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BEHAVIOUR OF MASONRY CIRCULAR TANKS

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1. ABSTRACT

Economic, temporary and fast-erected water storage tanks are needed in new developing societies, construction sites, industrial and agricultural projects. Brickwork circular tanks may represent the best solution for such cases. The available design procedures adopted for brickwork tanks are based on the principles of reinforced concrete tanks. This is not entirely satisfactory since the assumptions, which govern the theory of reinforced concrete water retaining structures, do not necessarily apply to reinforced brickwork water retaining structures. Therefore, the main motivation for conducting the research program described herein is to increase the knowledge about the behaviour of brickwork circular tanks, then, to develop guidelines for practical applications of these masonry tanks.

Two circular specimens of brickwork representing a segment of deep circular water tanks were constructed using the solid cement bricks available in the Egyptian market. The two specimens have 1000-mm internal diameter and 230-mm total height with three courses of brick units. The first specimen is 250-mm thick with a 1Φ 6-mm reinforcing bar over each of the first and second courses, while the second specimen is 120-mm thick without reinforcement. The two specimens were tested under uniform internal pressure generated from a steel set-up with eight link arms by applying a vertical load from a hydraulic jack with 100 KN capacity. The cracking patterns and displacements produced by this loading were recorded and discussed. Furthermore, a nonlinear finite element computer program is especially developed by the authors and has been used in analysing the two tested specimens. The analytical results calculated using the present computer program compare well with the obtained experimental ones. Finally, the influence of the main parameters affecting the behaviour of the brickwork circular tanks has been investigated throughout a parametric study.

KEYWORDS : Masonry Circular Tanks – Experimental – Nonlinear Analysis - Finite Element - Material Nonlinearity.

ملخص البحث :

في المجتمعات العمرانية الجديدة و مواقع الإنشاء و المناطق الصحراوية و الصناعية و الزراعية الحديثة و في محطات تعبئة أنابيب البوتاجاز تتطلب الحاجة إنشاء خزانات مياه مؤقتة لأغراض متعددة منها علي سبيل المثال استخدم هذه المياه في خلط و تشغيل الخرسانة و إطفاء الحرائق و الري و الشرب و الصرف الصحي و أيضا في الأغراض الصناعية الأخرى ويتطلب الأمر في معظم الأحيان أن تكون هذه الخزانات سريعة الإنشاء و سهلة التنفيذ بحيث لا تحتاج إلى متطلبات ولا تكنولوجيا متقدمة لإنشائها و يفضل أن تأخذ هذه الخزانات حيزا محدودا من الأرض وان تكون منخفضة التكاليف و

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اقتصادية وقد ذهب التفكير في أن كل هذه المميزات تتوفر في الخزانات المبنية من الطوب الأسمنتي المصمت مع استخدام تسليح خفيف أو بدون تسليح0

في هذا لبحث تم إجراء اختبارات معملية علي عينتين دائريتين تمثلان شريحتين من خزانين دائريين مبنيين من الطوب الأسمنتي المصمت إحداهما بسمك 250 مم و مسلحة بسيخين من صلب تسليح قطر 6 مم و الأخرى بسمك 120 مم بدون صلب تسليح ، و ذلك بهدف دراسة تصرفهما تحت تأثير ضغوط داخلية منتظمة التوزيع تمثل ضغط المياه في منطقة أقصى ضغط في مثل هذه الأنواع من الخزانات العميقة 0 وقد تم استخدم النتائج المعملية لدراسة مدي دقة التحليل اللاخطي المقترح باستخدام طريقة العناصر المحددة عن طريق برنامج تم إنشاؤه و إعداده علي الحاسب الآلي بواسطة الباحثين 0و قد تمت مقارنة نتائج الدراسة التحليلية مع مثيلاتها المعملية و ذلك بهدف استخلاص النتائج التي توضح سلوك هذا النوع من الخزانات0 وفي نهاية البحث تم استنتاج مجموعة من النتائج الهامة والتي تفيد الباحث و المهندس المصمم لهذه الخزانات0

