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Analysis and Design of Load Bearing Masonry Structures

By

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ABSTRACT

Masonry is the oldest building material that is still widely used in the building industry. There is a remarkably increasing need nowadays for masonry construction, both financially and socially. However, the analysis of the mechanical behavior of masonry constructions is a true challenge, due to non-homogeneous nature, anisotropy, low tensile strength and other factors. Also, the masonry element exhibits obvious nonlinear behavior. This research focuses on the nonlinear analysis of unreinforced masonry structures. The primary aim is the development and validation of accurate numerical representation of masonry structures considering its nonlinear behavior, which can be easily used by the practicing engineer. The nonlinear analysis is performed using a commercially-available computer program, which renders the approach easily and efficiently applicable by a practicing engineer. Also an experimental program was conducted as part of this research in order to evaluate the ability of the mathematical model proposed to reproduce masonry mechanics by comparing the obtained numerical to experimental results. Validation of the model was also ensured by means of comparison between the calculated numerical results and experimental results available in the literature.

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INTRODUCTION

Masonry is still widely used as a construction method. This is mainly justified by wide availability of the material, simplicity and economy of construction, as well as its good mechanical and aesthetic properties. Masonry use has now been reduced mainly to non-structural elements, such as cladding or infill panels. However, nowadays there is a general demand for the use of masonry for housing in Egypt as there is an awareness of the advantages of masonry construction regarding economy, durability and sustainability. In spite of the simplicity associated with building in masonry, the analysis of the mechanical behaviour of masonry constructions is a true challenge. Masonry construction is made up of two different materials: masonry units which may be stone, brick or concrete units, and mortar. Associated with the characterization of the mechanical properties, a large variability is usually found, due to workmanship and use of natural materials. Also, masonry is a material that exhibits distinct directional properties due to the mortar joints, which act as plans of weakness.

The conclusions of these events proved the suitability of such construction from the economic, durability and environmental points of view. These recommendations predict possible increased application of masonry construction in Egypt in the near future. Therefore, the need for a consistent approach to the study of masonry structures becomes evident. There is need for availability of accurate yet simple to use numerical tool, which is capable of describing the behavior of the structure from the linear stage, through cracking and degradation until complete loss of strength.

Properties of Masonry Assemblages

a) Uniaxial compressive behavior of masonry normal to bed joint

The compressive strength of masonry in the direction normal to the bed joints has been traditionally regarded as the main structural material property. This value may be obtained experimentally by prism test for bricks and blocks. The Egyptian code of Practice relates the compressive strength of the masonry prism to the compressive strength of unit and mortar type using the standard compressive test, as given in Table 1.

Table 1 Masonry Characteristic Compressive Strength (f'm) According to ECP [3]

Unit Compressive Strength (Kg/cm2)	Mortar Type		
	1 , 2	3	4
50 (non bearing walls)	22	20	18
80	34	32	-----
100	42	41	-----
150	53	48	-----
200	64	58	-----

For design purposes, the Egyptian code of Practice [3], adopting the working stress design method, specifies the allowable values for compression and tension stresses, shown in Table 2.

Table 2- The allowable values for stresses of unreinforced Masonry elements (Solid brick unit).

Stress type	Allowable values
Axial Compressive strength (Fac)	0.2 f'm
Bending compressive strength (Fm)	0.25 f'm
Permanent Tensile Strength	0
Temporary Tensile Strength Normal to bed joint	0.9 Kg/cm2 – mortar type 1
Temporary Tensile Strength Parallel to bed joint	1.6 Kg/cm2 – mortar type 1
Modulus of Elasticity (Em) - Kg/cm2	700 f'm
Modulus of Regididty (Gm) - Kg/cm2	0.4 Em

b) Uniaxial tensile behavior of masonry

For tensile loading perpendicular to the bed joints, failure is generally caused by failure of the relatively low tensile bond strength between the bed joint and the unit. As a rough approximation, the masonry tensile strength can be equated to the tensile bond strength between the joint and the unit [2], and this value is concluded to be 10-30% of masonry compressive strength.

c) Stress Strain Curve

The stress strain curve can be determined from the masonry prism compressive strength, measuring the stress and the accumulated strain from the specimen, plotting these values yields a stress strain curve.

d) Modulus of Elasticity (Em)

Referring to the Egyptian code of practice [3] and masonry structures behavior and design text book “Hamid and Drysdale” [2] the modulus of elasticity can be determined depending on the compressive strength of the masonry prism from equations as follows.

For clay masonry: $Em = 700 \times F'cm$

Contemporary Structural Analysis of Masonry

Masonry is a material which exhibits distinct directional properties due to the mortar joints which act as planes of weakness. In general, the approach towards its numerical representation can focus on the micro-modeling of the individual components, unit (brick, block, etc.) and mortar, or the macro-modeling of masonry as a composite [7]. Depending on the level of accuracy and the simplicity desired, it is possible to use the following modeling strategies, see Figure 1

- Detailed micro-modeling - units and mortar in the joints are represented by continuum elements whereas the unit-mortar interface is represented by discontinuous elements: see fig(1-a)
- Simplified micro-modeling - expanded units are represented by continuum elements whereas the behavior of the mortar joints and unit-mortar interface is lumped in discontinuous elements: see fig(1-b)
- Macro-modeling - units, mortar and unit-mortar interface are smeared out in the continuum: having unified total properties see fig(1-c)

