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Experimental and numerical analysis of large ferrocement water tanks

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Abstract

In the current work the ferrocement construction technique is revisited with the purpose of applying the material in civil engineering structures, particularly in large water tanks for water treatment stations. Although it is not a new technology, ferrocement continues to be an attractive alternative. The plastic potential, the unsophisticated construction techniques and the low cost justify its use, especially suitable for developing countries. However, modelling studies of this material are rare in the literature; this is what justifies the studies currently being conducted to improve current practices of design, as well as to further advance the understanding of the material. This work describes experimental and numerical tests for large ferrocement tanks, part of the water treatment facility in Divinópolis, Brazil. Different finite element models have been used in the analyses in order to evaluate the effect of some adopted simplifications. Some comparisons of the investigated approaches with the experimental data are also included, as well as remarks on the use of different constitutive models, homogenisation techniques and accuracy of the modelling data.

Keywords: Ferrocement; Finite elements; In situ instrumentation; Water supply facility; Low cost material

1. Introduction

Ferrocement is usually employed in thin walled structures constructed of cement mortar reinforced with layers of continuous and relatively small diameter steel wire meshes. Its main characteristic is the quantity and dispersion of the steel reinforcement. The closely spaced and uniformly distributed reinforcement turns the fragile cement mortar into a resistant composite, significantly different from the conventional reinforced concrete.

One of the main advantages of ferrocement is that it requires no formwork, which allows great flexibility to conceive and allows it be fabricated into very general shapes, some 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 <1.0 cm^2/cm^3), it can undergo large deformations before cracking. However, for water retaining applications, it is common practice to use some kind of protective coating to enhanced leakage protection, as the even and closely spaced distribution of the steel bars can lead to microcracks in the mortar.

Ferrocement continues to be an attractive alternative to reinforced concrete and steel structures in a number of specific situations. The material has been used in several countries in structures such as boats, school buildings, water tanks, etc. [1]. The plastic potential, the simple construction techniques (requiring minimum of skilled labour, Fig. 1) 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 1848 he built ferrocement boats, water tanks and vessels in France. Later, during the Second World War, the Italian architect Pier Luigi Nervi revisited the technology for several structural concepts

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Fig. 1. Construction of ferrocement water tanks.

Fig. 2. Ferrocement water tank in Divinópolis, Brazil.

in civil engineering, including warehouses, aircraft hangars, boats and complex roof structures. (A review on the subject can be found in Refs. [1,2].) In relation to ferrocement usage for small-capacity water tanks, some recent applications of ferrocement have been reported in Cuba [3], Bangladesh [4] and India [5].

In spite of the initial concern regarding ferrocement (reinforced concrete having a much better known behaviour), progressively it is becoming commonplace in civil engineering design solutions. Nowadays it is common to employ ferrocement in thin (membrane-like) structures and a number of examples can be found in Brazil [6,7]. In the Brazilian state of Minas Gerais, large cylindrical tanks, some with a volume of over 700 m^3 (Fig. 2), 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, with capacity ranging from 3 to 150 l of treated water per second.

The water treatment plant in Divinópolis was inaugurated in June 1998, and it is the largest of its kind built in ferrocement in Latin America. The construction costs were reduced to 30% of a conventional reinforced concrete solution. In this work, two water tanks were chosen to be monitored during operation, in order to access the best approach to model such structures using the finite element method, as described in the remaining of the text.

Due to the relatively poor knowledge about the material, including lack of reliable design and detailing tools and guidelines, structural computations in ferrocement still represent a major problem. Empirical formulations are often used, many based on procedures developed for reinforced concrete; hence, over- or under-estimations in design often occur. 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 homogenisation techniques (volume-weighted average of the materials) and the use of the composite bulk material properties (direct experimental results) are possibilities that can be considered.

Therefore, the main objective of this paper is to present the results obtained in the investigation of the ferrocement application in water treatment plants in Minas Gerais, Brazil. Alternative approaches, all based on the FE results and its underlying hypotheses, are shown. The research also encompasses aspects such as the construction technique and its implications in the overall final structural response. A number of experimental results are used to access the accuracy of the numerical models employed.