الكلمات الدالة : خزانات الطوب الدائرية _ التجارب المعملية _ التحليل اللاخطي - طريقة العناصر المحددة _ تصرف المواد اللاخطي0

2. INTRODUCTION

Generally, the new developing societies, industrial and agricultural regions need economic, temporary and rapid erected water storage tanks. These tanks are used for construction works, fire fighting, irrigation, sanitary and portable water for drinking. However, in such cases, and due to size and site access restrictions, it is believed that the most economical material to be used in constructing such tanks is the brick masonry with or without reinforcement, hollow or solid, grouted or ungrouted. These tanks are made using hard and dense materials such as brick or stone masonry, which are firmly laid with full cement mortar joints. When a two-centimeter layer of rich cement mortar is applied to the inside face of the tank, the structure remains watertight. In some cases, it may need cricumferential steel reinforcement, which can be laid in the horizontal mortar joints. The mortar lining should be carefully constructed by keeping it properly damp for several days to a week to avoid any kind of cracks.

In the analysis of reinforced concrete circular tanks, the assumption is that the modulus of elasticity of the material is the same in tension as in compression, and it is also assumed isotropic (ACI 1995,1998). This will not be the case with brickwork elements so that a strict analysis of reinforced brickwork tank would require knowledge of the anisotropic properties of the brickwork used. It should be mentioned here that, neither detailed design information nor construction of reinforced masonry tanks is available in the Egyptian code for design and construction of masonry buildings (2001), nor in the Egyptian code for design and construction of concrete structures (2001).

Therefore, the present research addresses the experimental and analytical behaviour of masonry circular tanks. The two-fold objective is (1) to increases the knowledge about the behaviour of brickwork circular tanks, and (2) to develop the guidelines for practical applications of these tanks.

Two specimens composed of three courses with 230-mm height, 250, 120-mm thickness and 1000-mm internal diameter were constructed and tested under uniform internal pressure (see Fig. 1). The specimens are named “A”, and ”B”. Specimen “A” is 250-mm thick and reinforced with a 1 Φ 6-mm circular reinforcing bar over each of the first and the second courses, while specimen “B” is 120-mm thick and is without any reinforcement. Specimen “A” represents a prototype segment of a reinforced brickwork circular deep tank with internal diameter D =1000-mm, thickness t = 250-mm and height H = 6000 mm. On the other hand, specimen "B" is of a small scale 1:2 representing unreinforced segment of a brickwork circular deep tank with internal diameter D = 2000-mm, thickness t = 250-mm and height H = 6000 mm. The direct small-scale modelling technique, which was successfully applied to nonlinear problems of reinforced and prestressed masonry and concrete structures, has proven to be a powerful technique and is proposed as an economical alternative to full-scale testing (Abboud et al. (1990)).

3. RESEARCH SIGNIFICANCE

There is a few available experimental work studying the behaviour of reinforced and unreinforced brickwork circular tanks (Structural Clay Products (1975), and Johnson (1982)). Also, there is a limited consistent methodology available to the practicing engineers for modelling and analysis of brickwork circular tanks. Consequently, the behaviour of brickwork needs to be examined experimentally and analytically when used as reinforced or unreinforced circular tanks.

A lot of work is therefore, needed to obtain a better understanding for the behaviour of masonry circular tanks. Consequently, an experimental work and parametric studies have to be carried out on the different parameters affecting the structural behaviour of such structures.

4. OUTCOME OF RESEARCH

The first objective of this paper is to experimentally and analytically study the effectiveness of some factors affecting the behaviour of brickwork circular tanks. The second objective is to present an analytical model to represent the structural behaviour and to establish design parameters for these structures. Cracking patterns, failure modes, load-displacement relationships, and ductility will be obtained to characterize the response of such structures under water pressure.

The outcome of the first part of the experimental and analytical studies is to get data that express the composite strength and deformation characteristics in terms of the properties of the constituent materials. These data are very important in the design phase to select the proper and efficient material properties to be used for specific applications.

The second part of the analytical study will be devoted to model brickwork circular tanks. Effective parameters will be studied to provide information needed for the development of a proper methodology for the design and construction of masonry circular tanks. A nonlinear finite element method using an axisymmetric plane stress rectangular element will be employed to conduct this part of the analytical study.