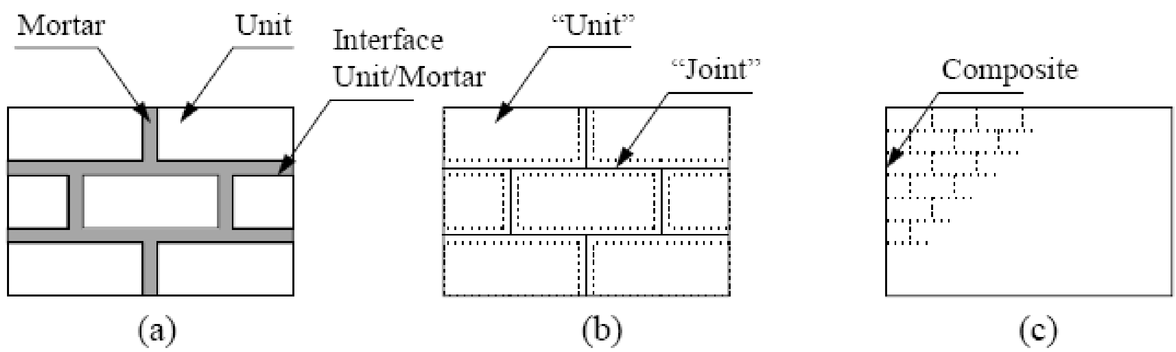


Figure 1- Modeling strategies for masonry structures: (a) detailed micro-modeling; (b) simplified micro-modeling; (c) macro-modeling. [5]

NUMERICAL MODELING

A numerical study is carried out to integrate the applicability of this procedure for analysis of masonry structures. The result of this study are presented and discussed compared to linear analysis in order to justify the importance of nonlinear analysis. The numerical model considered in the study, mainly contains some concepts such as assuming a homogenous composite material made of units and mortar.

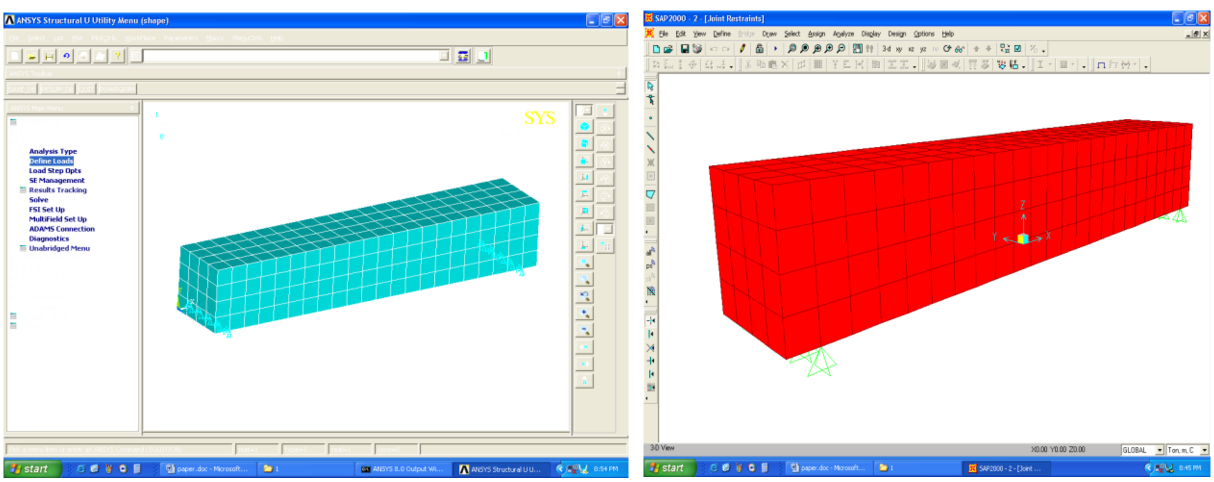
Numerical Study

The numerical investigation contains numerical and experimental study for a simple masonry beam. Seven beams are studied, all having the same breadth of 40 cm and different in spans. The minimum required depth for stability of the beam is evaluated assuming the maximum limit for compressive and tensile stresses. The minimum depth is determinate by trials through several runs made to reach the minimum possible beam height H for each beam under its own weight as stated in table 3.

Table 3: Proposed beam spans

Beam Span	Linear & nonlinear Results
L (cm)	H (cm)
100	--
150	--
200	--
250	--
300	--
350	--
400	--

The numerical study contains both linear and nonlinear runs for models to estimate the relation between the depth of the masonry beam H and the span of the beam L with a certain limits of allowable tensile and compression stresses.



a) ANSYS MESH[1]   b) SAP MESH

Figure 2 Finite element mesh used in the study of beam.

Results of the Numerical Analysis

The results of the runs are given shown in Table 4 showing the relation between the depth of the beam with regard to the span of the beam, and this relation is plotted in fig 3. The results listed below emphasize the gap between linear and nonlinear analysis, it comes from the concept of redistribution of tensile stresses among the structure and the cracks which made by these tensile stresses and do not cause the failure of the structure.

