



# Finite Element Modeling and Analysis of a Historic Masonry Regulator

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## ملخص البحث

تحتوي شبكة الري في مصر على العديد من المنشآت المائية التي تم تشييدها في القرنين الماضيين، ونظرا لأهميتها الوظيفية وكذلك أهميتها التاريخية فيجب الحفاظ عليها لقيمتها الاقتصادية والأثرية. ويستلزم ذلك إجراء تقييم انشائي لهذه المنشآت في حالتها الراهنة بهدف التأكد من سلامة هذه المنشآت أو تعيين مدى احتياجها للتدعيم لتتحمل الأحمال المتزايدة. يهدف هذا البحث الي الدراسة والتقييم الانشائي لأحد قناطر الري من القناطر بهدف تعيين مدى تحملها في حالتها الراهنة للأحمال الواقعة عليها، ومدى احتياجها للتدعيم لرفع كفاءتها الانشائية. وتتم الدراسة التحليلية عن طريق التمثيل الرقمي والتحليل اللاخطى باستخدام برامج الحاسب. كما يتم استعراض نتائج الدراسة التحليلية ومناقشة ومقارنة النتائج و عرض الاستنتاجات والتوصيات.

## Abstract

This paper presents numerical modeling and structural analysis of a 75-year-old masonry head regulator constructed on an irrigation canal in Egypt. Numerical modeling by finite elements and nonlinear analysis are carried out using commercial software ANSYS. The finite element model represents the current condition including characterization of the deteriorated material properties. Nonlinear analysis is conducted to evaluate the structural behavior under the applied and the worse expected loading condition to assess its structural efficiency and safety margin and strengthening requirements. The result of the numerical modeling for the regulator will be presented and discussed in terms of compression and tensile stresses and deformations of the structure.

**Keywords:** masonry, vault, hydraulic structure, assessment, finite elements, nonlinear analysis.

## 1. Introduction

Regulators and barrages are hydraulic structures constructed to raise the upstream water level of the river to allow water to get diverted through a canal situated at one of its banks, or to control downstream water discharge. The irrigation network in Egypt has a large number of hydraulic structures constructed in 19<sup>th</sup> and 20<sup>th</sup> centuries, typically constructed of stone and brick masonry in addition to plain or reinforced concrete. Many of these structures are suffering material deterioration, aging, increased loading, environmental effects and other adverse actions. There are concerns regarding the safety and serviceability of these important structures, whereby a national project was carried out including structural assessment of several old irrigation structures.

An example of a typical old regulator in Egypt is considered in this study; Al-Shoalaa Head Regulator constructed in 1942 and located on the Bohiya canal at km19.00. Numerical modeling is made using finite elements and nonlinear analysis is performed using commercial software ANSYS v.15 [1]. The finite element model and nonlinear

analysis parameters are described. The numerical results are presented in terms of deformations and stresses, and are discussed.