5. EXPERIMENTAL PROGRAM

The experimental program consisted of testing two segmental specimens with 1000-mm internal diameter and 230-mm total height and representing brickwork circular deep tanks. One specimen is 250-mm thick and has a 1Φ6-mm steel reinforcement bar at the top of each of the first and second courses. The other specimen is 120-mm thick without any reinforcement. The details of the two specimens are shown in Fig. 1. The considered parameters are: the tank thickness, diameter and modelling scale factor. The specimens were tested under uniform internal pressure as shown in Fig. 2 . Two techniques were used to get the uniform internal pressure. In the first technique, an air bag was used, but this technique failed due to the explosion of the air bag. In the second technique, a steel set-up with eight link arms was used to get the required uniform pressure by applying a vertical load from a hydraulic jack with 100 kN capacity. The link arms transfer the vertical load to horizontal loads, which produce a uniform pressure, using a circular steel plate as shown in Fig. 2.

5.1 Material Characteristics

The materials used in the construction of the tested specimens (bricks, cement and sand) are typical to those commonly used in building construction in the Egyptian market, which complied with the requirements of ASTM (1982) and material specifications. The following materials were used in the present work.

(a) **Bricks:** The bricks used were solid cement bricks available in the Egyptian market with dimensions 60 x 120 x 250-mm, and specific weight γ_b = 19.2 kN/m^3.
(b) **Mortar:** Type S cement/lime mortar was used. The mortar mix is consisted of one part of Type II Portland cement, 1/4 part of hydrated lime, and three parts of sand by volume conforming to ASTM C270-82. The water-cement ratio was 0.70.
(c) **Steel Reinforcement:** Reinforcing steel used was in the form of normal mild plain bars (Grade 240/350) conforming to ASTM (1982). Three specimens of steel bars were tested under axial tension using Tinius Olsen Universal testing machine to get the steel reinforcement mechanical properties. The average yield stress (f_y) is equal to 230 MPa, the ultimate strength (f_{cu}) is equal to 355 MPa, and the modulus of elasticity (E_s) is equal to 210 GPa.

5.2 Construction of Test Specimens

The specimens were constructed in running bond using the previously-mentioned materials by a clever mason. To obtain a measure of the inherent compressive and tension strength of the specimens, a set of secondary specimens accompanied with the main specimens were made. These secondary specimens consisted of:
(a) Brickwork Prisms: Six brickwork prisms were constructed in the form of five- stack bonded brick. These prisms were tested under an axial compressive load perpendicular to the bed joints to determine the prism compressive strength (see Fig. 3). It should be noted that, these prisms were tested at the same time as the main specimens. The average compressive strength (f_m) of these prisms is 6.5 MPa.
(b) Splitting Tension: To determine the tensile strength of the brickwork, three assemblages were constructed in the form of five-running bond brick and tested under splitting load according to ASTM C1006-84 (as shown in Fig. 4). The average modulus of rupture (f_t) was 0.7 MPa.
(c) Shear Specimens: Three brickwork shear specimens were constructed in the standard shape and according to the ASTM and were tested in the universal machine in compression to get the shear stress of the brickwork joints (see Fig. 5). All tested shear specimens were failed by a shear slip initiated by debonding at the brick-mortar interface. The average shear stress (τ) of mortar was 0.20 MPa.

Additionally, three 150-mm mortar cubs were taken at random during construction, cured in water, and then tested after 28-days. The average compressive strength of mortar (f'_m) was 13.5 MPa for specimen A, Fig. 1. Finally, six brick units were selected at random. Three of them were tested in compression and the other three were tested in splitting tension. The average compressive stress of the brick unit (f_b) is 7.0 MPa.

5-3 Test Set-Up and Instrumentation

Figure 2 shows a schematic view of the test set-up. As illustrated in this figure, the total applied load was monitored using a pressure dial gauge with 20 MPa capacity. Specimen deformations, crack widths, and strains were measured by a set of four dial-gauges with a precision of 0.025 and 0.0025 mm (three for displacements and one for strain) arranged along the specimen circumference as shown in Fig. 2.

