes (see Fig. 6.3).

The D-regions can be modelled with a fine FEM mesh and the stress trajectories determined. After that, the tension and compression zones of the stress trajectories are combined to form the struts and ties in a strut-and-tie model (STM). The

Fig. 6.3 Bernoulli regions (B-regions) and discontinuity regions (D-regions).



internal forces in the adjoining B-regions, the support reactions and the loads acting supply boundary conditions for the STM. In contrast to the very regular B-regions, a separate STM has to be developed for every D-region. However, STMs are already available for many cases which can be adapted to the actual situation of a particular tank.

The necessity for and the advantages of designing with STMs will be illustrated by way of two examples. The first of these is the change in depth of the base slab, which is dealt with in detail in [3]. The second is the force transfer from the stressing anchorage and the ensuing flow of forces in the buttress [4].

Fig. 6.4 shows an example of a change in depth of a beam, which in this case is applied to the slab/footing transition. The moments in the adjoining regions lead to tensile and compressive forces acting on the edges of the STM. Using the STM, which traces the load paths, the forces are combined on the left and right sides. What we learn from this is that different moments with different signs lead to

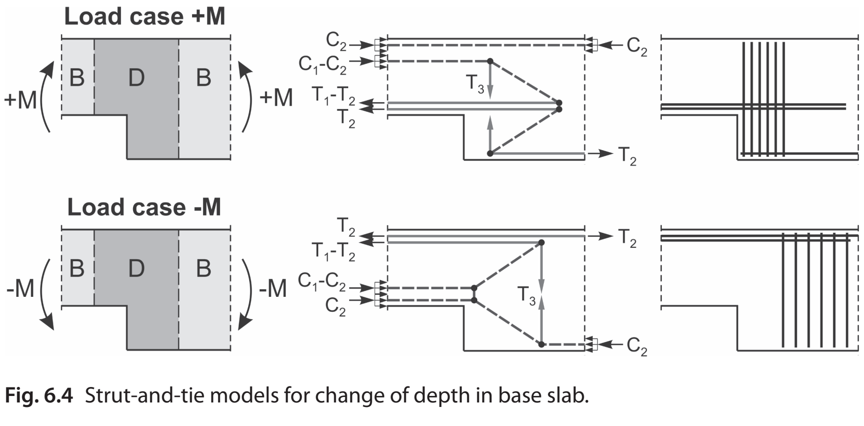


Fig. 6.4 Strut-and-tie models for change of depth in base slab.

considerable changes in the position and arrangement of the horizontal and vertical reinforcement – something that it is not apparent in the FEM calculations.

The flow of forces in the buttress depends on the geometry and stressing sequence and is therefore different for every tank. On small tanks the buttresses can be widened to avoid reverse curvature of the tendons. With larger tank diameters, on the other hand, it is hardly possible to avoid reverse curvature, as the tangential deviation from a circular arc takes place only very gradually, which would therefore make the buttress very wide and very thick. In the design of the buttress the aim should be to avoid reverse curvature, or at least to reduce it, which means that fewer stirrups (links) are required within the buttress cross-section. Additional stirrups are required in the middle of the buttress if the tendons have reverse curvature and the radial forces then act outwards. Even if the ends of the tendons are straight, the confining effect of the prestress is lacking. Furthermore, it is not difficult to provide an additional vertical U-shaped tendon in a widened buttress to produce a more uniform compressive stress state.

