Palestine Polytechnic University

Deanship of Graduate Studies and Scientific Research

Master of Architecture – Sustainable Design

Structural Static Evaluation of Historic Stone Building (Case Study: Zahdeh Building in Hebron Old City).

Afnan yahya Al-karaki

Supervisor

Dr. Haitham Ayyad

Dr. Ghassan J. Dweik

A thesis submitted in partial fulfillment of requirements of the degree

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The undersigned hereby certify that they have read, examined, and recommended to the Deanship of Graduate Studies and Scientific Research at Palestine Polytechnic University:

Structural Static Evaluation of Historic Stone Building (Case Study: Zahdeh Building in Hebron Old City).

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Graduate Advisory Committee:

Dr. Haitham Ibrahim Ayyad

(Supervisor), Palestine Polytechnic University

Signature:―――――――――――――― Date:―――――――――

Dr. Ghassan Judeh Dweik

(Supervisor), Palestine Polytechnic University

Signature:―――――――――――――― Date:―――――――――

Dr. Belal Mahmoud Almassri

(Internal committee member), Palestine Polytechnic University.

Signature:―――――――――――――― Date:―――――――――

Dr. Khalid Fahed Qawasmi

(External committee member), KR@S International Trade.

Signature:―――――――――――――― Date:―――――――――

Thesis Approved by:

Name: Nafeth Kamal Nasereddin

Dean of Graduate Studies & Scientific Research

Palestine Polytechnic University

Signature: ………..…………………

Date: ……………...……………

Structural Static Evaluation of Historic Stone Building (Case Study: Zahdeh Building in Hebron Old City).

Afnan Yahya Alkaraki

ABSTRACT

This thesis includes both analytical and experimental studies of the nonlinear behavior of historic buildings. The ancient historical buildings are of great importance, as they represent the architectural heritage and the image of history. Hebron contains many historical buildings, so it is necessary to preserve them in order to pass them to the future generations.

Structural behavior of historical stone buildings and the mechanical properties are significantly different from that of modern structures, Also, the mechanical properties of composed old stone and mortar are not available.

Accurate structural analysis of stone buildings is a true challenge. Being composed of stone units bonded by mortar, consequently, the mechanical behavior of stone buildings is characterized by complexity and a lack of homogeneity of structural building materials, in addition to differences in mechanical properties between stone units and mortar or the absence of this binding material at all.

The aim of the present research is to develop an assessment method of historical stone structures, and set a formulation for non-linear static analysis, also determining the mechanical properties values of stone building materials such as modulus of elasticity and compressive strength.

An experimental study was conducted in order to determine the mechanical properties of stone building materials and to validate the accuracy of the adopted modeling. Validation of the model was ensured by comparing the numerical results with the experimental results available in both the experimental chapter of the thesis and the literature. A numerical modeling study was performed based on the analysis of the structural behavior, which was carried out through a non-linear static analysis based on a macro finite element model, using a commercial program (ANSYS), nonlinear analysis gives a description of the actual behavior, and capacity of the structure. A description of the modeling, material characterization, and solution parameters was given.

The result obtained when conducting the numerical analysis of the model of a Zahdeh building is that the building can bear its loads in its current condition, and it also has the ability to bear loads equivalent to two floors. The proposed methods, both in conducting experiments and structural analysis, are suitable for the structural assessment process and can be applied to similar building models to preserve, both the architectural heritage and the historic buildings.

Keywords: Historical Buildings, Mechanical Properties, Compressive Strength, Stress–Strain, Modulus of Elasticity, Non-linear analysis, Macro modeling, Finite Element, ANSYS.

التقييم الإنشائي الإستاتيكي لمباني تاريخية حجرية (حالة الدراسة: مبنى آل زاهدة في البلدة القديمة في الخليل).

أفنان يحيى مطلق الكركي

المستخلص

للمباني التاريخية القديمة أهمية كبيرة لأنها تمثل التراث المعماري وتعكس صورة تاريخ المدينة. تحتوي مدينة الخليل على العديد من المباني التاريخية، لذلك من الضروري الحفاظ عليها وصيانتها بشكل دوري من أجل إيصالها إلى الأجيال القادمة.

يختلف السلوك الهيكلي والخصائص الميكانيكية للمباني الحجرية التاريخية اختلافًا كبيرًا عن تلك الموجودة في المباني الحديثة. يعد التحليل الإنشائي الدقيق للمباني الحجرية تحديًا حقيقيًا. كونها تتكون من وحدات حجرية مرتبطة بالمونة الجيرية، ان السلوك الميكانيكي للمباني التاريخية يتصف بعدم تجانس مواد البناء وذلك يعود إلى الاختلافات في الخواص الميكانيكية بين القطع الحجرية والمونة الجيرية أو حتى عدم وجود المونة.

الهدف من هذا البحث هو تطوير طريقة لتقييم المباني الحجرية التاريخية، ووضع صيغة للتحليل الساكن غير الخطي، وكذلك تحديد قيم الخواص الميكانيكية لمواد البناء الحجرية مثل معامل المرونة مقاومة الضغط.

أجريت دراسة تجريبية لتحديد الخواص الميكانيكية لمواد البناء المستخدمة في المباني التاريخية القديمة وللتأكد من دقة النمذجة المعتمدة. حيث تم التحقق من صحة النموذج من خلال مقارنة النتائج العددية مع النتائج التجريبية التي تم الحصول عليها من خلال فحوصات المختبر ومن الدراسات السابقة.

تم إجراء دراسة النمذجة العددية بناءً على تحليل السلوك الانشائي، والذي تم من خلال تحليل ثابت غير خطي يعتمد على نموذج العناصر المحدودة الكلية، باستخدام برنامج تجاري (ANSYS)، حيث يعطي التحليل غير الخطي وصفًا للسلوك الفعلي وقدرة تحمل المبنى. لقد تم إعطاء وصف للنمذجة وتحديد خصائص المواد والمعاملات اللازمة لإجراء التحليل والنمذجة العددية. والنتيجة التي تم الحصول عليها عند إجراء التحليل العددي لنموذج مبنى الزاهدة هي أن المبنى يستطيع تحمل أحماله في حالته الحالية، كما أن لديه القدرة على تحمل احمال بما يعادل وزن طابقين. ان الأساليب المقترحة في كل من التجارب المخبرية والتحليل الإنشائي، مناسبة لعملية التقييم الإنشائي ويمكن تطبيقها على نماذج مباني قديمة مماثلة، وأثبتت الدراسة قدرة التحليل العددي والنمذجة على تحديد قدرة تحمل المباني الحجرية، بالتالي تعتبر مناسبة للتقييم الإنشائي، وذلك للحفاظ على التراث المعماري والمباني التاريخية.

الكلمات الرئيسية: المباني التاريخية، الخصائص الميكانيكية، مقاومة الضغط، منحنى الاجهاد والتشوه، معامل المرونة، التحليل اللاخطي، النمذجة الكلية، العناصر المنتهية، برنامج Ansys.

DECLARATION

I declare that the Master Thesis entitled" Structural Static Evaluation of Historic Stone Building (Case Study: Zahdeh Building in Hebron Old City)." is my original work, and hereby certify that unless stated, all work contained within this thesis is my independent research and has not been submitted for the award of any other degree at any institution, except where due acknowledgment is made in the text.

Student Name:

Afnan Yahya Al-karaki

Signature:________________________ Date:________________

DEDICATION

Praise be to God, a lot of good praise until praise reaches its end.

To the soul of my dear father, may God have mercy on him. To my dear mother, may God give her good health.

To my dear husband and children for their continuous encouragement and support.

To my brothers, sisters, family and friends for their motivation and unconditional love that has provided me with the drive to reach and achieve my goals.

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Praise be to God Almighty always and forever for His boundless generosity and kindness to complete any good study.

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I would like to express my deep gratitude and thanks to my thesis supervisors, Dr. Haitham Ayad, and Dr. Ghassan Dweik, for their help, support, patience, continuous guidance, scientific suggestions, encouragement to continue and progress, and the valuable advice they provided at every stage of this study, so I am honored and proud of my master's thesis supervisors.

Finally, great thanks to everyone who has contributed to the success of this work.

Table of Content

List of Abbreviations

ACI	American Concrete Institute
ASTM	American Society for Testing Materials
fc	Uniaxial Compressive Strength of composite stone &mortar
fs	Uniaxial Compressive Strength of stone
fm	Uniaxial Compressive Strength of mortar
ft	Uniaxial tensile strength
σ	Stress
Ϭ t	Flexural Strength
σxp	Principal stresses in x direction
σyp	Principal stresses in y direction
σzp	Principal stresses in z direction
$\boldsymbol{\rho}$	Density
ε_{o}	Peak Strain
ε	Strain
Ec	Modulus of Elasticity
α, β, γ, a	Coefficients empirically derived based on Experiment
w/c	Water/Cement
ν	Poisson's ratio.
Exp W30	Experimental of Model Wallette of 30cm length at 3month
Exp W 40	Experimental of Model Wallette of 40cm length at 3month
Exp3 P 20	Experimental of Model Prismatic of 20cm length at 3month
Exp1 P 20	Experimental of Model Prismatic of 20cm length at one month
L.M	Lime Mortar
L.M.M	Lime Mortar Mixture
hs	Height of stone and mortar models
ts	Thickness of stone and mortar models

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Chapter 1
Introduction

1.1 Introduction

Palestine witnessed several different periods of its history, so it has a great architectural heritage even though it is a small country (Abuarkub & Al-Zwainy, 2018).

Traditional Palestinian architecture used stone on a large scale, especially limestone (Angiolilli & Gregori, 2020), which is the main material in buildings with bonded lime mortar, accordingly, lime, clay and gypsum are traditional binders that have been used by builders for centuries, with the knowledge that cement and reinforced concrete were not available at that time, so it began to appear in the nineteenth century (Hadid, 2002).

The traditional Palestinian construction method for walls is based on the use of thick limestone without external plastering. In addition to the use of double leave walls of stone, the space between the layers is filled with mud (Hebron Rehabilitation Committee, 2017).

Historical building are a reflection of the culture, history, and science of their builders. As evidence of the innovative spirit of ancient cultures, stonework has been utilized to construct the oldest monuments and is found the most remarkable (Amer, et al., 2021). Also, it is a fundamental part of the heritage in many countries (Duran & Chavez, 2022). So Historic structures can be defined as "existing structures with significant cultural value to the society" (Asteris, et al., 2015).

Stone structures are the most durable, available and one of the oldest building materials (Smoljanovic, et al., 2018). That is why this type of construction is popular for early builders as it has the advantage of structural stability and aesthetic value (Li, 2012).

stone structural building is a heterogeneous material mainly composed of units and joints. Units are rubble or ashlar, regular or irregular stones. Mortar can be clay, bitumen, chalk lime/cement-based mortar, glue or others. The mechanical behavior of stone structural elements exhibits non homogeneity and directional properties, and generally common features: high specific mass, low tensile and shear strengths and low ductility (brittle behavior), in addition to cracking due to weakness and brittleness of mortar joints. (Autiero, et al., 2020 ; Hamdy, et al., 2018 ; Kamal, et al., 2014).

In general, historical building structures have the ability to bear vertical loads safely and in a stable manner, while it is sometimes sensitive to horizontal loads. (Betti.M, 2016; Eslami. A,2012). Old stone building structures have a high compressive load bearing capacity but much lower tension capacity (Evgeny, et al., 2023; Orduña,2017). Structural elements compatible with the structure of the old building were used, in which the transfer of loads occurs mainly through compressive stresses and does not depend on tensile or shear strength (Binda, et al., 2005; Orduña ,2017).

In old historical building structures, crack patterns are caused by reasons including: the inability to transmit significant tensile force, aging, natural damage, or loading conditions (Briccola& Bruggi,2019; Li,2012). However, cracks are not necessarily symptoms of a potential failure, because stresses can automatically reach a purely compressive state, which explains that cracking zones does not necessarily produce building instability (Briccola & Bruggi, 2019). Sudden collapse of the structure can occur without (or minimal) warning signs of impending structural failure of historic building structures, either due to previous reasons (Li, 2012).

The safe and economical operational solution for evaluating heritage structures is based on detecting the beginning of the damage, then performing a structural analysis that requires essentially the knowledge of the mechanical properties of building material, which is beneficial to the efficient and effective restoration (Li,2012; Giaccone,2020). Stone buildings complex mechanical behavior and brittle behavior in tension is a major reason for the high nonlinearity of the mechanical response of building structures (Briccola & Bruggi, 2019). So, the evaluation of historical building structures is a challenging task, mainly due to the inelastic and inhomogeneous mechanical response of the material (Autiero, et al., 2020).

The most popular application of numerical tool for structural analysis is the finite element method, which is strong formulation that is used abundantly for solving problems structural. Static Analysis is considered one types of structural analyses, in which the fundamentals of structural analysis are based on the application of simple static equations to the equilibrium of a structural element, where used to determine displacements, stresses, etc. under static loading conditions. A static analysis can be divided to linear or nonlinear, where nonlinear analysis includes plasticity, stress stiffening, large deflection, large strain (Gaur & Srivastav, 2020; Nikolic, et al., 2016; ANSYS, 2013).

Nonlinear structural behavior commonly results from nonlinear stress-strain relationships, with considered the following causes, which categories:

• Changing status.

• Geometric nonlinearities.

• Material nonlinearities (ANSYS, 2013).

Since the nineteenth century, the basis of graphics statistics has been provided by Simon Stephens, the development of structural analysis began from classical statistical methods to advanced finite element analysis methods using new numerical and computational methods. So, the old structural analysis has thus become easier, however it is still very difficult when compared to modern structures (OZEN, 2006).

Modeling old stone buildings is a difficult process, due to several reasons, including:

- The mortar joint between the layers of stones, which is the weak point of the structure.
- Complex geometry, so that successful modeling needs an accurate geometry description.
- The materials constituting the structures are heterogeneous and anistropic composite.
- Limited information available on the behavior and properties of structural materials.

So, the finite element method is best suited for analyzing building structures, and nonlinear analyzes give acceptable results, and are relatively insensitive to the change of some parameters (Pegon, et al., 2001; OZEN, 2006; Li, 2012).

Popular ideal structural behavior used in the analysis can be categorized into: elastic behavior, plastic behavior and nonlinear behavior (OZEN, 2006). The most effective method of analysis is nonlinear analysis, for its ability to trace the structural response of a building structure from the elastic stage through cracking and crushing to failure. Numerous nonlinear constitutive models have been developed to analyze historical structural buildings, the best and most common model of plasticity and continuum damage mechanics.

Achieving the best real properties of building materials for historic buildings, by providing sufficient information on the behavior of these materials and buildings. A non-destructive testing method can obtain valuable information, but not provide sufficient information about the properties of materials that are needed in advanced modeling. On the other hand, the destructive tests that are performed either on site or by removing large samples from the building, give accurate results, but require high cost, effort, and exposing the building to damage (Oliveira, 2003).

Experimental studies and numerical models are an integrative method for conducting a structural analysis of a building, to give a complete and comprehensive description of mechanical behaviors, and an understanding of response structural buildings.

Determining the compressive strength of ancient historical buildings is of fundamental importance for structural evaluation, since building structures are mostly stressed in compression (Marotta, et al., 2016; Lourenço & Pina-Henriques, 2006).

In recent years, researchers have focused on reviving and restoring historic buildings, to preserve the ancient heritage and deliver it to future generations, and to pay attention to traditional architectural elements that made buildings sustainable.

In this research, the structural evaluated process Zahdeh building in Hebron old city is analyzed, based on an integrated approach which includes a set of experimental, simulations, and numerical analysis.

In order to bridge the knowledge gap in this field, the behavior and mechanical properties of traditional stones available in Hebron Old city, mortar, and the prismatic models were studied, under compressive loads, taking into account rubble stone with low strength mortars. Numerical analysis using nonlinear analysis is performed through finite element for an old building in the Hebron Old City, using the ANSYS program, based on Willam-Warnke criteria failure. In addition, A macro-modeling method including units and mortar is followed.

All the experiments were carried out at Building Materials Technology Laboratory of PPU, in cooperation with Stone and Marble Center, Hebron.

1.2 Problem Statement

Historical buildings are importance in documenting an entire civilization and era. As that found of many ancient historical buildings that need a structural evaluation in order to preserve its sustainability, durability, the architectural style, and revive them to be suitable for use. The process of evaluating and modeling historical buildings is difficult challenge for several reasons, the main difficulties in evaluating the performance of historical buildings is summarized in the following points:

- Complex geometry, difference in mechanical properties of structural elements.
- Lack of knowledge about the mechanical properties of the building's components, due to the lack of studies around experiments that carrying old stone and mortar as equivalent materials.
- Inelastic and heterogeneous materials consisting of stone and mortar, where the modulus of elasticity of stone different from the mortar.
- The mechanical behavior of ancient structural elements is heterogeneous, owing to the fact that it is made up of more than one material with different properties.
- Modifications, repairs and other interventions during their life, often times, these repairs were carried out with almost different materials.

The analysis of building structures is usually performed to assume linear isotropic behavior, as this type of analysis reduces the structural capacity, and not giving accurate results or real values. In addition to the non-applicability of concrete laws to old building materials. Therefore, nonlinear analysis, which is capable of describing the behavior of the structure from cracking until complete loss of strength, has been adopted.

Over the past years and currently, adding loads or floors to existing buildings and changing the uses of buildings occur at different stages of time and without proper planning and urban oversight, and the mixing of uses appears in the same building. This problem appears clearly in one of the cases of random addition, as in Figure 1.1. Therefore, the process of evaluating historical buildings must be carried out.

Figure 1.1: Random additions at different time stages in Hebron. source: researcher

1.3 Research Questions and Hypothesis

Based on the identified problem in the previous section, the following research questions need to be addressed:

1.3.1 Main research question:

Can the old historical buildings have the ability to carry their current load for long and short term, but in this study short term analysis is done?

1.3.2 Sub-questions:

1. What is the impact of the structural evaluation on preserving the historical buildings?
2. Is it possible for old historical buildings to bear additional loads?
3. Is the structural analysis of old buildings similar to modern buildings?
4. Could ancient building structures collapse , either because of their old age or the additional loads?

1.3.3 Hypothesis:

It is hypothesized that the process of structural evaluation of ancient historical buildings is the most important stage for preserving the architectural heritage and historical buildings.

Historical building has low tensile strength and cracks with a quasi- brittle softening behaviour.

In the structural analysis, the material properties were considered to be isotropic and homogeneous throughout the building.

1.4 Research Goal and Objectives

The main objective of this study is to develop a method for assessment of load carrying capacity of historical stone buildings by using experimental and nonlinear methods.

Particularly, the study has the following sub-objectives:

1. To perform a parametric experimental test, such as uniaxial compression, flexural test, to provide a sufficient set of data concerning the historical stone buildings, to be used in numerical modelling.
2. To determine mechanical properties of constitutive materials which contain stones and mortars materials of ancient building, in addition to describe stress-strain behavior.
3. To identify suitable numerical constitutive models, that include both elastic and inelastic behavior, taking into account the non-linear analysis method.
4. To perform a FE model, which can predict the behavior of the historical stone buildings.
5. To check if the historical buildings can sustain an extra load.

1.5 Research Significance and Relevance

The research is important for preserving of historical buildings, This, in turn, extends the life of buildings to reach future generations.

Palestine possesses an enormous wealth of ancient and historical buildings constructed of stone with different shapes and types. Historical buildings in Palestine are affected by the religious aspect, due to the presence of many mosques and churches, such as the Church of the Nativity, Al-Aqsa Mosque, and the Dome of the Rock, which had a great influence on its member society, and occupy a special place in all societies. Hebron is a very important religious site due to the presence of the Ibrahimi Mosque, where the old city grew around it. The ancient city of Hebron is proud of its many heritage buildings which are still in everyday use.

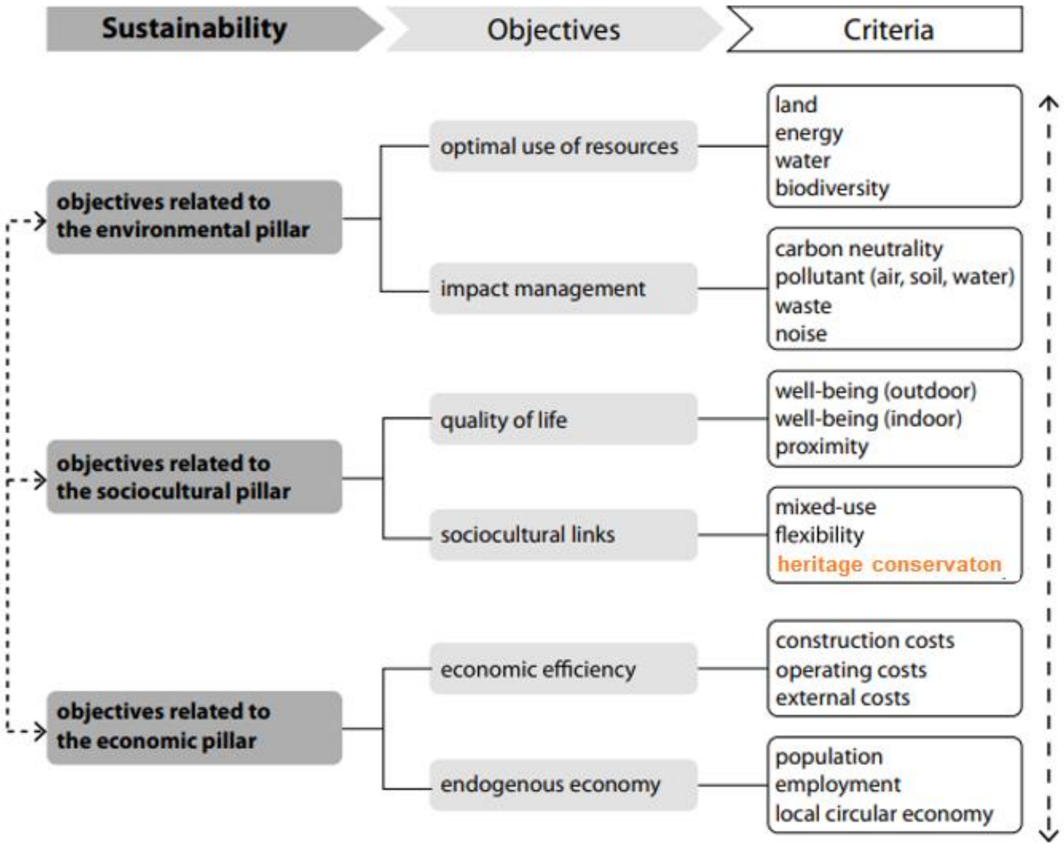

Figure 1.2: The main pillars of sustainability. source: (Rey, et al., 2022)

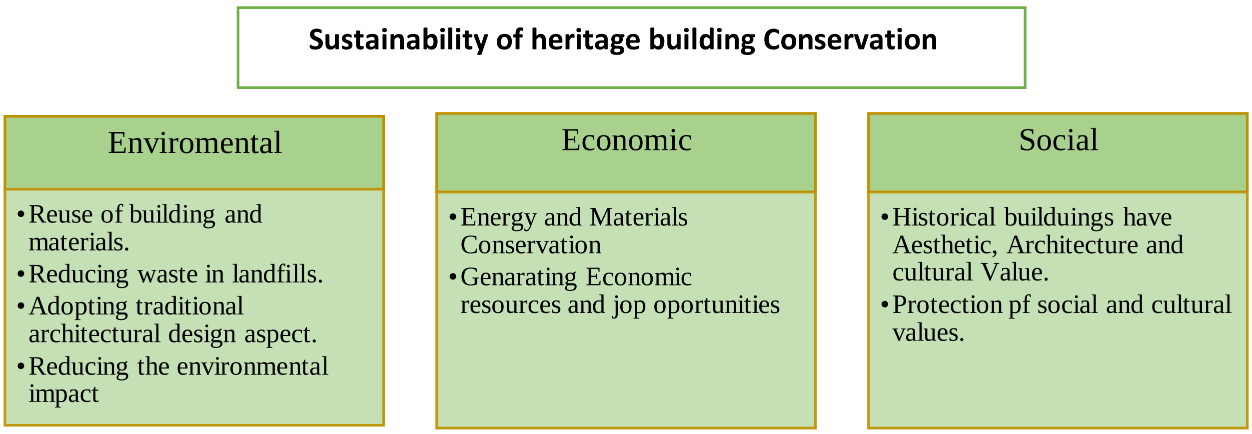

Figure 1.3: Sustainable historic conservation strategies. source: researcher.

The structural evaluation phase of historic buildings represents the first step in the conservation of these buildings. The process of preserving heritage historical buildings is considered an integral part of sustainability that relates to the social cultural pillar, as is clear in Figure 1.2, and through Figure 1.3, heritage buildings conservation achieves most of the pillars of sustainability. Currently, Palestinian historical buildings are an important asset, due to their cultural and architectural value.

From a structural point of view, there are weak points of historical buildings. So, there is a real need of conservation of this invaluable architectural heritage for future generations. This goal necessitates going through a comprehensive scientific procedure of assessment of these structures. In addition, nowadays there is an increasing awareness of the importance of this construction system, whereas the system of construction has many advantages over the widespread reinforced concrete system such as economy, durability and sustainability. With the knowledge that most of the built environment in old city center of Hebron is made of stone buildings, which represents a rich and varied architectural heritage.

The experimental results provided in this study could be utilized not only in the nonlinear finite element analysis of the case study structure, but also in the numerical analysis of other similar buildings constructed in this region with similar components and at around the same time.

1.6 Research Approach

This study includes quantitative and qualitative research methods. The research methodology is mainly based on experimental tests and numerical analysis. A literature review was conducted to describe methods and tools that are needed in experimental tests and numerical simulations, based on published empirical and analytical research.

Structural assessment, is a wide activity, involves several and different types of complementary requirements. These can be summarized and ordered as:

1) On-sight visits to the Old City of Hebron and the case study building took place many times aiming at:

- Preliminary tasks (field surveys, geometrical characterization, historical investigations, etc.)
- Diagnosis of existing and observed damage, looking for respective possible causes.
- Obtaining the structural and architectural plans for the building.
- Measurements of walls thickness, mortars and stones dimensions
- Taking photos for the building from inside and outside.

- On-sight collection of stones of different types and sizes to conduct experimental tests.
- Conducting tests by Schmidt Hammer to obtain compressive srength of mortar and stone in different places inside and outside.

2) Experimental tests of stone and mortar using non-destructive methods in the laboratory.

3) Conducting validation between experimental and numerical analyses (models) of flexural beams and wallet samples using ANSYS.

4) The analytical models are compared with experimental models to verify results and validate used analytical parameters.

5) Conducting numerical simulation of the case study building depending on mechanical properties of experimental test and empirical equations according to code.

5) A macro finite element model was used in this study for detailed analysis of the nonlinear behavior of ancient structures.

6) Numerical simulations of the structural response under relevant to mechanical properties of materials and pertinent loading conditions.

7) Determine the condition of the building, whether it is:

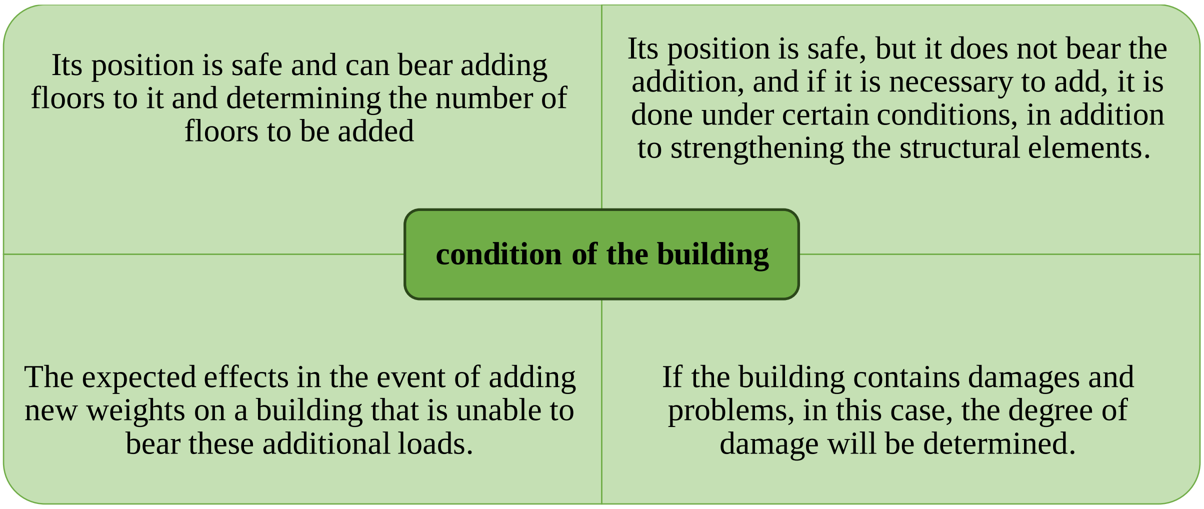

Figure 1.4: Determine the condition of the building. source: researcher

1.7 Scope and Thesis Outline

This thesis consists of six chapters.

Chapter 1 – Introduction

This chapter contains a brief introduction to the research. A comprehensive background about Problem Statement, research questions and hypothesis, purpose, research significance and the general methodology of this thesis are presented.

Chapter 2 – Literature Review

This chapter presents a literature review, containing all topics that have been studied in the areas of this research and where the previous researchers arrived in their research.

Chapter 3 – Building Description

This chapter describes the architectural and structural of the Zahdeh building, the building materials used, and the problems that the building suffers from.

Chapter 4 – Experimental Work

This chapter demonstrates the experimental work, which is one of the main large parts of the work of this thesis. The details of materials, equipment, the test set-up and the work steps are presented. In addition, the equations that were used in the calculations are explained with tables and diagrams that showed and demonstrated the tests results of stone, mortar and model samples of stones and mortar, also a discussion on the results is presented with comparisons of the results with previous study and analytical predictions values.

Chapter 5 – Numerical Analysis and Modeling

This chapter demonstrates numerical analysis and modeling, which is one of the main parts of this thesis. In this study, numerical analysis methods such as FEM were relied on for structural analysis, thus it became possible to model the complex behavior of the structures of ancient historical buildings. A macro modeling strategy was also adopted.