5.4 Testing Procedure

Prior to testing, the main specimens were inspected and the outside surface was whitewashed to highlight the crack progression during loading. The test procedure is based on the fact that deep circular tanks have an internal liquid pressure in the ring direction with a maximum value, which is almost uniform at 0.10 to 0.20 of the tank height measured from the bottom as shown in Fig. 6. As mentioned before in the above sections, the uniform internal pressure is simulated using a hydraulic jack and eight-radial link steel arms. This system gives uniform internal horizontal pressure with a magnification factor = (x/y) of the vertical applied load as shown in Fig.2.

The specimens were tested under monotonic incremental internal pressure using the arrangement shown in Fig. 2. The displacements and strains were recorded using dial gauges. Also, cracks propagation, first crack and ultimate loads were recorded.

6. EXPERIMENTAL RESULTS

The cracking patterns for specimens "A" and "B" are shown in Figs. 7 and 8, respectively. The cracks occurred first in the vertical mortar joints and top bed joints at pressures of 45 % and 62 % of the ultimate pressures for specimens "A" and "B", respectively. As the pressure was increased, other cracks formed near the first crack, and these cracks propagated through the thickness of the specimen and then widened until failure of the specimens took place. Also, the pressure degradation was relatively moderate and was mainly caused by the widening of the cracks. Cracking width, cracking pressure, and cracking pressure at descending branch are given in Figs. 7 and 8. From observations of the test results, it can be concluded that the factor of safety for both reinforced and unreinforced brickwork circular tanks represented by specimens "A" and "B" are 2.33 and 1.67, respectively. (where factor of safety = cracking pressure / (γ_w * H), and $\gamma_w = 1x10^{-5}$ N/mm^3, H = 6000 mm). The experimental cracking and ultimate displacements and pressures for the two specimens are given in Table 1.

7. ANALYTICAL MODELLING

7.1 General

As a result of the literature review of the available analytical models for brickwork tanks (Manning (1972) and Johnson (1982)), it is clear that, almost little of them could efficiently be used for the nonlinear analysis of masonry tanks. Therefore, to avoid the points of weakness in the previous models, the material nonlinearity is considered in the proposed finite element model presented in this paper.

Accordingly, a proposed finite element model was intended to be constructed to efficiently predict the nonlinear behaviour with sufficient accuracy. The analytical model has been derived from basic principles of mechanics. The loads are applied incrementally and iterative corrections are performed in every increment to bring the nonlinear system into equilibrium (see Fig. 9).

7.2 Finite Element Idealization

This study presents a practical method for estimating the stiffness and the load capacity of brickwork tanks, as well as the internal stresses in these structures using basic four nodded rectangular plane stress axisymmetric elements having two degrees of freedom (u, v) at each node as shown in Fig. 10. The stiffness matrix of the plane stress axisymmetric element is available in most textbooks of matrix analysis. Further details about the element used throughout this study may be found in (Hinton and Owen (1977) and Zienkiewicz and Taylor (2000))

7.3 Material Modelling

Idealized stress-strain curves for brickwork in both compression and tension utilized throughout this study are shown in Figs. 11 and 12, respectively. Also, the idealized stress-strain curve for reinforcing steel is illustrated in Fig. 13. More details about stress-strain idealization for masonry and steel reinforcement may be found in (Park and Paulay (1975), Ewing, et al. (1987), and Gupta and Maestrini (1990)).

7.4 Computer Program

A nonlinear finite element computer program is developed by the authors and coded in the FORTRAN 77 programming language. The computer program uses the stiffness formulation with an incremental-iterative solution method. It should be mentioned that this method is a straightforward computational strategy, and is reliably convergent. The selected computation algorithm is an incremental iterative one, where displacements and loads are applied incrementally, and iterative corrections are performed in every increment to bring the nonlinear system into equilibrium (see Fig. 9).

The developed program has been used in studying many factors and parameters affecting the behaviour of brickwork circular deep tanks under internal water pressure. Then a parametric study has been done to get some important conclusions.