2. Geometry and material characterisation

The analysis was performed for a typical tank in the water treatment plant, with a diameter of 20 m and height of 2.68 m. The wall thickness was 8.0 cm. The steel volumetric ratio ranged from 1.08% to 2.03% in the bottom, for the hoop direction, and from 1.08% to 1.62% in the vertical direction. The specific surface ranged from 0.5 to 0.94 cm^2/cm^3. Two types of welded steel wires meshes were used: PB 196 and EQ 98. The former is composed of a grid of 2.56 mm diameter wires, spaced by 5.0 cm, whilst the latter has 3.0 and 5.0 mm wires in orthogonal directions, spaced by 20 and 10 cm, respectively. The steel grid is welded and not galvanised. Note that, due to the wall thickness and the amount of reinforcement involved, one can regard the tank as a "thin reinforced concrete" as much as a "thick ferrocement" structure. In fact, the tank can be classified as placed in the region between what satisfies the ferrocement criteria and what is considered reinforced concrete. Nonetheless, throughout this work the terminology ferrocement is used.

The mechanical properties of ferrocement have been the subject of a number of previous studies [8–13]. In this work, four series of tests were carried out to determine Young's modulus and Poisson's ratio for the mortar in compression yield stress for the mortar matrix in tension and Young's modulus and Poisson's ratio for the composite in tension.

(a) *Mortar under compression:* Standard compression tests indicated the average values of $E = 11383$ MPa, $\nu = 0.20$ and a compressive strength of $f_{cj} = 25.40$ MPa.
(b) *Mortar under tension:* The specimens were prepared with the following dimensions: diameter = 10 cm and height = 30 cm, and the Brazilian test was carried out. The tensile strength was calculated using (1), resulting in an average value of $f_{ct} = 1.75$ MPa

$$f_{ct} = 0.85\frac{2F}{\pi dL} = 0.55\frac{F}{dL} \quad (1)$$

(c) *Composite under tension:* As shown in Fig. 3, $6 \times 23 \times 31$ cm^3 specimens, with 2, 4, 6 and 8 steel meshes, were used. The strain gages were attached to one of the steel wires located at the centre of the piece, far from the point of application of the load. The wires were protected and connected before the introduction of the mortar. The strain was then measured in the elastic range, following the assumption that, under constant stress, the deformations at each point would be the same for the mortar and steel wires, before the crack initiation.

In order to determine the variation of the elastic modulus with the percentage of steel reinforcement, the obtained stress–strain curves for different percentage of reinforcement was plotted, determining the values of E for six different specimen with increasing volumetric steel participation. The E versus steel percentage curve was then generated using linear regression.

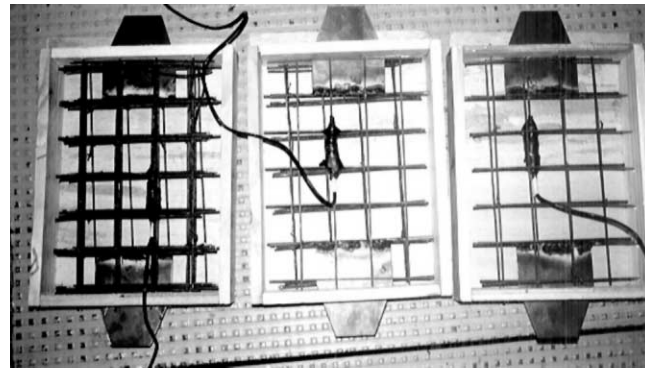


Fig. 3. Formwork for 2, 4 and 6 steel meshes specimens.

After curve fitting the results for E for the linear elastic range (to be classified later in this item as anti-corrosive I), Eq. (2) was obtained, where the Young's modulus is given as a function of the ratio between steel and mortar areas (A_s and A_m, respectively) in a cross-section of the composite.

$$E = -1242.9\left(\frac{A_s}{A_m}\right)^2 + 6348.9\left(\frac{A_s}{A_m}\right) + 502.52 \quad \text{(MPa)} \quad (2)$$

A comparison of the values given by Eq. (2) with standard estimates can be performed, based on the expression given in Ref. [14]:

$$E = v_1 E_1 + \mu v_2 E_2 \quad (3)$$

where μ is the efficiency factor for the fibres, assumed here as 1; v_1 is the volumetric fraction of mortar; v_2 is the volumetric fraction of steel and E_1 and E_2 are the elastic modulus of the matrix and the fibre in tension, respectively. Note that, in the calculations, E_2 above was assumed to be 10% of the compressive value.

In the tank, where the steel volumetric rate ranged from 1.08% to 2.03%, the obtained values for the elastic modulus of the composite under tension using Eq. (3) compared reasonably well with the values given by Eq. (2), with a maximum difference of 25%.