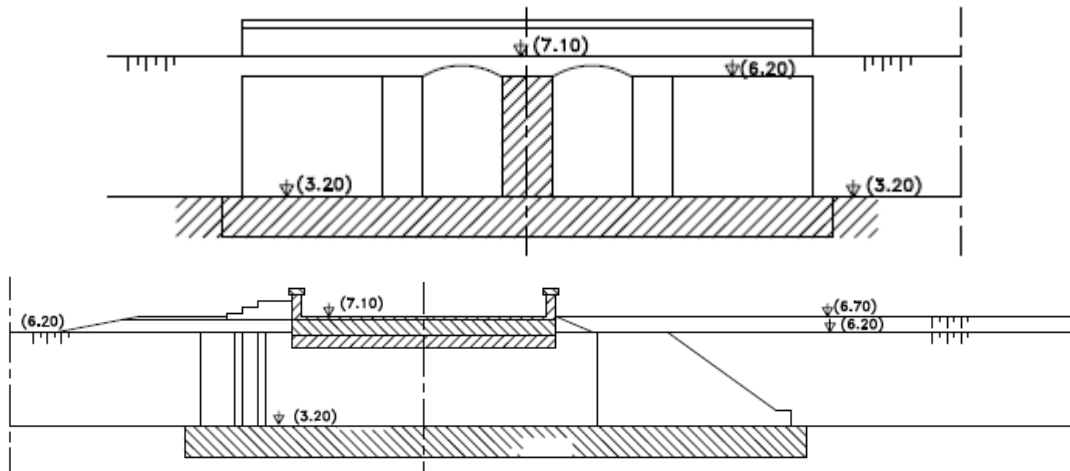
## 2. Structure description

Al-Shoalaa Head Regulator was constructed in 1942 on km 19.00 of the Bohiya irrigation canal. The regulator consists of two gate openings of 6.00 m width separated by a masonry pier, supporting a masonry roadway arch bridge; all supporting systems of piers, abutments, and wing walls are built over a concrete apron raft founded on the canal bed. The upstream and downstream views of the regulator are shown in Fig. 1, together with longitudinal and cross sections.



(a) upstream view

(b) downstream view



(c) longitudinal and cross sections

Fig. 1. Alsholaa Head Regulator

## 3. Numerical modeling and nonlinear analysis

### 3.1 Modeling and nonlinear analysis approach

The complex irregular nature of masonry construction makes accurate structural analysis a challenge. Linear elastic analysis commonly used in practice does not accurately estimate the ultimate response of masonry and should not be used to conclude their strength and structural safety margin. Nonlinear analysis is considered to give better description for the behavior and capacity of masonry structures in many cases [2].

To represent the heterogeneous and anisotropic nature of masonry construction using finite elements, different modeling strategies may be followed that are reviewed by Roca et al [3]. Discretization of the structure can be performed using the following three

approaches: (i) detailed micro-modeling, where masonry units and mortar joints are distinctly modeled as materials with different geometry and mechanical properties whereas the unit-mortar interface is represented by discontinuous interface elements accounting for possible crack or slip planes; (ii) simplified micro-modeling, bricks are modeled by continuum elements while mortar joints are lumped in discontinuous interface elements; (iii) macro-modeling, masonry is modeled as an isotropic continuum material characterized by different nonlinear softening laws in tension and compression [4].

Comparison of the three main modeling strategies for masonry conclude that although detailed micro-models are capable of addressing some of the complexities, their application is primarily restricted to small-scale structures with regular geometric forms [2, 3]. The macro modeling (smeared, continuum or homogenized) is more practice oriented due to the reduced time and memory requirements as well as a user-friendly mesh generation, and describes the structural behavior with acceptable accuracy [5].

### 3.2 Finite element mesh

A three-dimensional finite element model was made for the whole regulator structure using the commercial software ANSYS v.15 [1], as shown in Fig. 2. In the three-dimensional model the masonry components (arches, abutment, wing walls and piers) are represented by macro-meshing strategies using solid elements to define the individual blocks and zero thickness joint elements at their interfaces (stone-to-stone joint type), as shown in Fig 2.

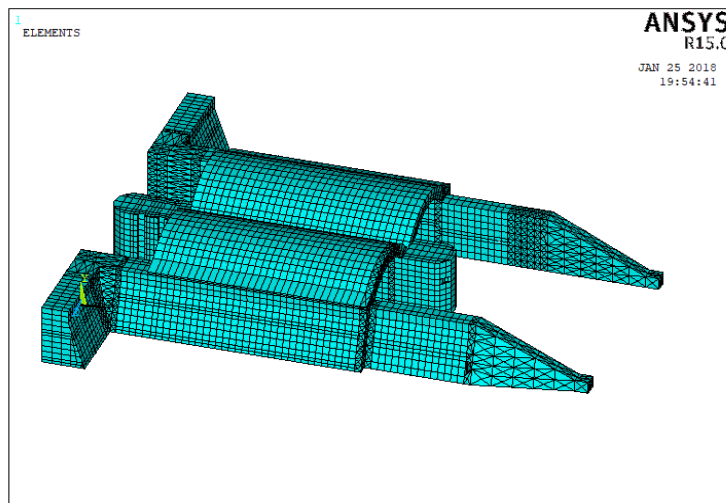


Fig 2. Three-dimensional finite element mesh for the regulator

### 3.3 Material properties

Laboratory tests were made on cores extracted from the regulator elements, the determined material properties are listed in Table 1. The material properties of masonry adopted in the analysis are as follows.