Whether or not transverse reinforcement is required at the edge of the buttress depends on the stressing sequence. If the tendons of one ring are tensioned one after the other, the loading situation is that shown in Fig. 6.5b. At the side of the buttress that is tensioned first, transverse reinforcement equal to about $P/6$ ($P =$ prestressing force) will be required. If the stressing sequence is uncertain,

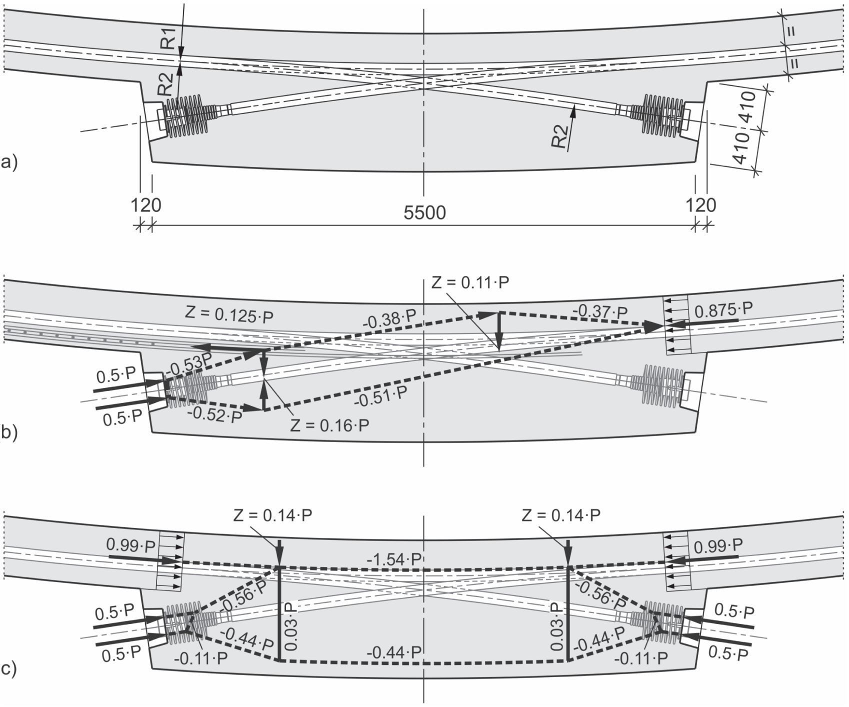


Fig. 6.5 Strut-and-tie model of buttress during stressing: a) layout of tendons, b) flow of forces when stressing from one side only, c) stressing from both sides simultaneously.

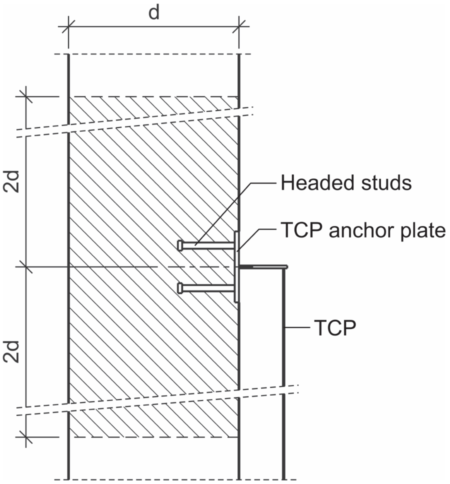
the recommendation is to provide reinforcement on both sides. Also required are bars equal to about $P/8$ laid parallel with the tendons and tying the buttress into the wall. The exact values depend on the particular STM. After the second tendon has been stressed, the flow of forces is as shown in Fig. 6.5c. If both tendons at a buttress are stressed simultaneously, the flow of forces shown in Fig. 6.5c develops immediately.

6.4 Liquid Spill

The concrete outer tank (secondary container) must be designed to accommodate the maximum amount of liquefied gas in the primary container. It is assumed that the annular space, and hence the secondary container, is filled gradually. This load case is known as “liquid spill”. In addition to the entire contents of the inner container leaking out, it is also necessary to investigate the consequences of only small amounts escaping and leading to small patches with a very low temperature. This is the “cold spot” load case.

