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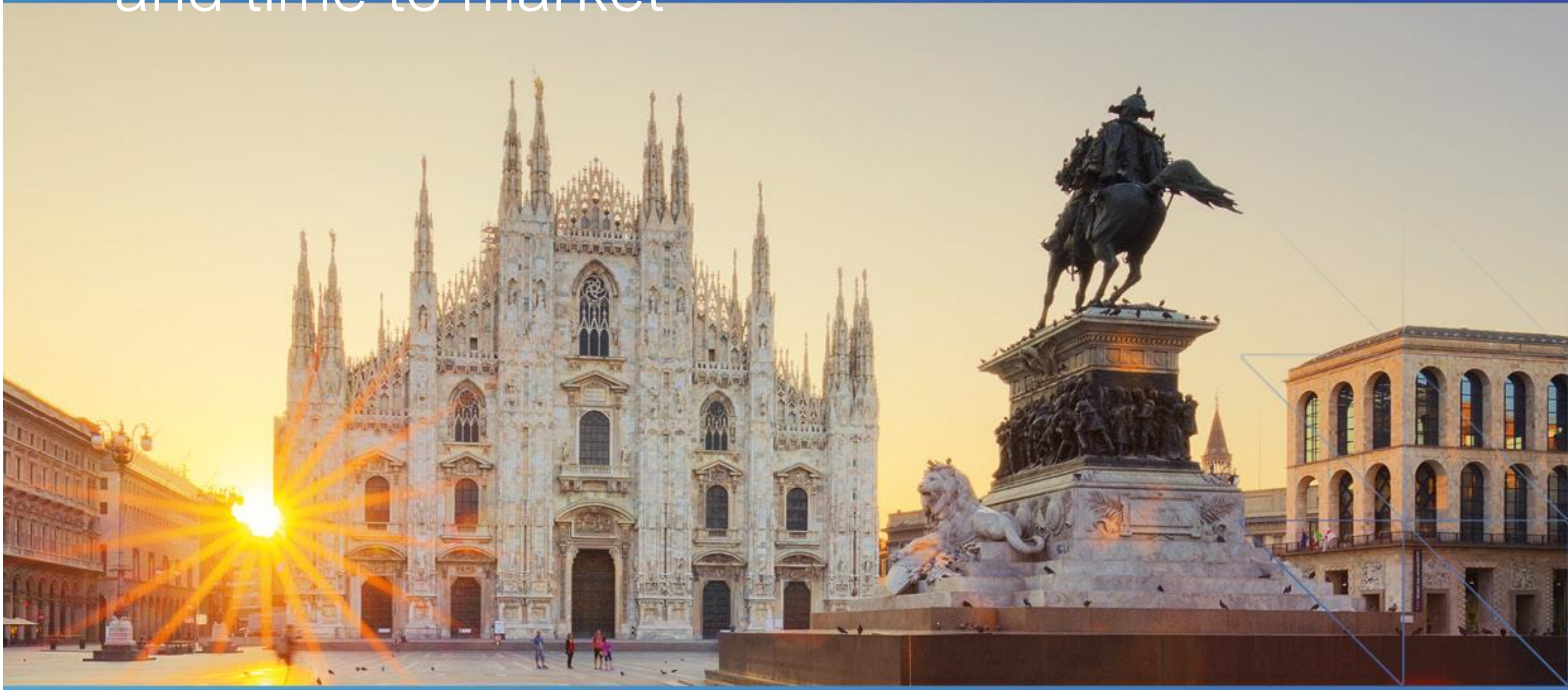
Automated analysis and design of LNG storage tanks: reducing engineers' time and time to market



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Abstract

In the construction industry, design automation programs for various structures have been developed, but in relation to LNG tanks there have been difficulties in improving the design efficiency due to specific challenges, including the need to combine results from thermal and structural analyses, model staged construction and include creep and shrinkage effects.

The analysis of such tanks seems to require a 3D solid continuum FE model to properly represent the conduction of heat through walls, slabs and insulation layers, along with the effects of the structural loads such as wind and seismic. However, extraction of load effects for design purposes (e.g. bending moments and shear forces) from such models is not straightforward - for this reason 3D shell models are favoured. Shell models, on the other hand, generally lack the ability to model the conduction of heat through-thickness. The use of a cartesian reinforcement arrangement in some areas of the roof and base slab, and circumferential/radial arrangement in other areas presents a further challenge when obtaining suitable design effects. Computing the section capacity with consideration of prestress changes at different stages is also required.

An efficient design approach, adopting a 2D axisymmetric model for the thermal analysis, a 3D shell model for structural loads and furthermore considering seismic effects, demands an integrated methodology extending to the combination of results and design checking, with detailed attention to the varying reinforcement orientation.

Methods have been developed that include converting thermal results into loadings for 3D shell model, based on the requirements of ongoing LNG tank projects for various companies including KOGAS (Korea Gas Corporation) and KGT (Korea Gas Technology Corporation). These enable all the required design checks to be done in a single 3D shell model bringing together results from thermal, seismic, and staged construction analyses with design checks performed to the various international standards. Results output by way of summary reports, graphs and contours in consideration of the mixed reinforcement directions is also provided.

The London University Structural Analysis System (LUSAS) software was used to develop the required tools, applying the latest FE technology to automate the modelling and design of LNG storage tanks. Customisation and automation through an open API enable users with basic programming knowledge to create the various user defined features required, extract results and combine them with speed and accuracy in the desired format.

