FERROCEMENT WATER TANKS: NUMERICAL ANALYSIS AND EXPERIMENTAL RESULTS

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SUMMARY: The present work describes experimental and numerical tests for a 750000-litre ferrocement tank, part of the water treatment facility in Divinópolis, Brazil, in an attempt to further understand the mechanical behaviour of this low cost composite material in Sanitary Engineering applications. Aspects of the construction technique and its implications in the overall final structural response are discussed. Different finite element models have been used for the analysis in order to evaluate the effect of some adopted simplifications. A comparison of the investigated approaches is made, including remarks on the use of different constitutive material properties, homogenisation techniques and accuracy of the modelling data. Some experimental results, described in this paper, are used to access the accuracy of the models.

KEYWORDS: Ferrocement, Finite Elements, *In-Situ* Instrumentation, Water Supply Facility, Low Cost Material.

INTRODUCTION

Although ferrocement does not represent a new material, as it dates back to the middle of the last century, it continues to be an attractive alternative to reinforced concrete and steel structures. It has been used in several countries in structures such as boats, school buildings, water tanks, etc. The plastic potential, the unsophisticated construction techniques (requiring minimum of skilled labour) and the low cost justify its use, especially in developing countries. Nonetheless, modelling studies of this material are rare in the literature.

Historically the work of Jean Louis Lambot can be regarded as the first use of ferrocement in structural applications. In the middle of the last century he built ferrocement boats, water tanks and vessels in France. Later, during WWII, the Italian Pier Luigi Nervi revisited the technology for several structural concepts in civil engineering, including warehouses and complex roof structures. A review on the subject can be found in reference [1].

In spite of the initial concern in relation to ferrocement (reinforced concrete having a much better known behavior), progressively it is becoming common place in civil engineering solutions. Nowadays it is usual to employ ferrocement in thin (membrane-like) structures and a number of examples can be found in Brazil [2,3]. In the Brazilian state of Minas Gerais, large cylindrical tanks, some with a volume of over 700 m^3, have been constructed, and a research co-operation program is currently being conducted between university and industry to improve current design practices, as well as to further advance in the understanding of the material. These tanks are used in some of the water treatment facilities of the "Companhia de Saneamento do Estado de Minas Gerais" (COPASA-MG). They started to be employed in 1991 in small-size water treatment plants. Around 50 plants using the technology are operational at the moment, each producing between 3 and 150 litres of treated water per second.

Ferrocement is characterised by the quantity and diffusion of the steel reinforcement. The closely spaced and the uniformly distributed armature turns the fragile cement mortar into a resistant composite, significantly different from the conventional reinforced concrete. Hence, ferrocement can be regarded as formed by a matrix (mortar) and layers of steel, adequately positioned. One of the main advantages is that it requires no formwork, which allows great flexibility to conceive, for example, double curvature thin surfaces shells, very complicated to build with standard masonry, reinforced concrete or steel. Due to the percentage in volume of steel (above 2.0%) and its specific surface (not less than 1.0 cm^2 per cm^3), it can undergo large deformations before cracking. However, for water retaining applications, it is a common practice to use some kind of plastic protective coating to enhanced leakage protection, as the even distribution of the steel bars can lead to microcracks in the mortar.

Figure 1 - Construction of ferrocement water tanks in Divinópolis, Brazil

One of the problems faced by anybody interested in ferrocement structural computations is the relatively poor knowledge about the material, including lack of reliable design and detailing tools and guidelines. Currently some empirical formulations are used, many based on procedures developed for reinforced concrete, hence over- or under-estimations in design are frequent. As far as the finite elements calculations for composites is concerned, different formulations and elements are available. The difficulty is to choose the correct modelling strategy for the particular case of a ferrocement structure. Approaches such as the use of

layered elements (with separated layers of steel and cement mortar), the homogenization techniques (volume-weighted average of the materials) and the use of the composite properties (direct experimental results) are possibilities that can be considered. This paper investigates the most favorable option based on the FE results and its underlying hypotheses.