Walkus [15] proposed limits on deformations and crack openings, based on the risk of corrosive attack on the steel (Table 1). During the laboratory tests for the characterisation of the composite it was possible to draw the graph shown in Fig. 4, based on the technological states in relation to permeability as proposed by Walkus [1] for the ferrocement, for different number of steel wires. In the first two stages, the composite could be considered as a homogeneous material, while in the third the steel would take all tension. Strain larger than 100 μm could result in corrosion of the steel mesh,

Table 1
Technological states

Regime	State	Crack opening (μm)	Strain × 10^{-6}
Elastic	No leakage	$w \leqslant 20$	$200 \leqslant \varepsilon$
Elastoplastic	Anticorrosive I	$20 \leqslant w < 50$	$200 \leqslant \varepsilon < 435$
Plastic	Anticorrosive II	$50 \leqslant w < 100$	$435 \leqslant \varepsilon < 645$
	Corrosive	$w \geqslant 100$	$\varepsilon \geqslant 645$

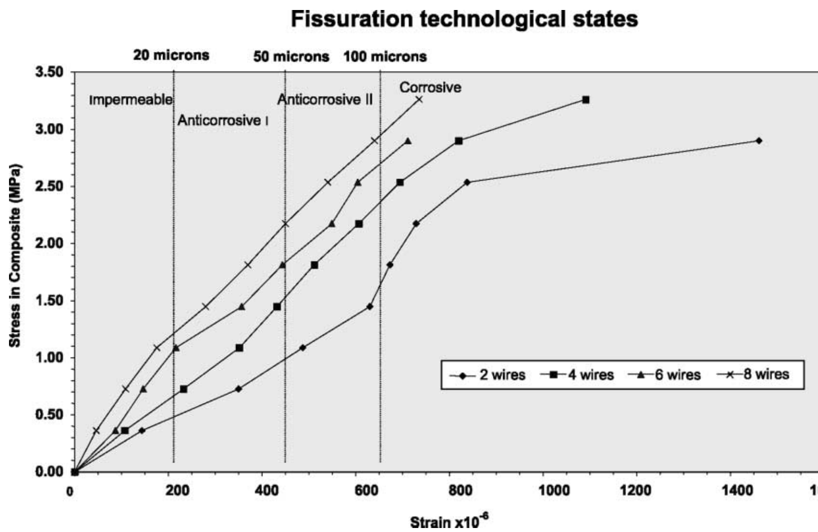


Fig. 4. Permeability according to the stress/strain in the composite and amount of steel wires.

leading to failure of the structure. The obtained data for strain in the composite is compared with these limits in that figure.

3. Experimental verification

Strain measurements were performed in 40 points while filling the tank. The mechanical properties obtained in the laboratory were Young's Modulus and Poisson ratio in compression for the mortar and the same parameters in tension for the composite, using standard testing procedures, as shown above (see [16] for further details.)

One millimetre type QFLK-1 strain gages (manufactured by TLM) were used, installed in the steel wires. First, the gages were attached to 20×20 cm^2 patches of the steel wire mesh. The surfaces were prepared, and the gages 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, epoxy and high fusion tape. Two devices were installed in each set of wires, one in the horizontal, and the other in the vertical position. This set of wires after instrumentation was called "sensor" (Fig. 5). The installation of the sensors in the tanks was done after construction. This required making a cut in the walls and steel, in a depth that allowed the welding of the sensors. Lines of sensors were installed in different positions in the tank wall. The original mortar mixture proportions were used in order to rebuild the wall.

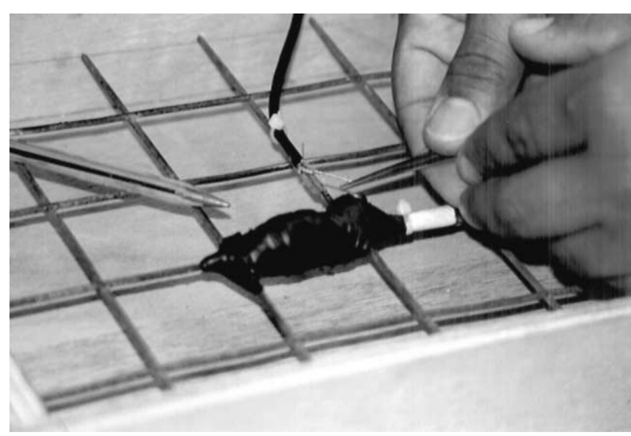


Fig. 5. "Sensor".