Solutions to the challenges encountered have enabled improvements in the efficiency of the analysis and design process for LNG storage tanks to reduce the engineers time and time to market by an estimated 20-30%. With less time spent on simulation and design checking, engineers will be able to produce accurate and reliable analyses of LNG tanks while optimising designs and reducing projects costs.

Keywords: LNG storage tanks; thermal design; staged construction; finite element modelling; concrete design; design optimisation; API automation.

Introduction

Storage tanks are critical structures which have stringent requirements when it comes to analysis and design verifications of the containment capacity. These include, but are not limited to:

- Static analysis under operation loads, testing, wind and other normal conditions.
- Staged construction, temporary openings, creep and shrinkage effects.
- Thermal effects, heat radiation from fire, and accidental leakage.
- Dynamic analysis under seismic conditions.
- Other accidental situations such as: blast, impact or burnout.

The most common type of LNG storage tanks is the cylindrical full-containment type in accordance with API 625 [1], consisting of a self-supporting 9% Ni steel inner tank, which contains the LNG, and an outer concrete tank that encases and protects the inner tank. Insulation is placed between the two tanks.

Structural verifications of concrete and steel tanks are performed by using Finite Element (FE) technology to idealise and represent the tank geometry, material properties, boundary conditions and load scenarios. Different types of analyses and objectives demand different modelling strategies. These can mainly be grouped into:

- 2D axisymmetric models: 2D continuum modelling for structural and thermal effects which can be considered symmetric around the tank circumference.
- 2D lumped-mass models: simplified beam and joint models which can be especially useful for considering fluid-structure-interaction and soil-structure-interaction in seismic dynamic analyses.
- 3D shell models: the most versatile and convenient approach to represent structures with large areas compared to their thicknesses and subject to 3D structural loading in any direction (e.g. wind).
- 3D solid models: highly advanced models that are required for detailed nonlinear concrete behaviour, non-symmetric thermal effects (e.g. fire exposure) and for any other situation not covered by the previous approaches.

Examples of these finite element models are shown in Figure 1.

Limit-state design philosophy in modern codes relies upon the superposition and factorisation of different load scenarios to create a number of design combinations from which main results can be obtained. For tanks and other structures, these are usually known as Serviceability Limit States (SLS) and Ultimate Limit States (ULS), which can result in hundreds of different design check combinations.

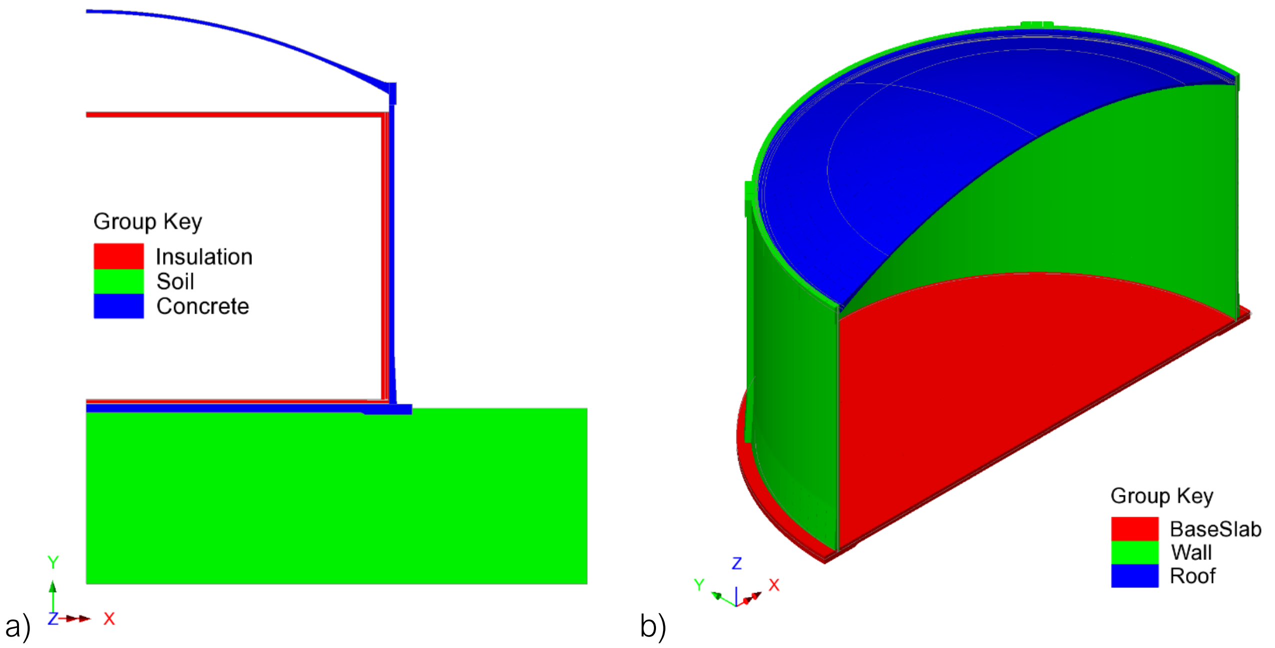


Figure 1 – Examples of a) 2D axisymmetric model and b) 3D shell model

Currently, a big challenge for engineers is that different load conditions are tackled by different modelling approaches, making the combination of results from different models difficult and prone to errors. In this regard, an Application Programming Interface (API) has been developed within the finite element software used to analyse the tanks - LUSAS (London University Structural Analysis System) -, which has the ability to automate the building of multiple models for different analysis conditions and bring together results into a single integrated model. More importantly, the API can help to streamline the process of results extraction and design verifications by catering for complexities in the rebars and prestressing arrangement for cylindrical tanks with domed roofs. This API tool has been referred to as the LNG System, although it can be used to analyse and design any type of cylindrical storage tank made of steel and concrete.