Table 4 Results of Numerical analysis

L (cm)	ANSYS linear	SAP linear	ANSYS nonlinear	Percentage %
	H (cm)	H (cm)	H (cm)	
100	7	7	2.5	0.36
150	15	17	7.5	0.44
200	25	30	10	0.33
250	50	55	12.5	0.23
300	80	85	20	0.24
350	115	120	40	0.33
400	150	160	70	0.44

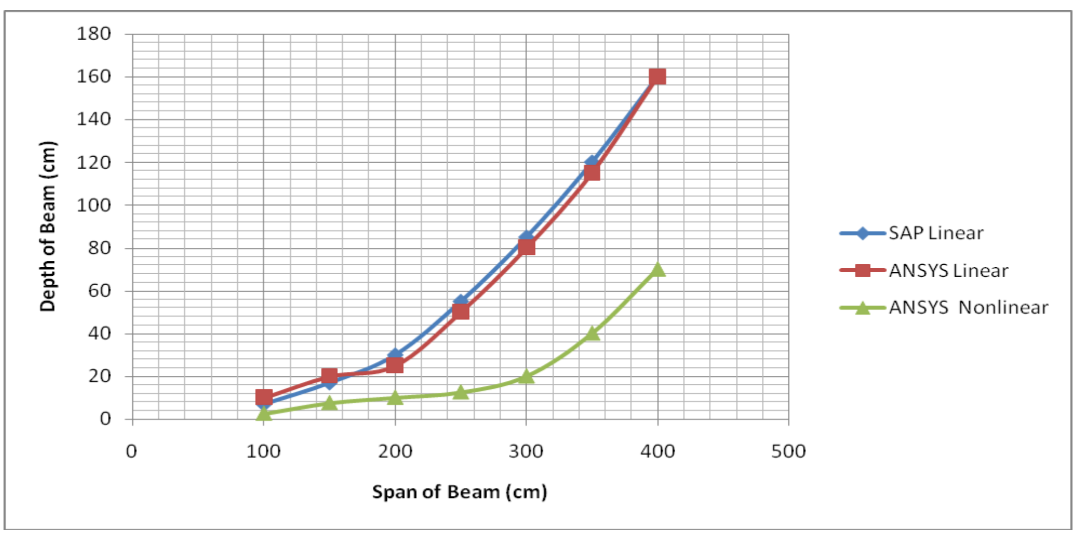


Figure 3 Results of Numerical study

Experimental Program

As verification for the previous numerical study, three different beams of the previous analytical study were chosen to estimate the accuracy of the nonlinear model or the nonlinear results. Also the study concern about estimating the correct tensile and compression stresses limitations for masonry structures, these values may be used instead of the very low stresses values listed in the Egyptian Code of Practice [3].

Material Properties Evaluation

The mechanical properties of the masonry assemblage are a main concept in studying such structures; therefore, these experimental samples were prepared to evaluate the most important mechanical properties to be able to specify a stress-strain curve for the masonry building material used in the studied samples.

The brick unit test

Compression test was made to a brick unit with dimensions (200x100x60 mm), the test apparatus is set up using wooden plates as shown in fig 4

Figure 4 compressive test for masonry unit and crushed sample

The mortar test

Compression test was made on a mortar cube with dimensions (100x100x100 mm), in accordance with the Egyptian code for masonry structures and using mortar type 2 as shown in table 2.1. The test apparatus is set up using steel loading plates as shown in fig 5

Figure 5 the mortar cube test

The prism test

This test is recommended by several codes [3], to give the value of the compressive strength of masonry [f'cm], the test was made to find the compressive strength of the masonry prism, the prism consists of five brick units connected to each other with mortar joints, the test apparatus is set up using steel plates as shown in fig 6 as described by several specifications.

Figure 6 the masonry prism test and crushed sample

Test results

The compressive strength of the three specimens; for each brick unit, mortar cube and prism, are given in table 5 as average of 6 samples.

Table 5 Test Results

Specimen	Crushing Load (ton)	Strength ((Kg/cm2)
Brick unit	11.5	57.5
Mortar	11	110
Prism	8.5	42.5

Test Sample Dimensions

Three experimental models were selected from the numerical study to verify the finite element model. The dimension of three beams chosen for testing are sketched in fig 7 and listed in table 6.

Figure 7 the dimension of the masonry beam

Table 6 Dimensions of test samples

Beam ID	L (cm)	Actual depth of the sample (cm)	ANSYS nonlinear H (cm)
A	300	21	20
B	200	10	10
C	100	10	2.5

The masonry beam The masonry form

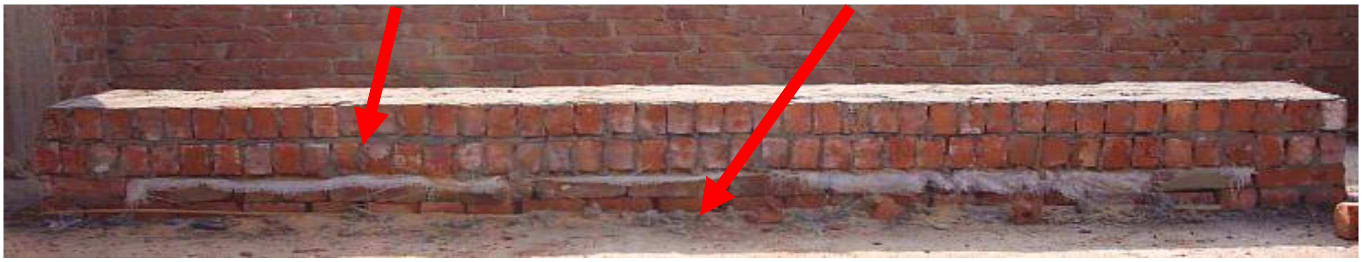


Figure 8 the finished masonry beam with the masonry form.