There are no stipulations regarding this scenario or the flow rate of the escaping liquefied gas. If a leak develops in the primary container and LNG escapes, it flows into the annular space between the inner and outer tanks. At the start of this process, the LNG remains in the region of the thermal corner protection (TCP). Once the level reaches the upper edge of the TCP, this represents the maximum load on the anchorage of the TCP in the concrete wall, as the cast-in steel cools and contracts while the concrete wall maintains its temperature and thus does not contract. The ACI 376 Committee is currently working on a “Code for Thermal Protection”, which should include clear stipulations concerning the cast-in steel and its anchorage in the concrete wall. It must be ensured that the steel does not become detached from the wall, thus allowing LNG to flow behind the TCP. The 2011 edition of ACI 376 called for a maximum crack width of 0.20 mm in an area above the TCP anchorage equal to at least twice the wall thickness (see Fig. 6.6).

Fig. 6.6 Fixing of thermal corner protection (TCP).



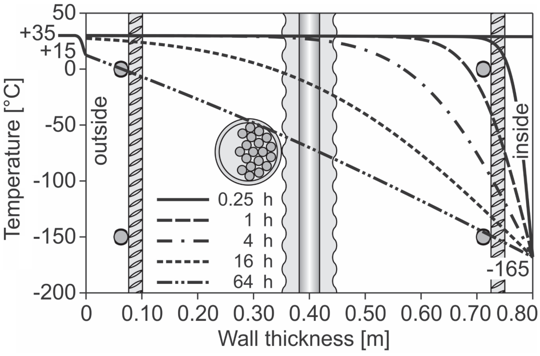


Fig. 6.7 Temperature gradient in concrete wall, development over time.

If liquefied gas continues to leak out, the level rises further. The LNG comes into direct contact with the concrete wall, which starts to cool as a result. It takes almost three days for a linear temperature gradient to become established (see Fig. 6.7).

The change in temperature in the wall over time cannot be known because the flow rate of the leaking LNG, and hence the rise in the level, is unknown. At the same time as the cooling effect infiltrates the concrete, so the level of the liquid rises, cooling the surface of the concrete higher up the wall – the two effects are superimposed. In order to be able to approximate the temperature-time relationship, various constant liquid levels are examined and the ensuing internal forces plotted as an envelope. Four or five levels are usually prescribed in tank specifications: the maximum possible level, one level above the TCP anchorage and several other levels in between.

The effects of a changing level on a wall of constant thickness have been investigated in [5]. It was shown that the level of the liquid has a direct influence on the bending moment. In the upper half of the tank the maximum bending moment is affected only marginally by the level of the LNG. The maximum bending moments are found in the region directly above the TCP anchorage and occur with a liquid level just a few metres above the TCP anchorage, because this creates curvature in two opposing directions which almost coincide (see Fig. 6.8).

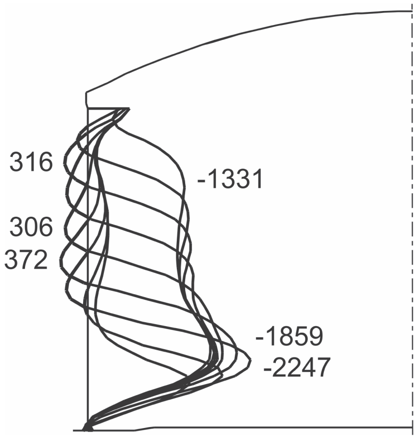


Fig. 6.8 Bending moments for different liquid levels.

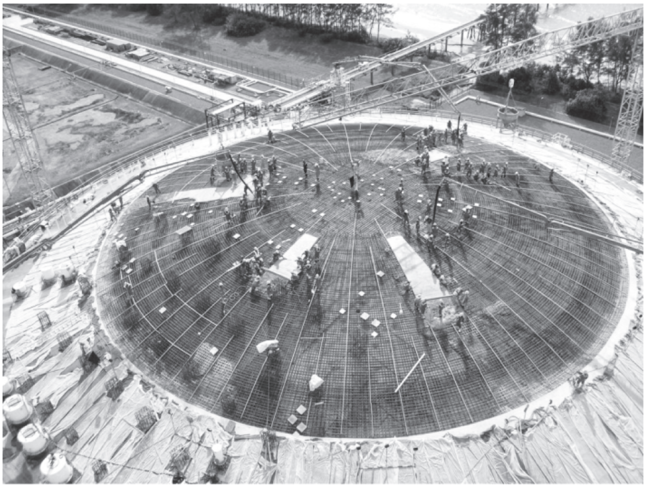
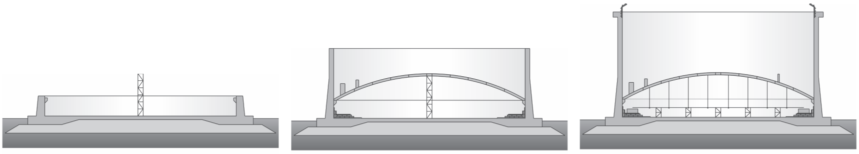