The automation of the model building tasks also provides a fundamental advantage to engineers during the design process. The dimensions, materials, foundation arrangement and other details of a tank are usually varied as the design progresses from a feasibility study, the basic engineering and to the final stage of detailed design. Moreover, engineers might want to compare and understand different tank configurations and options to optimise designs and ultimately save costs by efficient selection of tank properties and dimensions. All these trials and repetitions are time consuming and the possibilities to investigate these will be limited for projects under constant time pressures. The automation provided by the LNG system API allows engineers to quickly evaluate different scenarios originating from a single tank definition, encouraging research and innovation in the storage tank construction industry.

Integrated solution

In the developed LNG system, a series of wizards automatically create FE models and perform design checks under various analysis conditions. This system enables all the required concrete checks to be performed in a single model by bringing together results from thermal, seismic and staged construction analyses into a single 3D shell model.

Combining 2D thermal and 3D structural results

Variations of ambient temperature throughout the year and the cryogenic temperatures of the stored liquid require a detailed thermal analysis of the LNG tank, which includes aspects such as insulation components and ground heat transfer (if not elevated).

The purpose of a thermal analysis is to obtain the temperature profile through the thickness of the structure and derive the thermal strains and stresses induced by the temperature gradient.

The thermal analysis should be followed by a structural analysis that uses the results of the thermal analysis (i.e. temperature distribution) as the input loading. This type of analysis is called thermo-mechanical semi-coupled analysis.

LNG tanks can be modelled using diverse types of models, depending on the objective. For thermal results, the tank is better idealised using either a 3D solid model or a 2D axisymmetric model. However, for other type of loading (e.g. seismic, wind), a 3D shell model is a better choice. In this context, developing a systematic approach that allows engineers to apply thermal results from a detailed 2D model into a shell model, even if in a simplified way, is a powerful tool.

Temperature results in the 2D axisymmetric model are not directly applicable into a 3D shell model, as assigning arbitrary temperature values through the thickness of the shell is not possible. Shells can only consider uniform temperature distribution and linear gradients.

Converting a generally varying through-section temperature profile for application to a shell model presents a particular modelling problem. If the structure is modelled using continuum elements, this can be modelled explicitly. However, if the structure is modelled using shell elements the application of a nonlinear profile directly will not be possible.

To overcome this limitation an approximation has been made to convert the generic nonlinear temperature profile into a simplified addition of a uniform temperature plus a linear gradient.

One potential method to compute the equivalent uniform temperature and linear gradient is outlined in Chapter 11.2 of [2]. As a first step, the equivalent “restrained” forces and moments that are caused from the nonlinear profile of temperatures are computed. These are subsequently converted back to a uniform temperature and linear gradient to be applied in the shell model.

In the past, engineers would typically extract the stresses derived in the 2D model from the coupled analysis, perform through-thickness stress integration to obtain sectional forces and combine them in a separate spreadsheet with the force results from a 3D shell model. In the LNG system, the 2D temperature profile results are automatically transformed into an equivalent temperature loading and applied to the 3D shell structural model, as shown in Figure 3.