- Masonry Compressive strength ( $f'_m$ ) = 4.3 MPa
- Modulus of Elasticity ( $E_m$ ) = 595 MPa
- Weight Density = 18 kN/m<sup>3</sup>
- Major Poisson's ratio = 0.15
- Tensile Strength assumed to be  $0.1 f'_m = 0.43$  MPa [..].
- Stress-strain relation for masonry is shown in Fig. 3.

Table 1. Material properties determined from tests

Material	Unit weight (kN/m <sup>3</sup> )	Compressive strength (N/mm <sup>2</sup> )				Tensile strength* (N/mm <sup>2</sup> )
		Maximum	Minimum	Average	ACI 214R-2	
Clay brick	17.6	14.2	2.4	7.01	4.3	0.43
Concrete	24.5	37.2	26.7	31.13	26.7	2.67

\*Tensile strength is assumed to be 10 % of compressive strength.

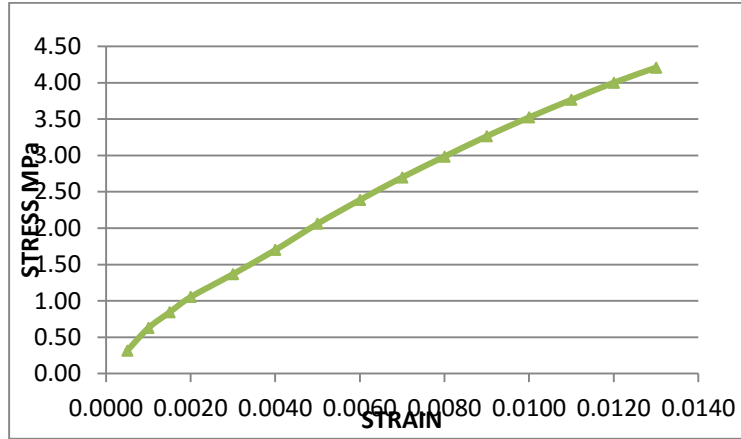


Fig. 3 Adopted stress-strain curve for the clay brick masonry

### 3.4 Loads and load cases

The loads acting on the regulator structure were calculated, listed as follows.

1. Dead load: the own weight of the structural element and the fill material till road surface.
2. Live load: pedestrian and vehicles loads on the road and bridge.
3. Water static pressure on piers, abutment and raft, calculated for the upstream and downstream from the equation:

$$P_w = \gamma_w * h \quad \text{where:} \quad \gamma_w = 10 \text{ kN/m}^3 \quad \text{and} \quad h = \text{depth of water}$$

4. Earth pressure: static earth pressure on abutment and wing walls, calculated as

$$P = \gamma_s * h_s * k_a \quad \text{Where:} \quad \gamma_s = \text{soil density, } h_s = \text{depth of soil column and } k_a = (1 - \sin\phi) / (1 + \sin\phi).$$

5. Surcharge: Surcharge of about 1.0 t/m<sup>2</sup> distributed on soil behind the wing wall due to effect of traffic was taken into consideration for earth pressure calculation

The regulators structure is subjected during its lifetime to construction or maintenance condition and operation condition. Therefore, two load cases were studied.

**Case A:** Construction case: the applied loads on the regulator are the regulator own weight, the filing above the regulator arch and the back filling on the regulator side which represent the lateral earth pressure without the presence of water.

**Case B:** Operation case: the applied loads on the regulator are maximum water level, live load, and earth pressure with the ground water pressure. Maximum upstream water level (6.20) and downstream water level (3.00).

### 3.5 Nonlinear analysis parameters

The nonlinear analysis parameters adopted are as follows:

- Shear coefficient along opening cracks (ShrCf-pO) = 0.2.
- Shear coefficient along closed cracks (ShCf-CI) = 0.8

- Tension limit, cracking limit (UnTensSt) = 0.43 MPa
- Compression limit, crushing limit (UnCompSt) = 4.3 MPa

#### 4. Numerical results

The results obtained from the nonlinear analysis regarding deformed shape in x- y- and z-direction and stresses in x- y- and z- directions due to the studied load cases are shown in Figs 4 to 9.