Numerical and Experimental Evaluation of Masonry Beams carrying Capacity

The masonry tensile strength can be concluded from the masonry compressive strength and this value ranges from 0.1 to 0.3 of the value for compressive strength [2]. So the tensile strength will be □ ten = 0.1x425 = 42.5 t/m2 considering minimum tensile limit.

Tensile Limit evaluated from Experimental testing

The developed tensile stress limit from the experimental test could be verified using the failure load of the beam calculated as modules of rupture, backing to the model making a new run with the new material properties and new applied loads (failure loads), to reach the appropriate tensile limit.

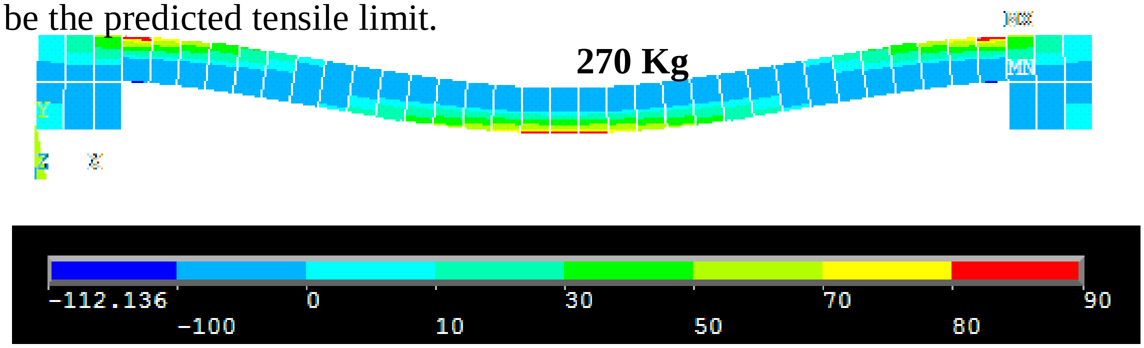
Experimental Determination of failure load of beam (B)

After releasing the masonry form, we prepare the test for determination the failure load, the loads was considered as sand packages with incremental loads of 50 kg see fig 9 The failure occurred at 270 kg as shown fig 10.

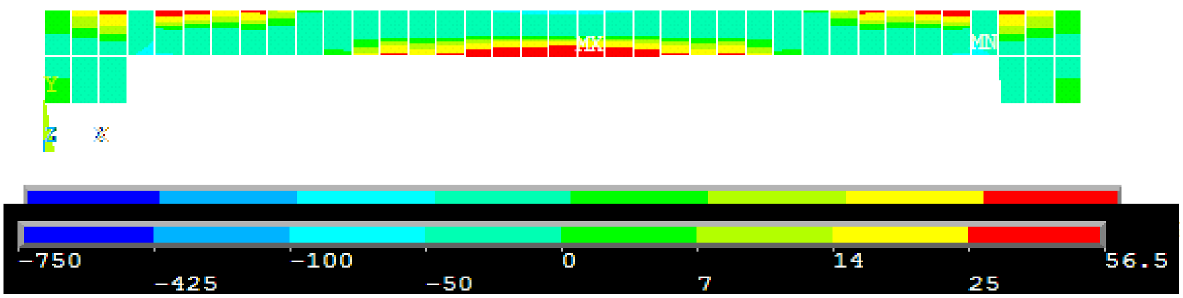
Figure 9 Loading and instrumentation for beam

Numerical Verification of failure loads of beam (B)

After determination of the failure load, experimentally this load was applied to the numerical models and a nonlinear analysis was performed as shown in fig 10, to find the actual tensile limit, we started running the model with tensile strength of 42.5 t/m2 then increasing this tensile limit till the failure occur in the model, Then the value considered will be the predicted tensile limit.



(a)



(b)

Figure 10 analysis results of beam (b)

(a) Linear Modeling in ANSYS, (b) Non-linear Modeling in ANSYS

Discussion of Numerical and Experimental Results

The actual limit for tensile stresses predicted from the model = **56.5 t/m^2** this limit represent a ratio of 0.13 of compressive strength, and the ratio appear to be within the range founded in text books and reported by the research as we discussed before. To ensure that limit of tensile stresses, we will use that tensile limit in new runs with the same material properties to expect the failure load of beam (A) and (C) then comparing this load with the actual failure loads of the same beams.

Numerical Prediction of failure loads of beam (A),(C)

Using the adopted ANSYS model with the proparties stated before, making runs for beams (A), (C) to predict the faluire load using the estimated tensile stresses from the beam (B). Using the estimated tensile stresses of 56.5 t/m2 with new runs for the beam (A),(C). The predicted faluire load will be 500 Kg for beam (A) and 510 Kg for beam (C).