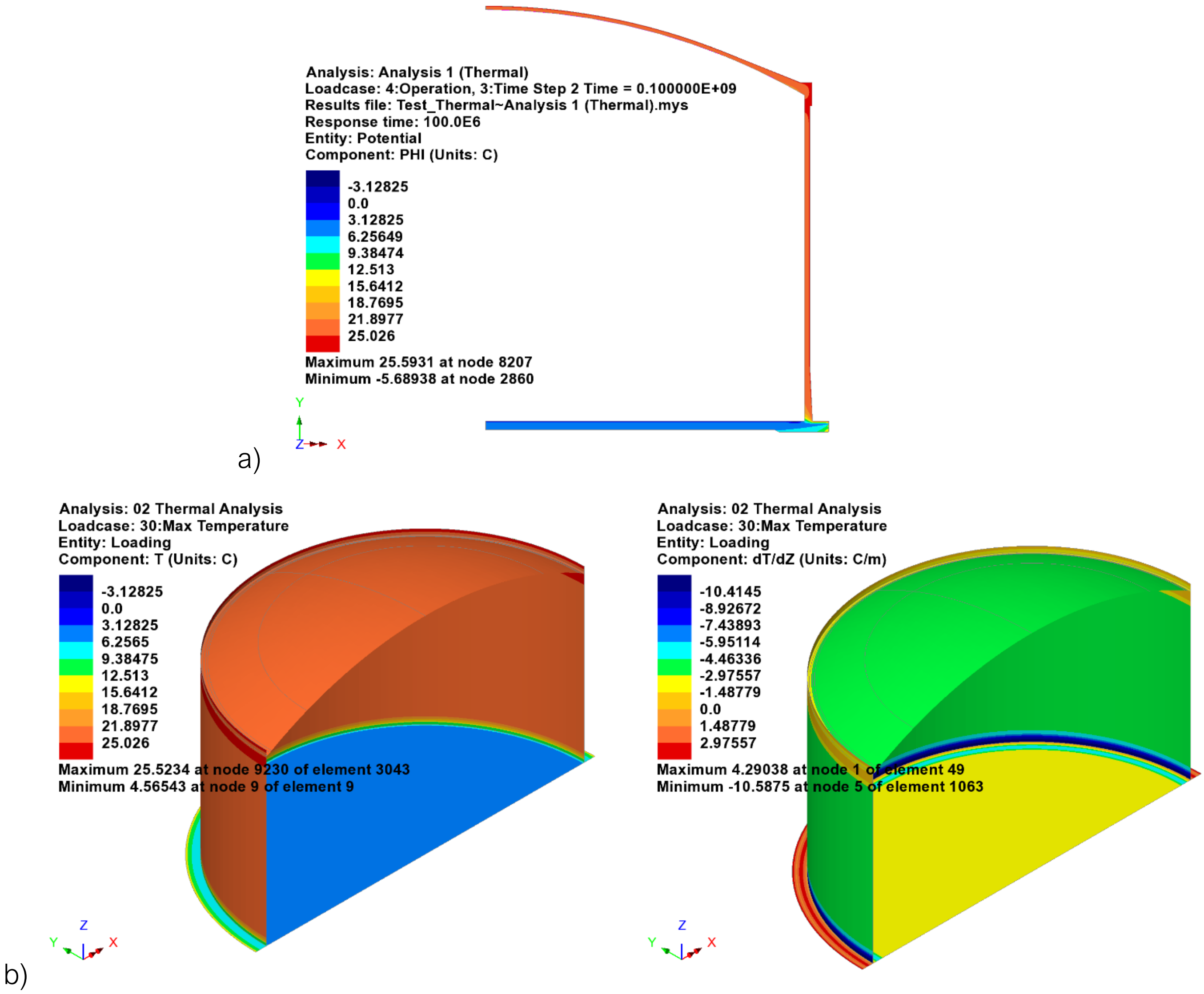


Figure 2 - a) Temperatures from 2D model; b) uniform temperature and gradient loads on 3D model

The structural results comparison for the temperature loading between a 2D and a 3D model for a typical LNG tank example are shown in Figure 3. The match in results shown in Figure 3 verifies the adequacy of the implemented approach.

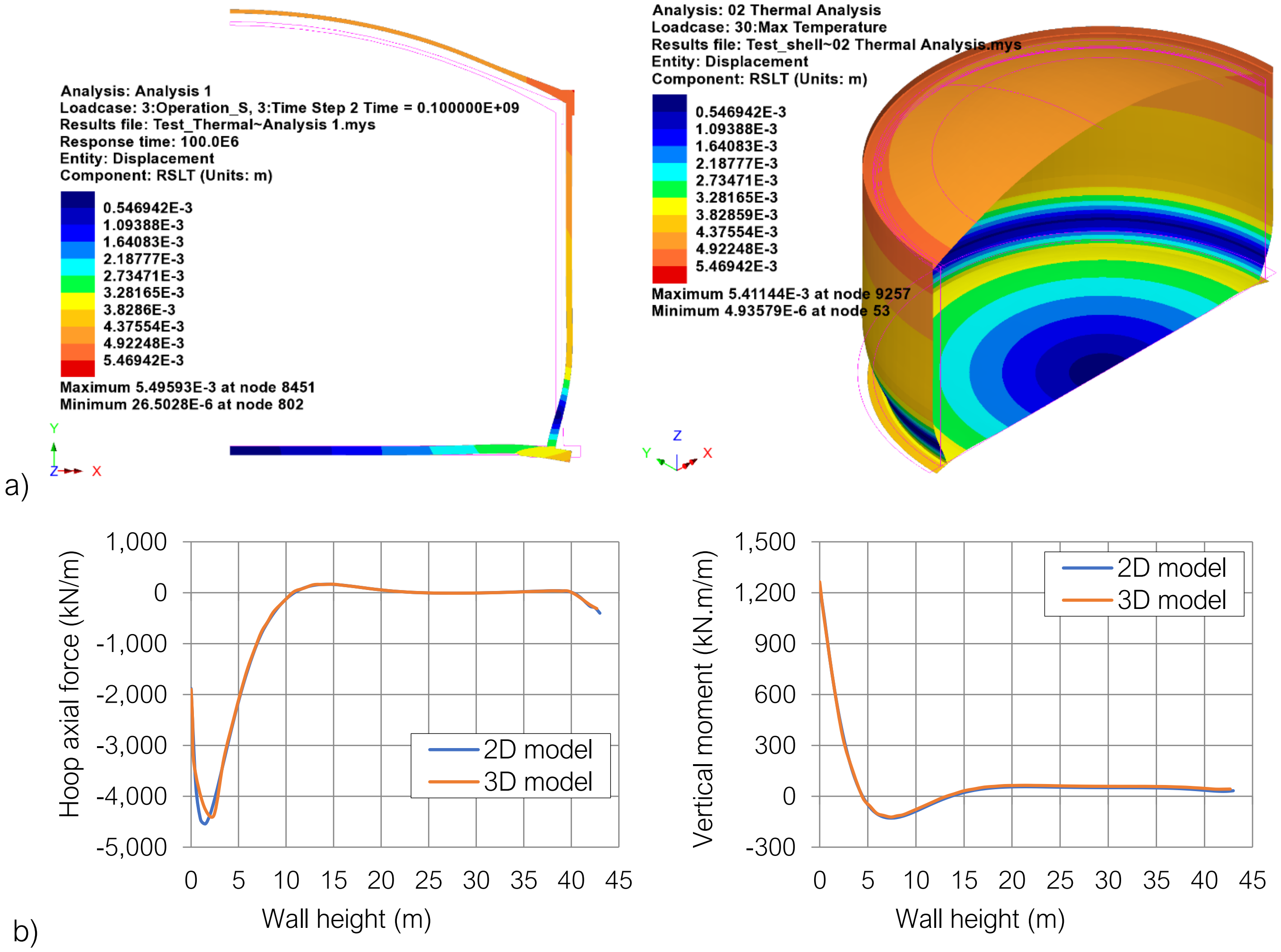


Figure 3 Thermal results comparison: a) deflections and b) wall axial forces and bending moments