Chapter 6 – Conclusions and Recommendations

This chapter gives a summary of thesis and lists the main findings of this research; the general conclusions are stated. Conclusions are made on the experimental work and numerical analysis and modeling which include: calculations, results, comparisons, validations, simulations and analysis. Potential further research issues are also included in this chapter.

CHAPTER 2

Literature Review

2.1 Introduction

This literature review provides a review of historical stone work buildings, historical buildings in Palestine, sustainability of historical buildings, materials, properties, bond issues, bond characteristics and other information related to compression, flexural and tensile strength testing of stone work assemblages, as the numerical analysis, modeling, The purpose of this research was to find, read, and analyze the body of literature which been published by books, journal articles, conference articles, and to clarify the mechanical properties of the old building materials composites for the values of compressive strength, tensile strength, modulus of elasticity, and Poisson's ratio, as well as the tools and devices that were used, the type of testing methods used for the experimental measurements, in addition to the programs that were selected to conduct the simulation.

2.2 Historical Buildings in Palestine

Palestine is a country with a small and unique area, because of its historical, cultural and religious importance. Palestinian architecture has gone through many civilizations thousands of years ago, and was affected in each era by the prevailing civilizations, so architecture was an accurate expression of those different civilizations (Abuarkub & Al-Zwainy, 2018; Al-Ju'beh, 2009). Architecture in Palestine was based on the basic principle of security and beauty. Security is achieved by using very hard stones in construction, and beauty in designing buildings that ensure comfort and safety for its residents (Baker & Yousef, 2005).

Palestine is rich in historical heritage buildings and religious sites such as the Al-Aqsa Mosque, the Dome of the Rock, the Church of the Holy Sepulcher, the Church of the Nativity and the Ibrahim Mosque, so that the cultural heritage in Palestine is called "white gold" for its unlimited wealth that supports the economic and social aspects. Where historical buildings have been documented through the Riwaq Register, 50,320 historic buildings located inside and outside the historic centers of 422 towns and villages the number of historical buildings in Palestine is 50320 with a number of 708 residential areas, while the number of historical buildings in the city of Hebron is 10322 with a number of 156 residential areas, thus the percentage of the total number of historical residential areas in Hebron represents 22.03% (Al-Ju'beh, 2009). Currently, Palestinian historical buildings are an important asset, due to their cultural and architectural value.

2.2.1 Traditional residential buildings in old Hebron city

Hebron is one of the oldest cities in the world and has been famous since ancient times for its historical buildings. Many buildings in the Old City are over 500 years old, although the city witnessed many wars and colonizers throughout its history, it is still distinguished by its ancient history characterized by continuity and renewal, as this city did not disappear at a certain historical stage of the war or earthquake. In addition, Hebron is one of the most sacred religious sites for Muslims, where is the Ibrahimi Mosque. Thus, Hebron's Old City grew around this religious site in different periods, Different traditional elements of Islamic architecture can be found like buildings with open courtyards. The Old City is the historic heart and soul of Hebron, and its architecture and the structure of its regions can be traced back to the Mamluk period, also known as 'The Golden Age' of Hebron (Shaheen, 2021; Hebron Rehabilitation Committee, 2017; al-Orzza, et al., 2016).

Most of the residential buildings in Hebron Old City date back to the end of the Mamluk era, at least the ground floor, or sometimes some parts of it; As for the rest of the floors, it dates back in most of its parts to the Ottoman era, 1517-1917 AD. In the Mamluk era, al-Hanbali described the dwellings of Jerusalem and Hebron, saying: As for the construction of Bayt al-Maqdis, it is very precise and perfect, all of it made of white carved stones, and its roof is crosse volts, and there is no brick or wood in its construction (Dweik & Shaheen, 2017).

As for the city dwellings in the Ottoman era, especially at the end of this era, they converged; This led to the vertical expansion at the expense of the horizontal urban expansion; The dwellings were attached to form a wall of the city, and consisted of 'three floors': the ground floor, the first, and sometimes another floor was built above the first called the "palace" or the "attic"; This indicates the abundance of local building materials (stones, lime, clay...) as well as the increase in family size, which led to overcrowding (Dweik & Shaheen, 2017).

2.3 Sustainability of Historical Buildings

Sustainability is an important consideration when it comes to buildings, the most sustainable and resilient buildings known to date are historical buildings.

Sustainable cultural heritage as defined by Jelincic & Glivetić " Preserving cultural heritage for future generations, at the same time finding balance and harmony between cultural heritage and the people who wish to experience it." (Jelincic & Glivetić, 2020)

Historic buildings and sustainability are closely related, so preservation of historic buildings and sustainability are natural partners (Jelincic & Glivetić, 2020), as it tends to be environmentally sustainable in nature, as they are built from local materials and respond to the climate and location, (Wilkinson & Remøy, 2017; Alves, 2017; COCEN, 2013). They were constructed without modern technologies, as performs the environmental functions efficiently, such as: ventilation, daylighting, thermal comfort, etc. (Historic Preservation Office, 2019). The durability and sustainability of all social, cultural, economic and environmental pillars are achieved in historic buildings (Jelincic & Glivetić, 2020). In addition, the preservation and reuse of historical buildings reduce the consumption of resources and materials, so there is less waste in landfills, and the consumption of energy is lower than the demolition of buildings and the construction of new ones.

The reality that historical buildings survive today is due to the presence of distinctive characteristics in them: the way, shape, and dimensions of structures, and the properties of composite materials (Mustafaraj, 2013).

Despite this, most historical buildings suffer from structural and non-structural problems (Ali, 2013), starting from weakness, damage and to collapse over time, due to accidental actions, such as earthquakes, accumulated damage due to traffic, wind loads, temperature, soil settlements, and lack of use, as well as a lack of structural understanding of these buildings, all these factors represent a significant risk to the architectural heritage (Lourenco, 2002), so the process of structural analysis of buildings is the first step for repairing and modification (Ali, 2013).

Thus, the process of strengthening historical structures protects the structure for a longer time, improves the bearing capacity, and extends the service life of the buildings; to reach future generations (Mustafaraj, 2013).

One of the most important factors to consider in the architectural heritage is the cultural and aesthetic value of the structure, which cannot be evaluated by fixed criteria. Thus, when the process of rehabilitation of historic buildings is the result of urgent and necessary circumstances, it must be taken into account that each intervention is commensurate with safety objectives and guarantees durability with minimal damage to architectural heritage values (Abdulsalam & Ali, 2015).

The process of preserving and renovating historical Palestinian buildings is considered the most sustainable in terms of construction activities for several reasons, including: Preserving the environment and heritage social values, reducing waste of materials, and energy consumption, minimizing used of raw materials, limiting of negative environmental impacts, and learning from the skills, abilities, and creativity of the builders that led to the creation of historic buildings (Historic Preservation Office, 2019).

(Salameh, et al., 2022) focused on the heritage value of preserving historical buildings in a sustainable manner; from an environmental, economic, and social perspective. Where a case study was evaluated in the city of Nablus, Palestine, at the architectural and urban levels. The results proved several things, namely: that traditional passive design solutions have many advantages over modern solutions, the thermal performance of the traditional building was more effective, the preserving heritage is essential to protecting identity in preserving the past for future generations, and the preserving historical buildings has direct positive effects on all aspects of sustainability; environmental, social and economic.

(Redden & Crawford, 2020) mentioned that historical buildings have high cultural heritage value, also play an important role in responding to climate changes and environmental challenges, preserving buildings is an opportunity to revive traditional experiences, protect cultural identity and heritage, and provide enhanced environmental outcomes, so, they can be fit for modern needs.

(Said & Alsamamra, 2019) emphasized that the traditional Palestinian architectural style has an architectural and construction style that meets the requirements of sustainable green building, as well it is characterized by its energy-saving elements.

(Awad, 2017) has found that there is an increasing number of conservation projects for historic buildings across Palestine, to protect and preserve architectural heritage.

(Barthel-Bouchier, 2013) also emphasized the importance of preserving traditional buildings that can protect the identity and heritage of society, and that the beginning of the idea of preserving historical buildings was acquired gradually, where heritage can contribute effectively to the formation of sustainable societies, and therefore historical buildings are considered the second nature of human beings.

In Riwaq's study, it highlighted on the architectural heritage, as well as on the design of the Palestinian house was in harmony with nature and the climate, as one of the most important distinguishing features of Palestinian traditional architecture is the presence of architectural and construction elements that serve the climatic conditions (Al-Ju’beh, 2009).

(Curtin, et al., 2006) mentioned many advantages that are available in historical buildings, which are living evidence of the quality of these engineering structures, including: excellent durability of construction, sound insulation, heat insulation, fire resistance and accidental damage.

(Hadid, 2002) explained that the methods that were used to overcome the climatic conditions and achieved solutions to environmental problems are: using local materials at affordable prices, the yard inside the dwelling, the orientation and the elevation provide shade and block the sun's rays. In addition, the thick stone walls serve as a tool for heat insulation, Vaulted surfaces reduce the area exposed to sunlight, as well as prevent the pooling of winter water on the surface the home.

From the researcher's point of view, it was found that the observations and results reached in previous studies regarding the sustainability of historical buildings are realistic and were sensed through repeated field visits to those buildings.

2.4 Materials

Building materials have an important and efficient role in determining the properties and behaviors of building structures (Donduren & Sisik, 2017). Historic materials represented the earth, bricks or stones, lime, and wood, that used in stone work feathered by very complex mechanical properties, so that the construction is characterized by a composite character, making it challenging to model (Roca, et al., 2010). Each era has its own character, rules, and standards in the use of building materials and construction methods (Qawasmeh & Maraqa, 2016).

2.4.1 Stone

The mountainous nature had a role in determining the building materials consisting of very hard limestone (Qawasmeh & Maraqa, 2016).

The stone was used in its natural form or in the refined, carved form in the ancient construction. The building with stone has deep roots in the Palestinian building culture. The city of Hebron has a wide range of high-quality rocks suitable for use in construction, including granite, limestone, and sandstone (Qawasmeh & Maraqa, 2016).

Geologically, stones are classified into three categories: sedimentary, igneous, and metamorphic (CUPA, 2012). Available in stones many distinctive properties of strength, hardness, density, durability, formability, natural aesthetic, low maintenance, recyclability, and high strength when compressed as in the construction of a wall (Vierra, 2016; Qawasmeh & Maraqa, 2016; Prikryl & Torok, 2010), but it is weak in tensile forces, so in the ceilings and horizontal spans, the system of arches and cross vaults are used (Strickland, et al., 2010). Thus, to its high-performance and unique properties, natural stone is excellent material choice as it plays the main role in sustainable architecture (A.Klemm & D.Wiggins, 2016; CUPA, 2012).

Stone is one of the oldest building materials in the world, that has been used for centuries (Atiyat, 2015), where its use has great assets in the building culture, as it gives a distinctive character to the built heritage, usually there is a link between the stone type and a specific place (Fort, et al., 2013), also, the main building material used in Palestine is the local natural stone (Hadid, 2002), that is used in construction by traditional way, where the stone wall composed of two leaves filled up by mortar or mud, but nowadays building using old way is hard and expensive (Carabelli, 2019).

As a result of the above, stone is a valuable building material that has high compressive strength despite its ancient use and longevity, so it can be reused wherever possible.

2.4.1 Mortars

Mortar has a very important and complex main role; it is used between the units in the structural members; it plays a crucial function in linking stone pieces into a single mass.

During construction it should be easily workable - it should spread easily and retain water, so that it does not dry out and harden too quickly, and harden in a reasonable time to prevent pressure under the weight of the units placed above (Curtin, et al., 2006).

In the stage that hardness is reached, the mortar must have acquired sufficient strength to resist, be able to transfer compressive, tensile and shear stresses between adjacent units, to be highly durable. Although sufficient strength is necessary, it must be a suitable mortar compatible with the strength and durability of the blocks. So cracks in mortar are easier to repair than cracks in stone units, thus the use of a strong mortar, the result is not necessarily a stronger structural element, because the strength of the mortar is not directly related to the strength of the structures built with this mortar (Curtin, et al., 2006).

Lime is made by heating limestone (calcium carbonate or calcite, CaCO3) to temperatures ranging between 1000- and 1800-degrees Fahrenheit, in a kiln (Dweik, 2017).

The serviceability and stability of the historical structure are to set by the link between the unit and mortar, which is why it is crucial to comprehend this complicated attribute to structural evaluation (Choudhary, 2015).

The mortar used in Palestinian historical buildings consists of two main components: the binder (hydraulic lime) and Aggregate (sand, gravel, pottery, ash, straw or other organic elements) (Hadid, 2002).

Lime mortars are chosen for historic masonry restoration because of their greater stability, and compatibility with traditional building materials by their physical features. which allows accommodating expansion and contraction in operation without compromising the wall. Lime mortars' When utilized properly between stones, lime mortars perform as a benefactor layer, preventing the nearby substance from decomposing. Because lime has a relatively high vapor permeability, steam can permeate into it, allowing the structure to 'breathe limestone (Qawasmeh & Maraqa, 2016).

2.5 Mechanical properties of materials

The basic mechanical properties of historical materials include compressive and flexural tensile strength, the bond strength between the unit and mortar, modulus of elasticity, Poisons ratio, and stress-strain response of constituent materials. The basic physical properties of historical materials include water content, volumetric weight. In this research, the properties studied are the water absorption of old stones, the compressive strength and density of stones, mortar, and a composite of stone and mortar used in the form of a prism, Wallette, in additional of flexural strength of beams.

As per (Lithospheric Strength Profiles) "A strictly homogeneous material is one in which all pieces are identical. In other words, material composition and properties are independent of position." And the definition of an isotropic material "is one in which the mechanical properties are equal in all directions: material properties are independent of the direction in which they are measured."(Tectonics, 2020).

It is necessary to understand the strengths and weaknesses of the old building structures, to understand the behavior, and exploitation of their structural potentials, and to be able to evaluate the structure, as these buildings are strong in compression and weak in tension, also understanding deformation properties are required, to compute the settlement of historical structures to predict differential motions in buildings, in order to be able to evaluate the structural performance of historical buildings (Khair & Hossain, 2005).

The structural behavior and performance of historical buildings can depend on several factors: compressive strength, tensile strength, shear strength, modulus of elasticity, load-deflection curve, unit weight, size, wall thickness, number of walls leaf, structure configuration, and various sorts of loads that the buildings are subjected to, as well as its performance is influenced by the slenderness ratio and openings in the masonry walls. (Khair & Hossain, 2005; Binda, et al., 2005). Therefore, it is necessary to carry out the experiments to fulfill the purpose (Estefania, et al., 2018). So, tests on both individual building materials and equivalent materials follow two methodologies: Destructive Tests (DTs) and Non-Destructive Tests (NDTs). DTs allow directly obtaining mechanical parameters of building materials and structures, and the method of their implementation is generally standardized. When assessing masonry walls, some DTs can be performed in the laboratory and on site, but for heritage buildings the procedure for DTs on those buildings is limited due restrictions that put for preserving the heritage built, so the Non-destructive testing is generally required. On the other hand, it is possible to perform minor destructive tests on site for walls as (single or double flat-lever tests), even the implementation of such tests is not applicable at archaeological sites. NDTs are useful, but they are usually not able to produce accurate results, and must be calibrated for each specific type of construction, to comply with the original structures. Incorporating DTs and NDTs, it can be a comprehensive diagnostic approach, depending on the investigation structure and desired outcomes (Autiero, et al., 2020).

Testing complete building structures is expensive and difficult and requires appropriate equipment (Mohammed, et al., 2011). Because of this, reliable models have been developed on a small scale represents the behavior of structures at a large scale, taking into account the requirements of the model conditions and origin size, in order to truly reproduce the behavior in full on the scale. Since the fifties of the last century, this technique has been used. In general, all studies showed success in using small models which represent building behavior (Milani, et al., 2021).

(Mohammed, et al., 2011) discussed the effect of scale or size on the structural behavior of the building under pressure. Modeling was used on a small scale, so that the tests included four measures: Prototype, half, fourth and sixth scale, the result of the research was that with the decrease in the scale, the compressive strength of the building increases, but hardness is not affected significantly.

2.5.1 Compressive Strength of Stone and Mortar Composite

Assessment of the strength of historical building involves some difficulties due to the diversity in the use of and materials methods of construction and many influencing parameters. The size of a unit, the thickness of the horizontal and vertical mortar layer, the bonding and quality of the units' connections, in addition to the essential characteristics of the materials used and the construction quality, plus environmental circumstances, all affect the mechanical behavior and compressive strength of historical building (Guadagnuolo, et al., 2020).

From structural point of view, the historical structure is mainly characterized by the strength of its capability of bearing the compressive forces applied to it. As a result, the determination of its compressive strength is critical (Ferretti, 2020). Compressive strength tests are commonly performed to measure a material's capacity to resist deformation under stress (Mahmoud, et al., 2019).

The material is typically thought to have reached a strength that is close to the maximum value after 28 days, it is assumed that the compressive strength value of lime mortar after about 60 days reaches its full strength, according to studies by (Gonen & Soyoz, 2021; Garcia, et al., 2012; Magenes, et al., 2010). With attention and taking into account that this process takes a longer period of time for lime mortar (Gonen & Soyoz, 2021). All building codes include equations for calculating the composite construction compressive strength (fc) as a function of stone (fs) and mortar (fm) strength, which one of the most widely used virtual relationships:

$$fc = \alpha \, . fs^{\beta} . fm^{\gamma} \quad \ldots\ldots\ldots\ldots \quad (1)$$

The coefficients α, β, and γ are empirically derived based on experimental investigations on current materials and vary from code to code. The above equation would necessitate precise coefficient values or additional correction factors (Guadagnuolo, et al., 2020; Ferretti, 2020). The hydraulic grade of the binding material and the compressive strength of the mortar have a major effect on masonry compressive strength, but the effect decreases as the masonry strength approaches its optimum, which is mainly associated to tensile and compressive strength for units. The relationship between mortar compressive strength and masonry compressive strength was non-linear. Eurocode 6 offered an excellent forecast for calculating the compressive strength of lime stonework, depending on the strength of the components of mortar and stone (Costigan, et al., 2015).

Eurocode 6, Costigan, et al., Kaushik, et al., Dayaratnam., Hendry & Malek, developed the numerical homogenization theory, Equation/ empirical expression for the estimation of historical building compressive strength as shown in table (2.1), which that some common empirical expression.

Table 2.1: Common models used to predict the compressive strength of historical stone building

Study Source reference	Equation/ empirical expression
Eurocode 6 (Eurocode 6, 2005)	$fc = 0.5 \, . fs^{0.7} . fm^{0.3}$
Hendry and Malek (Hendry & Malek, 1986)	$fc = 0.317 \, . fs^{0.531} . fm^{0.208}$

Dayaratnam (Dayaratnam, 1987)	$fc = 0.275 fs^{0.5} . fm^{0.5}$
Kaushik et al. (Kaushik, et al., 2007)	$fc = 0.63 . fs^{0.49} . fm^{0.32}$
Adrian Costigan et al. (Costigan, et al., 2015)	$fc = 0.46 . fs^{0.5} . fm^{0.5}$

2.5.2 Stress–strain relationships in compression

The stress–strain curves of stonework in compression explain the relation between applied stress and strain. The stress–strain relationship of stonework prisms and wallettes linked by mortars in compression is non-linear, according to Eurocode 6. The stress–strain curve can be obtained as a linear segment up to between 30% and 60% of the ultimate stress, above 60% ultimate stress a parabolic growing curve (up to a strain of 0.002), the peak stress is reached, and the material fails, or a horizontal level (up to 0.0035 strain) depending on the code. (Costigan, et al., 2015).

Equation suggested by Kaushik et al to calculate maximum strain at maximum stress increases as the compressive strength increases (Kaushik, et al., 2007):

$$\varepsilon_{o} = \frac{K}{fm^{\alpha}}\left(\frac{fc}{Ec}\right) \quad \ldots\ldots\ldots\ldots \quad (2)$$

fc and εc represent the compressive stress and strain of stone work, respectively, while ε_{o} represents the peak strain corresponding to fc (Kaushik, et al., 2007).

where K is fixed to 0.27 and α to 0.25 and λ=0.7, as (Kaushik, et al., 2007).

where K is fixed to 0.34 and α to 0.01, and λ=1.0, as (Costigan, et al., 2015).

The raising portion of the stress strain curve resembles a parabola with vertex at the maximum stress:

$$\frac{\sigma}{fc'} = 2\frac{\varepsilon}{\varepsilon_{o}} - \left(\frac{\varepsilon}{\varepsilon_{o}}\right)^{2} \quad \ldots\ldots\ldots\ldots \quad (3)$$

Where, (σ) is stress for a value of strain in stress-strain relationship.

2.5.3 Modulus of Elasticity of Stone and Mortar Composite

The modulus of elasticity of stonework is one of the most important characteristics to determine the stress-strain properties of structural elements that are considered while evaluating existing structures and designing new ones (Evgeny, et al., 2023; Gonen & Soyoz, 2021). The stiffness of the structural units and mortar mix determine the modulus of elasticity of the stonework. The secant method is used to calculate the modulus of elasticity using the stress-strain curve (Khair & Hossain, 2005). The modulus of elasticity of existing stonework walls can be evaluated differently from the stress design objectives. Various kinds of approaches for estimating the modulus of elasticity are discussed in building codes and research articles (Guadagnuolo, et al., 2020). The secant modulus (at 1/3 fc) is commonly used to determine the modulus of elasticity, which the linear part of the masonry compression stress-strain curve (Krzan, 2015).

Various studies and building codes have linked the modulus of elasticity Em to the equation below, which is applicable in general:

$$Ec = a.(fc)^{b} \ldots\ldots\ldots\ldots \quad (4)$$

Where a, b are coefficients, a ranged between 22 and 2500 and the coefficient b between 0.5 and 1.0 (Guadagnuolo, et al., 2020).

The modulus of elasticity may be calculated using standard analytical methods, and the results are substantially larger than those produced in the experimental. The variances arise because traditional approaches ignore the deformations of the mortar bed joint (Zavalis, et al., 2014).

2.5.4 Tensile Strength of Stone and Mortar Composite

Historical structures buildings, whether made of bricks or stones, are considered to have a low tensile strength. The inability of old stonework to transfer considerable tensile stresses explains the widespread crack patterns that can be seen frequently. Cracks, on the other hand, are not always indicative of a potential failure since stresses can spontaneously achieve a completely compressive condition, implying that cracked regions do not always result in structural instability. One of the key explanations for the high non-linearity of the mechanical response of old structures is brittle behavior in tension (Briccola & Bruggi, 2019). Due to the various shapes, sizes and materials, so it is difficult to link and derive the stonework unit's tensile strength with its compressive strength (Lourenco, 2002).

2.5.6 Review Experiments in Previous Work

(Gonen & Soyoz, 2021) investigated modules of elasticity of stonework structure in Turkey, by carried out tests of single-leaf wallets according to EN 1052-1 European standard under monotonic vertical compression. Ten wallets with approximate dimensions of 320x120x440 mm (length x thickness x height) were formed, using NHL mortar with an average thickness of 10mm. As Each wallet was built using eight stones of dimensions 150x120x80 mm and four stones of dimensions 75x120x80 mm. The adopted mortar has been tested after 28 days of curing, as well as stone compressive strength tested. The average value of the compressive strength for ten cubic stones with dimensions 10x10x10 mm = 23.3Mpa, Also, the average value of the compressive strength for twelve samples with dimensions 40x40x160 = 2.74Mpa. Wallets were tested using MTS servo-hydraulic test machine with 500KN capacity, two linear displacement transducers (LVDT) were put on each side of the wallets to measure the vertical displacements, also one horizontal LVDT was put in the middle of the wallets to determine the horizontal deformations. The calculations were for six wallets out of ten, the average results of the values for each of the material compressive strength = 12.34Mpa, and the modulus of elasticity 5490Mpa. The results compared with the values obtained from empirically RIL 805 standard, which were in agreement with each other.

In the study of (Wang, et al., 2021), rubble prism samples were formed, in order to carried out under uniaxial compression test to evaluate the failure mechanism and stress-strain characteristics, double leaf of stone were used, to form 8 prismatic samples with dimensions of about 500 x 300 x 600 mm (length x thickness x height). According to the European standard EN1052-1, 4 samples were built using clay (SPAi) and 4 samples using gravel (SPBi) according to the traditional local technology, ranging from The dimensions of the rubble stones are from 150 to 250 mm in length, from 100 to 200 mm in width, and from 40 to 70 mm in height, each layer of mortar is about 10 mm. After 28 days of treatment, it was tested using a compressive device electro-hydraulic with a capacity of 5000 KN. The result of the average material compressive strength with (SPA) was 2.11Mpa and the modulus of elasticity at (30-60%) = 41.5Mpa, and the average material compressive strength with (SPB) was 2.6Mpa, as the modulus of elasticity is 72.9Mpa. The compressive strength values were corrected with a correction factor of 0.73 based on slenderness ratio = 2, to compare the results with the code. Also, a test was conducted on smaller prismatic samples with dimensions 500 x 300 x 400 mm (length x thickness x height), the average value of material compressive strength with (SPA) was 2.8Mpa and 3.47Mpa with (SPB).The result obtained is that existence of significant discreteness characterizes of the compressive mechanical characteristics of rubble stone, because of diverse and irregular forms and sizes of natural stones, various building techniques, as well as the unpredictability of the geometric arrangement and configuration of units materials.

(Segura, et al., 2018) carried out a compressive strength test on composite samples of solid clay bricks and mortar under uniaxial compression in the laboratory, where two different sets of samples were adopted, the first set of 4 samples running bond walls (RBW) built with dimensions of about 639 x 148 x 658 mm (length x thickness x height) according to EN 1052-1 standard, the second set of 7 samples of stack bond prisms (SBP) with dimensions of about 312 x 148 x 288 mm (length x thickness x height) according to According to the ASTM C1314 standard, to make a comparison between the results of the two groups, so that the samples were built with methods and materials similar to the old historical buildings, the results of the tests were that the materials compressive strength and deformability are similar for the two groups.

(Arash, 2012) investigated mechanical properties of brickwork structure, by carrying out tests of mortar and cubes of bricks and mortar under uniaxial compressive strength. Nine samples' cubes of bricks and mortar with approximate dimensions of 215x215x215 mm (length x thickness x height), were built in the laboratory with two different types of bricks which are London bricks and Ibstock and three different types of mortars (M2, M4 and M6), the components of the mortar are cement, lime and sand in different proportions, as the mortar layers between brick rows are on average 10 mm thick. After a period of 40 to 120 days of cure, Compression-testing machine used to measure compressive strength. DEMEC gauges were placed to each sample using a special glue to measure the displacements. The results compared with the values obtained from empirically EC6, ICBO (1991), which were in agreement with each other. Other similar tests were carried out by(Eslami, et al., 2012).

In the study of (Garcia, et al., 2012) ashlar and rubble work stone prism were formed, in order to be carried out under uniaxial compression test to evaluate the failure mechanism and mechanical properties , double leaf of stone was used, to form 16 prismatic samples with dimensions of about 500 x 300 x 400 mm (length x thickness x height), 12 prismatic samples were built using ashlar style and 4 prismatic samples using rubble style according to the traditional local technology, each layer of mortar is about 10 mm. After 120 days of treatment, it was tested using an AMSLER universal compression test machine with a capacity of 5000 KN, four digital LVDTs were placed on the prismatic to measure the vertical displacements. The result of the average compressive strength of ashlar work stone was 8.07Mpa and the modulus of elasticity at (30-60%) = 446Mpa, and the average compressive strength of rubble was 1.84Mpa, as the modulus of elasticity is 62Mpa. A comparison was made between the results of the experimental tests and the standard values according to the code and previous studies, which were in agreement with each other The result obtained is that existence of significant discreteness characterizes of the compressive mechanical characteristics of rubble stone, because of diverse and irregular forms and sizes of natural stones, various building techniques, as well as the unpredictability of the geometric arrangement and configuration of units materials.

(Magenes, et al., 2010) selected materials and construction methods as for mimic those of actual buildings that were built using the double stone wall approach in Italy, carried out tests of double-leaf stone under vertical compression, to investigate mechanical properties such as the compressive strength, modulus of elasticity, Poisson's ratio. 6 specimens of the full-scale prototype with dimensions of 800x320x1200 mm were formed. Because there are no defined criteria for testing stone walls, the requirements for new masonry typologies were extended to stone masonry. Where the adjusted specimens' size is determined by the unit size, an average stone size was taken into account, the specimens to be tested were chosen based on this. As specimens were built using lime mortar and irregular stones, the irregular stones ranging from the dimensions of 100 to 150 mm in length, 320 mm in width, and from 200 to 350 mm in height, stone has good compressive strength of 165-172 MPa and flexural strengths of 19 MPa. the adopted mortar represented the historic construction material, its strength properties have been tested at different curing times, each layer of mortar is around 20-30 mm, after 28 and 60 days of cure, the mortar specimens provided average compressive strength values (1.71 and 1.78 MPa, respectively). prototype specimens were tested on a force-controlled compressive device, 8 Gefran PZ-12-A-50 displacement transducers were used to measure displacements, according to the EN1052-1. Four transducers were fixed to measure vertical displacement, two horizontal transducers were used to measure horizontal deformations and two transverse transducers placed in other direction of wall. Two different Poisson's ratio was determined using the deformation values, where two values of Poisson's ratio required because of the material's significant anisotropy. The result of the average for each of the compressive strength was 3.28Mpa, modulus of elasticity = 2550Mpa, Poisson's ratio in horizontal = 0.19, Poisson's ratio in transverse = 0.15, which have been obtained from compression test, The result of the average tensile strength = 0.14Mpa, which have been obtained from diagonal compression test. The results compared with the values obtained from the Italian code, and the results were in agreement with each other.

The experimental tests carried out by Oliveira et al. on the uniaxial compressive behavior of stone specimens, and prisms on two different geometries, one of them 2prisms made of three pieces in dimension 100*200*100mm^3, the other 2 prisms made of three pieces in dimension 200*200*100mm^3, were tested in a testing machine with a load capacity of 5000 KN, using axial LVDTS to measure displacement, and the modules of elasticity estimated at [30%–60%] stress range. The result was that the average compressive strength modules of elasticity of the stone prisms is 57.12 MPa,14.80GPa respectively (Oliveira, et al., 2006).