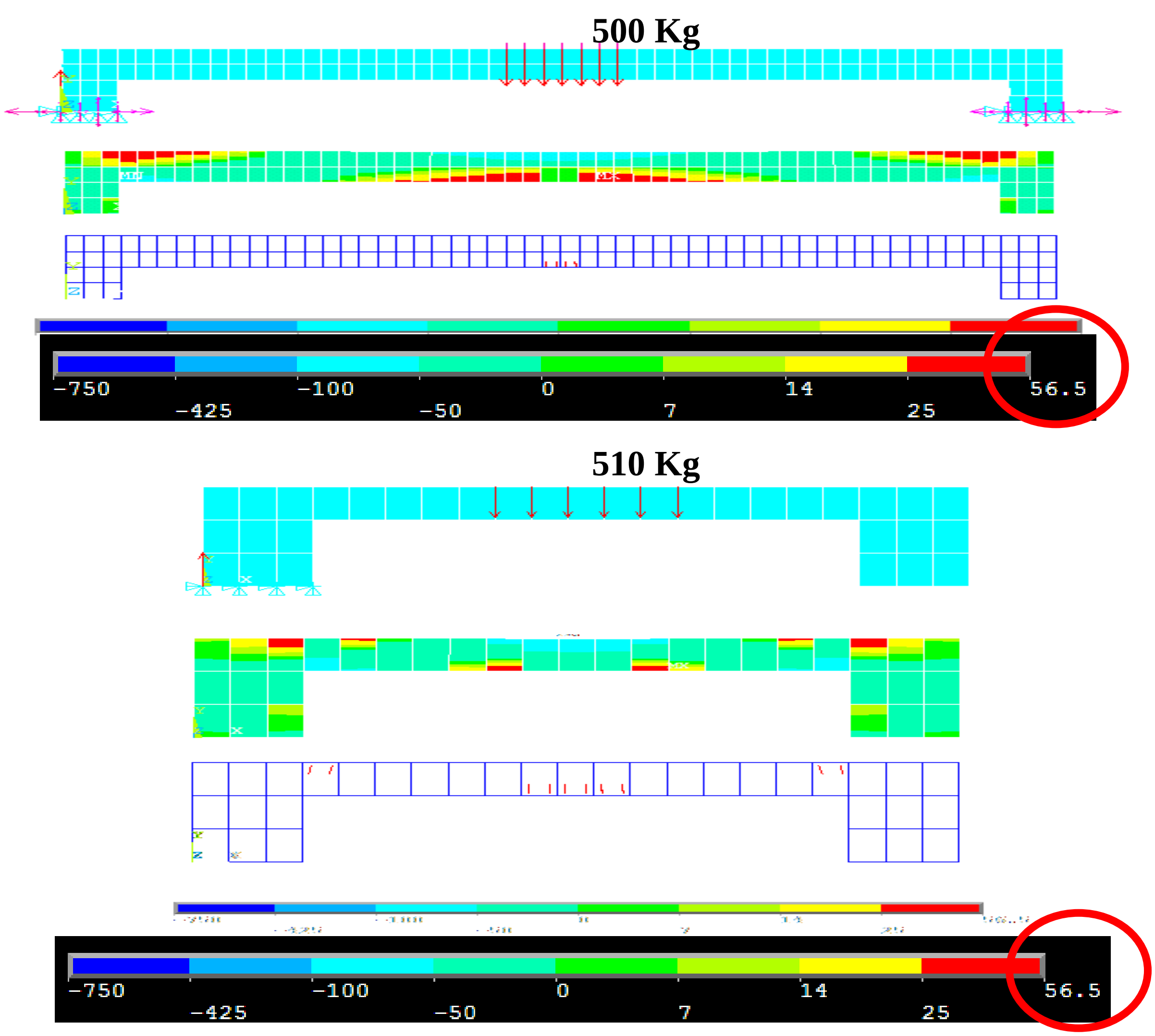


Figure 11 analysis results of beams (A)(C)

Experimental Verification of calculated numerical loads of beams (A),(C)

The following parts contain the experimental verification of the predicted failure load of beams (A), (C). We prepare the loading sand packages with load steps of 50 kg as shown in fig 12, the determinate failure load is 500 kg, the value fits the same value predicted from ANSYS and this proves both the predicted tensile value and the correction of the numerical value.

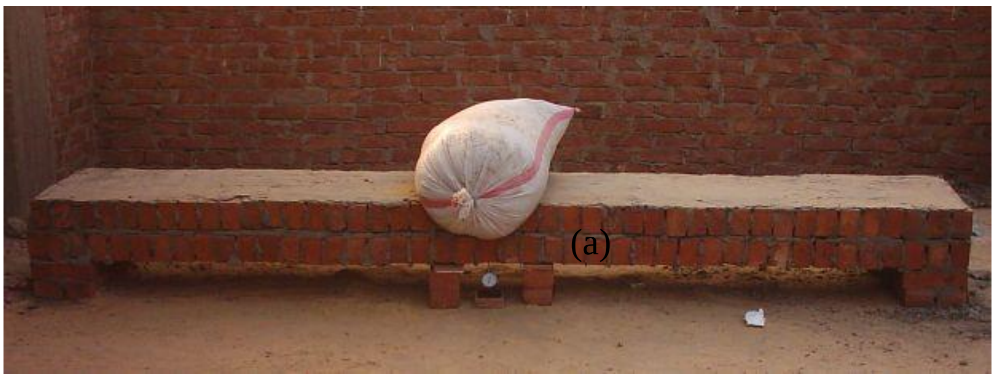


Figure 12 determination of failure load of beam.