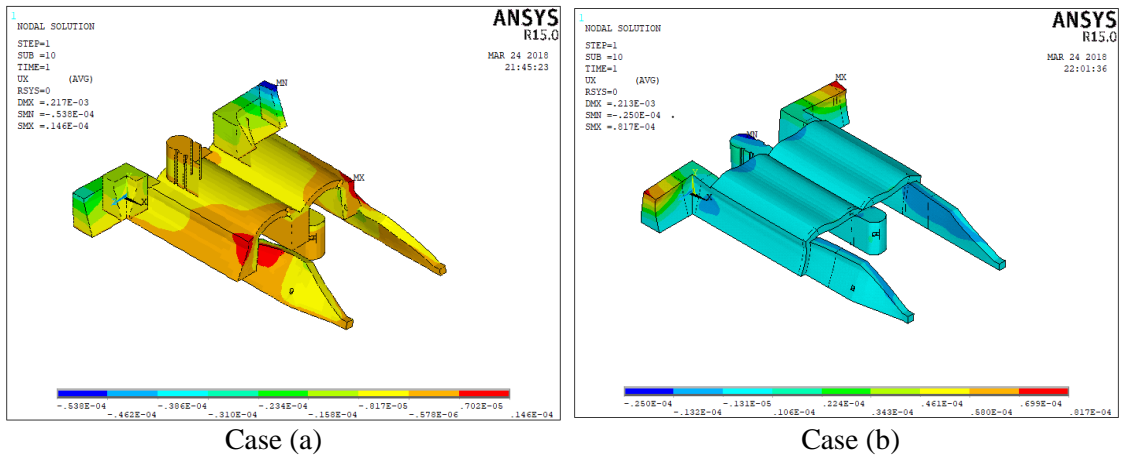


Fig. 4 Deformed shape in x-direction (regulator longitudinal axis)

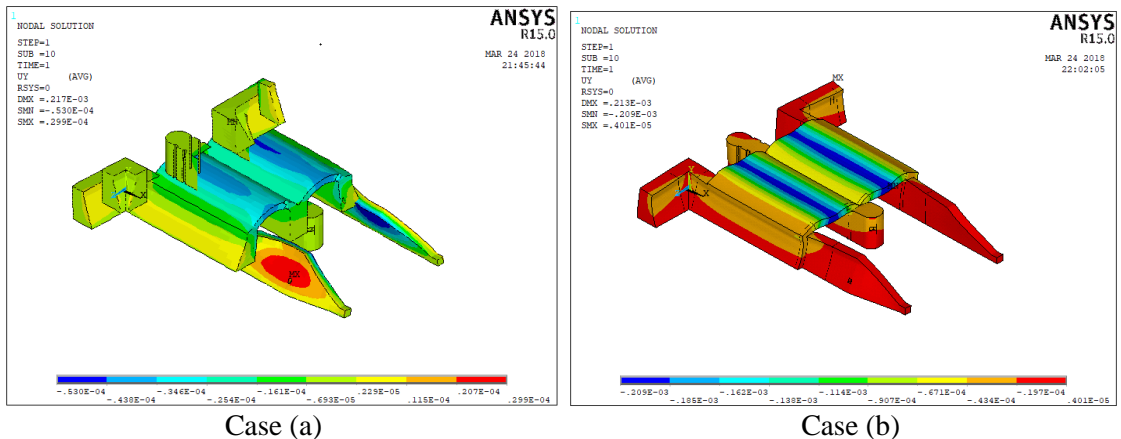


Fig. 5. Deformed shape in y-direction (transverse direction)