Fig. 8.7 Concreting the roof in circumferential rings.

Fig. 8.8 Temporary opening.

with the level of the base of the inner container. And the head should not be too close to the cast-in items anchoring the TCP. To avoid any potential clashes, many tank specifications specify a minimum distance of 1 m between the head of the opening and the TCP anchorage. When positioning the openings and the support corbels, it is also necessary to ensure a sufficiently high working space beneath the steel dome.

Prior to commissioning, the tanks must pass their hydrostatic and pneumatic tests. After testing, the inside of the 9% nickel steel tank must be cleaned following the contact with water, the temporary openings reinforced and concreted and the prestressing completed for these areas. A ring of nozzles in the roof above the wall insulation level enables perlite insulation to be blown into the annular space.



a) Laying a sub-base to distribute the loads
b) Construction of base slab with inclinometer and heating cables
c) Concreting the first wall ring with the temporary access openings
d) Provision of temporary supports for steel roof at centre of tank and on inside face of tank wall

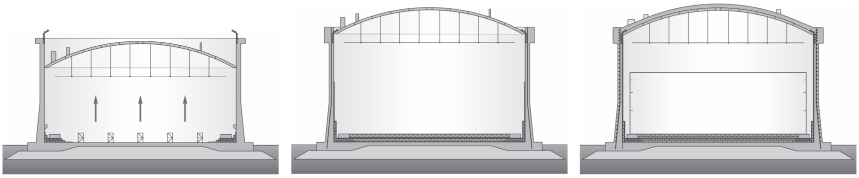
Phase 1

a) Construction of subsequent tank wall rings
b) Erection of steel roof with all access openings and roof penetrations
c) Installation of temporary roof drainage
d) Sealing steel roof against inside of tank wall
e) Start of insulation works

Phase 2

a) Construction of inner container support
b) Completion of concrete tank wall and roof ring beam with steel roof connection (compression ring)
c) Construction of suspended insulation deck

Phase 3



a) "Roof air raising" – steel roof (including all fittings and suspended insulation deck) lifted into position pneumatically

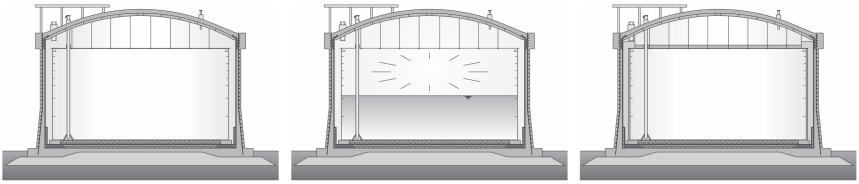
Phase 4

a) Fixing steel roof to ring beam
b) Completion of concrete ring beam
c) Installation of base and wall insulation
d) Fixing reinforcement for concrete roof

Phase 5

a) Concreting tank roof
b) Start of construction of steel inner container

Phase 6



a) Completion of steel inner container
b) Erection of roof platform
c) Installation of pumps and instrumentation

Phase 7

a) Hydrostatic and pneumatic tests

Phase 8

a) Drying, installation of perlite insulation
b) Purging
c) Cool-down

Phase 9

Fig. 8.9 Idealised construction phases.