Discussion of results

Considering all the previous data, experimental tests and numerical models we can conclude that the limit of the tensile stresses can be ranged from 0.1 to 0.13 of the compressive stresses. Noting that these tensile stress was along bed joints of the masonry which is the lowest value specified by codes. Also important issue in our thesis is the low limit of stresses that stated in the ECP [3] for either compression or tension stresses limits; these low stresses caused a non trust atmosphere for masonry structures and could be limit the wideness of using masonry structures, ignoring `all its benefits, from the structural and economical point of view. As we see and proved that the masonry has good limits for these stresses but we ignore it, so we should review our thoughts again.

CASE STUDIES AND APPLICATIONS

The study contains a calibration for the adopted nonlinear model by comparing the results obtained with existing building and published research results, and may be new structures to ensure the accuracy of the modeling procedures.

Numerical Study by comparison with Existing building:

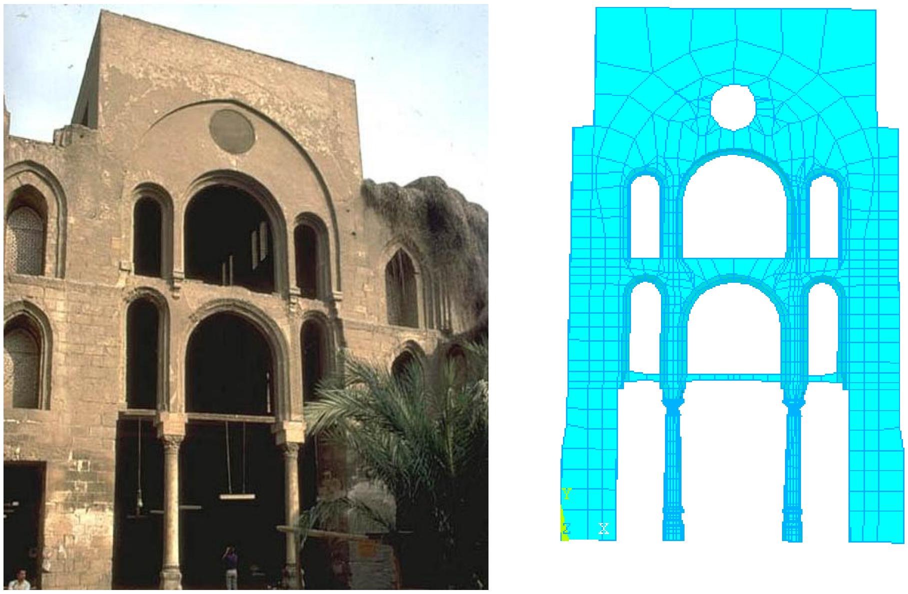


Figure 14 Qalawon Arch, and finite element model

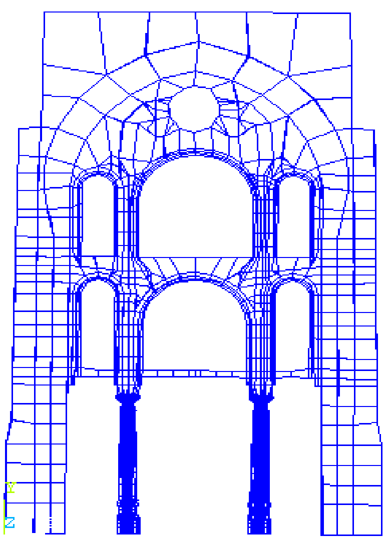
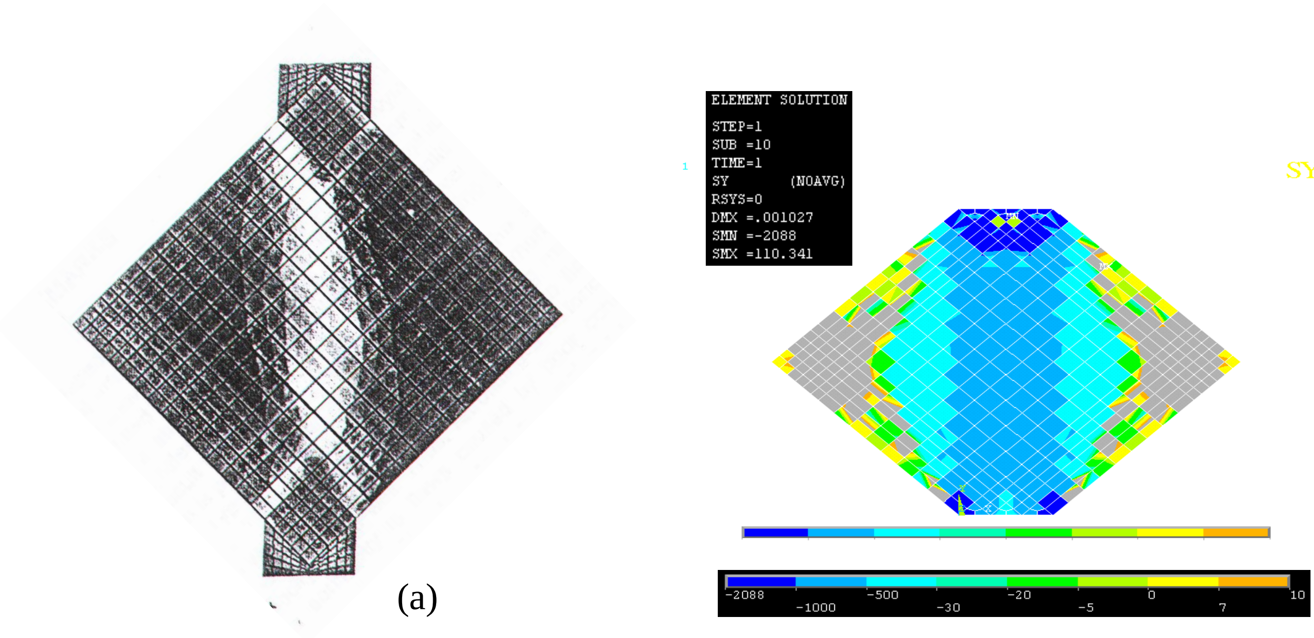