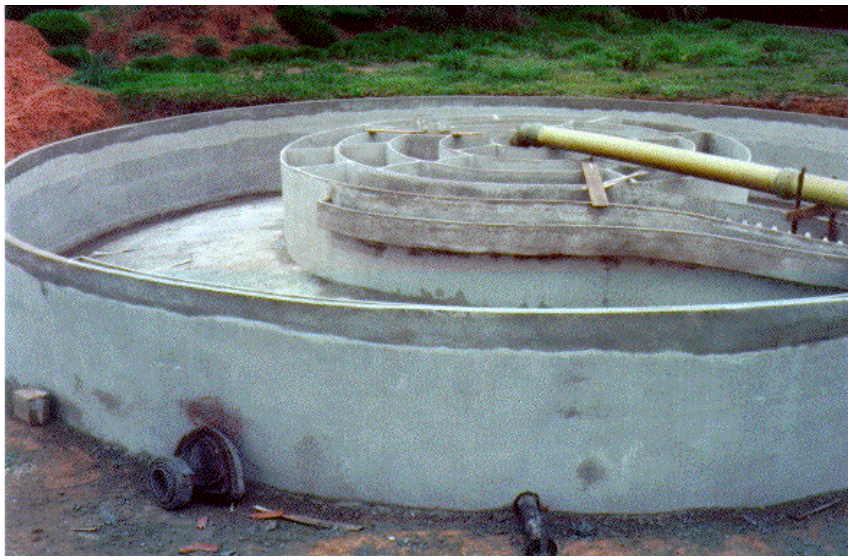

Figure 2 - Ferrocement water tank

FINITE ELEMENT MODELS

Different modelling approaches were used for the analysis of the tank, which was instrumented for the evaluation of the structural response when subjected to water pressure. In the first approach, the tank was modelled as an axisymmetric solid with material properties obtained directly from laboratory tests of ferrocement specimens in tension. In another model, axial symmetry was also taken into account, this time with each material considered independently. The steel was substituted by a compact layer of equivalent thickness, and the mortar with properties based on measurements obtained in the laboratory for compression. Two other models were used: one with a five-layer laminated shell element simulating the different material components and the other with a homogenised equivalent material, with mechanical properties obtained experimentally for each different steel volumetric participation. The models are described below, and shown in Figure 3. The analyses were performed using the LUSAS Finite Element System [4].

First approach – Axisymmetric solid elements

Two models using axisymmetric solid elements were applied in the analysis of the tank. In the first model, an orthotropic material was used with the ferrocement properties obtained directly from the experimental testing. The wall of the tank was divided into 3 parts along the height, depending on the density of steel wire meshes. An extrapolation from the experiments allowed for the calculation of the steel contribution in the mechanical properties in each part.

The second model used a layered approach in which the wire meshes were substituted by an equivalent steel membrane whose thickness was computed from the total amount of steel. The steel was then placed in two layers. The cement mortar was placed in the remaining wall. Due to limitations in the chosen axisymmetric membrane elements, this model can only be analysed using an isotropic material.

Second approach – Semi-loof shell elements

The second alternative employed in this work was the use of shell elements. Again two models were applied. The first one considered the same orthotropic material used for the axisymmetric solid model. Once again 3 regions for the tank wall were modelled using the experimental data. Only a section of the tank was discretised due to the axisymmetry.

A more elaborated model, with layers, was also used in conjunction with the shell elements. In this case the wall was thickness sub-divided into 5 layers where steel and cement mortar were discretised separately. The thicknesses of the steel layers were computed based on the total volume of the wire meshes. Again the steel was placed in two layers, separated by a central cement mortar layer and covered by two other mortar layers. Unlike the axisymmetric model, orthotropy was applied at the layers.

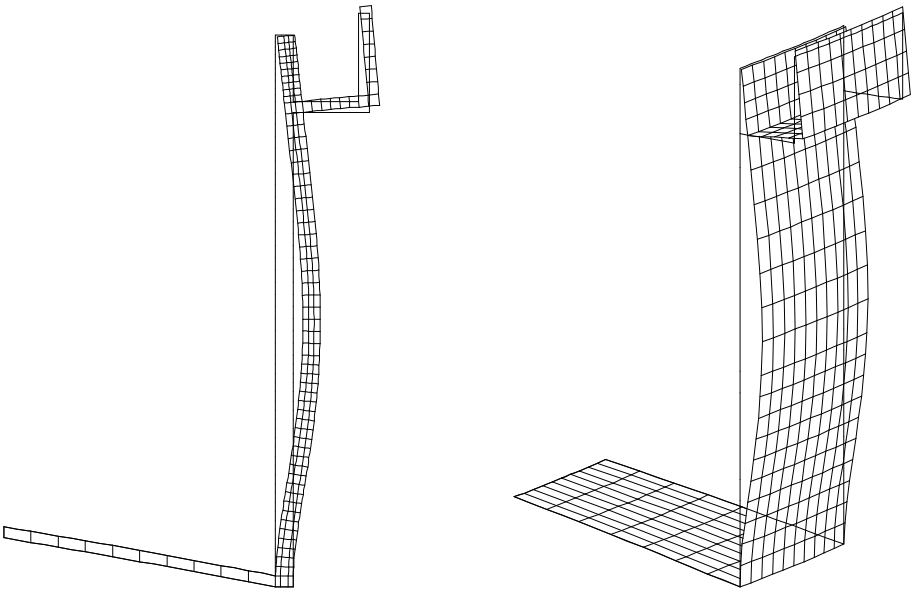

Figure 3 - Axisymmetric and semi-loof shell models: discretisations and deformed configurations

EXPERIMENTAL VERIFICATION

Strain measurements were performed in 42 points while filling the tank. The mechanical properties obtained in the laboratory were Young's Modulus and Poisson ratio in compression of the mortar and the same parameters in tension for the composite, using standard testing procedures.