(Anzani, et al., 2004) caried out tests of three-leaf wallets under monotonic vertical compression, for investigation mechanical properties and understand the stress-strain behavior. 4 wallets with dimensions of 310x510x790 mm were formed using two different properties stones which are (Noto and Serena), at DIS - Politecnico di Milano, the leaves were connected in two ways (with and without offsets). The adopted mortar was represented for the historic construction material, its strength properties have been tested at different curing times, as well as Stone compressive strength tested. The wallets were tested on an MTS press with hydraulic servo control (2,500KN), after a period of 75 to 172 days of cure, transducers were used to measure displacements. The result of Noto and Serena stones for each connection type as following: the compressive strength of PN with offsets was 6.4Mpa, modulus of elasticity = 2068Mpa, while compressive strength of PS with offsets was 15.32Mpa, modulus of elasticity = 2519Mpa, the Noto stone specimen's maximum load (with offsets) is roughly 10% greater than the other (without offsets), but for the Serena stone, the values remained constant.

Binda et al examined old stone walls to find out their properties, using drilled core test, the result was that the mortar crumbled and separated from the stone parts (Binda, et al., 2005).

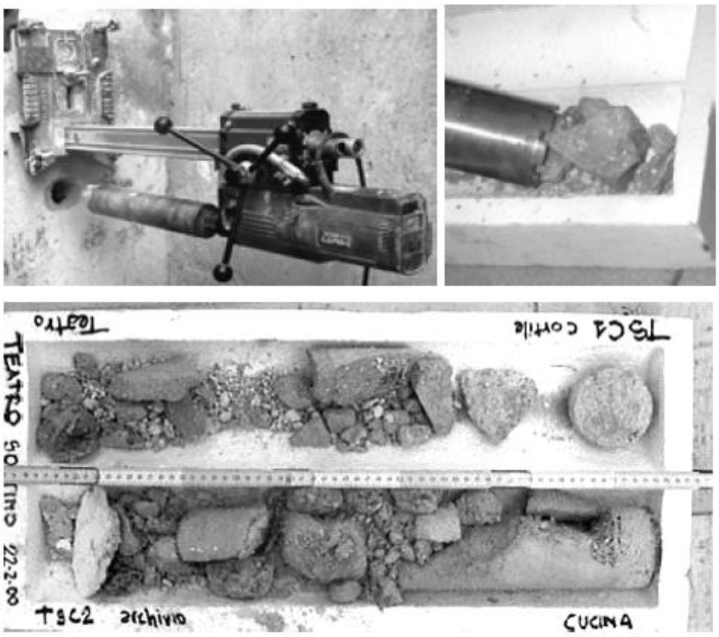

Figure 2.1: Drilling core phase. (Binda, et al., 2005).

A study by Kong et al use Schmidt's hammer test to find uniaxial compressive strength, procedures were demonstrated to avoid decreasing the accuracy of test results, where it is performed on building stones with a single grain size or unidirectional variation (Kong, et al., 2021).

The following table (2.2) summarizes the obtained results from different experiments in addition to the listed above:

Table 2.2: Summary of mechanical and physical properties of historical materials.

Reference	**Stone Type**	**Stone Compressive Strength**	**Mortar Compressive Strength**	**Stone and Mortar Composite**				
				Specimen Size			**Modulus of Elasticity**	**Compressive Strength**
				L	**T**	**H**		
		(MPa)	**(MPa)**	**(cm)**	**(cm)**	**(cm)**	**(MPa)**	**(MPa)**
(Wang, et al., 2021).	Tibetan rubble stone (SPA)	-----	1.0	50	30	60	41.5	2.11
(Wang, et al., 2021).	Tibetan rubble stone (SPB)	-----	1.3	50	30	60	72.9	2.6
(Gonen & Soyoz, 2021)	Clayey-Limestone	23.3	2.74	32	12	44	5490	12.34

(Alecci, et al., 2019)	Tuff	4.22	0.99	57	19	61	818	0.92-1.20
(Sandoli et al. 2019)	Tuff	4.60	1.93	14 - 22	16-22	30-40	385-393	2.36-2.39
(Marcari et al. 2017)	Tuff	8.00	6.60	100	25	100	1495-1869	2.67-2.70
(Bovo,et al.2017)	Sandstone Reconstructed no. 1	--	--	62.9	58.8	116.5	262	5.08
(Bovo,et al.2017)	Sandstone Reconstructed no. 2	--	--	59.5	60.4	120.9	449	4.63
(Bovo,et al.2017)	Sandstone Extracted no. 1	--	--	62.3	64.1	110.5	320	4.04
(Bovo,et al.2017)	Sandstone Extracted no. 2	--	--	65.7	63.4	133.0	488	3.73
(Bovo,et al.2017)	Sandstone Extracted no. 3	--	--	65.5	62.0	122.5	255	2.57
(Miccoli et al. 2015)	Tuff	5.21	3.32	50	11.5	50	587-1071	2.71-3.77
(Garcia, et al., 2012)	Sandstone1 (yellowish-grey) Sandstone2 (darker rocky)	40.0 64.6		50 50	30 30	40 40	446 62	8.07 1.82
(Grande, Romano 2012)	Tuff	4.13	7.14	61	15	60	781	1.97
(Magenes, et al., 2010)				80.0	32.0	120.0	2555	3.28
(Magenes & Penna, 2009)	Irregular stone	--	--	--	--	--	690-1050	1.0-1.8

(Magenes & Penna, 2009)	Soft stone masonry (tuff, limestone, etc.)	--	--	--	--	--	900-1260	1.4-2.4
(Magenes & Penna, 2009)	Dressed rectangular (ashlar) stone	--	--	--	--	--	2400-3200	6.0-8.0
(Augenti, Parisi 2009)	Tuff	--	--	61	15	65	2222	3.96

There are many previous studies on experimental tests on samples of models made of stone and lime mortar. Table 2.2 shows a portion of the experimental compressive strength tests, as the dimensions of the samples are shown in the table and the results varied in value from 1.4Mpa to 8.07Mpa. This discrepancy in the results values in previous studies is due to several reasons: the type and dimensions of the stone and mortar, the quality of the stone and mortar and the strength of the bond between them. Therefore, the following was found in previous studies: construction methods of models are similar, the dimensions and shapes of the models are different, every researcher uses the type of stone used in their buildings, mortar varies in its components and proportions, the scale of the models is either in the original dimension or in a miniature scale.

It was found that some compressive strength results in previous studies were approximately close to the results of the samples of models, due to the similarity of the strength of the stone and mortar and the dimensions of the samples. such as a study by (Garcia, et al., 2012), the dimensions of the samples were 50*30*40 cm and the stone strength ranged from 40 to 65Mpa.

Referring to previous studies, there was no gap to be filled or studied, previous studies were used to identify several matters in terms of experimental tests: the method of constructing samples, the appropriate scale and dimensions of sample models, the method of finding compressive strength, modulus of elasticity, and poison ratio. Taking into consideration that this study is applied to stone and mortar samples of ancient buildings in old Hebron city. This thesis is the first study in Palestine, in which the compressive strength, modulus of elasticity, Poisson ratio, and flexural test are found for composite samples of old stone and mortar.

2.6 Numerical modeling and nonlinear analysis

In the past, understanding the mechanism of designing historical buildings, relied on the basic theories of engineering mechanics and the strength of materials. But with the methods available nowadays and the great development in numerical analysis tools that depend on various theories and strategies, it became possible to model the complex behavior of structures, as in historical buildings (Costa, et al., 2014; Khair & Hossain, 2005). The main approach to studying the structural behavior of massive structures is numerical analysis. So that the two approaches were rapidly developed with the use of Computerized systems and advanced testing (Ramu, et al., 2013). Mostly the numerical analysis of building structures is performed using the finite element method (FEM) (Kamal, et al., 2014).

2.6.1 Finite Element Method (FEM)

Finite Element Method (FEM) is a computer-based numerical technique for solving several engineering problems in different fields, even geometrically complex (Reddy, 2015). So the FE analysis method is an effective way to simulate the behavior of structures (Li, 2012), also plays a major and important role in better understanding structural behavior where FE models can evaluate capacities beyond maximum load, failure analyzes, locations of stresses and cracks with their various patterns, displacement force relationship etc. (Khair & Hossain, 2005) , in addition that is a technique widely used in structure analysis of heritage building (Giaccone, et al., 2020), but the process of developing an accurate numerical model is a difficult task, due to the large number of assumptions and parameters that need to be defined and adopted (Li, 2012). Analysis of building structures is carried out, based on the degree of complexity, volume of input data and the accuracy of the desired solution (Smoljanovic, et al., 2018).

2.6.2 Idealization of structural behavior

In general, structural idealization is a process in which idealized or simplified models of complex structures are made for the purpose of analysis. One of the most important factors on which this ideal depends is the degree of accuracy required of the analysis because, usually, the more complex the method of analysis the longer it takes, and therefore the more expensive it is (Dr.T.H.G.Megson, 2019).

Many idealizations of behavior used in structural analysis (Lourenco, 2002), in general, Civil structures and their loads are most often complex thus require to simplified into a form that can be analyzed (Dr.T.H.G.Megson, 2019), When dealing with historic stone buildings, elastic behavior, plastic behavior, and non-linear behavior have been considered, the common ideals of behavior used in structural analysis (Lourenco, 2002).

2.6.2.1 Linear elastic behavior

In linear elastic analysis modulus of elasticity defined the stress-strain relationship (Elango, et al., 2015).Linear elasticity analysis based on elastic theory assumes that matter is subject to Hooke's Law (Lourenco, 2002). The adoption of application to building structures is insufficient because it does not take into account the non-stressed response and other essential features of the building behavior, in addition to its very limited ability to tension and the appearance of cracks at very low stress levels (Roca, et al., 2010; Lourenco, 2002).

The construction exhibits a complex nonlinear response even at low or medium stress levels. In general, the use of elastic linear analysis is not suitable to simulate the strength responses of ancient building. Also, it leads to inaccurate results, especially, for estimating the final response of building structures, thus it is not recommended to use it to deduce their strength and structural safety (Roca, et al., 2010).

2.6.2.2 Plastic behavior

According to Hooke’s law, all materials behave elastically when deformed below the yield point. This means that if the load is removed the materials return to their original forms. After yield point, materials start losing its elasticity and begin to plastic deform. This phenomenon of materials deforming plastically and leading to permanent deformation after a certain point is known as plasticity (Elango, et al., 2015).

Plastic analysis or limit analysis relates to an assessment of the maximum structural load at failure, where the material should exhibit a ductile response (Lourenco, 2002).

2.6.2.3 Non-linear behavior

In FEA the term nonlinearity is very important. It is not as simple as linear simulation (GraspEngineering, 2020), the first definition of its general behavior is modulus of elasticity and in nonlinearity the force versus displacement is not a straight line, so loading causes big changes in stiffness (Elango, et al., 2015). Most of the building structures do not have a linear relationship between force and displacement, the main reason is that the loading led to significant changes in the stiffness, and the reasons for changing the stiffness are:

• The material is not subject to the law of hooks, the occurrence of deformation (strain) beyond the limit of elasticity.

• Significant deformation due to small or larger loads

• Suddenly changing the connection status.

This method needs patience, good knowledge of FEA nonlinearity (physical behavior, geometry and stiffness changes during loading events). Problems related to FEA during nonlinear simulation: solution is not convergent, solution takes too much time, sudden changes in connectivity, displacement converge but moments are not or vice versa. So, the following must be followed: Repeat attempts, load step increments, resolved incrementally to account for the stiffness changes. setting up the solution and various connection setting is very important. It is not as simple as linear simulation (GraspEngineering, 2020).

Lourenco emphasized that the nonlinear analysis method is the most powerful analysis method, able to capture the full response of the structure from elastic stage, through cracking and crushing, until complete failure (Lourenco, 2002)

Nonlinear static analysis is used where the stiffness of the entire structure changes during the loading process, nonlinear effects can result from: geometrical nonlinearity's (large deformations), nonlinearity of the material (mechanical properties of materials change during loading), and physical contacts Changes. These effects create an unstable stiffness matrix during the application of the loading (Short, 2019). The majority of nonlinear deformation occurs in the mortar joints, due to the bed joints' effect and the stones' probable anisotropic characteristics, where linear stress-strain properties in stones (Khair & Hossain, 2005).

2.6.3 Strain-Hardening/Softening Model

A strain softening or hardening materials model can be used to represent the nonlinear behavior. When plastic straining occurs, some materials, such as Rock, lose some of their strength, which is known as softening, other materials, such as metals, however, display an increase in strength during plastic straining, which is known as hardening. Two strategies are examined while using the hardening model: The isotropic hardening model and the kinematic hardening model. In the perfectly plastic state, the yield surface remains identical and constant (Tectonics, 2020).

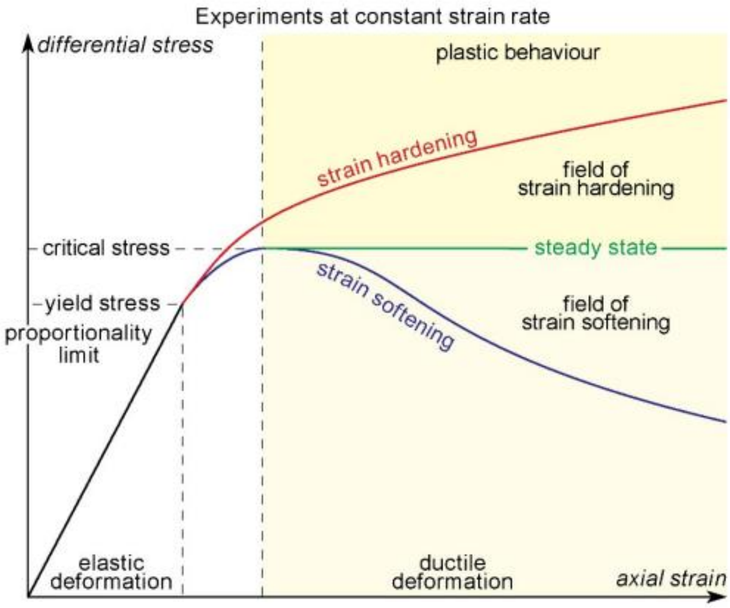

Figure 2.2: Material behavior under plastic loading *(Tectonics, 2020)*.

2.6.4 Rate – Independent Plasticity

It expresses an irreversible stress process that occurs in a material at moment is reached at a specific level of stress. The materials behavior related to it has several different types, some of which are as follows:

- Bi linear Isotropic Hardening
- Multi Linear Isotropic Hardening
- Multi Linear Kinematic Hardening

To understand Rate-Independent plasticity, the following items will be illustrated which is: Yield Criterion that determines the stress level at which yielding is started. Flow Rule that determines the direction of plastic straining. Hardening Rule that describes the changing of the yield surface with progressive yielding.

Types of Hardening Rules

- Kinematic hardening supposes that the yield surface remains constant in size and that the surface moves in stress space with gradual yield.

- Work hardening occurs when the yield surface remains centered about its initial centerline and with the plastic strain develops it expand in size.
- Isotropic Hardening occurs when the yield surface expands uniformly in all directions in the stress space (Elango, et al., 2015).

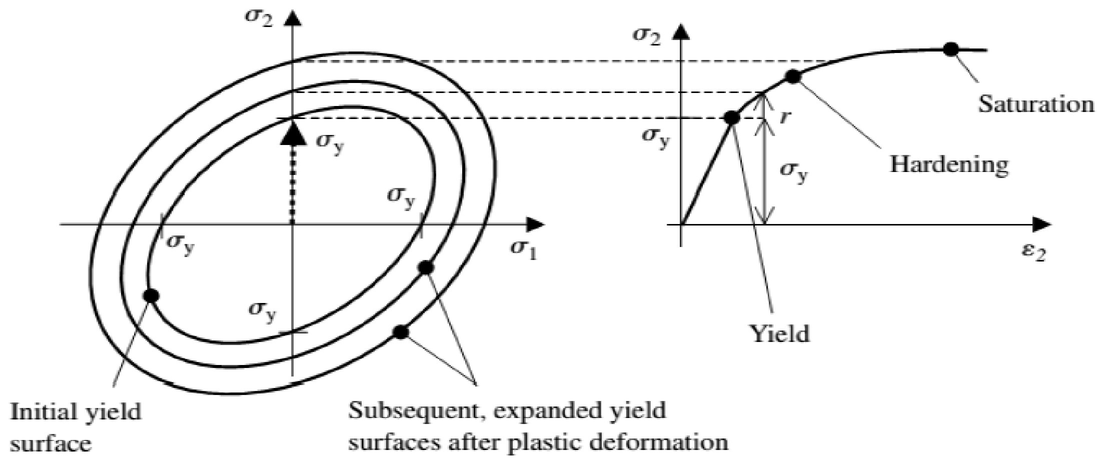

Figure 2.3: Isotropic hardening displaying the uniaxial stress-strain curve and the extension of the yield surface (Elango, et al., 2015).

2.6.5 Finite Element Modeling of Cracks

Several models have been developed that give a wide range of answers in describing the heterogeneous behavior of materials with different loading conditions, two main methods for modeling cracking, are the discrete crack approach and the smeared crack approach (Galic & Marovic, 2012).

The Smeared Crack Model

The smeared crack model has a multidirectional crack is assumed to develop after a principal elastic strain, that is get increasing attention for numerical simulation of fracture, it used to simulate crack initiation and propagation, while the inter-crack solid that has inelastic behavior is treated by a numerical method that includes the theories of plasticity and damage (Betti, et al., 2016).

2.6.6 Finite Element Failure Criteria (Yield Surfaces)

The 3D failure Criteria is usually expressed in terms of the states of stress, if stress occurs on the surface, the material reaches the yielding point and becomes plastic. Additional deformation of the material causes the stress state to remain on the yield surface, even though the shape and size of the surface may change as the plastic deformation evolves. This is because stress states that lie outside the yield surface are non-permissible in rate-independent plasticity (Elango, et al., 2015).

The most common failure criteria are Mohr-Coulomb criterion, Tresca's and von Mises shear stress criteria, Rankine's maximum principal stress criterion, Drucker-Prager criterion and Willam- Warnke failure criteria. For the modeling of historical stone structures, the most commonly used failure criteria are Drucker-Prager and Will am-Warnke failure criteria (Khair & Hossain, 2005).

Willam and Warnke Yield Surface

Willam and Warnke (WW) model proposed the failure surface that uses in ANSYS, which describes unconfined triaxial behavior of concrete. (Aghayar, et al., 2017) (Drobiec & Jasieski, 2017) (Zhang, 1993). by applying the Willam-Warnke yield criterion to masonry structures produces a several successful applications as in Li study (Li, 2012). where five parameters defined the Willam-Warnke surface are determined by the following five failure tests:

- uniaxial compressive strength (fcWW)
- uniaxial tensile strength ftWW
- biaxial compressive strength fcb
- two additional parameters ρ1 and ρ2 / confined biaxial compression strength (The high compressive stress point on the tensile meridian), (σmt, ρt). confined biaxial compression strength(The high compressive stress point on the compressive meridian.) (σmt, ρc) (Galic & Marovic, 2012).

Although five constants are needed, but in cases where the hydrostatic pressure is limited to √3 fcWW, the definition of the failure surface can be defined by only two parameters, ftWW and fcWW, so other parameters can be assumed as follows:

$$f_{cb} = 1.2 f_{cWW}, \quad \rho_1 = 1.45 f_{cWW}, \quad \rho_2 = 1.725 f_{cWW}$$

The model has the possibility of adding two parameters, which are denoted as βt and βc, which represent the reduction of shear strength for slip stress cross-face crack for open (t) or re-closed cracks (c) (ANSYS Inc, 1998)**,** the shear transfer coefficients βt, and βc, represents crack face cases, the value of typical shear transfer coefficients range from 0.0 to 1.0, where 0.0 represents a smooth crack which is open and 1.0 represents a rough crack which is closed (Khair & Hossain, 2005). The parameters required are the following:

• elastic parameters: E and ν;

• plastic parameters (DP): c, φ and δ;

• cracking and crushing parameters (WW): fcWW, ftWW, βt and βc.

Figure 2.4 represents the 3- D failure surface for states of stress that are biaxial.

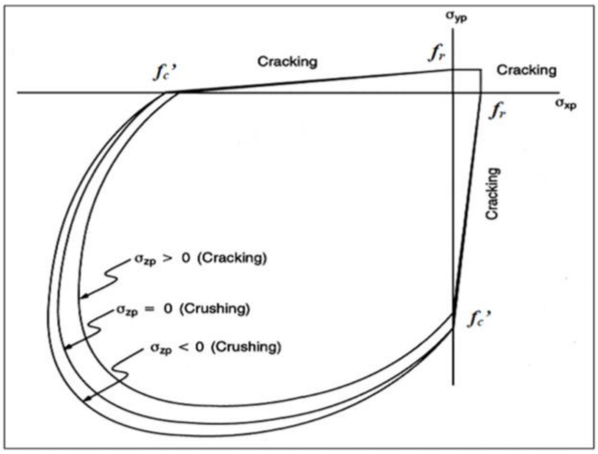

Figure 2.4: Surface in principal stress space <Jzp close to zero, [ANSYS 2014].

2.6.8 Numerical FE modelling strategies

Since historical buildings have heterogeneous and non-linear anisotropic materials, consisting of units (stones and mortar) with vertical and horizontal mortar joints, therefore, the modeling depends on both the dimensions and arrangement of the units and on the size of the joints. (Betti, et al., 2016). So Numerous models have been developed over the years with different degree of complexity and sophistication, from point of view of a numerical and a constitutive (Briccola & Bruggi, 2019).

Different modeling strategies can be relied on using finite elements, to represent the heterogeneous behavior of building structures, each one of these strategies needs specific set of material parameters and based on the required level of accuracy and type of problem (Khair & Hossain, 2005). These strategies are illustrated in the figure2.5 and can be described as follows:

(a) Detailed micro-modeling: continuum elements are used to model both mortar and units independently, where inelastic properties for each are assigned, the interface between mortar and units are modeled as discontinuous elements.

(b) Simplified micro-modeling: the behavior of mortar joints and unit-mortar interface is collected in discontinuous elements or interface elements, where expanded units are modeled as continuum elements.

(c) Macro-modeling (homogenization theory): equivalent-material approach that collected the units, mortar and mortar-unit interface in a homogenous continuum material, when the structure has large dimensions and stresses are uniformly distributed along the length Macro models are more applicable (Lourenco, 2002) .
The macro model proposes the building structure is homogeneous continuum, which has a finite element mesh, aligned with the criteria (Giordano, et al., 2002). It is worth noting that it is possible to apply macro modeling to stone historical structures, as it relies on the hypothesis of simplifying the design and analysis of the construction. The main drawback of this approach is the lack of ability to represent and capture local cracking at weak levels of the mortar unit interface (Khair & Hossain, 2005).

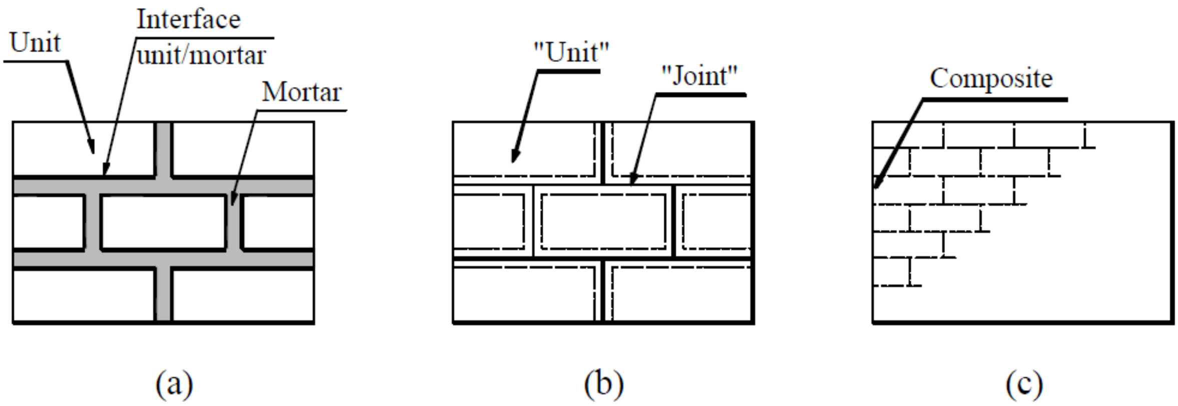

Figure 2.5: Modeling strategies for masonry structures: (a) detailed micro-modeling; (b) simplified micro-modeling and (c) macro-modeling. *(Lourenco, 2002)*

2.7 An Overview to Ansys

Nowadays, many computer programs allow making reliable 3D models used in engineering modeling applications building (Giaccone, et al., 2020).

ANSYS is a nonlinear FE based on a standard crack-stained approach. To predict construction failure, this model is able to determine the failure modes of crushing and cracking, as parameters for uniaxial tensile strength and compressive strength are necessary to determine the failure surface of the masonry. Hence, the failure criterion for a multi-axial stress state can be adopted in the Willam and Warnke failure criterion. It is also characterized by being widely range and general objectives software used to solve various Categories of engineering analysis. It has the ability to carry out linear static and nonlinear analysis, also has the capability of performing advanced engineering simulations accurately and realistic by its variety of the algorithms.

In general, to perform the structural analysis in the ANSYS program, three main stages are relied on:

• Building the model, where data input: element type, model geometry, real constants, material properties, and mesh generation.

• Apply loads, boundary condition and obtain a solution.

• Review results (Khair & Hossain, 2005).

In ANSYS, a concrete element cracks when the principal tensile stress in any direction lies outside the failure surface. The modulus of elasticity of the concrete element is set to zero in the direction parallel to the principal tensile stress direction after cracking. when all principal stresses are compressive and lie outside the failure surface crushing occurs; subsequently, the modulus of elasticity is set to zero in all directions (ANSYS Inc, 2014).

Element Types in ANSYS that is adopted for structural analysis are SOLID65, Link180, which are described in the following: SOLID65 a 3D structural solid element, has 8 nodes with 3 degrees of freedom at each node, translations in the nodal local x, y, and z directions. it is suitable for the modeling of stonework structures. The nonlinear behavior of SOLID65 element is based upon the Willam-Warnke yield criterion. It has able of cracking in tension with a smeared crack and crushing in compression with a plasticity algorithm. SOLID65 has two phases of the stress-strain relationship: linear elastic behavior and nonlinear behavior which occur after exceeded either of the specified tensile or compressive strengths. Cracking or crushing occurs when any of the three principal stresses exceeds the specified tensile or compressive strength at any of the eight integration points. (Li, 2012; Khair & Hossain, 2005).

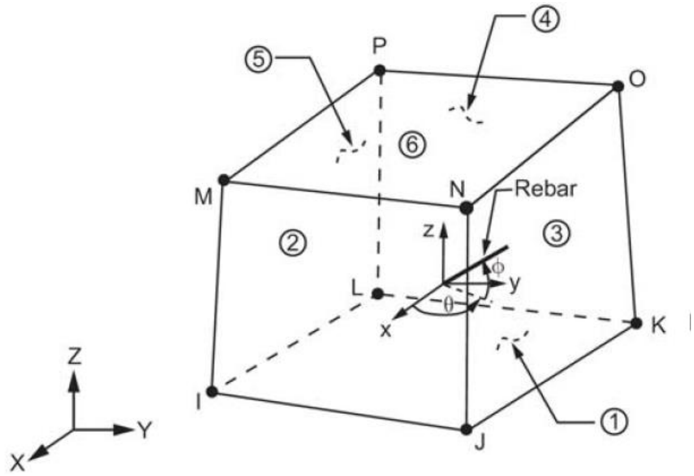

Figure 2.6: Solid65 Geometry *(ANSYS Inc, 2014).*

2.8 Review numerical analysis in Previous Work

There are many types of research that have been done related to building behavior, numerical models, and nonlinear analysis, to find stress, displacements, cracking, Patterns of failure, etc. Some of these studies will be presented:

(Ma, et al., 2022) presented and investigated the factors effects on the failure criteria of building structures, using FE numerical analysis. The result obtained contributes to giving technical guidance, to be a reference through which to predict the failure patterns of existing construction buildings.

The goal of Ravichandran's research was to determine the modeling option with the best balance between computational burden and accuracy of the results, as he suggested five alternative approaches to modeling using different methods, types of Finite Element Models in ANSYS Software, SOLID65, and SOLID185, using Drucker-Prager Productivity (DP) Standard and Willam-Warnke Failure Standard, due to its proven effectiveness in simulating building tensile strength, with model parameters fc, ft , βc , βt , the compressive stress-strain curve. The values of compressive strength and tensile strength were adopted by (Shahzada et al. 2012) experiments. The compression test of materials was carried out on prismatic samples, the jack method was used also, and the tensile test was performed on diagonal samples. The comparison was carried out under constant incremental lateral loading between experimental and numerical results. The results of the analysis show that the simplified model can be computationally efficient and is the modeling option for both static and dynamic nonlinear analyses (Ravichandran, et al., 2021).

(Almassri & Safiyeh, 2021) conducted research related to advanced finite element (FE) analyzes of an ancient historical building which is the Church of the Nativity located in Bethlehem (Palestine). A 3D FE model was generated using two types of commercial modeling software, DIANA FEA and SAP2000. The seismic behavior of the church was studied using pushover analyses. An incremental iterative procedure was used with monotonically increasing horizontal loads. results showed that the damage concentrates at the main lateral walls, mainly at the south and north alignment walls, and also at the vaults and at the connections of the vaults.

(Ferrero, et al., 2020) evaluated a school in Italy in terms of structural durability and the structure response of the seismic, which built from stone and mortar. A macro modeling approach was chosen, using a 3D finite element (FE) model, to represent building materials, the materials properties of stone masonry were adopted in the numerical model as the following: Specific weight 21KN/m3, Elasticity modulus 1740MPa, Poisson's ratio 0.2, Compressive strength 2.67MPa, Tensile strength 0.108 MPa, where the mechanical parameters were estimated based on the Italian Building Code as a guide (NTC2008). The analytical model gave accurate predictions, where the results show the failure mechanisms and cracking pattern.