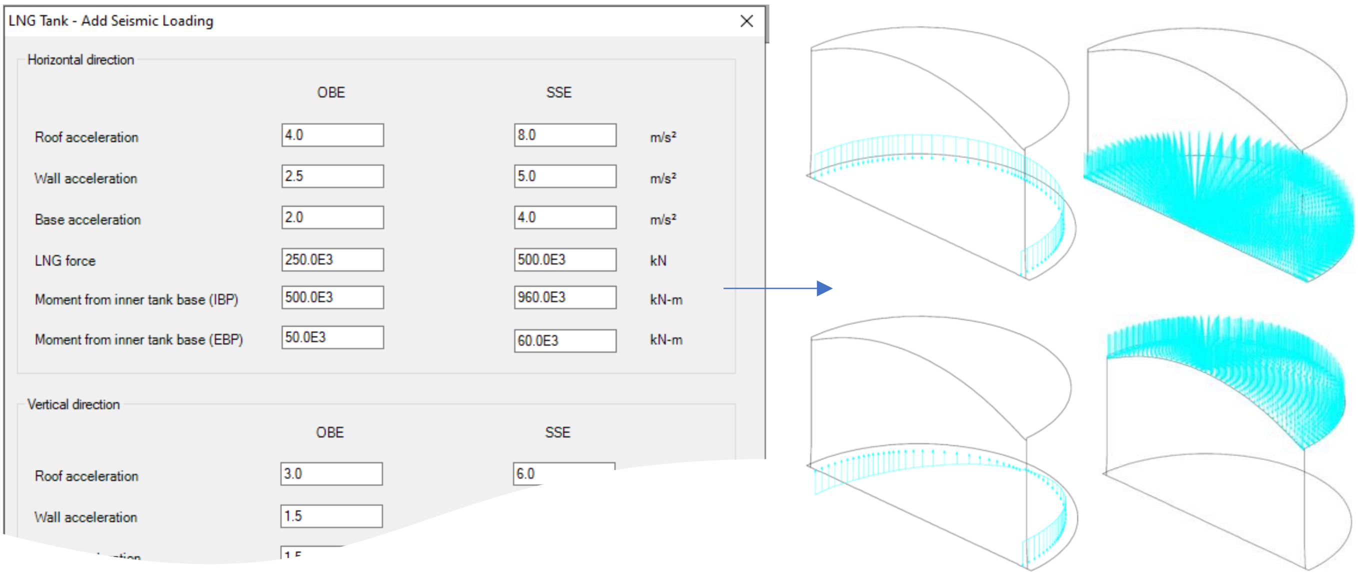
Combining 2D dynamic and 3D static seismic results

In order to capture the dynamic behaviour of the inner tank, outer tank, and foundation system, a seismic analysis that includes soil structure interaction (SSI) and fluid structure interaction (FSI) effects needs to be considered. Additionally, for base-isolated tanks, the dissipative capacity of the isolation system must be accounted for.

Complex dynamic analyses, including nonlinear and time-history analyses are usually required under earthquake conditions. In this context, a 2D lumped-mass beam-stick model that includes all major features of the tank under a simplified but accurate arrangement is a convenient approach to obtain the peak inertial and hydrodynamic effects from the seismic loading. The proposed lumped-mass model in the horizontal direction is based on the concept of using generalised single degree of freedom systems to represent the impulsive and convective modes of vibration of the tank-liquid system, according to the guidelines in Annex A of EN1998 [3] and ACI 350.3 [4].

While global results of peak accelerations for the concrete, steel and liquid parts are readily available in the 2D lumped-mass models, engineers will require detailed 3D stress distributions for the various parts of the outer concrete shell. The inertial and hydrodynamic peak effects obtained from the dynamic analysis can be transformed into equivalent pseudo-static loading for the 3D shell model. These loads include body force accelerations applied to the concrete mass and distributed loads and pressures on the inner tank and base.

The API developed in the LNG system not only generates the required 2D and 3D models, but also automates the process of seismic loading application on the shell model, as shown in Figure 4, facilitating the seismic evaluation which can be included as part of the design combinations within a single shell model.



LNG Tank - Add Seismic Loading

Horizontal direction

	OBE	SSE	
Roof acceleration	4.0	8.0	m/s²
Wall acceleration	2.5	5.0	m/s²
Base acceleration	2.0	4.0	m/s²
LNG force	250.0E3	500.0E3	kN
Moment from inner tank base (IBP)	500.0E3	960.0E3	kN-m
Moment from inner tank base (EBP)	50.0E3	60.0E3	kN-m

Vertical direction

	OBE	SSE
Roof acceleration	3.0	6.0
Wall acceleration	1.5	

Figure 4 – Equivalent pseudo-static seismic loading on 3D shell model

Combining staged construction, creep and shrinkage

The construction sequence of concrete tanks follows a pre-defined number of activities common to most cases. These activities include, but are not limited to the following:

1. Foundation and base slab construction.
2. Casting of wall in incremental segments. Temporary wall openings are included for access of personnel, equipment and materials.