A total of 40 gages were connected, with protected wires to avoid interference, to two data acquisition systems, one with 16 and the other with 32 channels. The system allows up to 1000 readings per minute, in real time.

The determination of the load, function of the water level, was done using a graded ruler, attached to the walls were the sensors had been installed. The predicted flow for filling the tank was 86.5 l per second. The strain gauges registered readings each tenth of a second in real time. Events were defined to have the measures registered every 15 min [16].

In order to define the dynamic effects due to the water movement during the filling of the tanks, accelerometers were placed in the walls. The measurements have shown that no considerable dynamic effect could be observed; hence static loading was considered for the numerical analyses.

After the treatment of the obtained data, including filtering to avoid perturbation, the load versus strain graphics were obtained to be compared to the numerical analysis.

4. Numerical models

Different modelling techniques were used for the analysis of the tanks, which were instrumented for the evaluation of the structural response when subjected to water pressure. In the first approach, the tanks were 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. A compact layer of equivalent thickness substituted the steel, and the mortar was modelled with properties based on measurements obtained in the laboratory for compression. Two other models were also 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. Note that, taking into account the experimental data and the fact that the tanks were filled slowly, they were analysed using static loading only. The models are briefly described below, and shown in Fig. 6. In both models, the boundary conditions were imposed to simulate a rigid foundation, i.e., the tanks were fixed in the base (no translation allowed). The analyses were performed using the LUSAS Finite Element System [17].

4.1. Axisymmetric solid finite element models

Two models using axisymmetric solid elements were applied in the analysis of the tanks. 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 three parts along the height, in accordance with the changes on the steel wire meshes density. An extrapolation from the experiments allowed for the calculation of the steel contribution in the mechanical properties of the composite in each part.

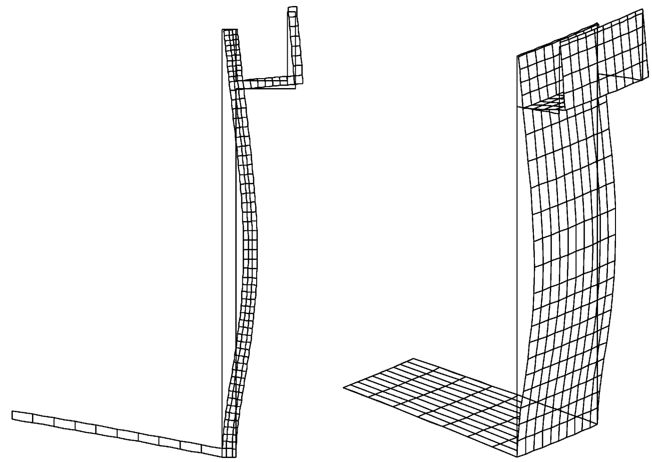
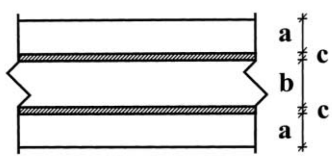


Fig. 6. Axisymmetric and semi-loof shell models: discretisations and deformed configurations.



Number and Type of Steel Wire Meshes	Dimensions
8 layers of EQ 98	a = 29.61mm b = 20.00mm c = 0.39mm
8 layers of EQ 98 + 2 layers of PB 196	a = 25.39mm b = 28.08mm c = 0.57mm
11 layers of EQ 98 + 2 layers of PB 196	a = 21.52mm b = 35.50mm c = 0.73mm

Fig. 7. Cross-section of the wall with lay-up.

The second model used a layered approach in which the wire nets were substituted by an equivalent steel membrane whose thickness was computed from the total amount of steel. The steel was then lumped in two layers. The cement mortar was placed in the remaining wall. Fig. 7 shows the cross-sections for the different lay-up used. It should be emphasised that, as mentioned before, the number and type of the steel wire meshes change along the height of the wall. Due to limitations in the available axisymmetric membrane elements, this model can only be analysed considering an isotropic material.

4.2. Semi-loof shell finite 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 model used for the axisymmetric solid. Only a section of the tank was discretised due to the axisymmetry.

A more elaborated material model, with layers, was also used in conjunction with the shell elements. In this case, the wall thickness was subdivided into five layers where steel and cement mortar were considered separately. The thickness of the steel layers was 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 (Fig. 7). Unlike the axisymmetric model, orthotropy was applied at the layers. Details of the numerical analyses can be found in Refs. [18,19].