One millimetre strain gauges type QFLK-1 (manufactured by TLM) were used, installed in the steel wires. First, the gauges were attached to 20cm x 20cm patches of the steel wire mesh. The surfaces were prepared, and the gauges attached with special glue. After welding the cables at the terminals, isolation was made, as well as protection against humidity and impact by applying wax, epoxi and high fusion tape. Two devices were installed in each set of wires, one in the horizontal, the other in the vertical position. This set of wires after instrumentation was called "sensor". The installation of the sensors in the tanks was done after construction. This required to make a cut in the walls and steel, in a depth that allowed the welding of the sensors. The 40 gauges were connected to two data acquisition systems with protected wires

to avoid interference, one with 16, the other with 32 channels. The system allows readings in real time with frequencies up to 600 Hz per second.

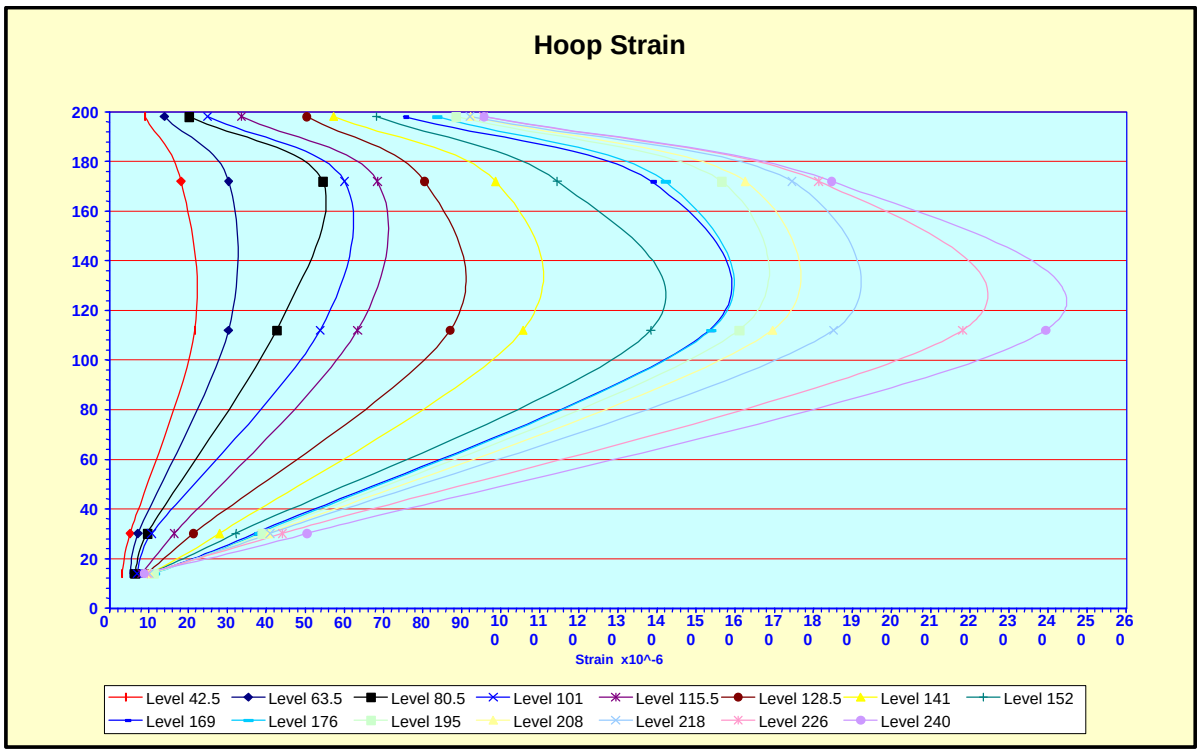

Figure 4 – Evolution of hoop strain for different water levels

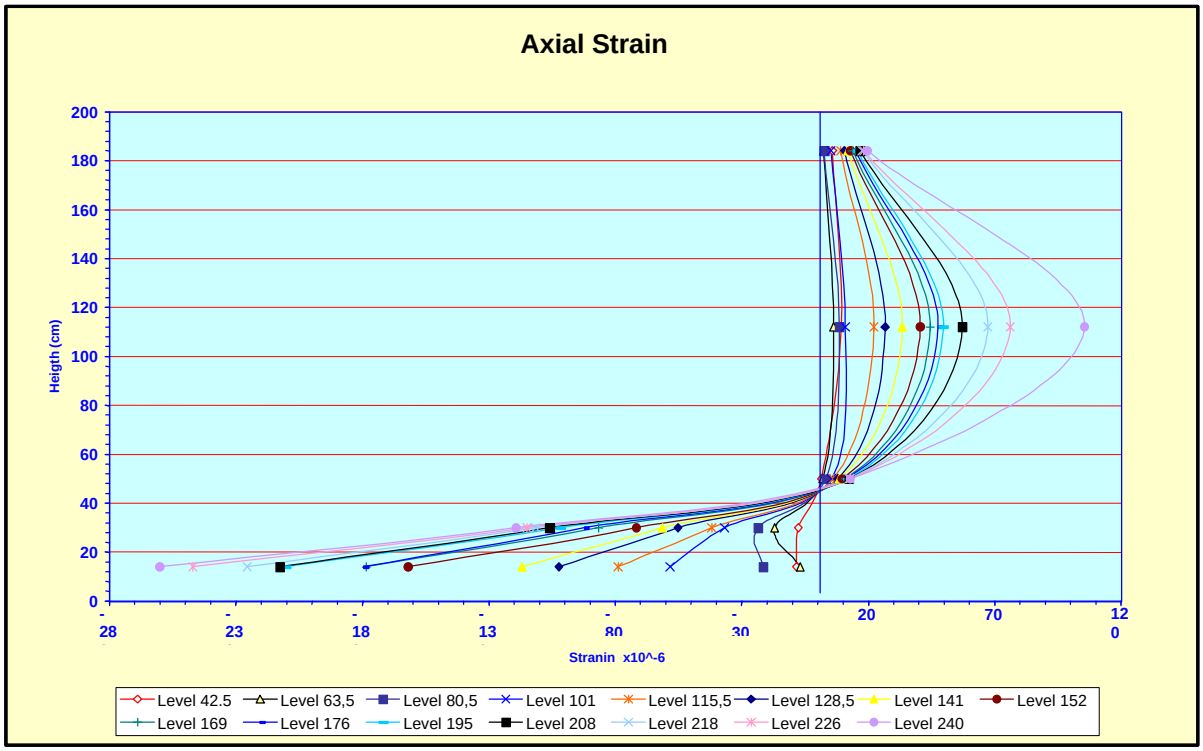

Figure 5 – Evolution of axial strain for different water levels