Figure 15 Finite element results; ANSYS crack pattern

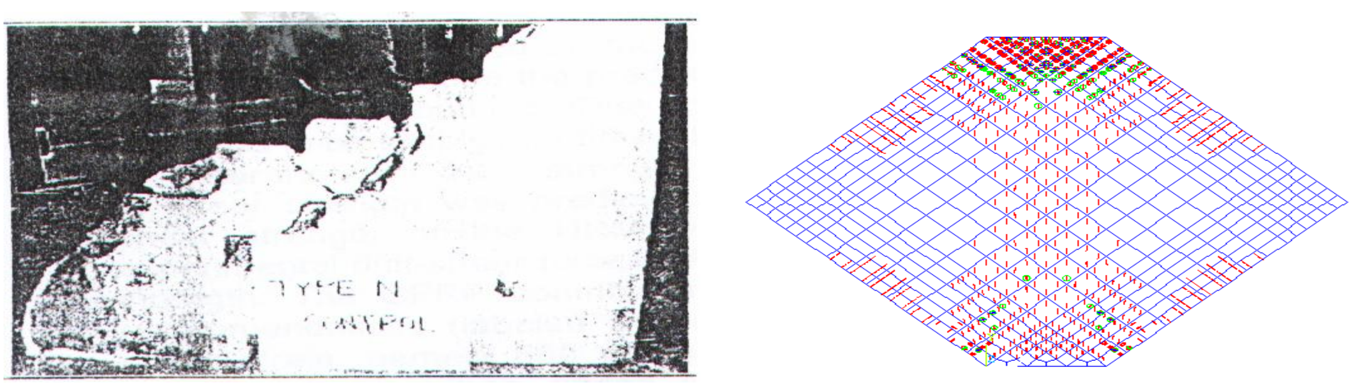
Numerical Study by comparison with Published Researches:

The analysis results shows that the ANSYS model gives the same results as shown in fig 4.10, and so the crack pattern and failure load determinate from the ANSYS model produce nearly the same results.



(a) (b)

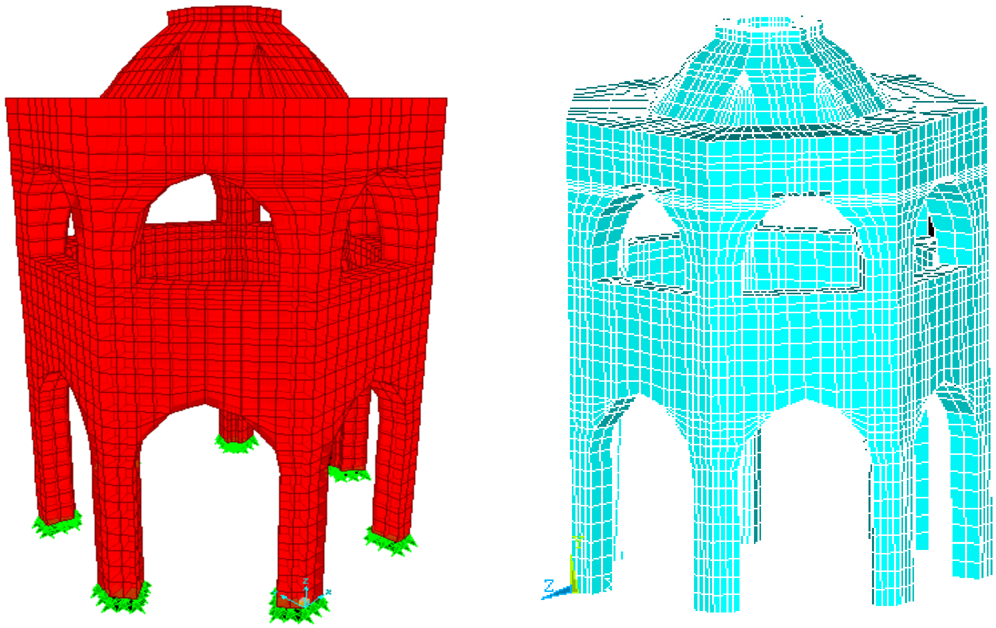
Figure 4.10 Finite element mesh and stresses; a) published Results, b) ANSYS model of present research