(Shrestha & Bhandari, 2020)have developed a model for determining the capacity of multi-leaf stone wall from its physical and mechanical properties that taken at experimental data. The bearing capacity of a multi-leaf stone wall was studied so that a “standard wall” was determined with different physical and mechanical parameters, in order to explore an analytical model that could represent the capacity of a multi-leaf building stone. 300 models of multi-leaf stone walls were analyzed in FE ANSYS APDL software, The Drucker–Prager failure surface has been employed in compression to model the nonlinearity of material of the walls as it is well-suited for brittle materials. The walls are represented by SOLID185, which has eight nodes and three degrees of freedom at each node, (CONTA174) are used to model mortar core between leaves. The analytical model is validated depend on the experimental tests done by Krzan, Multi-leaf stonemasonry walls with a length of 1 meter, a height of 1.5 meter, and a thickness of 0.4 meter have been investigated, where the range of compressive strength is 6 -7.34 MPa, tensile strength is 0.03 MPa, and the range of modulus of elasticity is 534 –1570 MPa. An acceptable good agreement was obtained between analytical and experimental results.

(Bhandari, et al., June 2019) discussed the properties of multi-leaf stone construction for ’Standard Wall’, which has a length of 1meter and height of 1.5 meter the thickness of the outer walls is 0.15 meter, and the thickness of core is 0.1 meter. The mechanical Properties of typical multi-leaf stone structure is defined by previous studies. A nonlinear finite element model of multi-leaf stone of wall was done by ANSYS APDL version 19.2. The walls are represented by SOLID185, the mortar core between leaves is modelled by CONTA174. The proposed model showed reasonable accuracy with the experimental model. The ultimate bearing capacity of the multi-leaf stone wall Increase with length, thickness and compressive strength increased, and with height decreases, but coefficient of friction between the leaves doesn’t have a significant effect.

(Campbell & Duran, 2017) simulated the models for a group of walls with different configurations, dimensions and sizes, to obtain the structural behavior, the ANSYS program was used, where the bricks were represented by the Solid 65 element, the contact area with CONTA178 element. So that the test results were obtained from previous studies. It was obtained displacement vs force curve; the analysis model has a good agreement with experimental results.

(Betti, et al., 2016), analyzed the structural behavior of the historic stone buildings in Italy, through the complete 3D model, analysis depends on the numerical FE technique and the macro-modeling strategy, using the commercial ANSYS. The masonry nonlinear behavior was defined by the combination of the DP plasticity model with the WW failure model. The mechanical characteristics were defined by in situ experimental of panel wall and based on Italian Recommendations (OPCM 2003; NTC 2008).

(Parisi, et al., 2016) a micro mechanic of model is proposed of two components, tuff stones and mortar were developed in LS-DYNA. The mechanical properties are assigned according to material test results. The accuracy of the model was evaluated by simulating nonlinear, response and crack patterns of composite in different geometrical, boundary and loading conditions related to axial and diagonal compression tests. where the numerical result is satisfied with experimental test.

A case study reported by Mahini in Iran that is based on a macro modeling approach to the assessment of historic buildings. Where brick and adobe samples were formed in the form of a prism, then numerical analysis of the prism samples was carried out by the FE ANSYS commercial software, which uses the smeared crack model approach and an eight nodded isoperimetric solid element SOLID65, to model the brick and adobe prism. The nonlinear stress-strain curves were obtained from the experimental results, and they were also calibrated with the numerical results, so obtained a good agreement between the two results, The results showed the efficiency of the proposed macro modeling, also through his research it was concluded that the smeared-model approach, in some failure modes in mortar joints and units cannot be captured, due to its simplicity (Mahini, 2015).

(Kamal, et al., 2014) compared program numerical modeling of the beams of the linear analysis using the SAP program and the non-linear analysis using the Ansys, and the result was that the nonlinear analysis gives a better description of the actual behavior and the ability of the structure. In general, when linear analysis is performed to simplify the analysis and design of building structures, this may reduce the structural ability of these structures, where the nonlinear analysis was carried out using the ANSYS program to represent the nonlinear behavior of macro-structure modeling was used in unreinforced brick masonry , the properties of the materials were adopted as to represent building materials as the following: Specific weight 18KN/m3, Elasticity modulus 2975MPa, Poisson's ratio 0.15, Compressive strength 4.25MPa, Tensile strength 0.5625MPa, Open shear coefficient 0.2, Close shear coefficient 0.8, also An experimental study was conducted in order to validate the accuracy of the adopted beam modelling and solution procedure. As for the results obtained from the nonlinear analysis under the influence of weight only, they refer to the presence of tensile stresses and several cracks, but did not cause structural failure, and to determine the capacity of the structure, the loads were gradually increased and the failure of the structure occurred when the increment loads by 35%, thus , it was reached that the adopted numerical modeling is appropriate for understanding the structural behavior of the existing heritage structures. The nonlinear stress–strain curve for the masonry material was defined and entered in the computer model having values based on the compressive strength of the brick unit.

(Costa, et al., 2014) in their study of evaluating existing buildings based on numerical simulation methods, stated that these methods are not easy or straightforward due to the limitations and complexities of analysis tools, even when imposed with full knowledge of current conditions and materials. Four different methods for analysis of existing building structures are also mentioned: linear static, linear dynamic, on-linear static ("pushover") and non-linear dynamic.

(Eslami, et al., 2012) evaluated historical building composed of brick and mortar in Iran, by 3-D non-linear analysis method performed using the FE ANSYS computer, with the aim of evaluating the load carrying capacity and capacity of the structure, macro-structure modeling was used in finite element analysis, due to adopting the concept of homogeneous materials and the compositional model of smear cracking, the brittle behavior of structure has been modelled through an suitable failure criterion, which is defined by two material parameters ft (uniaxial tensile strength) and fc (uniaxial compressive strength).The presence of a crack at the point of integration is also represented through modification of the stress–strain relations by introducing a plane of weakness in a direction normal to the crack face, and a shear transfer coefficient has been introduced (depending on the crack status: open; bt or re-closed; bc).

(Li, 2012) developed and calibrated a macro finite element model of the dome the macro-modeling approach is implemented using ANSYS, that is composed the brick unit, mortar joint, the parameters for Willam-Warnke model are used in the macro-model is executed to simulate incremental development of cracks, and to determine the load carrying capacity of a masonry dome numerically, also this study investigates three strategies of FE modeling of the dome: detailed micro-modeling, simplified micro-modeling, and macro-modeling, which these three different modeling approaches was evaluated by comparing the models to experimental data obtained in the laboratory, as detailed micro-modeling is the similar one of them to experimental.

(Barraza, 2012) in his study, proposed a model that has the ability to represent unsupported, supported, and confined structures walls, with different wall arrangements and configurations. To represent the in-plane nonlinear structural behavior of the construct. The model was implemented in ANSYS and then used for structural simulation, previously walls were tested in the laboratory in other research projects. An acceptable good agreement was obtained between the results of the proposed model with the results of laboratory tests.

(Khair & Hossain, 2005) used a macro modeling approach for a number of old walls structures, and for the small walls, the micro-modeling approach was used, by the nonlinear FE analysis using Ansys. The models were validated by experimental results. An acceptable good agreement was obtained between these results.

(Lourenco, 2002) emphasized that it is possible to model and analyze historical stone structures, as well as know the experimental behavior of historical building facilities, by choosing the appropriate type of analysis and entering correct data. As a result of the complex geometry of historical structures, usually includes massive structural parts, such aspires and buttresses combined with arches and vaults. So, such huge historical structures need models to represent their behavior, and the macro modeling strategy is the best which proposed by Lourenco.

Table 2.3: Summary of the results of numerical analysis of some previous studies that are similar to this study.

Reference	Country	TYPE of building	objectives	materials	Mechanical properties	Modeling approach	program	Results
Ferrero, et al., 2020	Italy	school	structural durability and the structure response of the seismic	stone and mortar	Italian Building Code as a guide (NTC2008).	A macro modeling approach	3D finite element (FE) model	The analytical model gave failure mechanisms and cracking pattern
Eslami, et al., 2012).	Iran	Building with dome	evaluating the load carrying capacity	brick and mortar	Eslami, et al., 2012). Test	A macro-structure modeling	FE ANSYS /Willam-Warnke	The presence of a crack at the point of integration, weakness in a direction normal to the crack face
(Li, 2012).	South Carolina is a southeastern U.S.	dome	determine the load carrying capacity of a masonry dome numerically	brick and mortar	Previous study	A macro modeling approach /micro-modeling	FE ANSYS /Willam-Warnke	macro-modeling/micro-modeling
(Shrestha & Bhandari, 2020).	Himalayan region of South Asia.	multi-leaf stone wall	Determine the bearing capacity of a multi-leaf stone wall	stone and mortar	Previous study Krzan,	A macro modeling	ANSYSDrucker–Prager	An acceptable good agreement was obtained between analytical and experimental results
(Kamal, et al., 2014).	Egypt	Beams	Comparison nonlinear analysis/ linear analysis	brick and mortar	Previous study	A macro modeling approach	FE ANSYS /Willam-Warnke	The result was that the nonlinear analysis gives a better description of the actual behavior and the ability of the structure.

Most of the previous studies in this study with regard to the subject of numerical analysis were carried out on buildings of different uses in Egypt, Iran, Italy, Spain, Turkey, South Carolina, and Himalayan South Asia, the macro modeling approach was used in the modeling using the finite element method with the help of the Ansys program. The objectives of the studies varied to include: structural evaluation of buildings and determining their durability or finding stresses, displacements, cracks, failure modes, etc. In Hebron, there are no previous studies available regarding the subject of numerical analysis to evaluate historical stone buildings. Therefore, this thesis is considered the first study in this field in Hebron that applied to a case study of an old building.

CHAPTER 3

Building Description

3.1 Introduction

Hebron old city is the physical witness to its history and its buildings are the mirror of the times and heritage. Therefore, the architectural and structural knowledge of the historical structure and the correct identification of its problems is the basis for conducting a realistic structural analysis and then developing a correct and applicable rehabilitation and maintenance plan, which leads to a good/economic rehabilitation.

In this chapter, the architectural and structural description of the Zahedah building will be presented, the building materials used, and the problems that the building suffers from.

3.2 Site Specificities

Zahdeh building is located in the center of the old city of Hebron as shown in Figures (3.1, 3.2), which can be reached by vehicle or on foot. The front facade of the building overlooks the street and Badran coffee shop, which is considered the most famous coffee shop in the old town, the Al-Qazzazin Mosque is also close to it. In addition to the presence of commercial traffic in this place, as a result of the extension of the market near it.

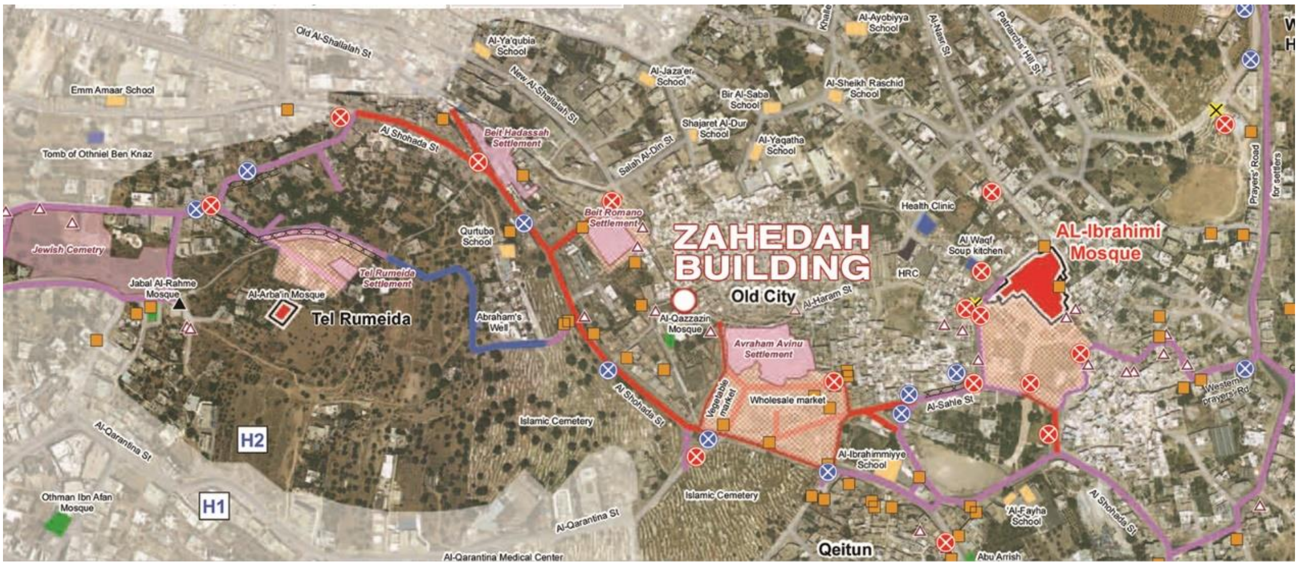

Figure 3.1: Accessibility path for Zahdeh building location in the old city. (Dweik,2012)

Figure 3.2: The location of Zahdeh building in the old city. Source: Gemology.

3.3 Description of Building

Zahdeh building has medieval-based architecture, which gives great value to it. The building is composed of two main floors, rising above the shops and stores. as shown in Figure 3.3, with a total area of about 550 square meters, where the first and second floors are residential. The building is roughly rectangular in shape, with an open and covered courtyard on the second floor. The access path between the levels of the floors is through three stairs, the first from the external entrance to the first floor, the second from the first floor to the second, and the last one is open from the second floor to the roof, all of them are made of stone stairs.

Figure3.3: Front facade of the building. Source: researcher

In terms of internal spatial organization, the three floors are as follows:

Ground Floor: The ground floor represents eight shops and stores oriented to a yard and a street, used for commercial needs for locals and tourists.

First floor: It has a main entrance, which is internal stone staircase that leads to the main central covered courtyard entrance around which the rooms are wrapped and moving from it to the second floor. As for the first floor, it consists of four rooms, a kitchen and a toilet with a covered courtyard that leads to a staircase to reach the second floor to an open courtyard as shown in Figures 3.4.

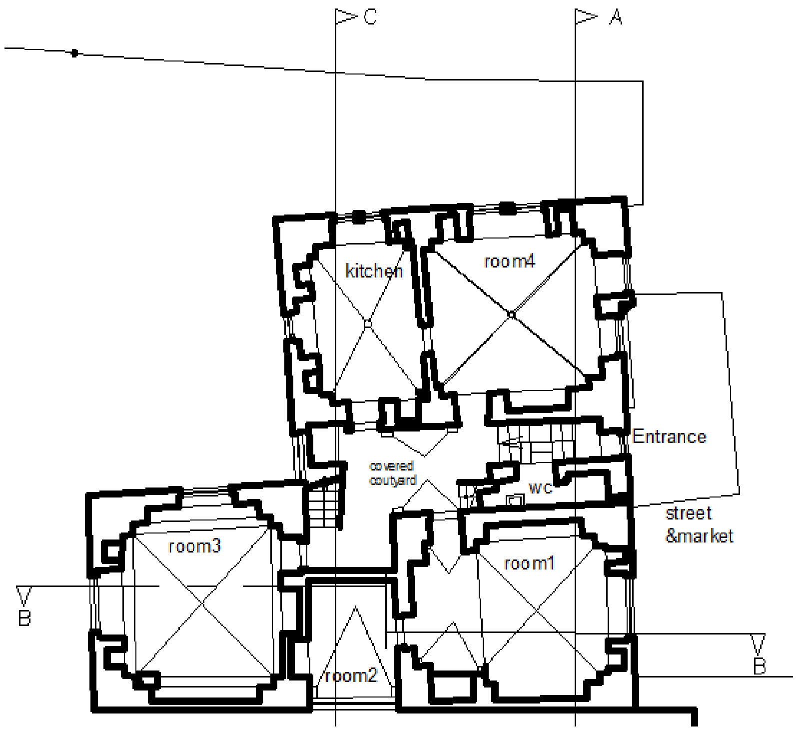

Figure 3.4: First floor. Source: Hebron Rehabilitation Committee

The second floor: contains six bedrooms and a covered courtyard that leads to an open courtyard with stairs to the rooftop as shown in Figures 3.5.

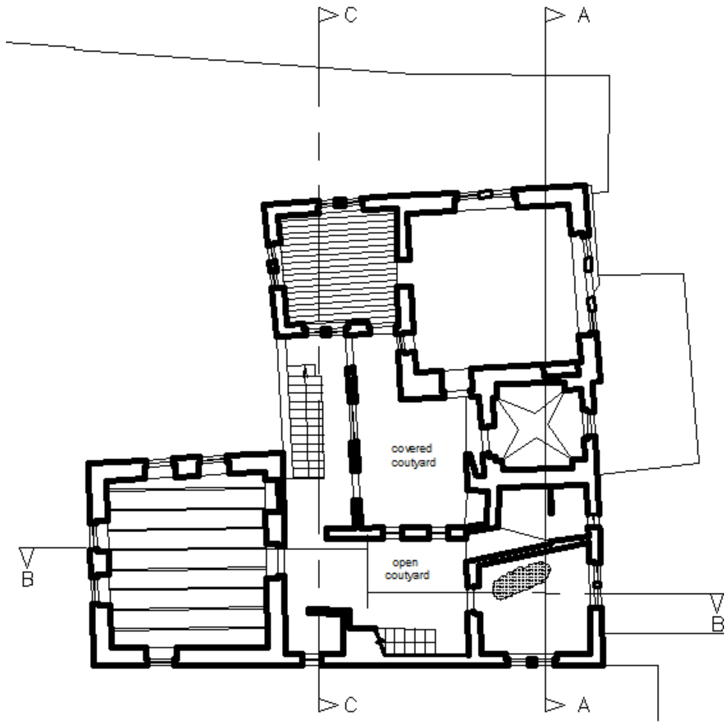

Figure 3.5: Second floor. Source: Hebron Rehabilitation Committee.

The building has historical importance is demonstrated by its architectural style, local traditional building materials used in its construction, and the diversity of its structural elements, it characterized by the art of architecture, which was built in several stages, was from the Ottoman era, which gives a great value, as it reflected in it the originality, simplicity and ensured privacy for its residents, also its distinguished location in the center of the old city. The building is planned to be used as a historical cultural center by the Hebron Rehabilitation Committee.

3.4 Structural characterization

A complete structural description requires that you have the original building design, plans, and specifications, as well as records of the interventions that occurred. It is also necessary to know the characteristics of the structural materials and to complete the visual examination of the existing buildings in order to conduct an engineering and structural analysis of the observed damages in the behavior of the structural elements. So, through the researcher's numerous field visits to the old Hebron City and the case study Zahdeh building, the building was surveyed, described, and visually inspected. This structural description of the building includes the following:

Building materials used, Architectural and Structural elements, visual inspection, damages and problems observed in the behavior of structural elements, interventions carried out to the building.

The purpose of the evaluation is to conduct a structural analysis of the building, with the aim of evaluating the building's ability to bear the loads on it, and if it is possible to make an addition to the existing building.

The materials and construction elements used in this building vary, as this is due to its construction in different stages and its restoration more than once.

3.4.1 Building materials

Local traditional building materials have been used, which are adapted to the environment of the region. The nature of the mountainous of Hebron city, which made stone the main material in construction, the walls were built of successive stone courses interspersed with doors and windows, and it was also used in cross vaults, arches, stairways and foundations, so the stone is considered the basic material because of its distinctive characteristics in terms of strength, durability and absorption rate, the structural stone may be utilized in its original shape or after being molded as a structural material. Rubble refers to naturally occurring or irregularly shaped stones, whereas ashlars refer to precisely rectangular shapes.

In addition to the use of other building materials, such as:

- Pottery: It is one of the local building materials and is used in ceilings as a filler for voids, in order to reduce the loads on the ceiling and walls. Thus, the broken pottery was used as a mound, whether on the ceilings or walls, mixed with rubble.
- Lime: It is used as a bonding material between the stones in the structural elements, and it is used in plastering and pointing works and to fill the spaces between the courses of the walls.
- Clay: It was used in filling voids in walls, foundations and ceilings.
- Ash: It has the advantage of reducing cohesion time and has good strength when used.
- Other construction materials were also used, such as zebar, which is the remnants of oils and is devoid of acids. It prevents permeability and works to

hold the materials together. It acquires hardness as time passes (Hebron Rehabilitation Committee, 2017)..

3.4.2 Architectural and Structural elements.

The old buildings represent a wonderful painting because of the art and architectural styles they contain that have their own distinctive characteristics. The case study building includes rich architectural and structural elements that give the building the heritage and architectural identity. These elements are: stone staircases, entrance, door and window openings, courtyard, walls, patriues, ceilings, Cross vaults, arches, and floors.

The structural system of the building is based on the following elements:

- Continuous foundations which loads are transmitted to it from the load-bearing stone walls, with thickness around 1 m (Hebron Rehabilitation Committee, 2017).
- Load-bearing walls with double limestone, total wall thickness between 40-120 cm, with a filler (soil, large aggregates) inside, the surrounding material is lime and sand and crushed pebble. Stone and mortar are used to construct double stone walls, which resist both vertical and horizontal loads in addition to serving as a structural element. It is typical for those walls to be very thick as shown in Figure 3.6, producing hefty, inflexible components with low tensile strength. The building's span and the strength of its retaining walls are related. The ground and first floors of the case-study building have substantial, 0.8 to 1.20 m thick, shale stone walls that are robust. A 0.40 m thick wall may be found on the second story.
- The stone pillars (Patriues) were built of limestone at the four corners of the rooms, through which the roof loads were transmitted to the foundations.
- The cross vaults that form the limestone ceilings, were used in the ground and first floor, in second floor has cross vaults ceiling in addition to the flat ceiling.
- I-beam steel panels, which transmit concentrated loads to load-bearing masonry walls, were used only in the second floor.
- Flat I-beam ceiling.

Figure 3.6: wall section. Source: researcher

3.4.3 Visual Inspection:

It is considered mainly expressing the condition of the building, and an important indicator in guiding the assessment towards the required examinations. It includes the examination of building facades, masonry stones, lime mortar and the internal examination of the building. Where the following was noted:

- The presence of slanted and vertical cracks in the walls, especially at the corners of the windows, in addition to the presence of transverse cracks. The occurrence of cracks of different types and multiple breadth is simple as shown in Figures 3.7.
- The occurrence of fragmentation of the mortar between the stones see in Figures 3.8.
- The occurrence removal of lime mortar. as shown in Figures 3.9.
- The occurrence of mold in the inner layers of the building as shown in Figures 3.10.
- The facades of the building are in good condition and there are no problems with them as shown in Figures 3.11.

Figure 3.7: Different types of cracks of. Source: researcher

Figure 3.8: Fragmentation of the mortar between the stones. Source: researcher

Figure 3.9: removal of lime mortar. Source: researcher

Figure 3.10: Mold inside of the building. Source: researcher

Figure 3.11: Good condition in external facades. Source: researcher

3.5.4 Interventions and modifications to the case study building**.**

Several interventions were made on the structure of the building, either due to poor mortar and bonding materials, moisture, mold and weather factors, subsidence, cracks, the earthquake in 1927, which led to the building being exposed to problems and partial damage. Some of the interventions:

- The cracks in the building's exterior facades were filled with cement mortar.
- Some of the interior walls were plastered with cement mortar.
- The internal cracks, whether in the ceilings or walls, were also filled with cement mortar.
- The ceilings of the second floor were demolished and rebuilt in the same way.

CHAPTER 4
Experimental Work

4.1 Introduction

This chapter demonstrates the experimental work, which is one of the main large parts of the work of this thesis. The details of materials, equipment, the test set-up and the work steps are explained. In addition, the equations that were used in the calculations are explained with tables and diagrams that showed and demonstrated the tests results of stone, mortar and model samples of stones and mortar. where experimental tests were carried out in building materials technology laboratory at Palestine Polytechnic University.

4.2 Materials

The following represents the materials that were used and tested, which is natural stone, lime mortar, lime mixture mortar similar to old one, and composite of mortar and stone, with the purpose of finding mechanical parameters such as compressive strength, tensile strength, modulus of elasticity, to adapt these parameters in numerical analysis and to enable the evaluation of historical buildings. The materials and construction methods used in this study were selected in method that mimic those found in actual buildings built using the double-leaf stone wall approach. these parameters in numerical analysis and to enable the evaluation of historical buildings**.**

1. Historical stone: A local building material extracted from rocks, which is characterized by its strength, hardness and beautiful shape. Particularly in Hebron city, available old stones have excellent mechanical properties making it a useful and suitable material for construction. The stone type is classified as limestone and sand stone. The old city of Hebron provided the natural stones. It is sedimentary rock, either sandstone or limestone from a geological standpoint. The existence of many buildings constructed with this stone in the old city of Hebron demonstrates its widespread use as a building material in the past. (Qawasmeh & Maraqa, 2016)
2. Lime mortar and lime mixture mortar: the mortar adopted in this research represents and resembles the old material that is found in a historical stone

building. It contains no cement; thus, it has lower strength values compared to modern mortars with Portland cement content.

3. Lime: lime mortar based on NHL 3.5 natural hydraulic lime, which is a powerful mortar alternative selection that offers all the flexibility that comes with natural lime, making it suitable for the preservation and restoration of historical buildings that were constructed with lime mortar (Stazi, et al., 2022).
4. Natural Fine Aggregate and sand.
5. Natural Coarse Aggregate (Sedimentary Rock Source): small irregularly shaped pieces of stone
6. Water: Potable water was used as mixing water.

Table 4.1: Mixing ratios for lime mortar

Volumetric ratio	1	3	
		1.5	1.5
Materials	NHL 3.5 Lime	Fine Aggregate	Sand

Table 4.2: Mixing ratios for the lime mixture mortar

Volumetric ratio	1	3		
		1.5	1.5	
			0.5	1.0
Materials	NHL 3.5 Lime	Irregular small pieces of aggregate	pottery	Clay

4.3 Equipment.

The following devices and equipment that used to test the materials in this research:

1. CNC machine.
2. Ball Mill Machine Los Angeles for grinding the broken stone.
3. Sieves to analysis the particle size distribution of the aggregate.
4. Scales, trowel, concrete mixing tub and balances.
5. Bucket of water and rag for cleaning the equipment before and after the test.
6. Curing tank for samples.
7. Steel molds for tensile strength testing.
8. Steel cube molds for compressive strength test (5cm×5cm×5cm),
9. Oven to dry samples and materials (for water absorption experiment).
10. Compression machine (Matest 24048, Italy Cpacity:1500KN).
11. Dial Gauge 25mm Travel X 0.01mm Divisions.
12. Flexural Testing machine.

4.4 Experimental program

From an engineering point of view, finding the mechanical parameters of historical structures is complex, and not always instantaneous, because it requires often expensive and time-consuming tests that are destructive and non-destructive. In this study, non-destructive tests were selected in order to preserve the architectural and historical heritage. An experiment was conducted to test samples from the core of the walls and floors using the core device. An attempt was made to extract more than one equivalent sample consisting of stone and old mortar, but each time the samples crumbled due to the weakness of the mortar and its lack of good adhesion to the stone. The experimental program includes a study that examined the mechanical and physical properties of stone structures using conventional mortars, as follows: compression tests on three different types of model samples and flexural tests on double leaf beams, as well as compression and tensile testing of lime mortar and lime mixtures samples, the compressive strength, water absorption and volumetric weight of unit's stone, In addition to conducting a Schmidt Hammer test at different locations of building elements on stones and mortar, to define the mechanical properties of equivalent materials (stone and mortar) of historical structures. The following steps were followed to achieve the objective of the study.

4.4.1 Preparation and Testing of stone units

Samples of rubble stones were selected from the old city of Hebron near the case study building, of different types to mimic the same stones as the historical buildings. About 100 stones were collected from collapsed historical building in near location of case study building as shown in figure 4.1,4.2 to the Stone and Marble Center of the Palestine Polytechnic University, in order to cut the stones using a CNC machine to obtain on stone pieces of parallelograms and different dimensions, as shown in figure 4.3. The compressive strength of stones was obtained from standard cubes (50* 50 *50 mm) and (10 * 10 * 10mm). 9 samples with dimensions of (50 * 50 * 50 mm) and 7 samples with dimensions of (10 * 10 * 10 mm) of different types of stone were tested on Matest hydraulic press machine with a capacity of 1500 KN, and at a speed of the low moving piston about 6 mm / sec, until the samples failed and the crushing load was measured as shown in figure 4.4.

Figure 4.1: source location of historical stone from collaps building. Source: researcher

Figure 4.2: Types of historical stones collected and transferred to the Stone and Marble Laboratory. . Source: researcher

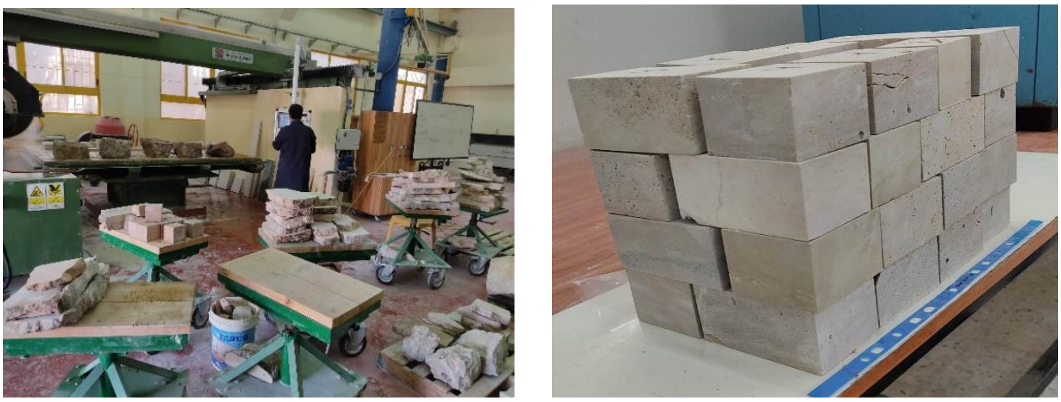

Figure 4.3: Stage of preparing the historical stone to cut it into suitable pieces by CNC for experiments. Source: researcher

Figure 4.4: Compressive strength of (10*10*10) & (5*5*5) stone. Source: researcher

Tests results Water content, mechanical and physical properties of different types of ancient stones are listed in table 4.3& 4.4.

Table 4.3: Water content of different types of ancient stones.