The determination of the load, function of the water level, was done using a graded rule, attached to the walls were the sensors had been installed. The predicted flow for filling the tank was 86.5 l/sec. The strain gauges registered readings each tenth of a second in real time. Events were defined to have the measures registered every 15 minutes.

After the treatment of the obtained data, including filtering to avoid perturbation, the load versus strain graphics were obtained (Figures 4 and 5) to be compared to the numerical analysis. During the laboratory tests for the characterisation of the composite it was possible to draw the graph shown in Figure 6, based on the technological states in relation to permeability as proposed by Walkus [5] for the ferrocement, for different numbers of steel wires.

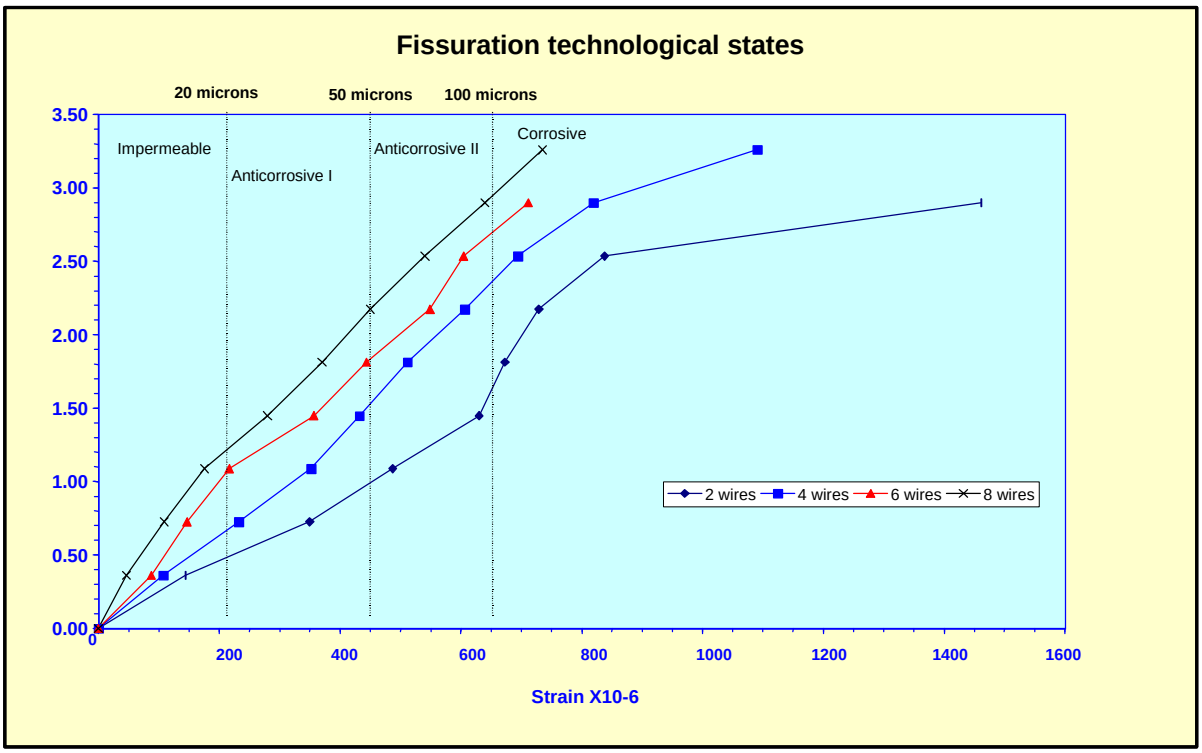

Figure 6 - Permeability variation with stress and number of steel wire meshes

NUMERICAL AND EXPERIMENTAL RESULTS – SOME COMPARISONS

Figures 7 to 10 show comparisons between the numerical results obtained by the different strategies of analysis used in this work. In Figure 7, the homogenised materials are compared, with the shell model slightly stiffer that the axisymmetric. It should be noted that the former model has 5051 degrees of freedoms, while the latter only 1496. The mechanical properties for the composite were obtained in a tension test, as described before.