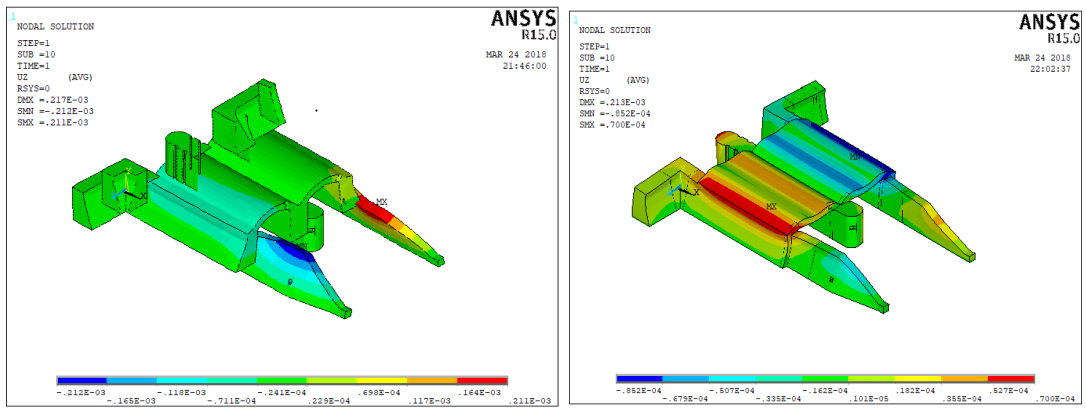
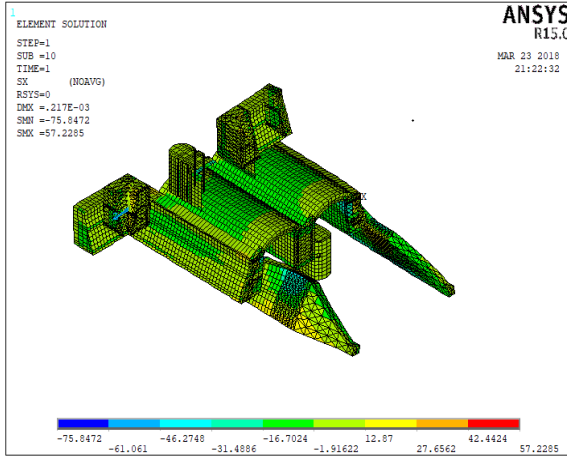
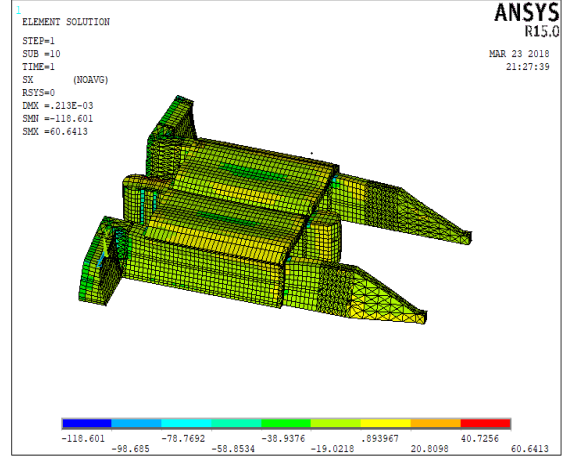


Fig. 6. Deformed shape in z-direction (vertical direction)

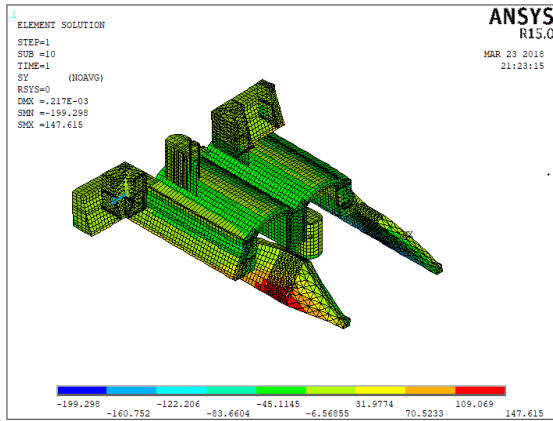


Case (a)

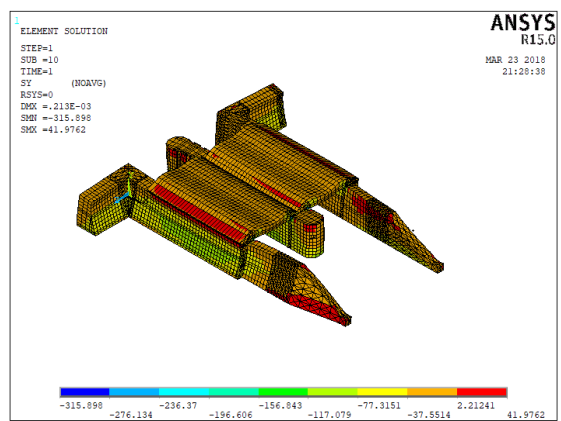


Case (b)