No. of stone	stone location in the building	Wet weight	Dry weight	Water content
unit		gm	gm	%
A.1	Around windows and doors / soft for engraving	254.0	225.9	12.5%
A.2		244.0	218.4	11.7%
A.3		245.5	219.3	11.9%
B.1	As a structural element in walls, patriues and foundation.	278.2	270.6	2.8%
B.2		311.7	303.4	2.8%
B.3		282.8	275.6	2.6%
C.1		511.8	506.4	1.1%
C.2		527.7	520.6	1.4%
C.3		494.7	486.0	1.8%

Table 4.4: Results of mechanical and physical properties of different types of ancient stones.

No. of stone	stone location in the building	dimensions	weight	density	loads	Compressive Strength
unit	------	cm	gm	gm/cm³	KN	MPa
A.1	Around windows and doors / soft for engraving	4.93*4.87*5.0	232.7	1.94	40.3	16.8
A.2		4.97*4.80*4.92	232.7	1.98	43.6	18.28
A.3		4.90*4.90*4.95	254.6	2.14	62.1	25.88
B.1	As a structural element in walls, patriues and foundation.	4.79*4.91*4.94	289.8	2.49	390.0	165.8
B.2		4.90*4.97*4.91	305.0	2.55	219.0	89.9
B.3		4.85*4.80*4.93	290.3	2.53	214.1	91.95
C.1		4.89*4.85*4.99	305.0	2.49	357.7	150.8
C.2		4.90*4.85*4.80	278.2	2.55	384.0	161.6
C.3		4.90*4.90*4.85	302.0	2.53	207.0	86.2
H.1		9.80*9.80*9.90	2305.2	2.42	680.7	70.88
H.2		9.30*9.95*9.90	2366.8	2.58	851.4	92.0
H.3		9.90*9.85*9.75	2390.2	2.51	1020	104.5
H.4		9.90*9.90*9.85	2334.5	2.42	677	69.1
H.5		9.40*9.90*9.90	2137.0	2.33	731.6	78.9
H.6		9.83*9.40*9.93	2390.2	2.40	632.8	68.8
H.7		9.30*9.40*9.94	2417.5	2.42	1165	127.4
Avg				2.40		88.7

Figure 4.5: Stress Strain curve of different types of ancient stones

Through the results obtained in the tables 4.3 &4.4, the stone has high strength, and the Compressive Strength values vary from one sample to another according to the type of stone, where the values range from 68.8 to 165.8Mpa, also its water absorption rate is within the Palestinian specifications for hard limestone, where the average is 2%. except for one type that gave small values for the strength, where the average strength values are 20.32Mpa, that's because a certain kind of soft yellow stone is engraved into various shapes for decorative purposes. It also has a high-water absorption rate, with an average of 12.03%.

Through the results obtained in the figure 4.5, the stones that have high strength describe the stress-strain relationship with strong and brittle, and the value of the modulus of elasticity is high, in contrast to the weak stone such as soft yellow stone, which describes the relationship of stress with strain as weak and ductile, and the value of the modulus of elasticity is low.

4.4.2 Preparation and Testing of old mortar

Mechanical testing, such as compression strength, is difficult to obtain because the sample is not large enough to be used as a specimen, where large samples of structural mortar cannot be removed from stone walls that already exist; also, the possibility of extracting reliable samples is very expensive and insufficient to constitute an experimental series. To overcome this problem, the tests are carried out on samples investigated according to conventional instructions.

This study shows the outcomes of a mechanical test campaign using conventional mortars, which was based on a historical analysis of mixed proportions. The proportions and components of the lime mortar samples were obtained according to the proportions used in the restoration by the Hebron Rehabilitation Committee. So, the choice of a suitable mortar is critical and difficult work to obtain a good agreement between experimental modeling of the structural behavior with historical building materials components, in addition, the old mortar used in the historical buildings in Hebron is diverse and has different compositions. Therefore, lime mortar was adopted according to recommendation by the engineer of the Hebron Rehabilitation Committee, based on conventional instructions.

Two types of lime mortar were formed, the first type is the lime mortar consists of lime, sand and fine aggregate according to the volume ratios mentioned in Tables 4.1, that used between the courses of the stones of the samples (prism or wallet) while the second type is a lime mortar mixture consists of lime, clay and small irregularly shaped pieces of stone, in addition to fly ash and pottery, according to the volume ratios mentioned in Table 4.2, that used to fill the contact area between double leaf.

The lime used is NHL 3.5 natural hydraulic lime, as for the fine aggregate and small gravels are obtained by crushing the leftover crushed pieces stone from the cutting process using a ball mill machine Los Angelos. The product sample was then passed through Mesh #12, so the passing through this sieve represents fine aggregate, while the retained on this sieve is small gravels (small irregularly shaped pieces of stone), Water was added at the site according to the homogeneity of the mixture and its workability, taking into account the interaction and hydration of lime and the absorption rate of aggregates, sand and clay.

During the construction of stone wallets and prisms, the same hydraulic lime mortar that was used to build all samples was tested. Samples of lime mortar were prepared in cube-shaped molds, with dimensions 50 x 50 x 50 mm for compressive strength testing. The two types of mortar were poured into cube molds on two layers and each layer was compacted 25 times distributed over the surface. Also, samples of mortar were prepared in tensile molds, to test the tensile strength, the mortar was poured and compacted 12 times using the thumb, according to the specifications. All samples were left to harden for 24 h, then carefully extracted from the molds, the curing period was continued for 14 days, and then stored at laboratory temperature until examined at 90 days of age. A total of 12 cubes to determine compressive strength, and 12 tensile samples to determine direct tensile strength were poured and tested, six for each type of mortar.

6 samples of lime mortar and 6 samples of lime mixtures were tested on Matest hydraulic press machine with a capacity of 1500 KN, at a speed of the lower moving piston about 6 mm/s, until the samples were failed and the crushing load was measured. 6 samples of lime mortar and 6 samples of lime mixtures were tested on Tensile machine with a capacity of 8 KN, until the samples were failed and the crushing load was measured. Tests results of lime mortar and lime mixture mortar are listed in table 4.5.

Figure 4.6: Compressive and Tensile samples of lime mortar and lime mixtures. Source: researcher

Figure 4.7: Compressive strength of lime mortar and lime mixtures. Source: researcher

Figure 4.8: Tensile strength of lime mortar and lime mixtures. Source: researcher

Table 4.5: Results of mechanical and physical properties of two types of lime mortar.

No. & Type mortar	dimensions	weight	density	Vertical loads	Compressive Strength	Tensile load	Tensile Strength
unit	cm	gm	gm/cm³	KN	MPa	KN	MPa
L.M. 1	5.05*5.33*4.85	226.1	1.73	9.7	3.59	1.64	1.18
L.M. 2	5.27*4.92*5.20	233.7	1.73	9.7	3.74	1.60	1.18
L.M. 3	4.96*5.06*5.24	223.1	1.70	10.7	4.28	1.60	1.14
L.M. 4	5.10*5.23*5.00	219.9	1.65	9.5	3.56	1.65	1.18
L.M. 5	5.20*4.95*5.10	223.5	1.73	10.3	4.00	1.58	1.13
L.M. 6	4.98*5.15*5.05	228.1	1.70	10.5	4.01	1.63	1.16
L.M.M. 1	5.03*5.00*5.00	210.7	1.70	12.4	4.96	1.44	1.01
L.M.M. 2	4.96*5.06*5.24	212.4	1.69	11.4	4.53	1.52	1.06
L.M.M. 3	4.85*4.80*4.93	208.1	2.68	12.5	4.99	1.36	0.92
L.M.M. 4	5.05*5.0*5.10	210.7	1.70	12.1	4.80	1.40	1.00
L.M.M. 5	4.95*5.05*5.20	212.4	1.69	11.6	4.76	1.50	1.07
L.M.M. 6	4.85*5.00*5.15	208.1	2.68	11.9	4.90	1.35	0.96

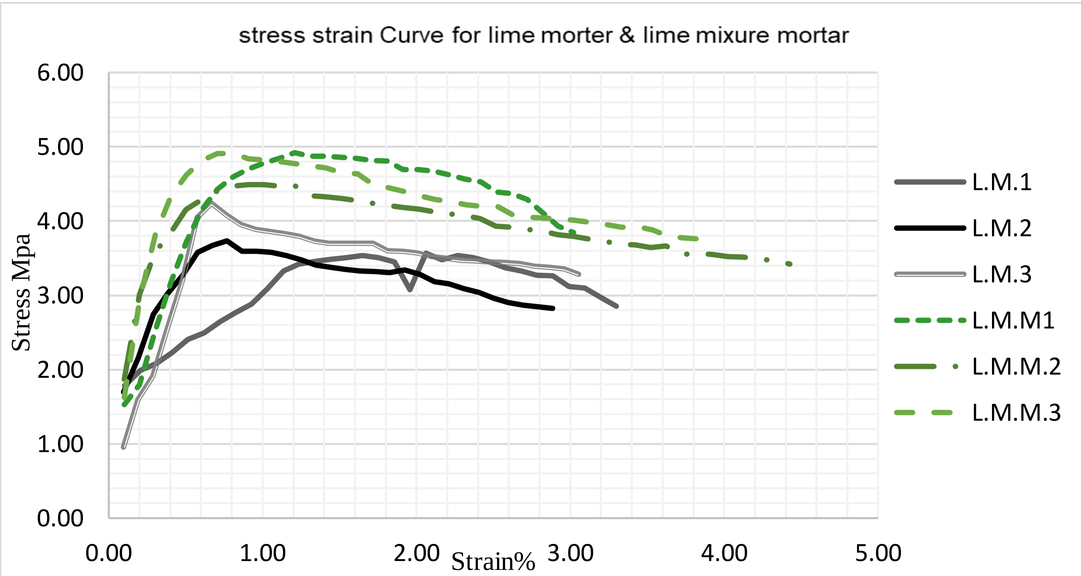

Figure 4.9: stress strain curve of two types of lime mortar.

The compressive stress-strain behavior, compressive strength, Tensile Strength, and density of mortars are determined from tests. In general, historical mortar is weaker and much softer compared to modern mortar. Previous research on historic stone buildings showed that ancient mortars are lime-based, with very poor compression strength and obviously influenced by deterioration processes at various levels, also the slow progress of lime mortars, which need centuries to fully mature. Table 4.5 shows some values of the compression strength of simulated historical mortar. Figure 4.9 shows the stress-strain relationships of different mortar types.

4.4.3 Preparation of model samples

The walls of the historical buildings in the old city of Hebron consist of a double-leaf stone wall, with a total thickness of about 80-120 cm. This is the common building method in Hebron, which dates back to the Mamluk and Ottoman periods. So that most of the current historical buildings are built with this technique. In Hebron, multiple-leaf stone walls can be found in historical buildings going back to the Mumluki and Othman periods. Therefore, samples of double-leaf samples were formed to represent the old building, but with a scale of 1/6.

The tested model samples were designed and prepared by reconstructing wall models using stones taken from the demolition of the old buildings of Hebron old city, taking care as much as possible that the walls are similar to those actually found in the historical buildings in the Hebron old city, in terms of stones and mortar mechanical properties, dimensions and arrangements stones. The scale adopted for the samples are 1/6 of the real scale, the 1/6 scale was chosen due to several reason: previous studies showing the conversion coefficients between the prototype scale and the 1/6 scale, the dimensions of the wall samples are similar to the dimensions tested previously, the dimensions for a 1/6 scale is more suitable for the devices available in PPU laboratories, Three different types of model samples that built in the laboratory according to specification ASTM C1314 (ASTM C1314, 2019), Prismatic samples were built in the style of typical ancient building walls, which include double-leafed stone and an inner core of low-strength mortar. The first type Included three double leaf wallets' samples with approximately total dimensions (30 ^{x} 15 ^{x} 22) cm^3 (length, width, height) respectively, with aspect ratio (hs / ts) of 1.5, four stone courses and three mortar layers, were built, using old mortar and stone pieces with dimensions ranging from 4-9 cm in length, 4-6 cm in width and 5 cm in height, for vertical compression tests, as shown in Figure 4.10. The first model was chosen that simulates the style of the walls of ancient buildings, and it is similar to what is found in previous studies, but with different dimensions.

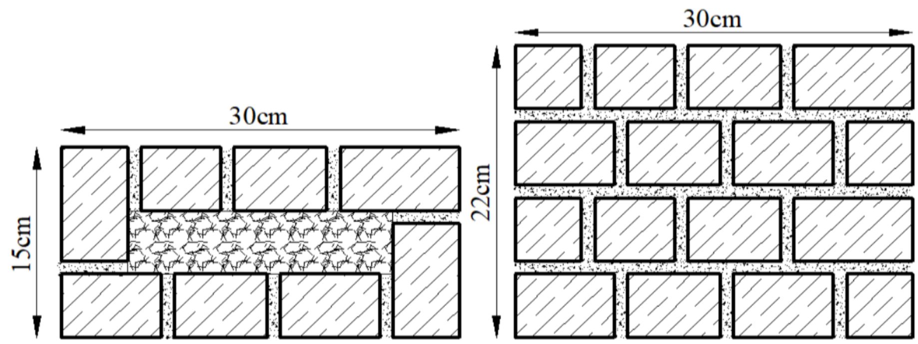

Figure 4.10: plan and elevation of 30 cm double leaf wallets. Source: researcher

The second category Included three double leaf wallets' samples with approximately total dimensions (44 ^{x} 15 ^{x} 22.5) cm3 (length, width, height) respectively, with aspect ratio (hs/ts) of 1.5, were built, using old mortar and stone pieces with dimensions ranging from 4-9 cm in length, 4-6 cm in width and 5 cm in height, in addition to put one stone within wall depth, for vertical compression tests, as shown in Figure 4.11. The second model, which simulates the pattern of the walls of ancient buildings, containing stone in the middle of the model in the direction of width, was chosen to ensure greater strength and cohesion as shown in Figure 4.12, this type has no similar in previous studies.

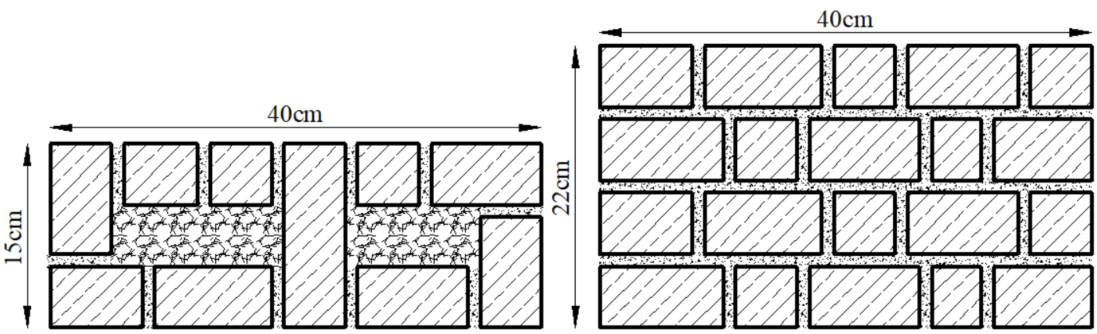

Figure 4.11: Plan and elevation of 40 double leaf wallets. Source: researcher

a: Front elevation

b: Side elevation

Figure 4.12: Front and side elevation of the pattern walls of ancient buildings. Source: researcher

The third category Included Six prismatic samples with approximately total dimensions (20 x 19 x 23) cm^3 (length, width, height) respectively, were built, using old mortar and stone pieces with dimensions ranging from 4-9 cm in length, 4-6 cm in width and 5 cm in height, for vertical compression tests, as shown in Figure 4.12. The third model, which simulates the pattern of the walls of ancient buildings, so that its cross-section is square in proportion to the dimensions of the experimental test equipment, is similar to what was found in previous studies.

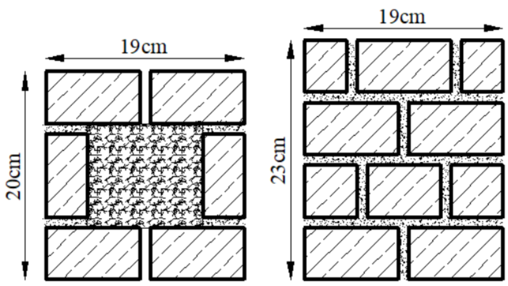

Figure 4.13: plan and elevation of 20*20 cm double leaf prisms. Source: researcher

Figure 4.14: preparing of 40 *15 cm double leaf wallets. Source: researcher

In each type of lime mortar mixture, the components were mixed and distributed homogeneously, then tap water was added, and it was manually mixed using mixing tools and a trowel for 10 minutes, the amount of water was added until the mixture became homogeneous and has the required consistency with ease of construction, according to the specification ASTM C172, in the construction phase of the samples the following steps were followed:

1. Prisms and wallets were rebuilt in the laboratory using stones taken from demolished buildings and mortar similar to old one, in a constructive manner that is representative of that found in situ and used in the old buildings.
2. Building the first course of stones arranged on a flat horizontal, non-porous and impermeable, to form a double leaf of wall, with the full lime mortar placed on the horizontal and vertical surfaces that parallel to the stones. Taking care to fix the stones in their correct positions, making a meshing distance between the stones, and building other courses until reaching the fourth course, as the average thickness of the mortar layers between the stone rows of 10 mm, then the joint area between double leaf stones was filled with a lime mortar mixture consisting of small irregular pieces of the same type of stone used combined with lime mortar. Attention should be paid to the place where the samples are constructed so that there is no source of disruption or damage until they are transported for testing.
3. After each stone was installed, any gaps were filled in with lime mortar between stone courses as needed, excess mortar was also removed, resulting in flat surfaces.
4. After fixing all the stones, lime mixture mortar was added in the gaps between double leaf if necessary. The additional lime mixture was also removed, making it

level with the top of the prism and in contact with the units around the perimeter of the mortar area.

5. All prisms were capped with a thin layer of dental plaster of 1–2 mm thickness to level the contact surface between the specimen face and platens of the testing machine. The strength of the capping was higher than that of the mortar joints and it was assumed to have no effect on the results, A bubble level was used to ensure that all samples had a horizontal surface.
6. Each sample was Labeled with the number, the date and time.
7. all samples were placed in a protected location free of vibration and disturbances.
8. Appropriate steps were taken to prevent the test samples from drying out after building of each sample, the processing was carried out through spray it with water at regular intervals, and cover it with a wet cloth for 14 days, then it was left uncovered in a laboratory environment. 3 prismatic were tested after approximately 28 days, while all wallets and 3 other prismatic were tested after approximately 60 days.

4.4.5 Testing of model samples

Within the framework of the methodology presented, a series of experimental for equivalent stone and mortar, the equivalent materials, construction method and bonding pattern represent and agree with those used in the old historic buildings to be evaluated. Which experimental include Compression and flexural test with 1/6 scale relative to real dimensions, designed to find the compressive strength, tensile strength, modulus of elasticity, and Poisons ratio, in order to assess the actual structural response of the main systems that constitute the building, and allowing for a fine-tuning of the numerical finite element models.

4.4.6 Measurement of Compressive Strength

The historical structure is mainly characterized by the strength of its bearing the compressive forces applied to it. As a result, the determination of its compressive strength is important. The compression tests were carried out on 3 types of samples using uniaxial Matest hydraulic press machine with a capacity of 1500 KN, after 28, 90 days, as follows:

1. Samples edge surfaces were checked using a surface smoothing device.

2. The dimensions of the samples were taken and recorded using the caliber measuring tool.
3. Two 20 mm thick steel plate was used, the first plate placed between the hydraulic jack /moving piston and the wallets samples, the second plate placed between the wallet's samples and the hydraulic fixed piston, in order to carry and distribute loads on a regular and uniform basis.
4. Placing the samples centrally in the testing machine, in such a manner that the specimen is fully in touch with the testing machine from top and bottom.
5. One ELE with a capacity of 250mm dial gauge was installed on the metal plate in order to capture the vertical displacement, enabling stress-strain diagram to be drawn and calculate the modulus of elasticity, two ELE with a capacity of 250mm dial gauges were installed on the sample faces in order to capture the horizontal displacement, the first one was placed in the longitudinal direction of the samples, the second one was placed in the transverse direction of the samples, then was installed in a central location on the mortar joint, ensuring that it was connected to the surfaces, to calculate the Poisons ratio, as in the figure.

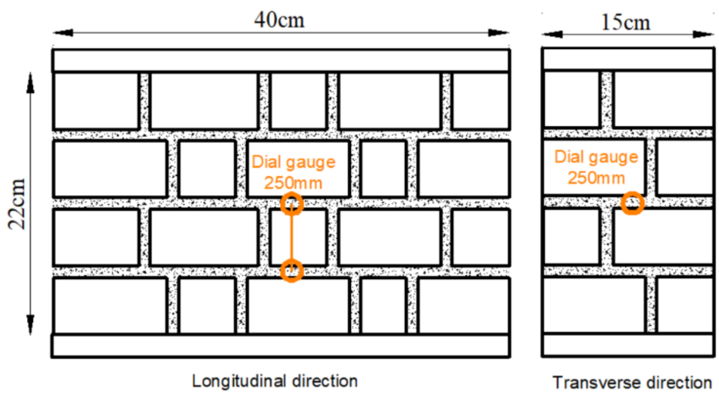

Figure 4.15: Dial gauges location. Source: researcher

6. The load is applied gradually and continuously at a speed of about 6 mm/sec, as the load reaches a peak, then decreases. If it drops a bit, the load may start to increase again, so wait until the load is steadily decreasing and can see clear evidence of a fracture pattern forming, after 15 to 30 minutes of begin loading, failure is reached.
7. The maximum load was recorded and the type and location of failure noted.
8. To represent Hebron buildings,15 stone prisms formed from ancient mortar were built Prismatic samples were built in the style of typical ancient building walls, which include double-leafed stone and an inner core of low-strength mortar. The

gap between the two wythes was filled with rubble - shards from dressing the stones, smaller stones and mortar. The walls were built with hydraulic lime mortar as were the original walls on Parliament Hill. The mortar had lime: sand ratio of 1:3, no portland cement was used. They were all built over steel plates to facilitate transport and to assure a flat surface on the universal testing machine, and placed to the test using a compression testing machine. smooth surface. Particular attention was given to ensuring parallel ends throughout the fabrication of the prism specimens. In addition, specimen tops were appropriately topped with a light layer of mortar to achieve a smooth surface.

Figure 4.16: Compressive Strength of 30 cm double leaf wallets. Source: researcher

Figure 4.17: Compressive Strength of 40 cm double leaf wallets. Source: researcher

Figure 4.18: Compressive Strength of 20 cm double leaf wallets. Source: researcher

4.4.7 Results and Discussion of model testing

The experimental results that curried out to testing prismatic / wallet samples on machine for testing materials on compression are given in table 4.6. They show the dimensions of test specimens, their weight, weight per unit volume, vertical loads, compressive Strength, the modulus of elasticity, peak strain and Poisons ratio for each of the test samples.

Table 4.6: Results of mechanical and physical properties of wallets and prisms.

No. & Type models	**dimensions**	**weight**	**density**	**Vertical loads**	**Compressive Strength**	**Modulus of elasticity at (30%-60%) fc´**	**Peak strain**	**Poisons ratio**
unit	cm	gm	gm/cm³	KN	MPa	MPa	%	%
Exp1 W30	32*15*22	25380	2.35	763	15.90	900-1100	1.30	0.17-0.22
Exp2 W30	31*15*22	25020	2.45	673	14.47	970-1090	1.50	0.14
Exp3 W30	32.7*15*22	26548	2.51	750	15.56	1100	1.10	0.24-0.25
Exp avg 30	-----	-----	2.44	----	15.31	900-1100	1.3	0.14-0.25
Exp1 W40	44*15*22.1	31820	2.18	614.7	12.42	500	1.7	0.19-0.27
Exp2 W40	44*15*22	31160	2.21	629.3	12.71	660-1160	1.56	0.24
Exp3 W40	44*15*22.5	29980	2.02	669.7	13.53	500-700	1.20	0.20
Exp avg 40			2.14		12.9	500-1160	1.50	
Exp1 P20	25.9*21.7*23	19234	2.0	639.0	11.37	800	0.57	0.17-0.22
Exp2 P20	25.3*20.9*23	19488	2.0	664.0	12.56	600-1150	0.65	0.29
Exp4 P20	23.4*20.3*23	19694	2.22	667	14.04	600-1230	0.78	0.25-0.35
Exp1 avg 20			2.1		12.7	600-1230	0.66	
Exp3 P20	20.1*19.3*23	20350	2.11	644	16.66	850	1.09	0.20-0.25
Exp5 P20	20.0*19.0*23	18814	2.15	630	16.58	600-1200	1.1	0.24
Exp6 P20	20.0*19.0*23	19238	2.20	606	15.95	700-1300	0.96	0.24
Exp3 avg 20			2.15		16.40	600-1300	1.05	

The models of the samples tested were designed to reproduce the building elements as similar as possible to those found in the historic buildings of Hebron Old City in terms of the mechanical properties of the materials and the arrangement of the stones.

Stone buildings are composite materials consisting of two materials that have completely different properties: stone is more solid and mortar is softer, so that the behavior of these constituent materials differs from that of their basic components. Mortar differs greatly in mechanical properties from stone units. Therefore, the natural of composite and complex geometry result in highly complex structural behavior, and this composite material is characterized as inflexible, inhomogeneous, and anisotropic. The compressive strength was calculated as the ratio between the vertical load applied by the piston of the device distributed on the surface of the sample to the initial cross-section of the sample, and the strain was calculated as the ratio between the vertical displacement recorded from the dial cauge to the length of the samples, and thus the complete graph of compression stress and strain was obtained.

The study of the mechanical behavior of all models under compression gave the following results at the age of three months, which are shown in Table 4.6:

The first model 30 * 15 * 23 gave an average value for compressive strength, modulus of elasticity, and poisons-ratio 15.31MPa, 900-1100 MPa, 0.14-0.25, respectively.

The second model 44 * 15 * 23 gave an average value for compressive strength, modulus of elasticity, and poisons-ratio 12.9MPa, 500-1160 MPa, 0.19-0.27, respectively.

The third model 20 * 20 * 23 gave an average value for compressive strength, modulus of elasticity and poisons-ratio 16.4MPa, 600-1300MPa, 0.20-0.25, respectively.

Through Figure 4.16 it was found that in terms of compressive strength values, the Exp P20 model sample gave the highest values, and the compressive strength values were multiplied by a coefficient according to the ASTM system, so the values decreased by about 20%.

To make comparisons easier, Figures 4.19,4.20,4.21 showed all of the compressive strength, elastic modulus, and maximum strain values for all of the models.

The post-peak behavior was generally very short and only a small portion of it could be recorded. The maximum recorder strain varied from 0.6 to - 1.9 %.

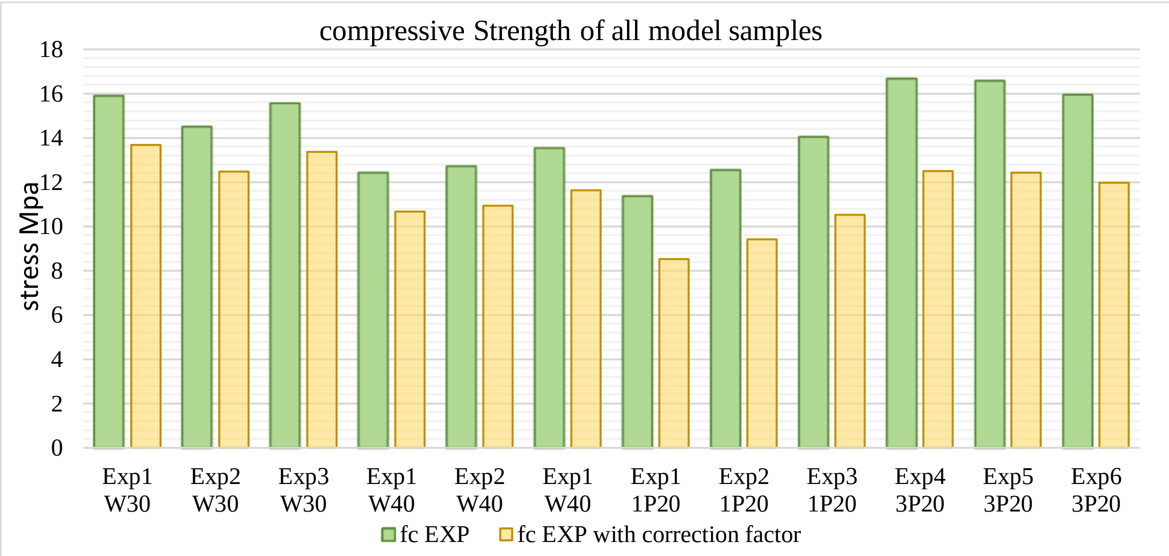

Figure 4.19: Compressive Strength of all model samples & fc with correction factor of slenderness.