(a) (b)

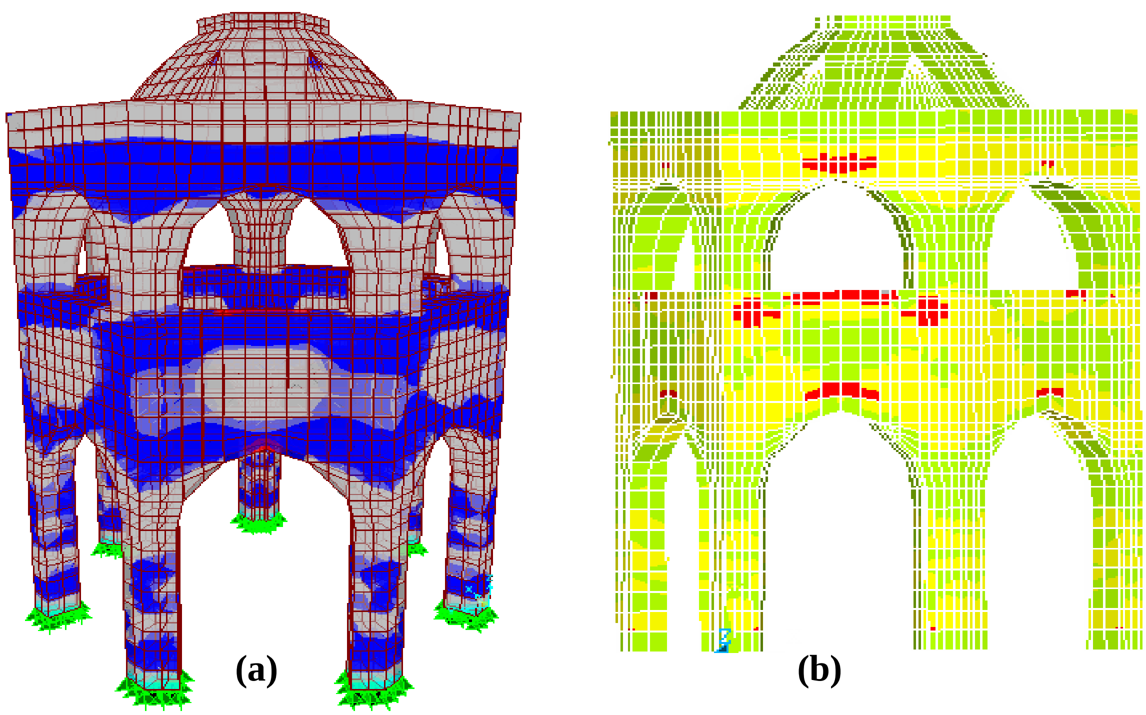
Figure 4.11 Experimental and numerical results; a) Study Crack Pattern, [6] b) ANSYS Crack Pattern of present study obtained by ANSYS model.

Numerical Study by comparison with New Masonry Constructions



(a) **(b)**

figure 4.40 The finite element model; a) SAP mesh, b) ANSYS mesh



(a) **(b)**

figure 4.41 The finite element results a) SAP result showing the tensile stresses at the tip of the arch exceeding the allawble stresses , b) ANSYS result confirming the sap results

The results of the finite element model linear and nonlinear analysis using SAP and ANSYS and so the crack pattern verifies some important issues.

1) The nonlinear analysis makes good presentation for the structural behavior of the masonry structures.
2) The understanding of the masonry structures behavior can save a lot of money used for the reinforcement that may be an obstacle for expand of using masonry construction.
3) Return the confidence of using masonry construction as a building technique for suitable cases.

CONCLUSIONS

The ultimate capacity of masonry elements and structures is considerably under-estimated if linear analysis is carried out. Nonlinear analysis gives a much better representation of the structural behaviour of masonry elements, as observed or determined experimentally, regarding ultimate capacity and cracking pattern. The vast difference between results of linear and nonlinear analyses is due to the fact that nonlinear analysis allows for redistribution of stresses among the masonry elements, after the masonry has cracked at certain locations. This is not accounted for if linear analysis is followed.

The nonlinear analysis procedure adopted throughout this research was proved to be efficient through comparing results with published numerical and experimental results. Due to using a commercially available computer program, nonlinear analysis of masonry structures should not be regarded as a complicated procedure suitable only for research, since it is possible to apply it by practicing engineers in design offices.

One important conclusion of the research is the validity of the created numerical model to study and understand the structural behavior of the existing heritage structures, or even to interpret the cracks or any structural problem encountered in it. The existence of simple yet accurate masonry design certainly broadens the application fields and allows for more creative and even daring designs in masonry. The numerical model can be used to analyze new structures, expecting its behavior or the problem that may be met, solving these problems before the construction process. Also the model can overcome the conservative fear of using such construction techniques.

The success of the numerical representation also gives the opportunity to suggest some modifications to increase the limit of the allowable stress which is stated in the code of load bearing masonry structures. The specified allowable stresses in the existing code are too low, as was demonstrated in the discussion of numerical results of this thesis. This results in a general atmosphere of non-trust in masonry structures which currently exists among designers and practicing engineers. This has led to limitation in the application of masonry structures, in spite of all its benefits from the structural and economical point of view.

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