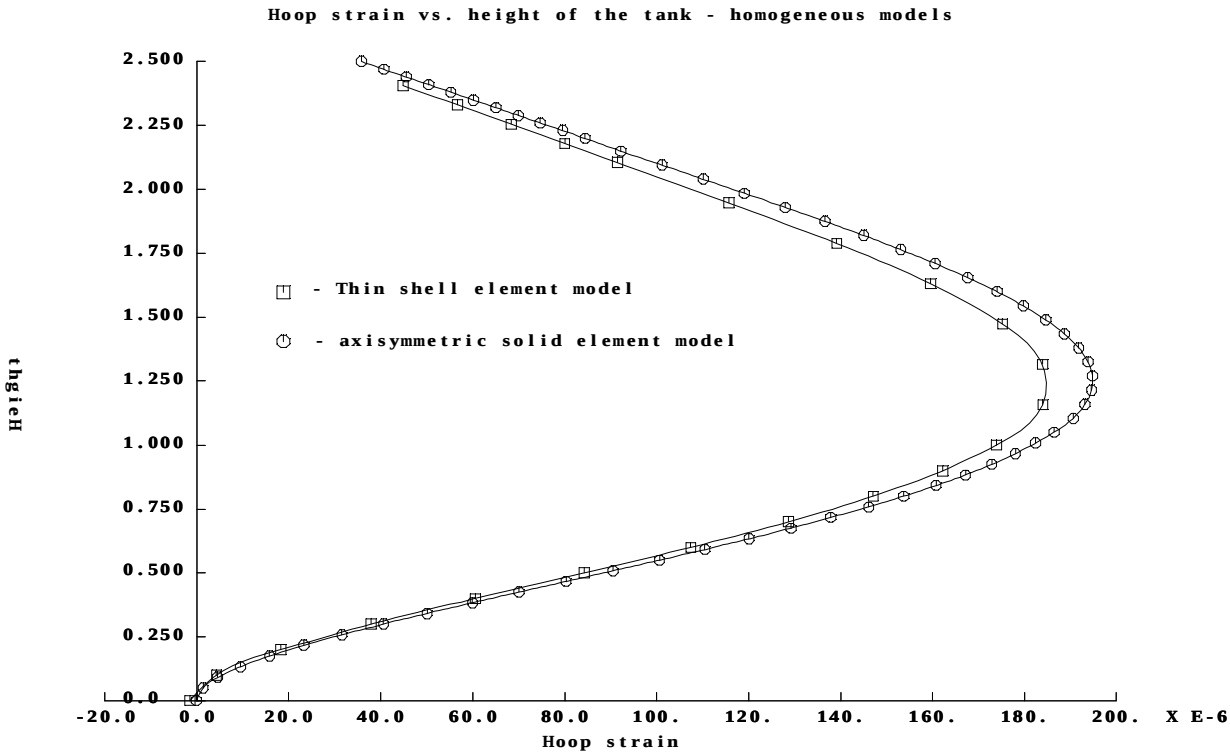

Figure 7 – Homogeneous FE models: Hoop strain

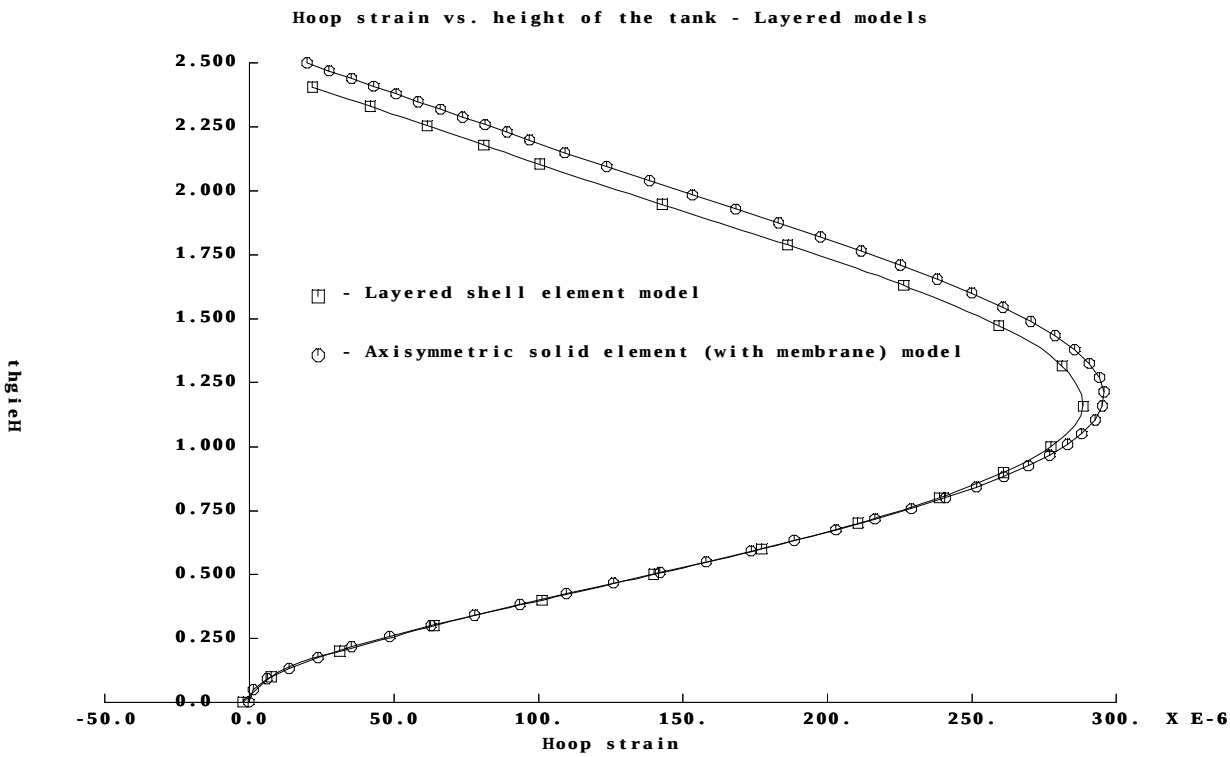

Figure 8 – Layered FE models: Hoop strain

Next, the layered models are shown in Figure 8. Again the results match very well and the additional work in constructing the mesh and processing the shell model is not justified for the description of the overall structure behaviour. The computational effort when considering layered shell models is approximately proportional to the number of layers. The results in

Figure 9 and 10 for the axial strain follow the same pattern as discussed above for the two pairs of models.