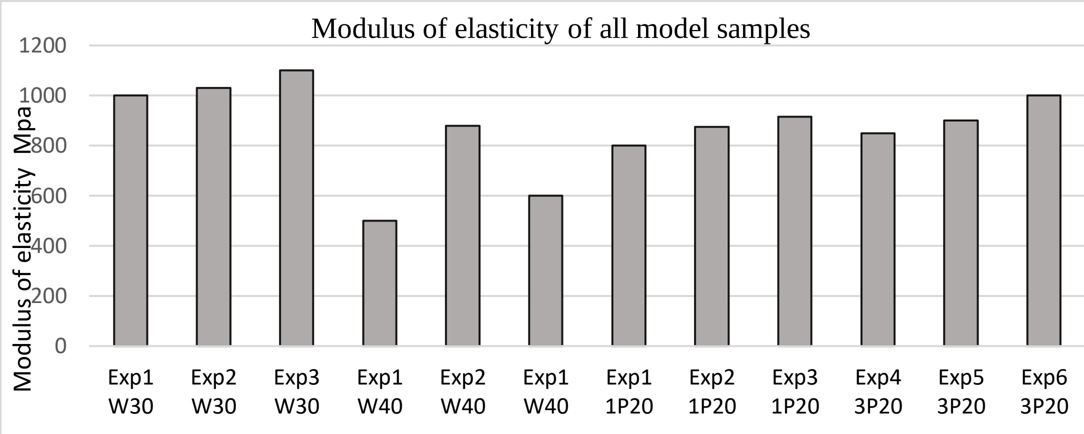

Figure 4.20: Modulus of elasticity of all model samples. Source: researcher

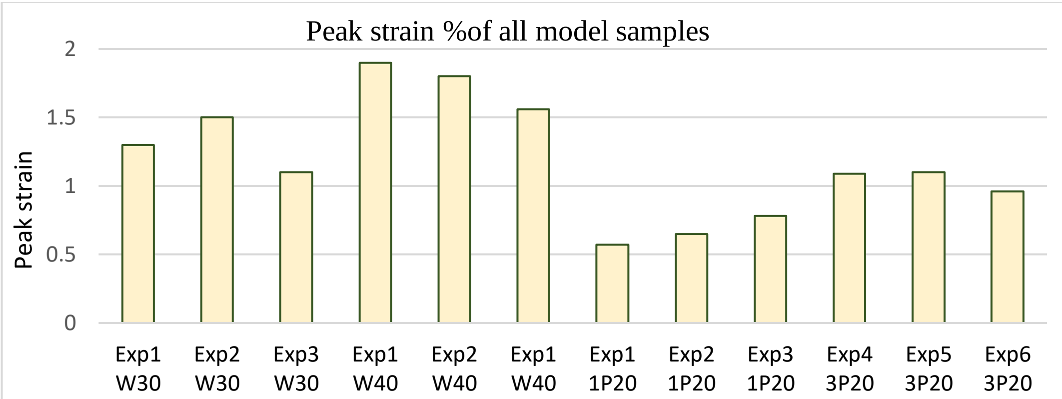

Figure 4.21: Peak strain % of all model samples. Source: researcher

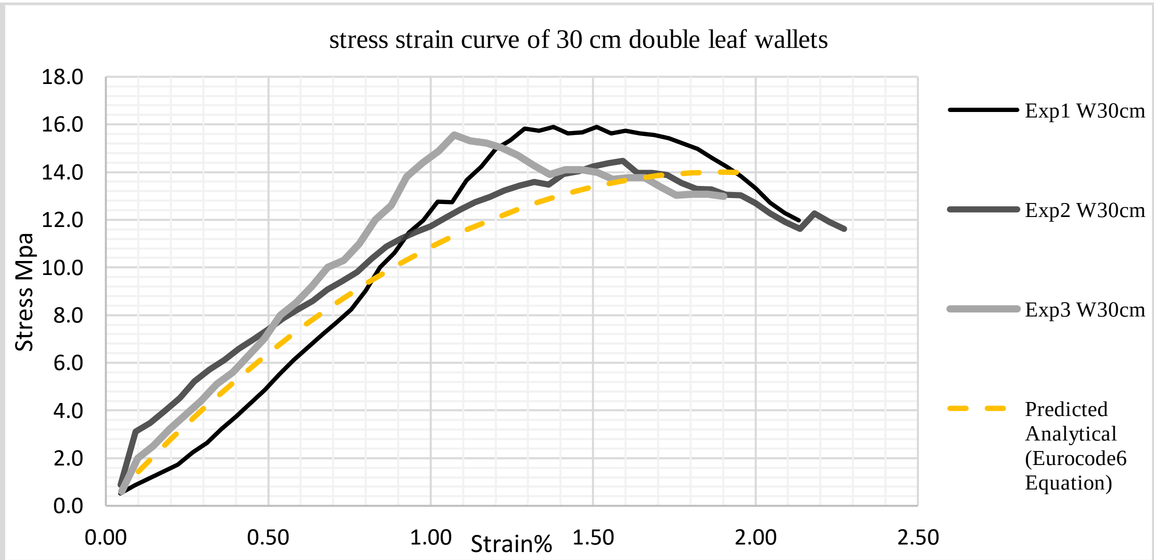

Figure 4.22 :Comparison of experimental stress–strain characteristics of 30 cm double leaf wallets with proposed analytical model (Eurocode6 Equation), R^2= 0.97

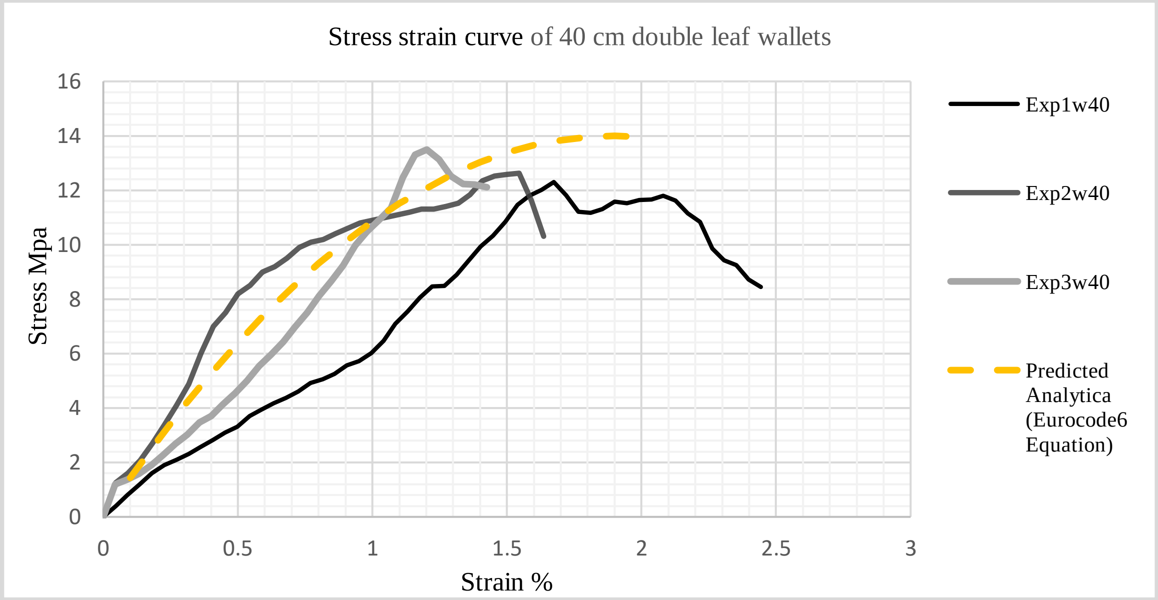

Figure 4.23: Comparison of experimental stress strain relationships curve of 40 cm double leaf wallets with proposed analytical model (Eurocode6 Equation) R^2= 0.906.

Theories that are followed in finding mechanical properties:

$$fc = \alpha \, . fs^{\beta} . fm^{\gamma} \; ………… \quad (1)$$

$$\varepsilon_{\circ} = \frac{K}{fm^{\alpha}}\left(\frac{fc}{Ec^{\lambda}}\right) \; ……………....... \quad (2)$$

where: K is fixed to 0.27, α to 0.25 and λ=0.7 according to (Kaushik, et al., 2007).

$$\frac{\sigma}{fc'} = 2\frac{\varepsilon}{\varepsilon_{\circ}} - \left(\frac{\varepsilon}{\varepsilon_{\circ}}\right)^2 \quad ………… \quad (3)$$

$$Ec = a.(fc)^b \; ……………..... \quad (4)$$

$$R^2 = 1 - \frac{\Sigma(fexp\, i - f\, pi)^2}{\Sigma\,(fexp\, i - fc'\, avg)^2} \quad …(5)$$

R2 is the coefficient of determination between the experimentally obtained values and values obtained by regression analysis. A value of R^2 close to unity indicates a good fit and that close to zero indicates a poor fit.

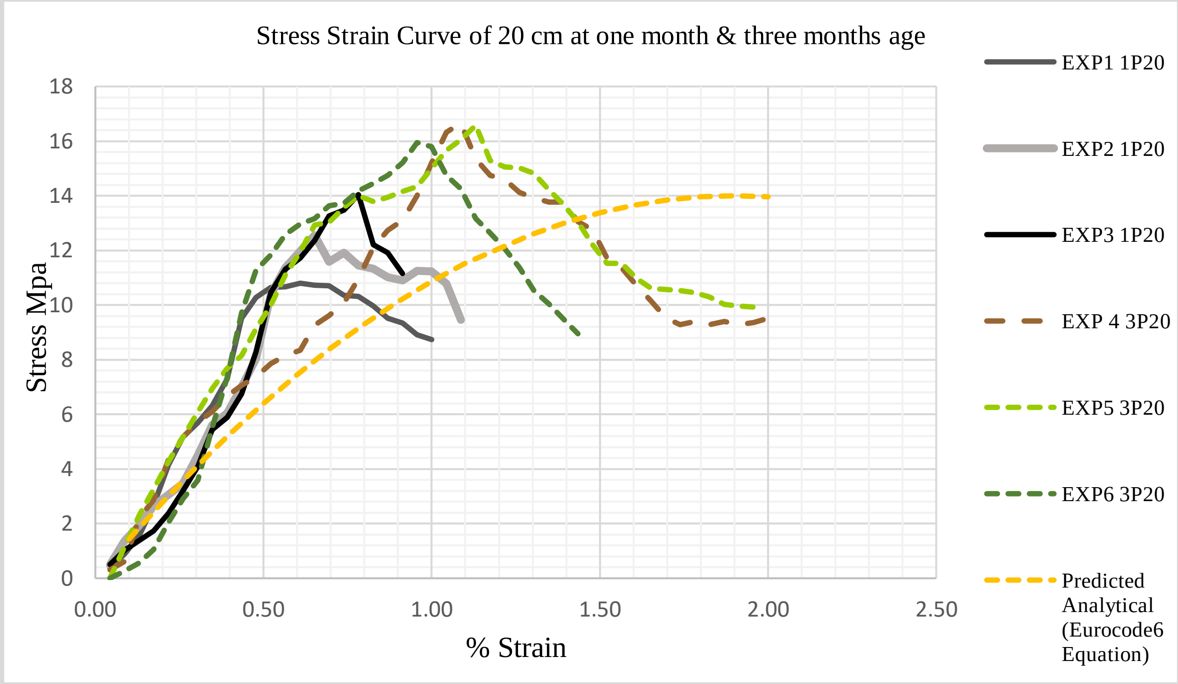

Figure 4.24 : Comparison of experimental stress strain curve of 20 cm at one month & three months age, with proposed analytical model (Eurocode6 Equation) R^2= 0.65.

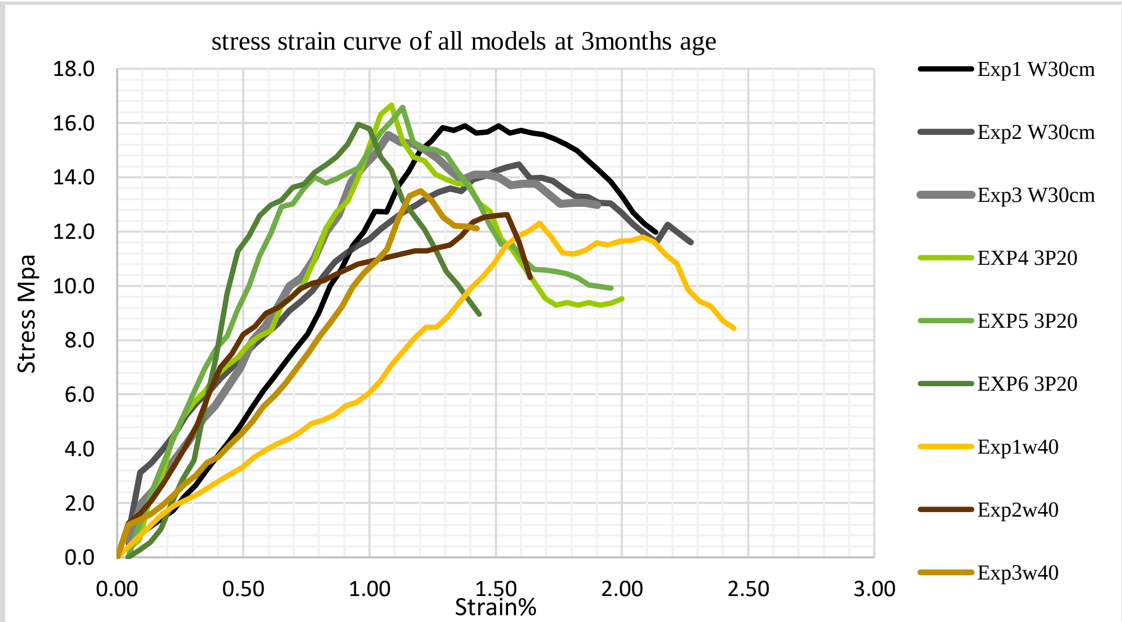

Figure 4.25: Stress strain curve of all models at 3months age

The stress-strain curves that represent the relationship between the applied stress and the strain were created in this study through compression experiments on various model samples. These experimental models were then compared to the predicted analytical curve that is shown in (Figures 4.22, 4.23, and 4.24). Through Equation No. 3, the stress at each strain point was calculated, thus the predicted analytical stress-strain curve was obtained, in order to compare it with the experimental results. where σ and ε are the compressive stress and strain of experimental models and ε_o the peak strain corresponding to fc.

The stress-strain curve was also drawn based on the analytical prediction equation of Erocode 6, in order to confirm the results of the experimental test, in which Figures 4.22, 4.23 There was agreement between the experimental curves and the analytical curve, and the value of R^2 (0.97) (0.906) respectively was very close to one.

The experimental curves and the analytical curve in Figure 4.23 have weak fitting and agreement, with an R^2 value of 0.65.

Referring to Figure 4.23, a difference and a gap were created in the strain. This is due to the presence of irregularity in the load distribution on the sample.

Figure 4.24 shows the stress-strain curve of the prismatic model, where three samples were tested at one month and three samples were tested at three months. The average values at one month were 12.7MPa, while the average values at three months were 16.4 MPa. This means that the samples at the age of one month gained about 78% from the strength of three months.

For the analysis of a structure, the determination of the stress-strain relationship characterizing the construction material is usually required.

In the stone and NHL buildings, initial plastic deformation is followed by an upward, more or less linear segment between 30% and 60% of the ultimate stress. So the material behaves linearly until about one-third(0.3 to 0.6) of the ultimate compressive strength, that means, above 60% ultimate stress, the relationship is no longer linear, and cracks start to develop. At about 0.75 to 0.80 of the ultimate load vertical splitting cracks start developing in the (stones & mortar) and propagate until the maximum stress is reached. As the load was increased gradually in most samples. Failure mechanisms occurred in model samples under compression by splitting cracks in the axial direction, (vertical and oblique cracks appeared in the mortar and stone on all sides of the sample models, the almost vertical cracks and swelling of the masonry prism are shown), to reach the peak load, and the material fails. After the maximum load is reached, the load starts to decrease gradually and leads to a collapse.

In this study, the Modulus of elasticity for the stone sample model was evaluated from the concentric compression tests using the load applied with the corresponding displacement where the modulus of elasticity for each sample was determined based on the initial stiffness obtained from the stress–strain relations at 30-60% fc, in another meaning Ec is calculated as the slope of the linear portion of the stress–strain curve obtained during the compressive strength test lying between 30% and 60%.

The modulus of elasticity was determined using Equation No. 4, and the value of a = 102 was selected based on a study conducted by Costigan, 2015. In his study, a lime mortar NH 3.5 was used with a volumetric ratio of 1 lime to 3 sands, and this study in this part is similar to what is in the current study.

The peak strain ε_o has been determined as the strain corresponding to the ultimate stress. Equation No. 2 was also used by (Kaushik, et al., 2007) to determine the ultimate strain values.

Poisson’s ratio was determined from the lateral strains measured at the mid-height of the samples divided by the average axial strain.

4.4.7 Rebound Number Test

To perform the Schmidt hammer, test the following is done according ASTM C 805 – 02 (ASTM C 805-02, 2020):

The test surface is selected, the material to be tested shall have a thickness of at least 100 mm and shall be fixed within the structure. The test surface shall also be prepared where the diameter of the test area shall not be less than 150 mm, and the surfaces shall be of smooth and flat formation. The hammer is tightly pressed such that the piston is perpendicular to the test surface. Until the hammer impacts, the tool is gradually moved toward the test surface. After impact, keep pressure on the hammer, then press a button on the tool's side to lock the piston in the retracted position. For each test region, the rebound number is read on the scale to the closest whole number and recorded. There must be no more than 25 mm between impact testing.

Rebound tests:

It is a more widespread method that gives an approximate drawing of the resistance, and it was possible through the use of the Schmidt Hammer device (Schmidt Hammer). The idea of this test is to measure an impeller directly adjacent to the desktop, then bounce this spring back, measure this bounce, and document numbers to the bounce number. It has been shown that there is a relationship between rebound and compressive strength of concrete.

Figure 4.26: Schmidt hammer test. Source: researcher

Table 4.7: Results of Compressive Strength of stone, old mortar and composite of stone &mortar using Schmidt hammer.

Location/ Type		External Wall	Behind window	Median Elevation	Yellow Stone	Grey Stone	Red Stone
Compressive Strength of stone	Rebound Number	54	30	48	25	50	56
	Value MPa	62	25	54	18	58	70
Location/ Type		Internal mortar for all Location					
Compressive Strength of old mortar	Rebound Number	12	10	14	10	12	10
	Value MPa	2.5	1.0	4.0	1.0	2.5	1.0

Figure 4.27: Core test with fragment sample. Source: researcher

Table 4.8: Comparison of Experimental Results on sample Prisms with Analytical Predictions for Compressive Strength

<table>
<tr><td rowspan="2"></td><td colspan="2" rowspan="2"></td><td colspan="4">Compressive Strength MPa</td><td colspan="2" rowspan="2">Modulus of elasticity MPa</td><td rowspan="2">Peak strain %</td></tr>
<tr><td>fc origin EXP</td><td>fc with correction Slenderness</td><td colspan="2">fc with correction Scale 1/6 to prototype</td></tr>
<tr><td rowspan="8">Experimental values</td><td colspan="2">Exp of models W30 avg</td><td>15.31</td><td>(CF=0.86)13.2</td><td colspan="2">(CF=0.62)8.2</td><td colspan="2">900-1100</td><td>1.3</td></tr>
<tr><td colspan="2">Exp of models W40 avg</td><td>12.9</td><td>(CF=0.86)11.1</td><td colspan="2">(CF=0.62)6.9</td><td colspan="2">500-1160</td><td>1.6</td></tr>
<tr><td colspan="2">Exp of models P20 avg</td><td>16.4</td><td>(CF=0.75)12.3</td><td colspan="2">(CF=0.62)7.6</td><td colspan="2">600-1300</td><td>0.935</td></tr>
<tr><td rowspan="2">Lab (cubes)</td><td>Mortar (fm)</td><td colspan="4">4.0</td><td colspan="2">----</td><td>----</td></tr>
<tr><td>Stone (fs)</td><td colspan="4">88.0</td><td colspan="2">----</td><td>----</td></tr>
<tr><td rowspan="3">Schmidt hammer</td><td>Mortar (fm)</td><td colspan="4">2</td><td colspan="2">----</td><td>----</td></tr>
<tr><td>Stone (fs)</td><td colspan="4">48</td><td colspan="2">----</td><td>----</td></tr>
<tr><td>composite of stone &mortar</td><td colspan="4">9.0</td><td colspan="2">----</td><td>----</td></tr>
<tr><td rowspan="8">Analytical Predictions values</td><td colspan="2">Common models</td><td colspan="2">Equation/ empirical expression</td><td colspan="2">Values MPa</td><td colspan="2">Values MPa
102 fc</td><td></td></tr>
<tr><td colspan="2"></td><td colspan="2"></td><td>fs=88, fm=4 MPa</td><td>fs=88, fm=2. MPa</td><td>fs=88, fm=4 MPa</td><td>fs=88, fm=2. MPa</td><td></td></tr>
<tr><td colspan="2">Schmidt hammer</td><td colspan="2">----</td><td>----</td><td>9.0</td><td>----</td><td>918.0</td><td>1.87%</td></tr>
<tr><td colspan="2">Eurocode6 2005</td><td colspan="2">$fc = 0.5\,.fs^{0.7}.fm^{0.3}$</td><td>17.4</td><td>14.1</td><td>1774</td><td>1438.2</td><td>1.95%</td></tr>
<tr><td colspan="2">Hendry and Malek1986</td><td colspan="2">$fc = 0.317\,.fs^{0.531}.fm^{0.208}$</td><td>4.55</td><td>3.95</td><td>464.1</td><td>402.9</td><td>-----</td></tr>
<tr><td colspan="2">Dayaratnam 1987</td><td colspan="2">$fc = 0.275fs^{0.5}.fm^{0.5}$</td><td>5.16</td><td>3.65</td><td>526.32</td><td>372.3</td><td>----</td></tr>
<tr><td colspan="2">Kaushik 2007</td><td colspan="2">$fc = 0.63\,.fs^{0.49}.fm^{0.32}$</td><td>8.8</td><td>7.1</td><td>897.6</td><td>720.0</td><td>1.6%</td></tr>
<tr><td colspan="2">Adrian Costigan 2015</td><td colspan="2">$fc = 0.46\,.fs^{0.5}.fm^{0.5}$</td><td>8.63</td><td>6.1</td><td>460.0</td><td>877.2</td><td>0.323%</td></tr>
</table>

The compressive stress-strain behavior, compressive strength, Modulus of elasticity, of different sample models are carried out, also, some main mechanical properties such Poisson's ratio and peak strain are also found in the test results. The compressive strength of composite mortar and stone has been calculated in several ways as follows, as shown in table 4.8:

- Through experimental examinations of three models build from two layers of stones, the space between the two layers is filled with old lime mortar and a small fraction of stone, as the first model consists of 3 samples with dimensions 30 * 15 * 23, the samples were tested at the age of 3 months, and the second model is 3 samples with dimensions 44 * 15 * 23, the samples were tested at the age of 3 months, and the third model consisted of 6 samples with dimensions 20 * 20 * 23, three samples were tested at the age of one month and three samples at the age of 3 months, the compressive strength value at one month was equal to 0.78 of the compressive strength for 3 months. The values were multiplied by a reduction correction factor according to ASTM for the slenderness.

Table 4.9: Slenderness correction factors for f´m (ASTM)

ASTM slenderness	1.3	1.5	2.0	2.5	3.0	4.0	5.0
correction factor	0.75	0.86	1.00	1.04	1.07	1.15	1.22

- Using the expected analytical equations of the Eurocode and previous studies, so that these equations include the strength of mortar and stone, which were adopted according to experimental tests.
- Using the Schmidt-Hammer test on separate samples of stone and mortar, the compressive strength of the stone and mortar component was calculated using the Eurocode6 equations.

From curves 4.5, 4.9, and 4.24, it was found when comparing the stress-strain curves of stone, mortar cubes, and specimen samples that the following is indicated:

- The stress-strain curve for stone and mortar lies between the stress-strain curve for stone and the stress-strain curve for mortar.
- The value of the compressive strength of the stone and mortar samples lies between the compressive strength of the stone and the mortar, as the sample model is stronger than the mortar and weaker than the stone. Also, through experimental tests of the samples, it was observed that the load was distributed uniformly over the entire area subjected to the load, that cracks occurred in the stone and appeared more clearly in the mortar, thus the samples gained their strength from the properties of both the stone and the mortar.

4.4.7 Measurement of flexural Strength

In this study, two types of samples were adopted when performing the flexural test. The first type includes three double leaf beams with approximately total dimensions (55 ^{x} 15 ^{x}10) cm3 (length, width, height) respectively, three stone courses and two mortar layers, were built, using old mortar and stone pieces with dimensions ranging from 4-9 cm in length, 4-6 cm in width and 2-3 cm in height, in order to determine tensile strength. the second type is the same first but with added two steel bar diameter 6mm, to produce the nonlinear behavior of beam, in order to make validation with FE numerical model.

The flexural test on 6 samples were carried out using Controls Flexural testing machine with a capacity of 50 KN, after 90 days, as follows:

1. Samples edge surfaces were checked using a surface smoothing device.
2. The dimensions of the samples were taken and recorded using the caliber measuring tool.
3. Placing the samples in the testing machine in proportion to the device supports and the pallet, so that the sample is in full contact with the testing machine from the top and bottom.
4. The load is applied gradually and continuously at a speed of about 10N/s, as the load reaches a peak, thus failure is reached. The samples of the first type had cracking suddenly and the sample was divided into two parts, but the samples of the second type had cracking occurred in a longer time and the sample would not be divided into two parts. The device was turned off so that it would not be damaged.
5. The loads were recorded with the beginning of the load with the vertical displacement, to draw the load deflection curve, as this curve has a major role in the validation process, also the maximum load was recorded and the type and location of the failure was noted.

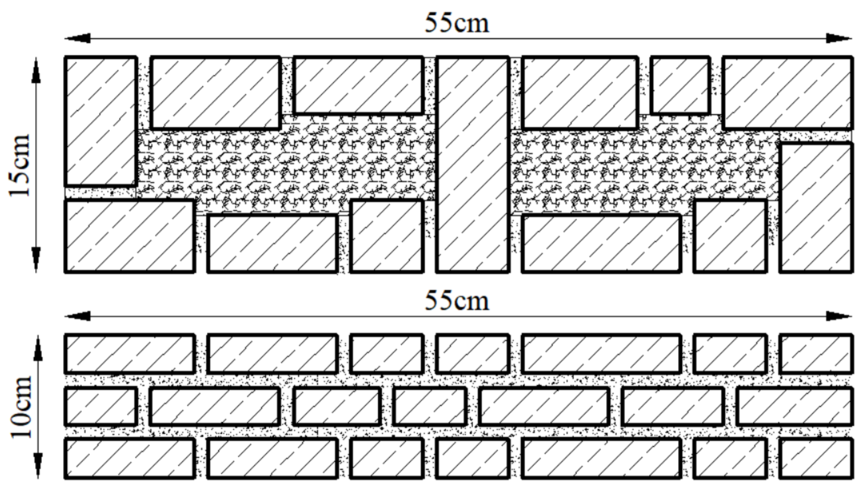

Figure 4.28: Plan and elevation of 55*15*10 cm double leaf beam. Source: researcher

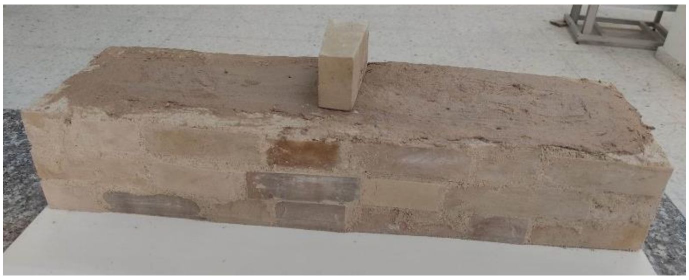

Figure 4.29: Flexural Strength sample of 55*15*10 cm double leaf beam. Source: researcher

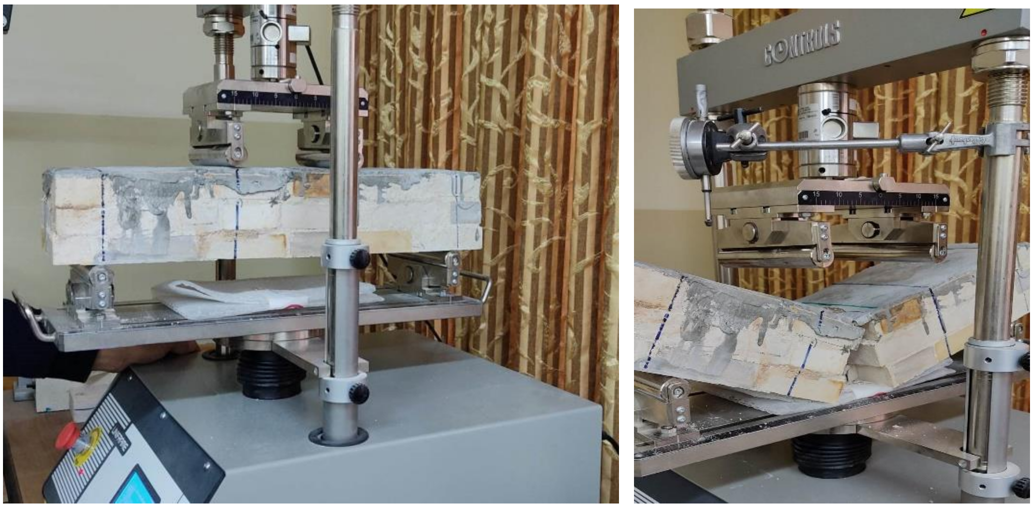

Figure 4.30: Flexural Strength sample of 55*15*10 cm double leaf beam. Source: researcher

Figure 4.31: Flexural Strength sample of 55*15*10cm double leaf beam with 2 steel barϕ6. Source: researcher

$$\text{Flexural Strength } \sigma\, t = \frac{W \times L \times 1000}{B \times D^{2}} \quad \text{……………… (6)}$$

Table 4.10: Results of Flexural Strength sample of 55*15*10cm double leaf beam with 2 steel barϕ6 and without steel. Source: researcher

No. of beams	**Dimensions of beams**	**55cm 15cm 10cm**	
	Steel bar	**loads**	**Flexural Strength Ϭ t**
unit		KN	Mpa
1	without	0.750	0.225
2	without	0.687	0.206
3	without	0.736	0.221
1	with 2 bar ϕ6	3.334	1.24
2	with 2 bar ϕ6	2.866	1.10
3	with 2 bar ϕ6	2.650	0.986

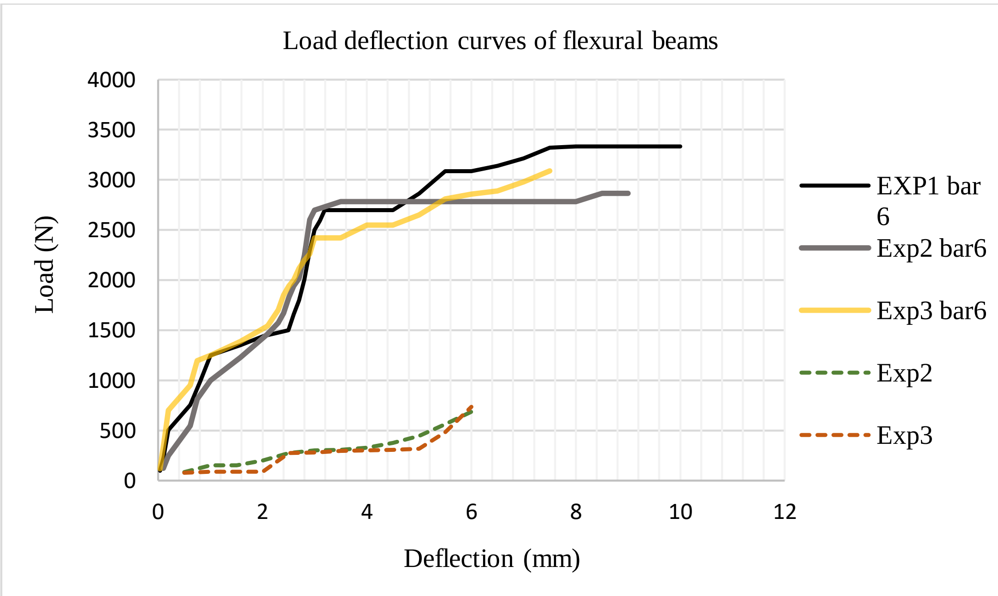

Figure 4.32: Load deflection curves of flexural beams with steel bar ϕ6 and without.