5. Numerical and experimental results. Some comparisons

Figs. 8–13 show comparisons among the numerical results obtained by the different strategies of analysis used in this work. In Fig. 8, 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 freedom, while the latter only 1496.

Next, the layered models are shown in Fig. 9. Again the results match very well and the additional work in constructing the mesh and processing the shell model is not justified. The computational effort when considering layered shell models is approximately proportional to the number of layers. The results

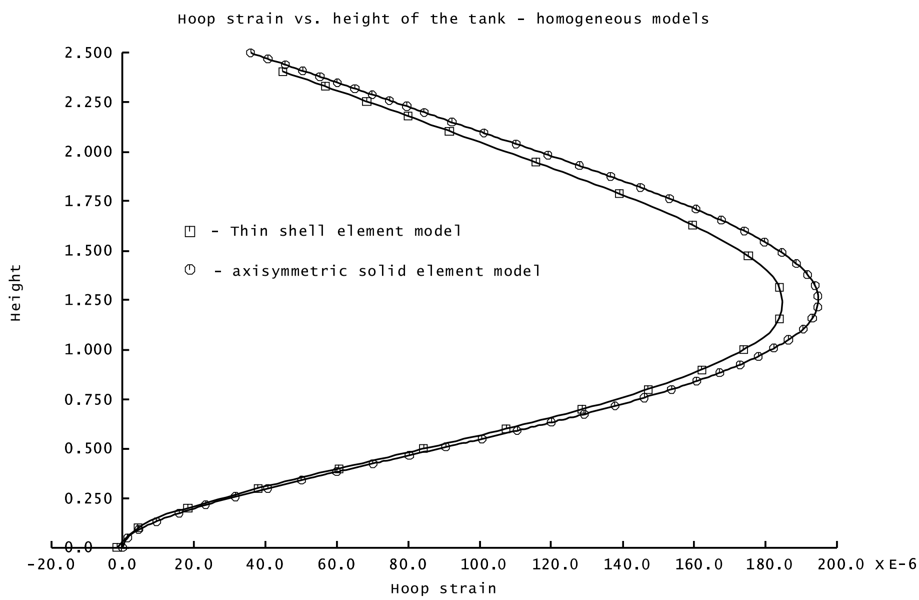


Fig. 8. Homogeneous FE models: hoop strain.

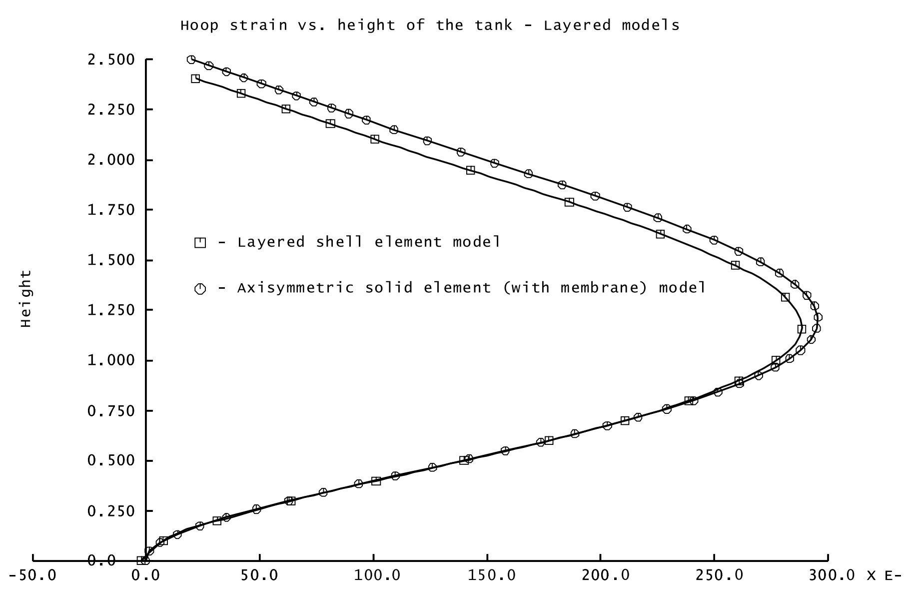


Fig. 9. Layered FE models: hoop strain.