Neglecting more complex foundation or ground improvement works, an LNG tank takes between 30 and 36 months to be built. The constraints placed on budgets and timetables have led to various forms of construction being developed and becoming established. For the operators of liquefaction plants, the returns that can be gained from shorter construction times and earlier commissioning are often greater than the costs of the measures needed to achieve that. "Roof air raising" is a typical example of this and the ingenuity of the engineers. Fig. 8.9 shows the general construction procedure for a 9% nickel steel full containment tank [2].

8.2 Wall Formwork

Just 10 to 15 years ago, it was normal to include continuous vertical cast-in elements in the concrete wall to which the steel liner could be welded. The number of cast-in plates usually matched the number of roof rafters, or was at least coordinated with them, and a multiple of four or eight. This regular grid was reflected in the number of formwork elements and reinforcement meshes (Fig. 8.10). The

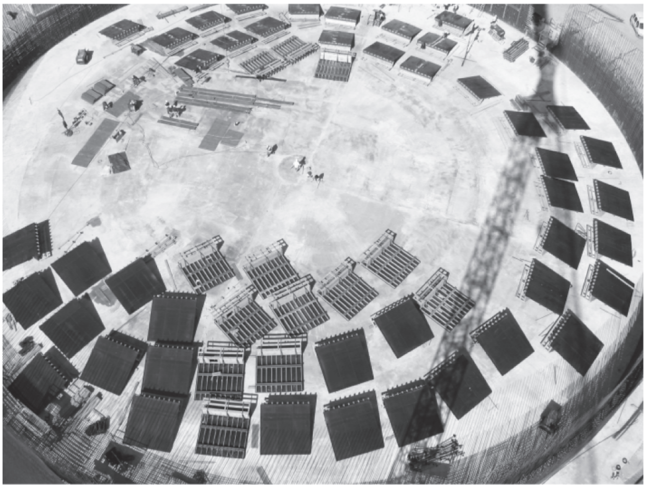


Fig. 8.10 Preparing the wall formwork elements.

spacing of the plates was 2.0–2.5 m, the width of the formwork elements twice that, i.e. 4.0–5.0 m, and the width of a reinforcement mesh again twice that. The cast-in plates were positioned in the middle of each formwork element and between each pair of adjoining formwork elements. In recent years, there has been a changeover from continuous cast-in parts to individual plates positioned at regular intervals.

That has had little effect on the dimensions of the wall formwork. Practical construction aspects such as ease of handling, limiting the weight with respect to crane capacities and the use of existing parts remain unaffected (Figs. 8.11–8.13). The height of one complete wall ring lies between 3.75 and 4.30 m.

Fig. 8.11 Climbing formwork being repositioned for next lift.

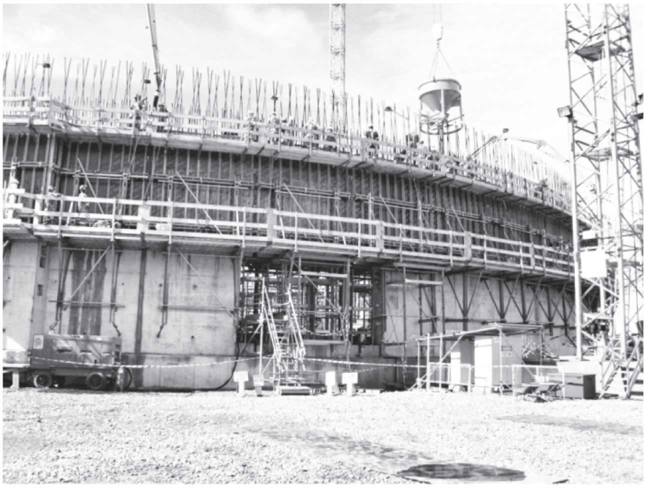


Fig. 8.12 Climbing formwork showing working platforms.

Fig. 8.13 Tank wall formwork.

The height of a wall ring depends on the pressure of the fresh concrete, the length of the vertical reinforcement and the amount of concrete that can be placed in one day. Three tie levels are required for such a wall ring, the topmost of which is above the concrete. To improve water-tightness, every tie must be provided with a waterstop.