CHAPTER 5

Numerical Analysis and Modeling

5.1 Introduction

This chapter demonstrates numerical analysis and modeling, which is one of the main parts of this thesis. In this study, numerical analysis methods such as FEM were relied on for structural analysis, thus it became possible to model the complex behavior of the structures of ancient historical buildings. A macro modeling strategy was also adopted. In order to implement numerical modeling of building structures using the macro modeling approach, it is necessary to have empirical data for prism samples that are required to use, the most important of these data are: compressive strength, tensile strength, stress-strain curves, modulus of elasticity and Poisons ratio. Experiments were performed to verify the mechanical behavior of stone work structure, as described in Chapter 4, and to use them in numerical modeling.

The main topic covered in this chapter, Double-leaf beam and Double-leaf Wallette of mortar and stone were validated by modeling it using the ANSYS nonlinear FE package, the results of these numerical analyzes were compared with the experimental results, as well as modeling and numerical analysis of the structure of the approved case study building.

5.2 Numerical Analysis and Validation of Modelling.

Three samples with different dimensions were modeled with SOLID65 element by nonlinear FE package ANSYS17.2. The Configuration, geometrical details and graphical representations of models with loads are presented in Figure 5.1 to Figure 5.6. The material properties, type of mesh and application of vertical force to samples are described and graphically presented in subsequent sections of this chapter. Finally Load deflection curve, cracking/crushing pattern and displacement are compared with available experimental results/numerical analyses for validation.

5.2.1 Description of Experimental Flexural Beams & Double-leaf Wallette Models

Configuration and geometrical details of the double-leaf stone beam, Double-leaf Wallette, and Flexure Concrete Beam models are shown in Figures 5.1,5.2,5.3.

- Flexural Sone Beams Models

Tension reinforced beams with bars 2 Φ 6 that have been simulated. The beam is a simply supported beam with a total length of 550 mm, and a clear span of 450 mm. The beam has a rectangular cross section of 150 mm in width and 100 mm in height. The beam was subjected to two concentrated static loads, spaced 150 mm apart.

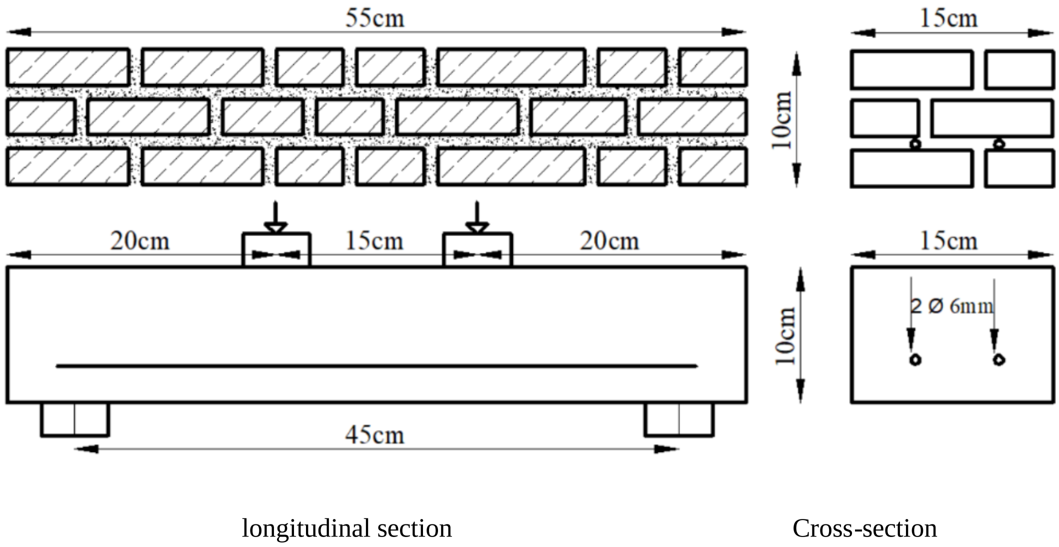

Figure 5.1: Description of Flexure Sone Beam Model Source: researcher

- Double-leaf Wallette

The Wallette has total length of 440 mm, and has a rectangular cross section of 150 mm in width and 220 mm in height. The Wallette was subjected to distribution static loads, at total length of Wallette. The results of the experimental investigation for the Wallets and prisms from the tests performed in this study were used to validate the models using ANSYS.

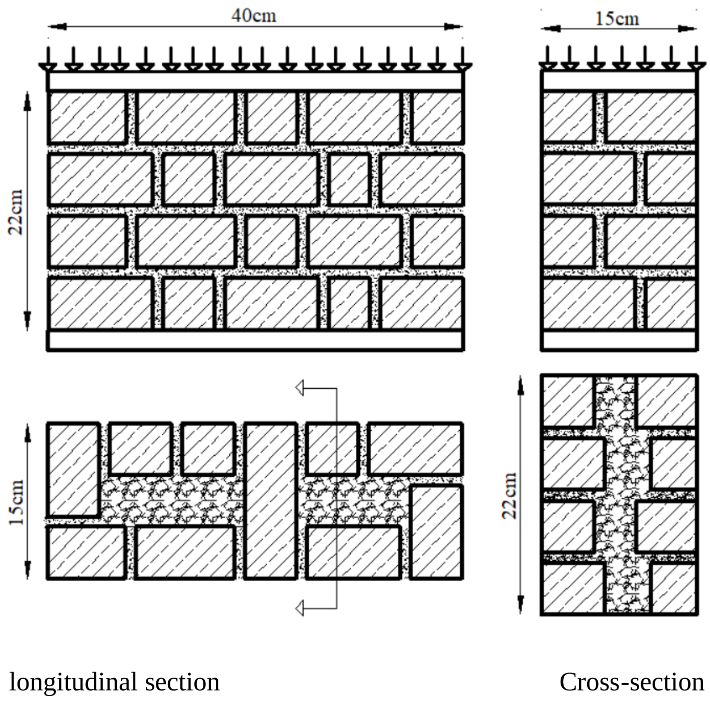

Figure 5.2: Description of Double-leaf Wallette model Source: researcher

- Flexural Concrete Beam Model

The beam is a simply supported beam with a total length of 3200 mm, and a clear span of 3000 mm. The beam has a rectangular cross section with 125 mm width and 250 mm height and a concrete cover of 25 mm was assumed. The beam was subjected to two concentrated static loads, spaced 1000 mm. Tension reinforcement of the beam is 2Φ12 mm. Compression reinforcement of the beam is 2Φ10 mm. And shear reinforcement of the beam is 6 mm diameter stirrups spaced at 150 mm (Balamuralikrishnan & Jeyasehar, 2009).

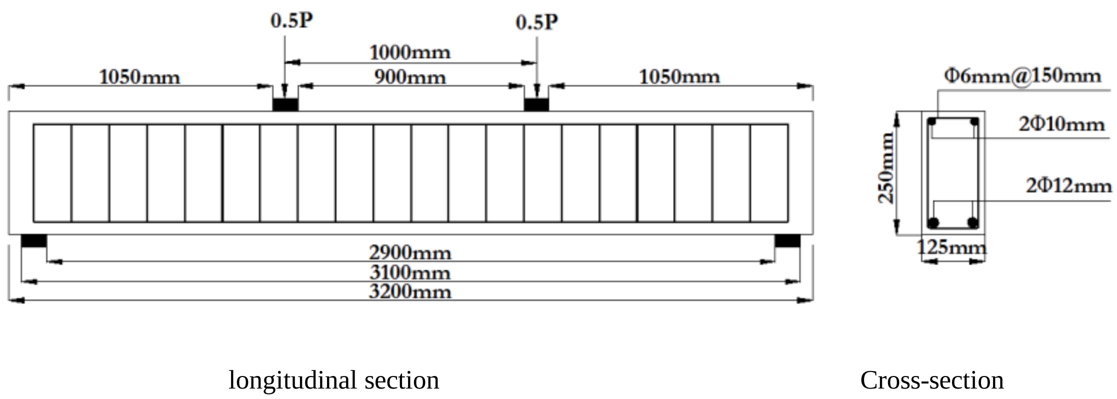

Figure 5.3: Description of Flexure Concrete Beam Model (Balamuralikrishnan & Jeyasehar, 2009).

5.2.2 Modeling Assumptions

To provide acceptable and good simulation of complex behavior the following are modeling assumptions made for the flexure beam model:

1. Mortar, stone and steel are considered and designed as isotropic and homogeneous materials.

2. The Poisson ratio is assumed to be constant throughout the loading period.

3. Steel is assumed to be a perfectly homogeneous and flexible - plastic material in tension.

5.2.3 Selection of Element Types Using ANSYS

A description of the types of elements used in ANSYS models is provided. The materials used are: stone with lime mortar, concrete, steel reinforcement, supports plate.

Solid 65 an eight-node solid element with three degrees of freedom, was used for modeling (stone with lime mortar) & concrete. Steel reinforcement was also modeled using the Link180 element, which has three degrees of freedom at each node and is a uniaxial element. As for Solid185 is a modeling element used to model the loading and support of steel plates, this element has eight nodes, each with three degrees of freedom.

5.2.4 Material Properties

Material properties are used to ensure applying FE model in the Ansys program. Solid65 element was used for modeling (equivalent materials for stone and lime mortar), so, is required for material properties necessary, which are linear and multilinear isotropic, as well as failure parameters. Modulus of elasticity, Poisson's ratio that required in linear isotropic, as for multilinear isotropic required stress strain diagram. Willam and Warnke (1975) failure criteria have been adopted. This failure criterion, which was first used for concrete, uses a smeared model to estimate for both cracking and crushing failure modes, as well as the application of the Willam and Warnke (1975) material model in ANSYS requires the identification of multiple parameters. These parameters are:

1. Open shear transfer coefficients.

2. Closed shear transfer coefficients.

3. Uniaxial tensile cracking stress (tensile strength).

4. Uniaxial crushing stress (positive), compressive strength.

Table 5.1: Material Properties of equivalent materials for ANSYS Flexure Stone Beam and Wallette Model.

Material Model	Element Type	Material Properties	
		Linear Isotropic	
		Modulus of elasticity (MPa)	Poisson’s ratio
equivalent for stone and lime mortar	Soild65	600-800	0.20
Concrete	Soild65	24000	0.20
Steel reinforcement	Link 180	200000	0.30
Loading and Supporting Steel Plates	Soild185	200000	0.30

Material Model	Failure Criteria	Open shear transfer coefficients	Closed shear transfer coefficients	Uniaxial tensile cracking stress	Uniaxial crushing stress
equivalent for stone and lime mortar	Willam and Warnke failure criteria	0.2	0.8	0.2 MPa	12 MPa
Concrete	Willam and Warnke failure criteria	0.2	0.8	2.9 MPa	27.54 MPa

5.2.5 Geometry

5.2.5.1 Geometry of Flexural Stone beams

A half of complete beam was adopted for modeling, getting the benefit of the symmetry of the beams. This method reduced considerably computation time and computer storage space requirements. Because just half of the beam is modeled, the model is 275 mm long, with a cross-section of 150mm x 100 mm. Two bar 6mm was modeled, 25 far from base of the beam, (50 mm far from center of the support plate). Only one loading plate and one support plate are required due to symmetry. 50 mm x 25 mm x 150 mm steel loading and support plates was used.

5.2.5.2 Geometry of Double-leaf Wallette

The whole wallet was adopted for modeling, the model is 440 mm long, with a cross-section of 150 mm x 220 mm, without a reinforced steel bar. Steel loading plates with a thickness of 20 mm were used to distribute the load from the machine over the sample area subjected to loading.

5.2.5.3 Geometry of Flexural Concrete beams

A half of complete beam was adopted for modeling, getting the benefit of the symmetry of the beams. This method reduced considerably computation time and computer storage space requirements. Because just half of the beam is modeled, the model is 1600mm long, with a cross-section of 250mm x 125 mm. Only one loading plate and one support plate are required due to symmetry. 50 mm x 25 mm x 150 mm steel loading and support plates was used.

5.2.6 Meshing

A rectangular or square mesh is recommended for getting good results from the Solid65 element. As a result, the mesh is established to create square elements. The nodes of the steel loading and supporting plates were linked with adjoining (stone and mortar) solid components. Merge items was used to combine nodes with the same position.

The overall mesh of two types of beams and steel plates was divided based on volumes of 25mm for the models, while for the wallet it was divided every 10 mm.

5.2.7 Loads and Boundary Conditions

To constrain the model and provide an optimal solution, displacement boundary conditions are required. For flexural (Stone & Concrete) beam models, the Boundary conditions are required added at places of symmetry, due to adopting half of the entire beam was used, to model the symmetry, nodes on this plane must be constrained in the perpendicular direction. These nodes have a degree of freedom constraint UX = 0, as well as where the support was modeled in such a way that a single line of nodes on the plate was given constraint in the UY, and UZ directions applied as constant values of 0. For wallet modeling, boundary conditions are required throughout the board in the UY, UZ, and UX directions applied as fixed values of 0, to establish that the model behaves identically to the experimental beam.as shown in figures 5.2, 5.3.

For flexural beams models, the loads were applied to the steel plate across the entire centerline of the loading plate. For the wallet, loads were applied to the steel plate in distributed form over its.

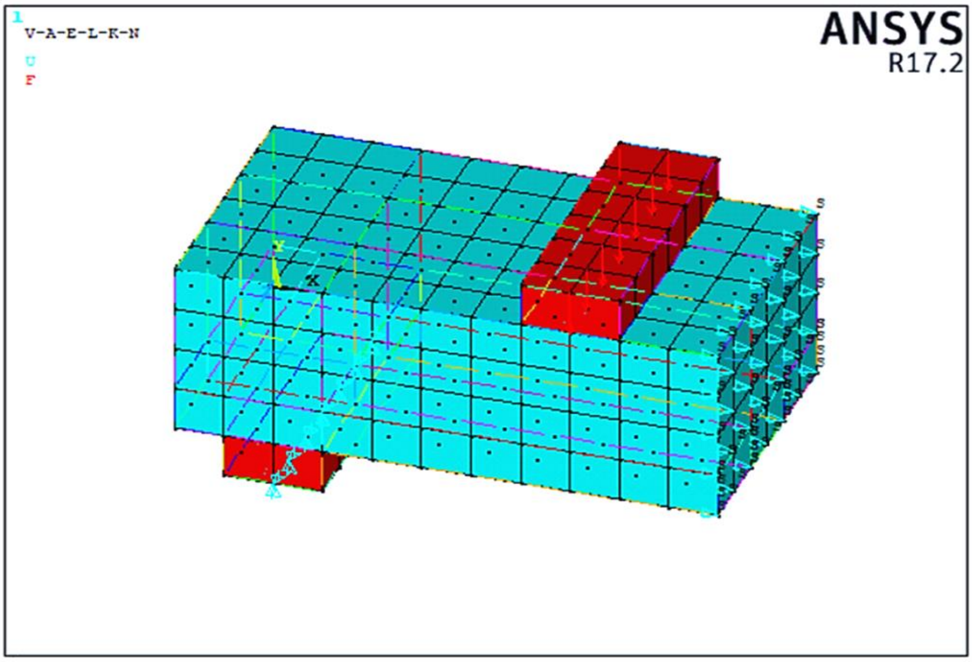

Figure 5.4: Flexure Beam model with loads and Boundary Conditions by ANSYS.

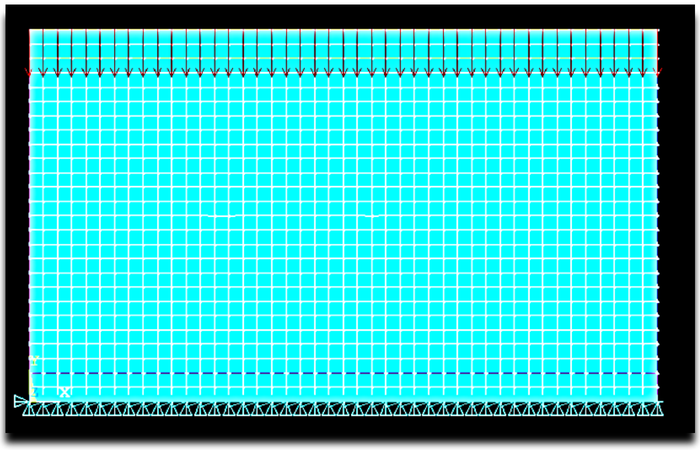

Figure 5.5: Wallet model with loads and Boundary Conditions by ANSYS.

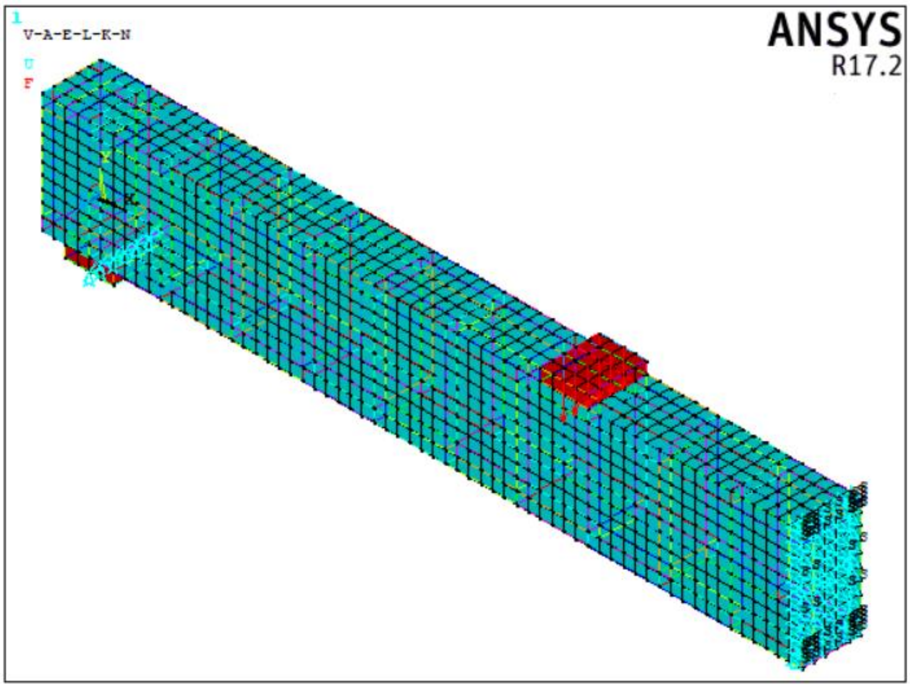

Figure 5.6: Concrete beam model with loads and Boundary Conditions by ANSYS.

5.2.8 Setting Nonlinear Solution Parameters

Setting solution parameters for an analysis include establishing the analysis type and common popular analysis options, as well as load step options. The analysis option was chosen to disregard large deformation effects such as large deflection, large rotation, and large strain (Small Displacement Static).

To avoid nonconvergence in nonlinear analysis, the load applied to the structures must be gradually raised. The overall load applied to a finite element model is divided into load steps, which are a sequence of load increments. The ANSYS program updates the model stiffness using Newton–Raphson equilibrium iterations (ANSYS Inc, 2014).

For both the flexure beam and wallet models, nonlinear static analysis was applied. Table 5.2 lists the most common commands used in the analysis.

Table 5.2: Nonlinear Analysis Control Commands.

	flexure Stone beam model	Wallet model	flexure Concrete beam model
Analysis Options	Small Displacement Static	Small Displacement Static	Small Displacement Static
Time at End of Load Step	750	3000	1.0

Automatic Time Stepping	ON	ON	ON
Time Step Size	10	50	0.05
Minimum Time Step	5	10	0.01
Maximum Time Step	50	100	0.05
Write Items to Results File	All Solution Items	All Solution Items	All Solution Items
Frequency	Write Every Sub Step	Write Every Sub Step	Write Every Sub Step

Set Convergence Criteria			
	Flexure Stone beam model	Wallet model	Flexure Concrete beam model
F (Ref. Value)	Calculated	Calculated	Calculated
F (Tolerance)	0.1	0.05	0.2
F (Norm)	L2	L2	L2
U (Ref. Value)	Calculated	Calculated	Calculated
U (Tolerance)	0.1	0.05	0.35
U (Norm)	L2	L2	L2

5.2.9 Validation of Numerical Modelling

The numerical results are validated by data available from experimental samples, by the modeling process. The selected failure model, setting the values for the input parameters, as well as the expected results, are all necessary to ensure the reliability of the numerical models.

Verification was done on three models with varied dimensions, as shown in the Figures 5.1 to 5.6, in order to verify the adopted modeling and nonlinear solution procedure. The first & third models were subjected to two concentrated static loads, while the second model was subjected to distributed static loads. Numerical modeling was performed. Numerical modeling was performed for models having the same dimensions, material properties, and loading conditions as the reported experimental.

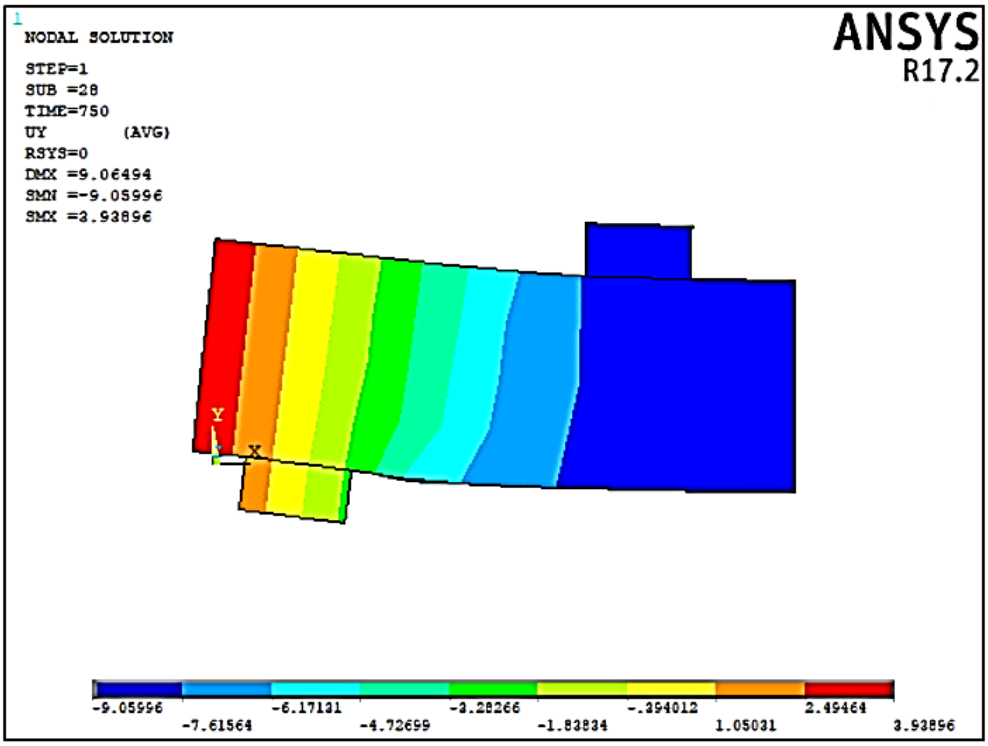

Figure 5.7: Deformed shape of Flexure stone with lime mortar Beam model by ANSYS.

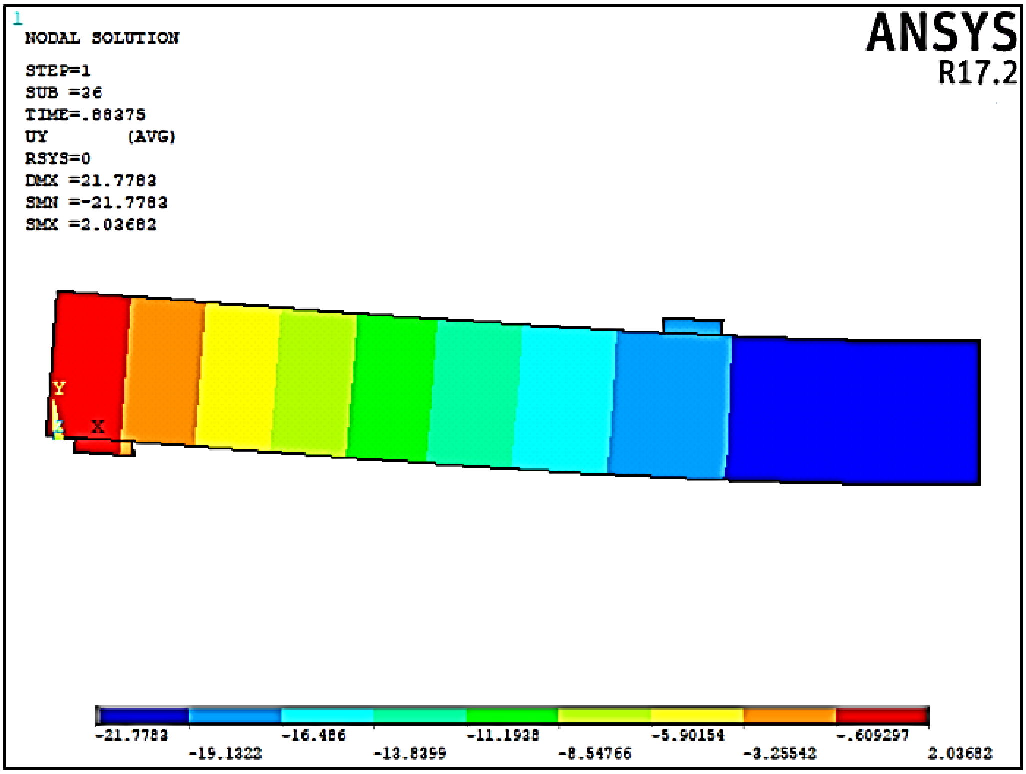

Figure 5.8: Deformed shape of Flexure concrete Beam model by ANSYS.

5.2.10 Crack pattern & Failure

The crack pattern is taken from Finite Element Analysis (ANSYS) by the last convergent loading step, shows that the crack pattern of ANSYS and the pilot beam is somewhat in agreement, but not completely. Where in the experiment the flexural beam failed in more than one place due to the presence of weaknesses in the bonding between the stone and the lime mortar, as it was moving and falling some stones, especially in the lower layer at the edges, in addition to the displacement of the rebar.

A cracking sign represented by a circle appears when a principal tensile stress exceeds the ultimate tensile strength. The crack pattern and failure mode obtained by the model is similar to the failure that occurred in the experiments, and the figures show the failure pattern.

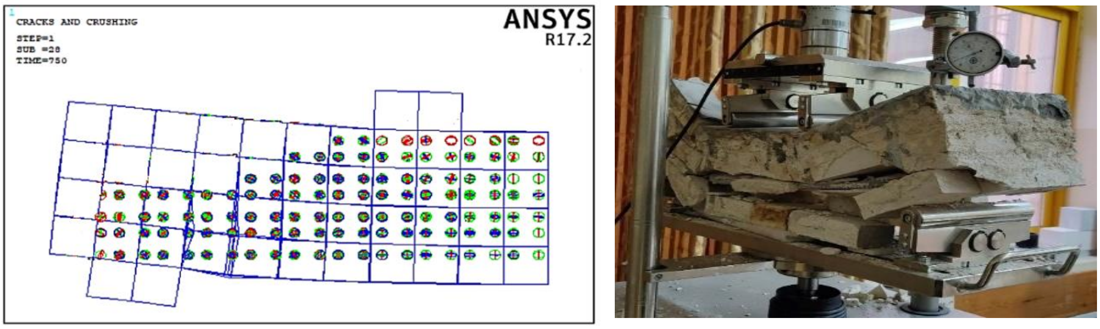

Figure 5.9: Crack pattern of Flexure Stone Beam model by ANSYS, compared to the experimental crack pattern.

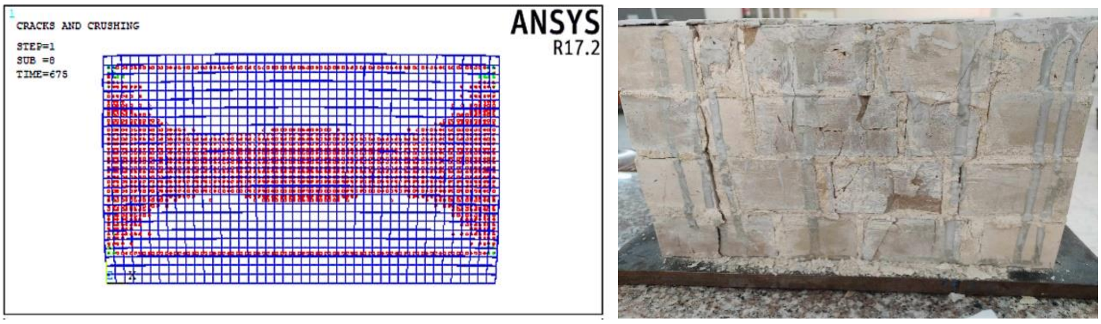

Figure 5.10: Crack pattern of wallette model by ANSYS, compared to the experimental crack pattern.