8. ILLUSTRATIVE EXAMPLES

8.1 General

The overall objective of the illustrative examples is threefold, (1) to demonstrate the efficiency of the proposed analytical model; (2) to verify the solution algorithm, element models, and material models; and (3) to validate the computer program. The illustrative examples, also presents the sensitivity of the computer program to the variations in the physical and material properties of the finite element model. The analytical results are compared with the experimental ones obtained from the test work done by the authors. The correlation between experimental and analytical results is based on the comparison of the most important aspects such as cracking patterns, failure modes and deformed shapes, as well as load-deformation curves, and strength. The calculated analytical results are found to be conforming to those obtained experimentally. The divergence between the analytical and experimental results is acceptable.

The configurations, dimensions and finite element meshes of the tested specimens (A and B) and the corresponding prototypes are shown in Fig. 14.

8.2 First Illustrative Example (Specimen "A")

The recorded internal pressure for the first crack and failure conditions for specimen "A" were 0.144 and 0.320 MPa, respectively while the predicted ones using the developed nonlinear finite element computer program for the model and prototype are 0.130, 0.338 MPa, and 0.138, 0.357 MPa, respectively, which means good agreement, as shown in Table 1. Figure 15 shows the experimental and the analytical internal pressure-displacement curves for specimen "A".

8.3 Second Illustrative Example (Specimen "B")

Similar to the first example, the recorded internal pressure for the first crack and failure conditions are 0.100, 0.157 MPa, and the predicted ones for the model and prototype are 0.093, 0.168 MPa, and 0.089, 0.139 MPa, respectively. Again, it can be concluded that good correlation between the analytical and experimental results is achieved. The experimental and analytical internal pressure-displacement curves for specimen "B" are shown in Fig. 16.

Table 1 gives a comparison of the experimental and analytical results for the first and the second illustration examples.

9. PARAMETRIC STUDY

9.1 General

The behaviour of reinforced and unreinforced brickwork circular tanks needs an extensive parametric study to provide a full understanding of their behaviour. Due to time and budget constraints, the experimental study can not be used to cover the effect of all parameters. Under such circumstances, the analytical study appears to be an effective and economical alternative, which can be used to extend the study by employing a suitable analytical model.

The configuration, dimensions and finite element mesh of the brickwork circular tank used throughout the parametric study are shown in Fig.17. The analysis is conducted under monotonic incremental water pressure using 100 increments.

To address the research objectives, the calculated loads at cracking, yielding, and ultimate loads, displacements, ductility factor, and lateral stiffness are compared with those of the corresponding control specimen, to illustrate the effect of the studied parameters on the behaviour.

9.2 Studied Parameters

The influence of the different parameters affecting the nonlinear behaviour and performance of both reinforced and unreinforced brickwork circular tanks has been investigated. The main parameters studied in this research are: (1) Brickwork compressive strength (f_m); (2) Brickwork tensile strength (f_t); (3) Height to diameter ratio (H/D) with constant thickness (t); (4) Diameter to thickness ratio (D/t) with constant height (H); and (5) Horizontal reinforcing steel ratio (ρ_h). The values of the studied factors are given in Table 2.

9.3 Studied Aspects

For each studied parameter, the following aspects are determined: (1) displacements, (2) stresses, and (3) cracking, yielding and ultimate pressures, and (4) lateral stiffness and displacement ductility factors. Cracking patterns and failure modes have been studied to characterize the investigated specimens.

9.4 Failure Modes and Cracking Patterns

When the first crack at the outer surface of the tank has appeared, it then propagates through the thickness. As displacement increased, more cracks occurred (as shown in Fig.18). All failure modes are characterized by tension failure. Figure 19 shows the deflected shapes of reinforced and unreinforced control specimens.

9.5 Analysis of Numerical Results

9.5.1 Effect of Brickwork Compressive Strength (f_m)

Generally, the increase of the brickwork compressive strength, and consequently the initial modulus of elasticity (assuming constant tensile strength) leads, as expected, to a decrease in the radial displacement, while the lateral stiffness is increased.