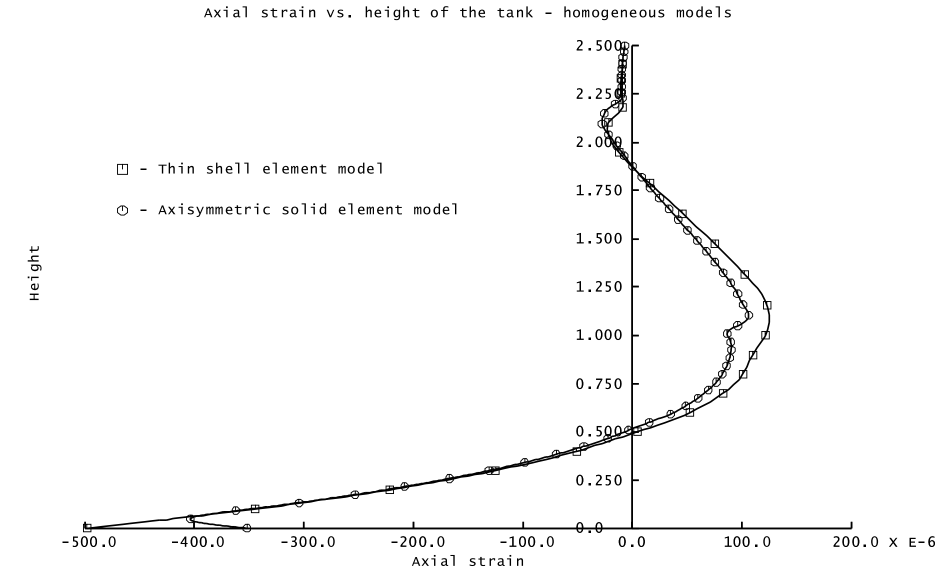


Fig. 10. Homogeneous FE models: axial strain.

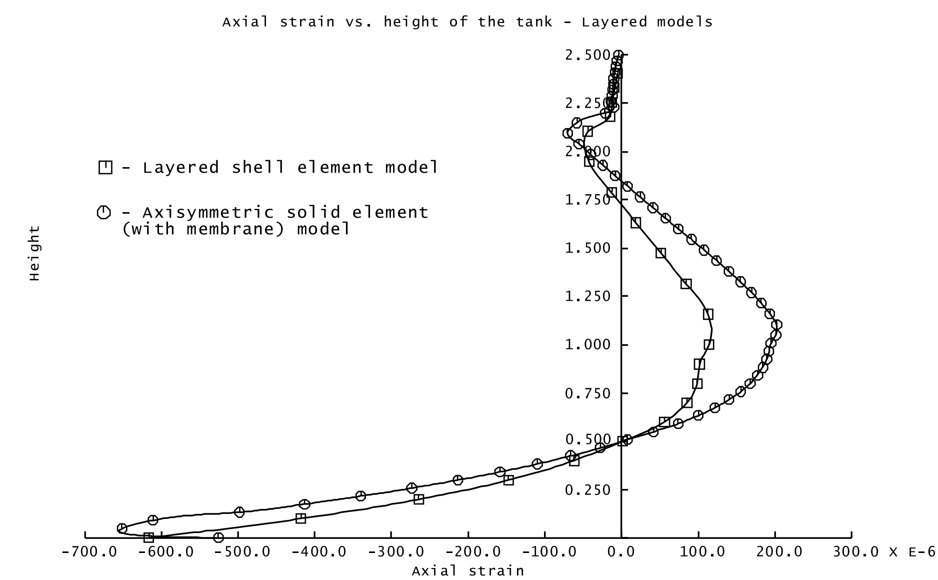


Fig. 11. Layered FE models: axial strain.

in Figs. 10 and 11 for the axial strain follow the same pattern as discussed above for the two pairs of models.

In Fig. 12, 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 Fig. 13. Furthermore, the peak strains fall into the anticorrosive region, when checking the curves in Fig. 4, with a safety factor larger than 2 for the corrosive state.