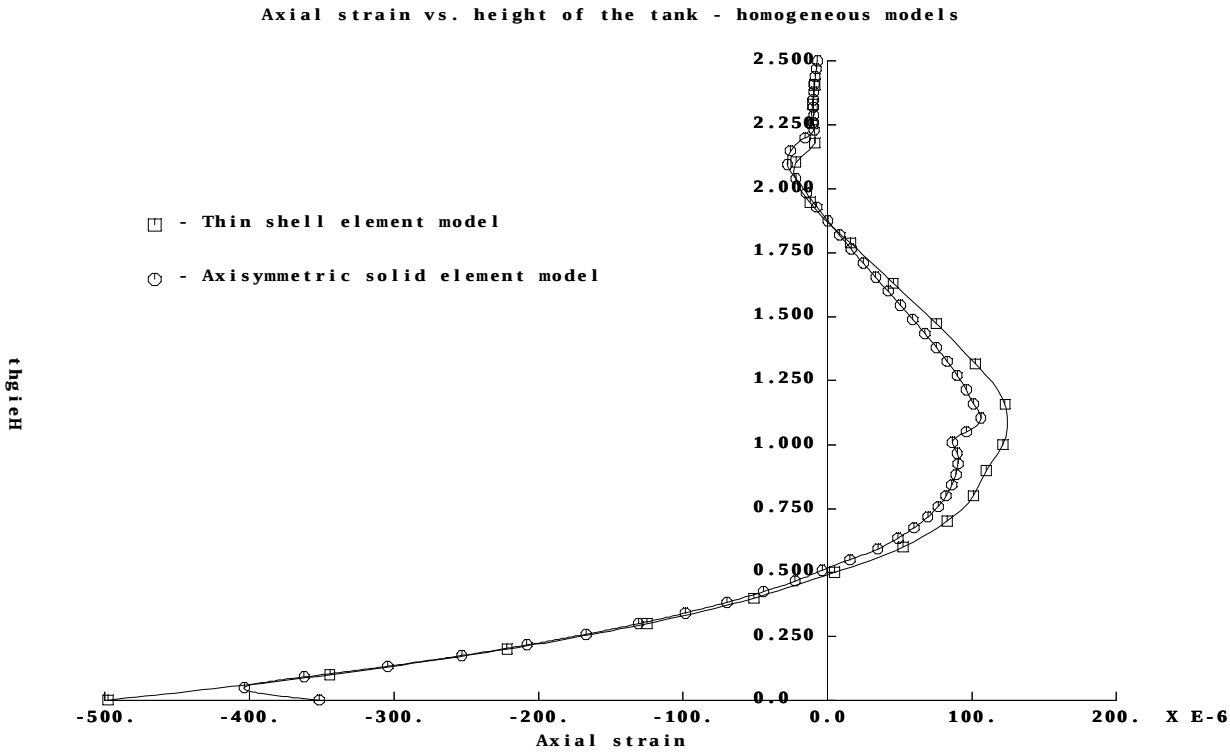

Figure 9 – Homogeneous FE models: Axial strain

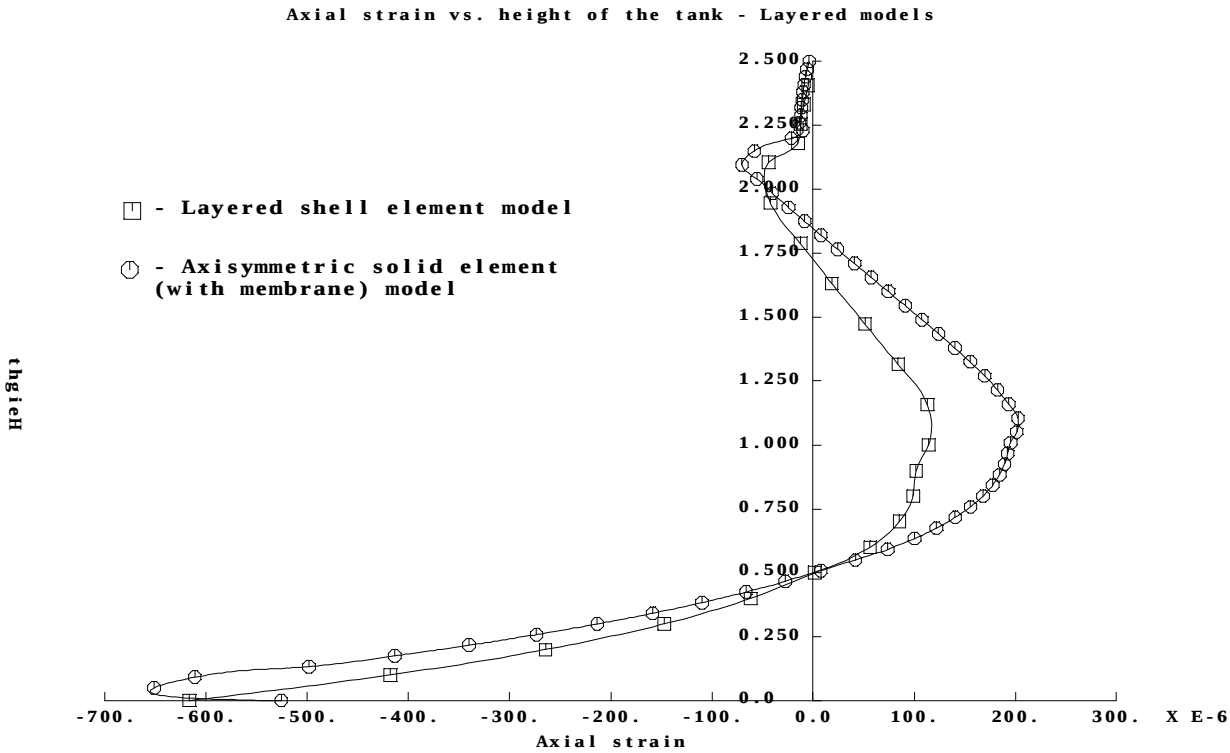

Figure 10 – Layered FE models: Axial strain

In Figure 11, the experimental results are compared with the layered and homogeneous models. The homogeneous models for the tank are more conservative, with difference in the

peak hoop strain reaching 25% when compared with the experiments. The same tendency is observed in the results for axial strains shown in Figure 12. The peak strains fall into the anticorrosive state (Figure 6) with a safety margin bigger than 2 for the corrosive state.