The increase of the brickwork compressive strength from 7 MPa to 12 MPa increases the maximum pressure and stiffness factor by about 9 % and 74%, respectively, with no effect on the cracking strength.

9.5.2 Effect of Brickwork Tensile Strength (f_t)

When the brickwork tensile strength increased from 0.5 MPa to 1.5 MPa (assuming constant compressive strength), the first crack, and ultimate pressures, the displacement at maximum pressure, and the stiffness factor are increased by about 100 %, 178%, 690 %, and 183 %, respectively. Also, the increase of the brickwork tensile strength limits the propagation of cracks.

9.5.3 Effect of Height to Diameter Ratio (H/D)

An increase in the tank height to diameter ratio (H/D) from 0.5 to 3 with constant thickness (t) and diameter (D) (i.e. an increase in the tank height), decreases the cracking pressure, displacement ductility, and lateral stiffness factors by about 26 %, 24 %, and 256 %, respectively, while it increases the maximum radial displacement, and the maximum pressure by about 410%, and 43 %, respectively.

For the sake of theoretical investigation, an increase in the tank height to diameter ratio (H/D) from 0.5 to 3 with constant thickness (t) and height (H) (i.e. a decrease in the tank diameter), increases the cracking pressure, maximum pressure, and lateral stiffness factor by about 220

%, 255 %, and 524 %, respectively, while it decreases the maximum radial displacement, and the displacement ductility factor by about 43 %, and 40 %, respectively.

9.5.4 Effect of Diameter to Thickness Ratio (D/t)

In deep circular tanks, if the thickness of the wall "t" is not small in proportion to the diameter "D", the stress σ_t due to ring tension T will not be uniformly distributed over the cross-section as shown in Fig. 20 (Farshad (1992)).

When the diameter to thickness ratio (D/t) is reduced from 14 to 6 (i.e. an increase in the thickness, with constant diameter), the cracking and ultimate pressures are increased by about 94 %, and 35 %, respectively, while the radial displacement is decreased by about 39 %.

9.5.5 Effect of Horizontal Reinforcing Steel Ratio (ρ_h)

An increase in horizontal reinforcing steel ratio (ρ_h) from 0.1 % to 0.2 %, increases the ultimate pressure, the displacement ductility, and the lateral stiffness factors by about 16 %, 25 %, and 20 %, respectively, while it has no significant effect on the first crack pressure.

10. CONCLUSIONS

In this paper, experimental and analytical studies were conducted to examine the behaviour of masonry circular tanks. Two specimens have been constructed and tested experimentally under uniform internal pressure. A nonlinear finite element axisymmetric model has been used to simulate the behaviour of brickwork circular tanks. Based on the results of this work, the following conclusions may be obtained:

1- The nonlinear finite element method is a valuable tool for analysing brickwork circular tanks under lateral pressure.
2- Good correlation is observed between the analytical and experimental results with respect to cracking, and ultimate pressures, and radial displacement.
3- Because the ring tension is the dominant mechanism due to the internal liquid pressure in deep brickwork circular tanks, the strength is related to the brickwork tensile strength rather than its compressive strength.
4- If the brickwork tensile strength is tripled, the first crack and ultimate strength are increased by about 100 %, and 178 %, respectively.
5- The cracking pressures for reinforced and unreinforced brickwork circular tanks are 45 %, and 62 %, respectively of the ultimate pressure.
6- The obtained factor of safety for reinforced and unreinforced brickwork circular tanks are 2.33, and 1.67, respectively, which means that a masonry circular tank is an economical alternative compared with the reinforced concrete circular tank, for limited diameters and heights.
7- The strength of brickwork circular tanks is very much dependent on the ratios of (D/t) and (H/D). The results obtained here support this conclusion.
8- The use of steel reinforcement with 0.1 % to 0.2 % at the middle of the tank thickness has no significant effect on the first crack strength, while it increases the ultimate strength by about 16 %.
9- Analysis of cost shows that brickwork circular tank (reinforced or unreinforced) is cheaper than the reinforced concrete tank by about 35 %. The major saving is in the cost of formwork and construction time.

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