3. Casting and partial prestressing of the top ringbeam.
4. Air lifting of the roof steel liner, frame and suspended deck, anchorage to the ringbeam, followed by complete prestressing of the ringbeam.
5. Casting of the concrete roof in sequential pours.
6. Prestressing of the tank horizontally and vertically, excluding the opening areas.
7. Construction of the inner tank, hydrotesting and other testing operations.
8. Closing of the temporary openings, final prestressing and installation of ancillary structures.
9. Final commissioning of the tank for operation.

The overall construction will generally take more than one year for larger tanks, resulting in a particular load history that will have implications on the tank stresses for the final condition. Moreover, temporary conditions such as the open-topped tank (i.e. no roof), the testing stages and the wall with access openings can prove critical to meet the strength and serviceability requirements.

In addition, concrete tanks exhibit time and load dependent stresses due to restrained shrinkage and creep strains. Specialised material models available within the LUSAS software can automatically cater for these additional stresses based on proposed equations from codes of practice such as EN1992 [5] or fib Model Code 2010 [6]. A viscous analysis in the time domain will allow engineers to capture the complex distribution of stresses across the tank due to these effects and their evolution from the initial stages of the tank construction to the long-term condition.

In the past, a simple approach involving hand calculations of peak shrinkage and creep strains for different parts of the tank, which were uniformly applied as external loads, was frequent practice. In this following novel approach, the limit state philosophy from the codes is followed while ensuring the creep and shrinkage effects are not overly simplified and therefore underestimated.

The shell model developed by the LNG system automatically considers the staged construction analysis with the pre-defined schedule, both with and without creep and shrinkage effects. With this approach, basic combinations can be established that will isolate the effects due to creep and shrinkage alone, which are required for the superposition of effects in the context of SLS and ULS design combinations. Although theoretically the results of the viscous analysis are nonlinear, the isolation of creep and shrinkage effects and subsequent linear superposition in the design combinations is a reasonable assumption.

Moreover, the staged construction analysis for the temporary conditions is part of a single model which coexists with other loading conditions for the as-built configuration, such as wind, seismic, or thermal, providing an integrated solution for the structural verification of the tank.

Concrete capacity checks

Reinforced and prestressed concrete members are subject to design verifications that involve sectional strength checks under SLS and ULS combinations. Among others, these include axial force – moment interaction, shear resistance, maximum crack widths and maximum stresses [5].

Traditionally for LNG tanks, these checks have been done by extracting forces and moments results from the different FE models and performing design check calculations in separate spreadsheets. The manipulation of results required to manage the complexities of the reinforcing steel arrangement and the different tendon stressing stages is time-consuming and cumbersome. With the inclusion of the design checking inside the FE model, these aspects of LNG tanks concrete members are automatically considered, and the design checks values can be represented conveniently in the graphical interface using contour plots over the whole tank geometry.

Mixed reinforcement orientation

For the purpose of section capacity checks, slabs and walls can, under certain circumstances, be regarded as beams in two independent directions (one-way slabs) as specified in Section 9.1 and 9.4 of GB 50010 [7]. Therefore, the effect of twisting moments or in-plane shear forces has usually been ignored when extracting design load effects in the tank components.

Axial, shear and bending effects have been obtained from shell results assuming two principal directions aligned with the reinforcement arrangements. While the cylindrical walls have a regular pattern of reinforcement aligned with the hoop and vertical directions, the base slab and the roof dome include variations in the reinforcement orientation from crosswise at the central areas to hoop / radial in the outer parts.

Results for the shell elements in the FE models are provided in a per unit width basis and for two orthogonal directions, following the rebar arrangements. Hence, forces and moments are obtained using a transformation of results according to local directions, which follow the rebar patterns. Global coordinate system (X, Y, Z), cylindrical coordinate system (r,t,z) and spherical coordinate system (r,t,p) are used as local directions. More details about the definition of local axes are provided in Table 1. It is noted that while cylindrical coordinates are adequate for the wall and base, spherical coordinates are enforced for the roof due to the domed shape.

Table 1 – Definition of local axes for shell results

Tank part	Local x	Local y
Base	Global X for crosswise rebars, radial (r) direction for the rest	Global Y for crosswise rebars, hoop (t) direction for the rest
Wall	Hoop (t) direction	Vertical (z) direction
Roof	Aligned with Global X for crosswise rebars, hoop (t) direction for the rest	Aligned with Global Y for crosswise rebars, polar (phi, p) direction for the rest

By using pre-defined results transformations generated by the LNG system, the post-processing of such a variable set of results orientation is automated and available within the graphical interface of the FE model and the results export facilities, as shown in Figure 5.