Fig. 7. Stresses in x-direction

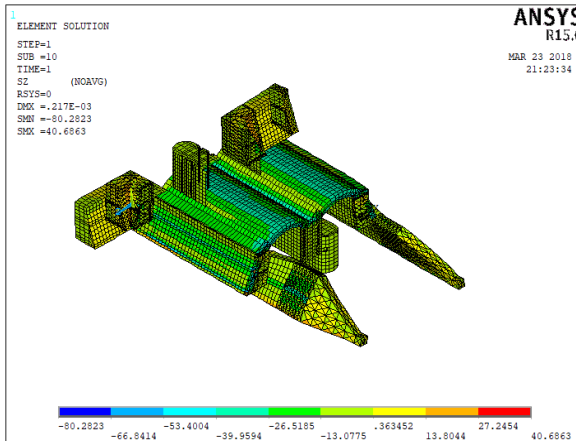


Case (a)

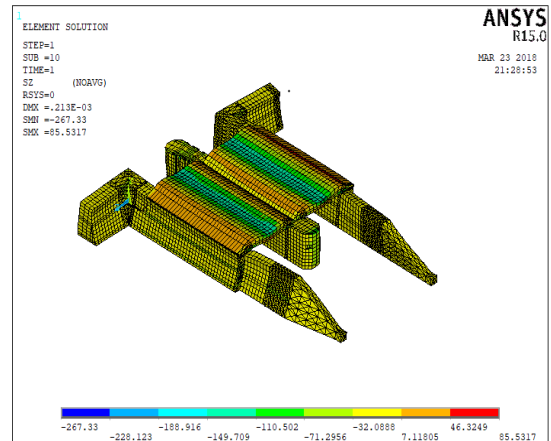


Case (b)

Fig. 8. Stresses in y-direction



Case (a)



Case (b)

Fig. 9. Stresses in z-direction



## 5. Discussion of results

For construction or maintenance case, no river water is present; the wing walls are subjected to surcharge acting vertically and earth pressure from one side without the existence of water at the other side. In this case, the obtained numerical results show that the maximum deformation in y direction is equal 0.03 mm and 0.05 mm out and in wing walls that because of surcharge and earth; also the stresses in the y-direction are greater. The maximum tension is equal to 147 kPa and maximum compression is equal 200 kPa as shown in Fig 8(a). It is noted that the experimentally determined average compressive strength and the calculated average tensile strength for the regulator brick masonry are 4300 and 430 kPa, respectively. The stresses are therefore considered much lower than the limit for safety.

In the operation case, the applied loads on the regulator are maximum water level, live load, and earth pressure with the ground water pressure. The numerically obtained deformed shape in y-direction is shown in Fig. 5(b). The deformation in y-direction occurring in the wing wall has maximum value of equal  $0.308 \times 10^{-5}$  m and minimum value equal to  $-0.681 \times 10^{-4}$  m and in the arch the maximum deformation is equal to  $-0.287 \times 10^{-4}$  m and minimum value equal to  $-0.203 \times 10^{-3}$  m. The deformation in z-direction shows as observed the effect of lateral loads on wing wall the deformation is  $0.679 \times 10^{-4}$  m and  $0.420 \times 10^{-4}$  m. Stresses in y-direction have maximum value in tension equal to 42 kPa and in compression equal to 267 kPa, the wing wall stresses maximum tension stress is 17 kPa and the highest compression is equal 69 kPa because of the vertical load, Fig. 8(b). In the z direction, stresses in the wing wall are subjected to lateral earth pressure from the outside and water pressure from inside, which reduce the stresses to be in tension 3 kPa and in compression 91 kPa Fig. 9(b).

## 6. Conclusion

In this paper, a three-dimensional numerical model by finite elements was made for a historic masonry head regulator using the macro-modeling approach, where the exact geometry and current condition are represented including characterization of material properties. Nonlinear analysis was carried out using commercial software ANSYS to evaluate the structural behavior under two different loading conditions. The critical loading cases (operational and construction) were studied.

The numerical results indicate that the stresses existing in the wing walls and arches of the regulator in its current condition due to the applied loads are much lower than the allowable limit. No cracks were observed in any of the structural elements. The numerically predicted deformations are also acceptable. However, the local deterioration or damage observed in parts of the regulator is not represented in this paper, and will be represented in further extension of this study. The obtained stresses are expected to show critical values at some locations.

## References

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