6. Conclusions

The paper presents results from the experimental and numerical analyses of large water tanks constructed using the well-known ferrocement material. From the undertaken investigation it can be observed that the construction techniques used do not guarantee some basic geometric parameters of the project, such as a constant wall thickness and voids control. For example, in situ verification has shown that the design wall thickness was exceeded in several points of the tanks. Also, due to the low quality control at the

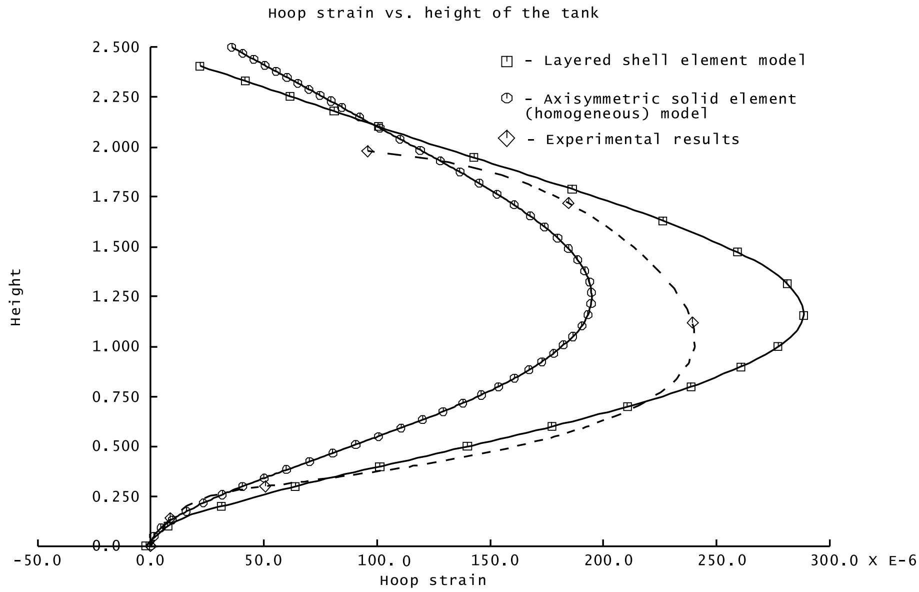


Fig. 12. Hoop strain: comparison of the different results.

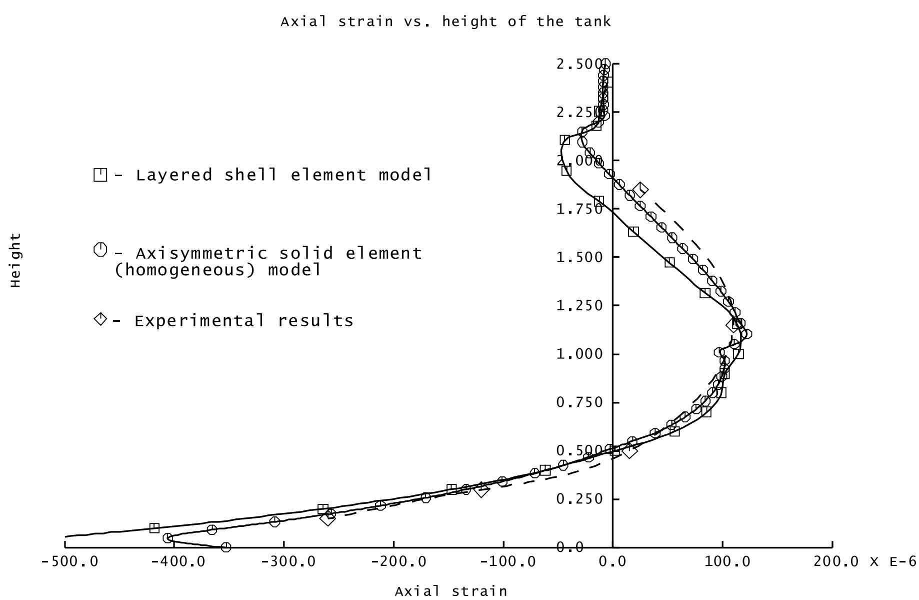


Fig. 13. Axial strain: comparison of the different results.

construction site, the mechanical properties are not homogeneous, as it depends on the skill of each particular worker, mortar density and drying conditions. The discrepancies between numerical and experimental results demonstrate that, in view of the uncertainty of the data, a very sophisticated model is not necessary.

Keeping these initial considerations in mind, the described models, even in its simpler two-dimensional versions, demonstrated to be sufficient for the determination of the stress and strain distribution in the structure. Numerical analysis can therefore be a useful tool for designing ferrocement water tanks at low cost and using a simple geometrical and material models. Further research is needed to generalise these conclusions for other ferrocement structures. On the other hand, this work and the experience of COPASA in building and maintaining ferrocement water tanks indicate that social and economic gains justify the continuation of the study.

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