For a tank diameter of 80–85 m a total number if 56 to 64 formwork elements are required to keep them manageable. Additional formwork elements and special parts are required on the outside due to the irregularities caused by the buttresses. It generally takes several days to dismantle and reposition a complete set of formwork.

Below the platform for fixing the steel reinforcement, there is normally another platform on the formwork for carrying out any finishing works on the concrete surface and removing and closing-off the climbing cones. The topmost (smaller) working platform is required for the concreting operations.

8.3 Reinforcement

Some 17 000 to 19 000 m^3 of concrete and about 4000 t of reinforcement, about a quarter of which is cryogenic reinforcement, are required for the LNG storage tanks frequently built these days with capacities of 180 000–200 000 m^3. Apart from the base slab, the orientation of the reinforcement in all components is defined by geometry and method of construction. On a pile foundation, the layout of the reinforcement must match the pile grid. Piles are usually positioned on an orthogonal grid in the middle of the tank and in two or three rings around the perimeter. Where the depth of the base slab differs for the middle and perimeter areas, the result is a staggered arrangement of the bar laps on the underside of the slab. If the orthogonal and radial reinforcing bars cross in one plane, a sufficient bending radius must be ensured for the bent splice bars; a bending radius of 15 or 20 d_s is appropriate (Fig. 8.14). Where a raft foundation is being used, the transition from radial to orthogonal reinforcement can be positioned as required, is not determined by geometry or construction method (Fig. 8.15). Neither approach has any clear economic advantages. The wall starter bars in the base slab are made from normal steel; cryogenic reinforcement is first required in the wall itself.

Various options are available for installing the wall reinforcement. It is normal to use individual bars, pre-bent reinforcement meshes (Fig. 8.16) and pre-assembled reinforcement cages (Fig. 8.17), with normal reinforcement on the outside of the wall, cryogenic reinforcement on the inside, spacers, ducts for

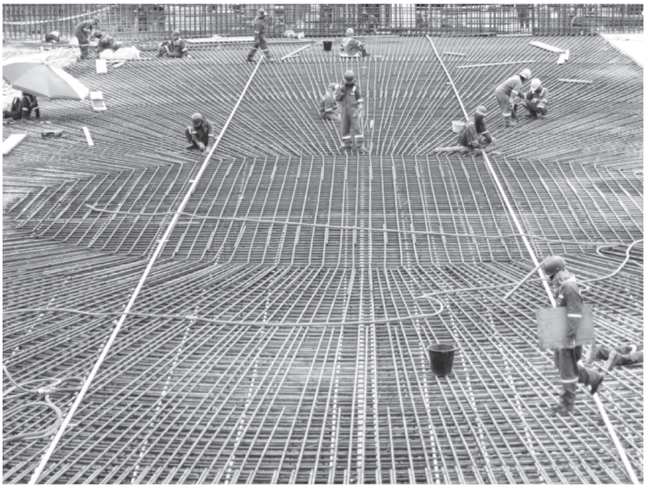


Fig. 8.14 Orthogonal reinforcement layout in middle of base slab.

Fig. 8.15 Radial base slab reinforcement for a smaller tank.

Fig. 8.16 Large reinforcement mesh suspended from a crane spreader beam.

prestressing tendons and, in unfavourable conditions, shear reinforcement as well. Meshes with 100% laps can be installed with a crane spreader beam; meshes with shifted rebars and 50% laps are more awkward to handle. As meshes and cages become larger and heavier, so it becomes more difficult to install them and the inaccuracies increase. The time-savings hoped for are paid for in terms of quality and accuracy of construction.

The dimensions of the buttresses should be chosen such that the tendons can be arranged without a change in curvature or, if unavoidable, with only a very small reverse curvature. With a larger reverse curvature, stirrups (links) will be required in the buttresses already crowded with criss-crossing ducts (see Fig. 8.18).