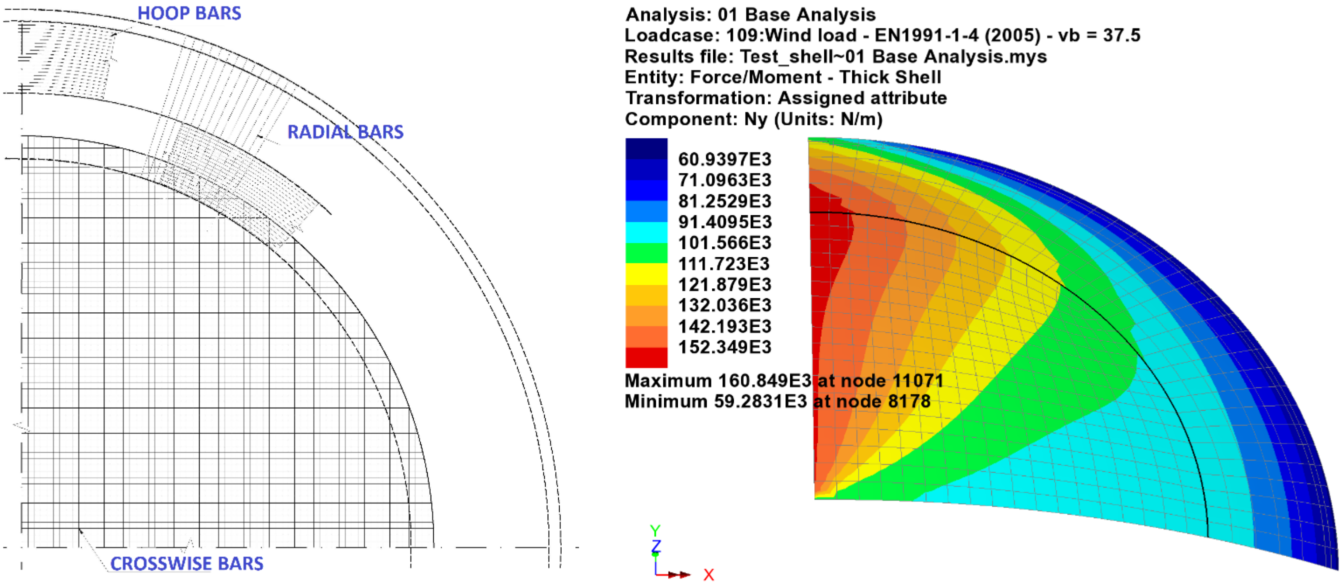


Figure 5 Roof example of rebar arrangement and shell results

Staged prestressing

The presence of prestressing tendons within the cross-section of the concrete wall affects the ultimate capacity calculations, especially for the axial force – bending moment interaction checks. These checks are conducted based on strain compatibility and equilibrium equations of the cross-section, and therefore the tendons effect must be accounted for.

As described for the typical construction sequence, tendons in the post-tensioned concrete wall are stressed at different stages. In particular, the following prestressing stages are critical during design verifications:

- Open-topped tank. Horizontal tendons are only stressed within the ringbeam.
- Complete tank with temporary openings. Tendons are only stressed away from the opening areas. Stressed tendons are considered to have experienced only short-term losses.
- Complete tank under operation conditions. All tendons are stressed and subject to long-term losses.

The design combinations prescribed by codes of practice can include hundreds of cases, some of which will pertain to the "construction" (open-topped), "testing" (tank with openings and short-term losses) and "operation" (final configuration, long-term losses) stages. While engineers can manually try to identify each combination and apply the correct cross-section properties to perform the design verification, it is a tedious process which can result in mistakes or complex spreadsheets arrangements. Using minimal input from the user when setting up the model, the API can label each combination appropriately and output design checks in a systematic manner for every combination, with consideration of the stage category.

Design process efficiency

There are multiple advantages in developing an API that automates the analysis and design of LNG tanks, including efficiency, accuracy, limitation of mistakes and reduction of engineer's time. With the systematic approach enabled by the LNG system, the overall design process is streamlined, from conceptual stage to the final detailed design, simplifying the design iterations and allowing for output customisation.

Structural design optimisation

The developed LNG wizards automatically create the multiple models required and provide design checks under various analysis conditions. The LNG system stores all input data within a comprehensive "tank definition" tool, which allows reusing of data for fast generation of multiple models.

With this tool, engineers can perform multiple iterations at preliminary stages of the design to produce an initial tentative geometry, based on selective design checks considered critical. For example, the 2D axisymmetric thermo-mechanical coupled model can be quickly generated to perform an initial spillage analysis, before progressing into a complex 3D solid model. The 2D model can be used to verify whether the proposed prestress design complies with the liquid-tightness requirements. Likewise, at later stages of the design, if a code requirement is not met, the user can quickly recreate the models if necessary after performing the required changes, repeat the analyses and proceed with the results extraction, all in an automated and efficient way.

More importantly, structural optimisation becomes easier by allowing engineers to quickly test different tank configuration options. Engineers can change input data in the tank definition such as tank shape or tank member sizes, generate the models via the wizards and perform initial design checks to evaluate adequacy. Companies can spend more time on research and innovation to design more sustainable, material-efficient and cost-effective tanks. For example, an engineer might compare a tank solution which includes tapering of the wall, versus a tank with constant thickness, using the same set of data and based on the same post-processing facilities provided by the LNG system.

The design iteration process is shown in Figure 6, where the tank definition is used by the wizard to generate the relevant models, and the available post-processing tools permit section capacity evaluation. The tank definition can then be adjusted, and the process repeated again.