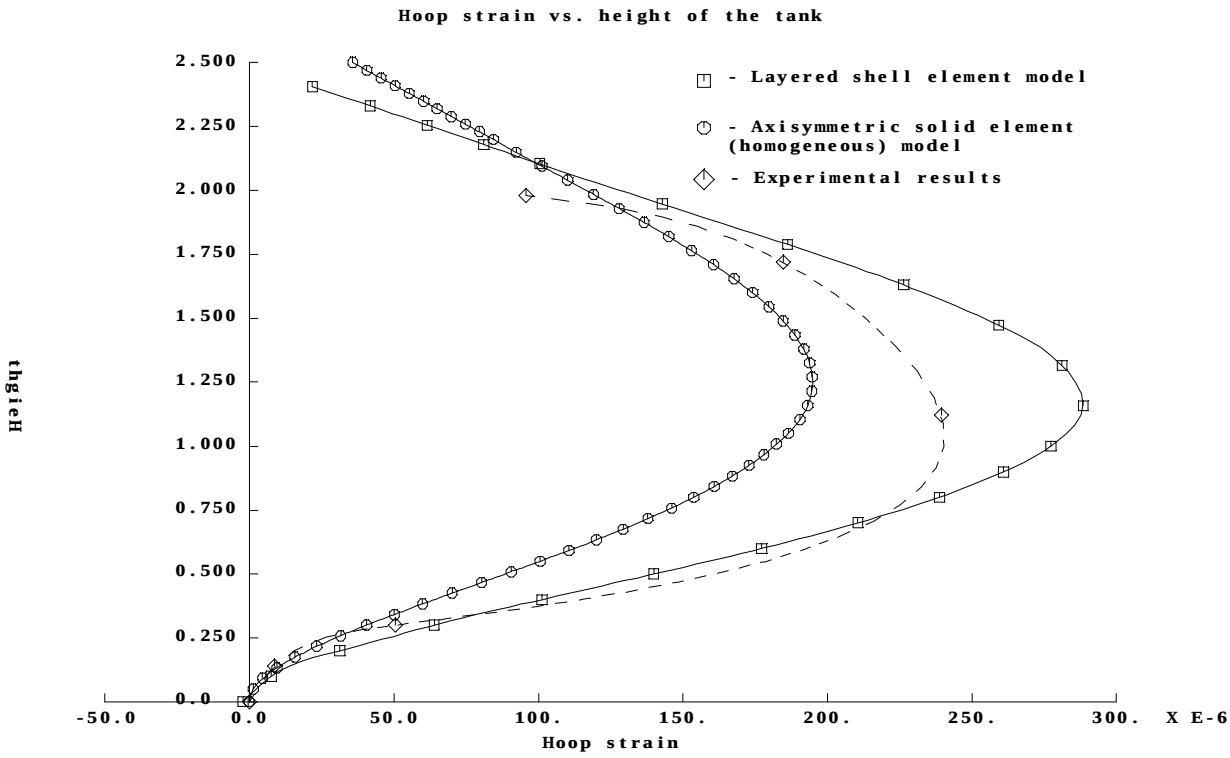

Figure 11 – Hoop strain: Comparison of the different results

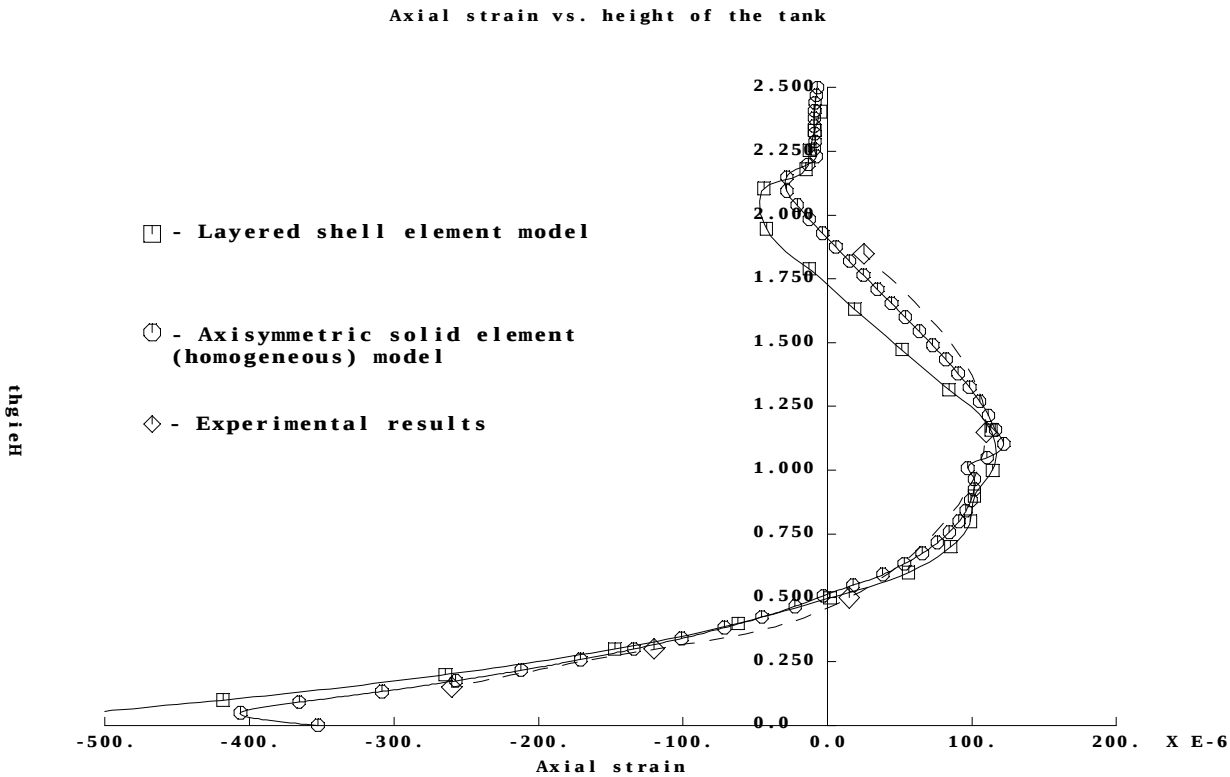

Figure 12 – Axial strain: Comparison of the different results

FINAL REMARKS

The construction techniques used in the construction phase, for the sake of simplicity, do not guarantee that geometric parameters, such as a constant wall thickness, agree with the project. *In situ* verification has shown that the thickness indicated in project was exceeded in many places. The mechanical properties are also not homogeneous, as it depends on the skill of the particular worker, mortar density, drying conditions, and little verification at work site is performed. The discrepancies between numerical and experimental results demonstrate that, in view of the uncertainty of the data, a very sophisticated model is not justified. Further research is needed in order to generalise the conclusions for this tank to ferrocement structures.

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