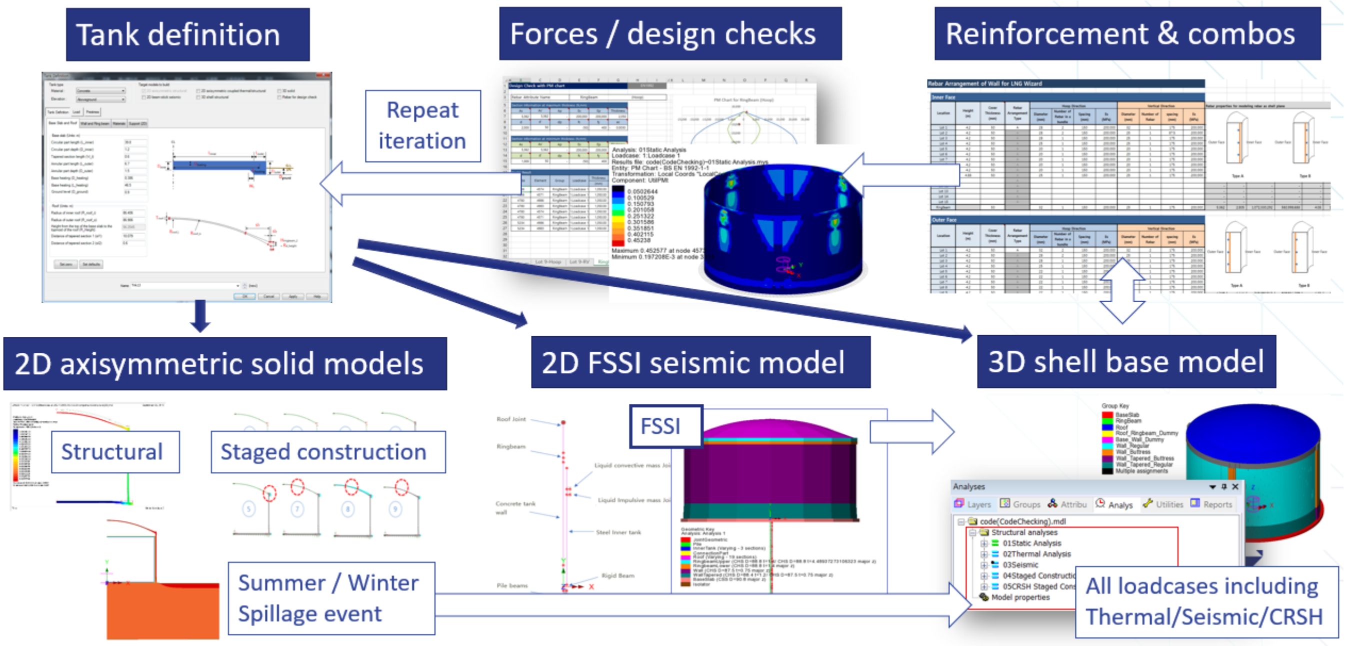


Figure 6 Design iteration process using API tank definition, model generation and design tools

API customisation

The LNG system provides engineers with comprehensive output options, including summary reports, graphs and contours, with consideration of the mixed reinforcement directions and magnitude and location of prestress at each stage. It also aids in the generation of multiple design combinations.

Engineers with basic programming knowledge can customise the LUSAS open API to create specific user defined features required, extract results and combine them with speed and accuracy in the desired format.

Some companies might have developed in-house dedicated spreadsheet computations for LNG tanks, based on their standardised approach to tank checking and reporting. At the same time, they might require additional computations for a particular project, satisfy a special requirement or consider a new code of practice. For all these cases, the API can interface between the software and the in-house application (e.g. MS Excel) by means of simple programming scripts so that the information is extracted and presented in the required format and including the desired results. While this task may seem daunting at first, adapting the existing tools to new requirements does not require expert programming skills and investing time in developing these scripts will usually pay off by reducing the engineer's time in the long term.

Time savings

Throughout this paper, advantages of using an automated API have been discussed, emphasising the reductions in time that can be achieved in the overall process of designing concrete tanks. Based on the experience drawn from past projects in using the LNG system, an attempt has been made to quantify reductions for certain tasks, comparing the typical engineer's times versus the time taken using the automated system. Table 2 assumes that the initial geometry and material properties are known and that there is no need to change these as the design progresses.

While the task durations are just a rough estimate based on past experience, it helps to identify how certain activities within the project can reduce the overall engineers' time by at least 30%, in a conservative estimate. The intuitive user interface also minimises the initial time required for learning and getting familiarising with the API.

Table 2 – Estimated time savings based on past projects

Task	Typical times (days)	API times (days)	Savings
Pre-processing of initial data	2	3	-50%
2D thermal analysis for operation conditions (summer/winter)	8	3	63%
2D dynamic analysis for seismic event (OBE/SSE; horizontal and vertical)	15	10	33%
3D shell analysis for operation conditions	12	8	33%
3D shell analysis for staged construction and creep and shrinkage	5	3	40%
Creating SLS and ULS design combinations in the shell model	2	1	50%
Extracting force and moment results from shell model	2	1	50%
Addition of thermal results to design combinations	2	0.5	75%
Addition of seismic results to design combinations	2	0.5	75%
Performing SLS and ULS checks with consideration of reinforcement orientation and tendon stressing	6	4	33%
Reporting of results	8	6	25%
Total	64	40	38%

Conclusions

Modelling and design automation programmes are commonly used for bridges and other structures, with an increasing demand to develop similar tools for LNG tanks and improve design efficiency. The specific challenges in modelling and design of concrete tanks are addressed by the developed LNG system, providing solutions that include:

- A series of wizards for building all the necessary models required for performing design checks, including 2D thermal, 2D static, 2D staged, 2D seismic, 3D shell, 3D staged, and 3D creep and shrinkage.
- Automated import of the thermal results and seismic results from 2D models which are used as loading in the 3D shell model. All design combinations can be generated in a single FE model, providing an integrated solution for all the design checks within a single FE model.

- Concrete section capacity checking that considers the rebar arrangement directions and the amount of prestress present at different stages, various design combinations and locations within the tank.
- Comprehensive design output options, including contour plots for the whole tank and design check reports in the engineering friendly spreadsheet format. All the details of the design check process including axial force - moment interaction charts and code specific design parameters for international codes of practice such as ACI [4], EN [5], GB [6][7] are generated in a single spreadsheet report for all the structural components such as roof, wall and slab.

The overall result of the above tools is an improved efficiency and accuracy for the design of LNG tanks, which can reduce engineers' time by at least 30%, allowing additional time for design optimisation and an overall reduction in engineering and construction costs.

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