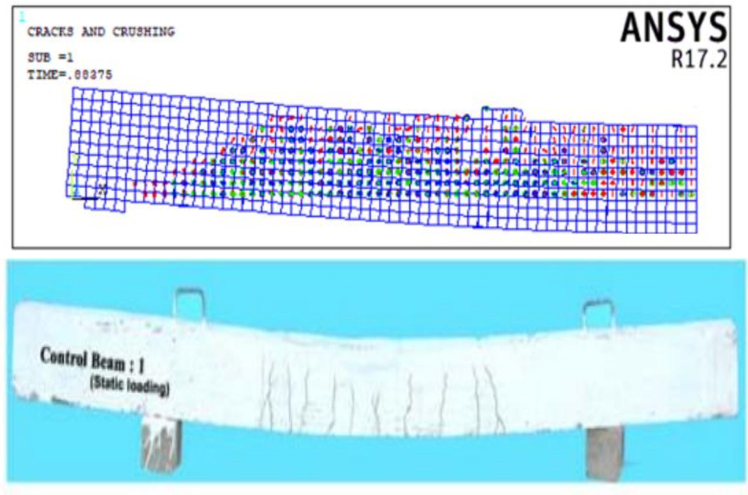

Figure 5.11: Crack pattern of Flexure Concrete Beam model by ANSYS, compared to the experimental crack pattern.

5.2.11 Loads and Deflection at Failure

A comparison between experimental and finite element ultimate loads, and ultimate capacity of the strengthened beams with ultimate capacity of the control beams.

Table 5.3: Comparisons Between Experimental and ANSYS Results – Failure Loads and Deflection

	Failure Load (EXP) N	Failure Load (ANSYS) N	Mid-Span Deflection at Failure (EXP) mm	Mid-Span Deflection at Failure (ANSYS) mm	Deflection at Failure (EXP) mm	Deflection at Failure (ANSYS) mm
flexure Stone beam1	3334	3416	10	9.06	--	--
flexure Stone beam2	2866	3416	9	9.06	--	--
Flexure Stone beam3	2650	3416	7.5	9.06	--	--
Wallet1	609000	610000	--	--	3.2	2.85
Wallet2	625000	610000	--	--	1.9	2.85
Wallet3	668000	610000	--	--	2.7	2.85
flexure concrete beam	41250	45100	21.13	21.7	--	--

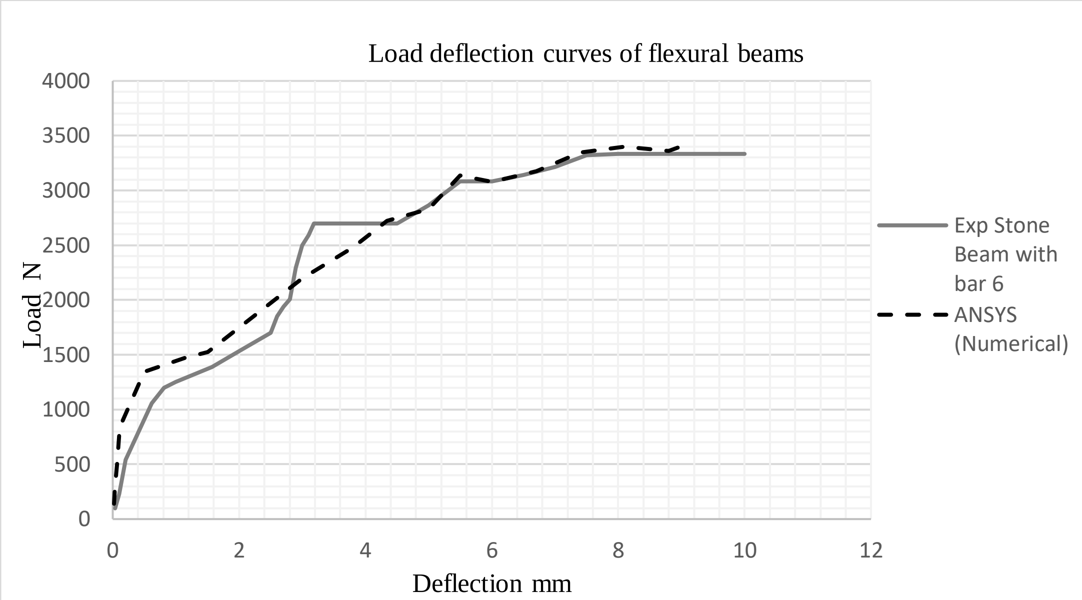

Figure 5.12: Comparison of Experimental and ANSYS Load Deflection Curves for Flexure Beam.

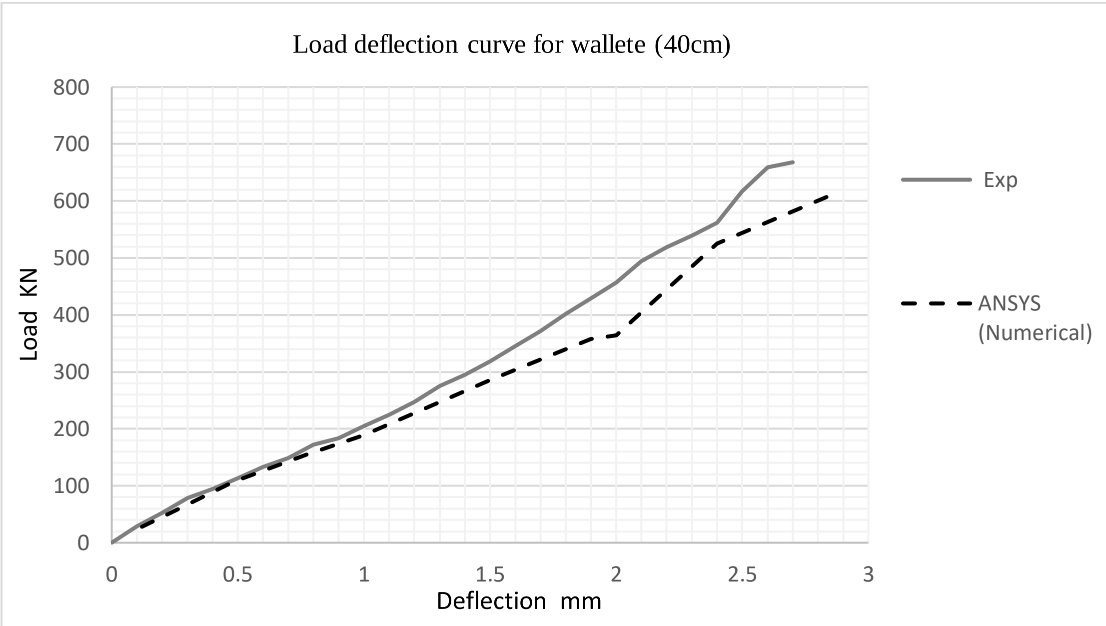

Figure 5.13: Comparison of Experimental and ANSYS Load Deflection Curves for Wallette.

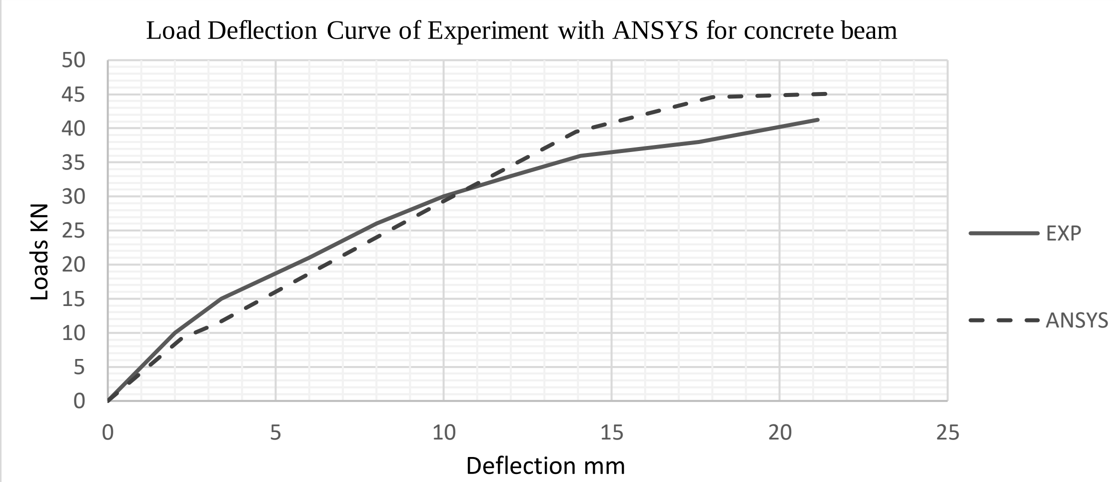

Figure 5.14: Comparison of Experimental and ANSYS Load Deflection Curves for concrete beam.

The results obtained from the numerical nonlinear analysis of models were compared with the experimental test results conducted in the lab for compression and flexural experiment. The ultimate load and the corresponding maximum deflection of the tested models as well as the load– deflection curves, and deformed shapes after failure have been investigated and compared with experimental test results for models, as shown in table 5.3 &figures 5.12,5.13,5.14.

The numerical load-deflection curves produced were compared to the experimental ones in Figure. According to the experimental data, the numerical results are satisfactorily validated. Results of the present numerical nonlinear analysis by ANSYS show good agreement with the experimental results, as seen in figure 5.12,5.13,5.14.

5.3 Numerical Analysis and Modeling of Zahdeh Building

Nonlinear analysis was performed as part of a structural examination of the existing building in order to interpret the occurrence of the fracture. So, the proposed numerical modeling has been applied over the existing historical building in order to show the ability of the proposed model to describe the behavior of the structure and to know its ability to bear the self-weight, and also if it can and has the ability to bear additional loads.

Ansys is capable in modeling nonmetal materials and effective to model a non-homogeneous material with nonlinear response. It has also the capability to predict and display the patterns of cracking and crushing of the material.

5.3.1 Description & Geometry of Zahdeh Building Modeling

The Zahida building was modeled and configured in precise ways, including all the details of the building's architectural and structural elements as it exists based on reality, using the CATIA V5R20 program and then exported to ANSYS.

Configuration and geometrical details of Zadeh Building model is shown in Figures 5.15&5.16.

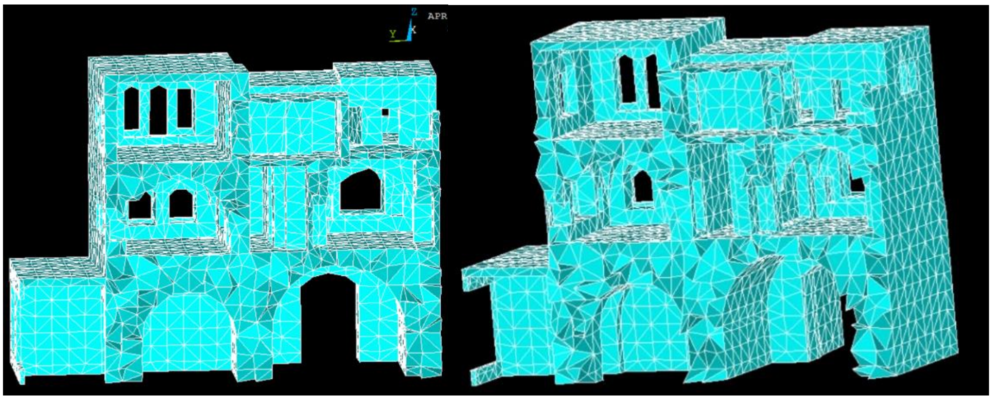

Figure 5.15: Section in Zadeh Building Model

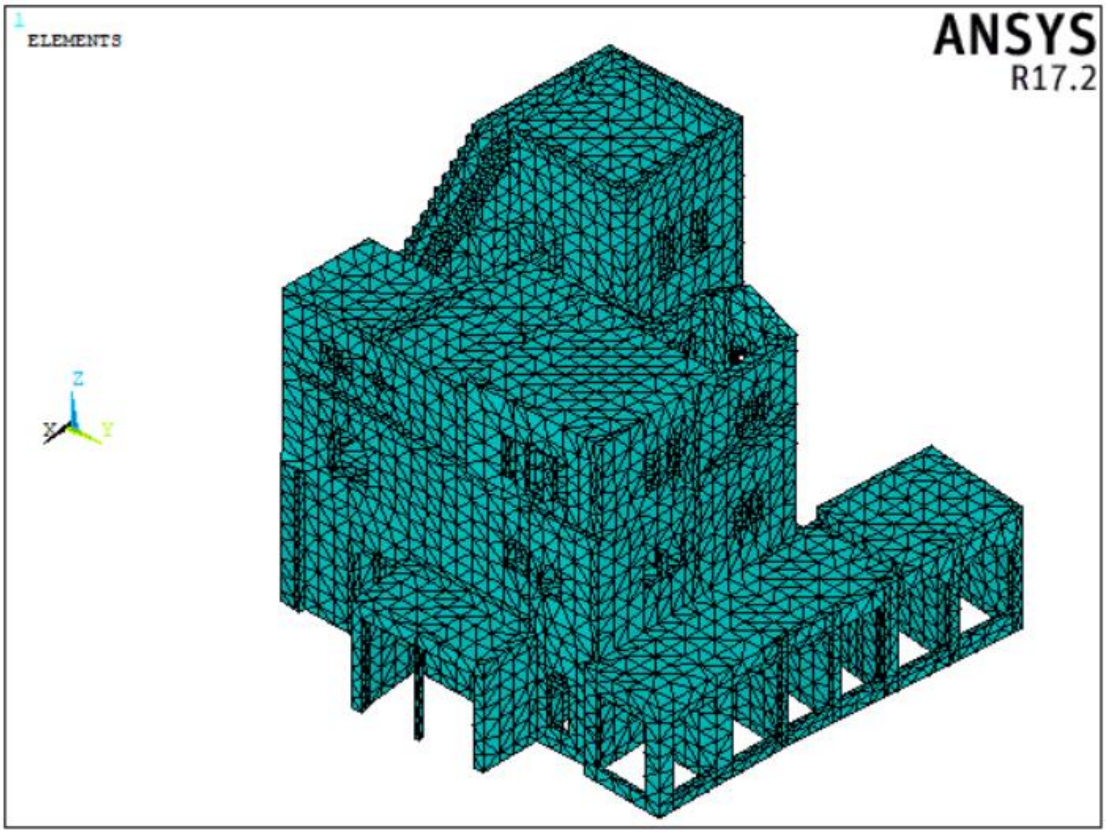

Figure 5.16: Zadeh Building Model Created in ANSYS with Overall Meshing of the Model.

5.3.2 Modeling Assumptions

To provide acceptable and good simulation of complex behavior the following are modeling assumptions:

1. Mortar and stone are considered and designed as isotropic and homogeneous materials characterized by different nonlinear softening laws in tension and compression.
2. The Poisson ratio is assumed to be constant throughout the loading period.
3. Solid 185 and Solid 65 were adopted to perform the nonlinear analysis.
4. Elastic behavior is assumed for the foundations modilling in the building.

5.3.3 Selection of Element Types Using ANSYS

Solid185 is a modeling element used to model (equivalent materials of stone and lime mortar) that represent Zahdeh Building materials, this element has eight nodes, each with three degrees of freedom. The most important aspect of this element is the treatment of nonlinear material properties.

5.3.4 Material Properties

The material properties and other constants required in macro modeling approach for the analyses of Zahdeh Building that include linear and multilinear isotropic, as well as failure parameters. Modulus of elasticity, Poisson's ratio that required in linear isotropic, as for multilinear isotropic required stress strain diagram.

Material properties were assumed based on the Schmidt hammer results for composite material available in the building. These were taken as mass density 22 KN/m^3, modulus of elasticity 1228 MPa, major Poisson's ratio 0.2, crushing limit 8 MPa, cracking limit 0.8 MPa, shear coefficient 0.2–0.8 for opened and closed crack, respectively. The nonlinear stress–strain curve for the composite material was defined according to equation (3). Willam and Warnke (1975) failure criteria have been adopted. Material properties are summarized in Table 5.4.

Table 5.4: Material Properties of Macro Models for ANSYS Zahdeh Building Model.Lists of /Material Properties and Constants Required

Material Model	Element Type	Material Properties		
equivalent for stone and lime mortar	Solid65 Solid185	Linear Isotropic		
		Modulus of elasticity	Poisson’s ratio	weight density
		843MPa	0.20	22 kN/m3

Failure Criteria	Open shear transfer coefficients	Closed shear transfer coefficients	Uniaxial tensile cracking stress	Uniaxial crushing stress
Willam and Warnke failure criteria	0.2	0.8	0.81MPa	8.1MPa

5.3.5 Meshing

It is important to notice that the selection of the correct type of mesh plays an important role in the accurate analysis of any structure. Two types of meshes, free and mapped mesh are available in the ANSYS17.2 package. A mapped mesh contains either only quadrilateral or only triangular elements. The geometry of the model should be fairly regular for volumes mapped mesh. Mapped mesh with triangular elements has been used in the meshing of the building model in this study, as this type of mesh is most suitable for Solid65 and Solid185 element.

5.3.6 Boundary Conditions and Loads

Boundary conditions: The support was modeled in such a way that on the plate was given constraint in the UX, UY, and UZ directions applied as constant values of 0.

Initially, the self-weight and the vertical loads have been applied to all slab which has different levels in the first load step to the numerical model. This was followed by the application of additional loads that represent floors load that possibly added to the existing building. Full Newton-Raphson equilibrium iterations and displacement control criteria have been used to facilitate the convergence of these solutions. The following is an illustration of the loads that have been placed, both in the current situation of the building and in the case of adding loads, in an approximate calculation way, showing the thickness of the walls and the height of the additional slabs based on the ACI code.

Table 5.5: Live loads that applied to all slab of the existing situation, live load=2KN/m².

Ground Ceiling	Levels In Z direction	-661.43	-649.43	-648.43	-643.43	-638.43	-628.43
	NO. of node	50	100	144	75	59	41
	Area m²	13.5	8.25	11.0	24.75	20.35	8.25
	Vertical loads (N)	590	270	150	660	690	405
First Ceiling	Levels In Z direction	-271.43	-252.43	-238.43	-232.43	-228.43	-218.43
	NO. of node	127	173	34	28	84	78
	Area m²	20.5	37.575	5.265	14.04	22.45	24.96
	Vertical loads (N)	350	450	350	500	535	650
Second Ceiling Load= 1.5KN/m²	Levels In Z direction	-741.43	-691.43	41.569	71.569	123.57	211.57
	NO. of node	137	74	59	50	80	95
	Area m²	38.3	18.9	13.5	12	25	37.5
	Vertical loads (N)	450	400	450	450	450	400

To represent the ability of the Al Zahdeh Building to bear additional loads, a method of adding floor loads to it was used, to know at what load failure occurs.

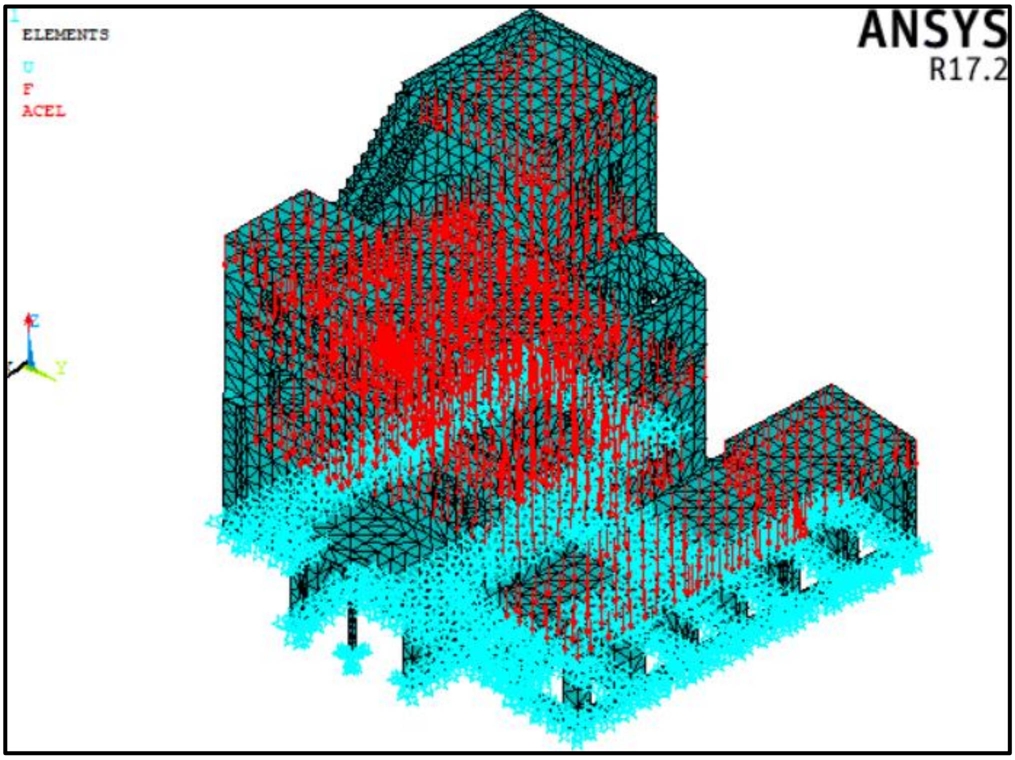

Figure 5.17: Loading &Support for exist Zadeh Building Model with adding load.

For the additional loads, the following was adopted in repeated floor: live load 2.0 KN/m^2, the volumetric weight of concrete $25KN/m^3$, slab thickness (h) 25 cm, wall thickness (d) 30 cm, floor height (L) 3 m, super dead load $2.25KN/m^2$. The service loads, then the design loads, were calculated for each slab, then the load was distributed to the walls. In the case of the last floor load, the super dead load is deleted, and the live load is changed to $1.5KN/m^2$.

Slab self-weight = $h \times \gamma$ concrete = $0.25m \times 25\ KN/m^3 = 6.25\ KN/m^2$.

Super dead load= $2.25\ KN/m^2$.

Live load $=2\ KN/m^2$ for repeated floors, but for last floor Live load $=1.5\ KN/m^2$.

Wall self-weight= $d \times L \times \gamma$ concrete = $0.3\ m \times 3m \times 25\ KN/m^3 = 22.5\ KN/m^2$.

Table 5.6: additional loads that applied to walls of the existing situation, live load=2KN/m².

Levels In Z Direction	NO. of node	Add one floor		Add two floors			Add three floors	
		Service Load KN	Design Load KN	Service Load KN	Design Load KN	Design Load KN	Service Load KN	Design Load KN
					first floor/LL=2 KN/m² second floor/LL =2KN/m²	first floor/LL=2KN/m² second floor/LL =1.5KN/m²		
+291.57	70	1500	1800	3000	3600	3250	4500	5400
+123.57	49	2250	3685	5100	7370	6123	7650	11055
+71.565	30	1635	2005	3270	4010	3775	4905	6015
+66.569	31	925	1130	1850	2261	2130	2775	3392
+41.569	35	1420	1740	2840	3480	3270	4260	5220
+11.569	41	1940	4240	3880	6360	5985	5820	8480

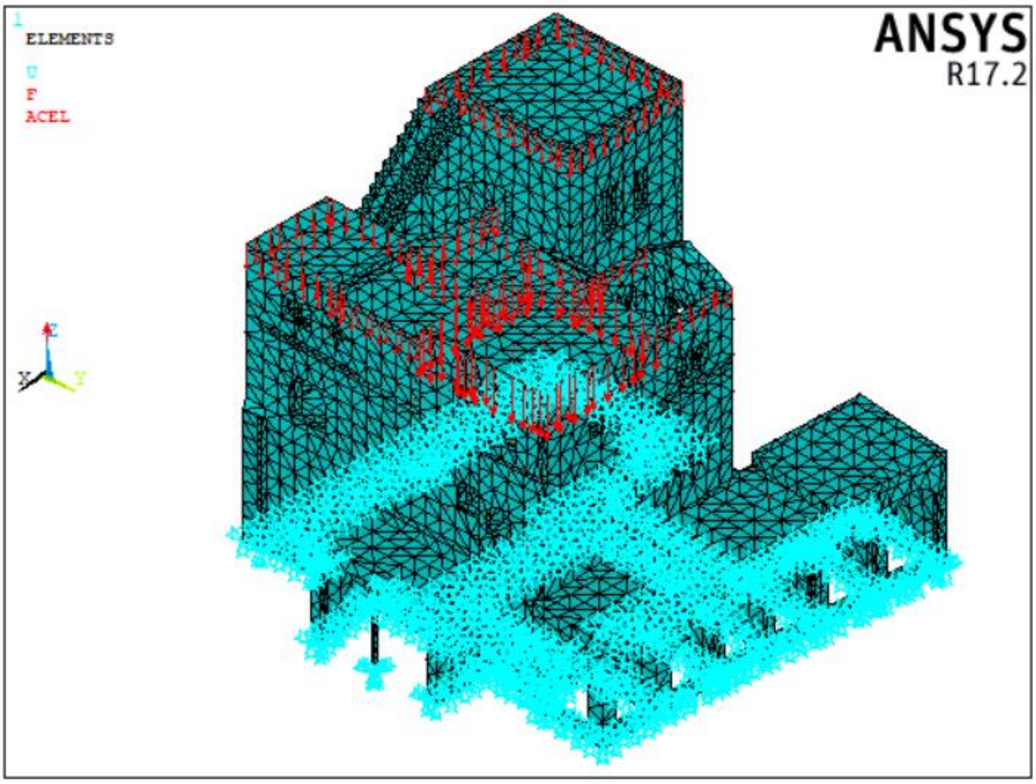

Figure 5.18: Loading &Support at added floors - Zadeh Building Model.

Table 5.7: Minimum Thickness of Two-Way Slab According ACI 318-11

Yield stress f_y[1], MPa	Without drop panel			With drop panel		
	Exterior panel		Interior panel	Exterior panel		Interior panel
	Without edge beams	With edge beams[2]		Without edge beams[2]	With edge beams	
280	$l_n/33$	$l_n/36$	$l_n/36$	$l_n/36$	$l_n/40$	$l_n/40$
420	$l_n/30$	$l_n/33$	$l_n/33$	$l_n/33$	$l_n/36$	$l_n/36$
520	$l_n/28$	$l_n/31$	$l_n/31$	$l_n/31$	$l_n/34$	$l_n/34$

Table 5.8: Minimum Thickness of One-Way Slab According ACI code 9.5.2.1

Element	Simply supported	One end continuous	Both ends continuous	Cantilever
One-way solid slabs	$l/20$	$l/24$	$l/28$	$l/10$

For Two-Way Slab, h min = 5.8/33, h min = 18 cm, for One-Way Slab, h min = 3.5/20, h min = 18 cm.

The proposed thickness of the additional slab is 25 cm.

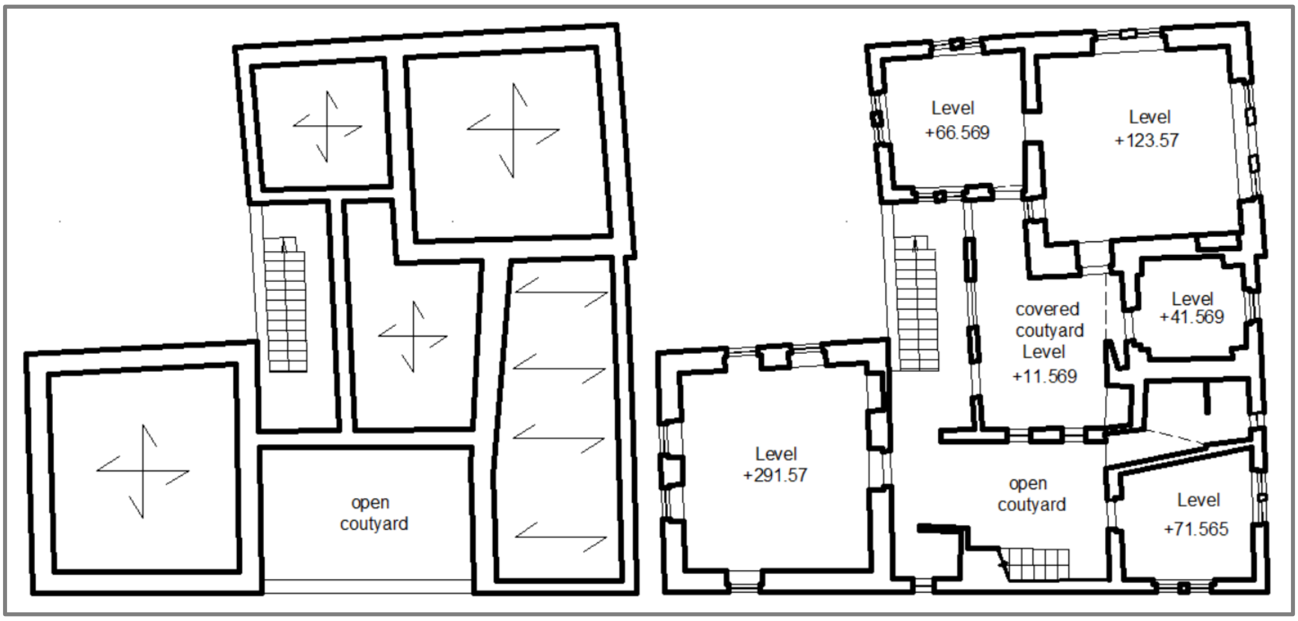

Figure 5.19: The loading direction of the proposed slabs, and the method of distributing the load on the existing walls according to the z-levels. Source: researcher

5.3.7 Setting Nonlinear Solution Parameters

One of the well-accepted main obstacles in modeling is the difficulty in the convergence of solutions. In nonlinear analysis, the total load delivered to a FE model is partitioned in to a number of load steps, or load increments. Prior to moving on to the next load increment, the stiffness matrix of the model is modified to reflect nonlinear changes in structural stiffness at the conclusion of each incremental solution. The model stiffness can be updated using Newton-Raphson equilibrium iterations. At the conclusion of each load increase, Newton-Raphson equilibrium iterations enable convergence within predetermined tolerances (Khair & Hossain, 2005).

Displacement controlled /based convergence criterion is well suited for stone building. In this study, Nonlinear Analysis Control Commands & convergence criteria shown in table 5.9.

Table 5.9: Nonlinear Analysis Control Commands.

	Zahdeh Building Model The existing situation	Zahdeh Building Model Added one floor
Analysis Options	Small Displacement Static	Small Displacement Static
Time at End of Load Step	1000	1000
Automatic Time Stepping	ON	ON
Time Step Size	50	50
Minimum Time Step	10	10
Maximum Time Step	100	100
Write Items to Results File	All Solution Items	All Solution Items
Frequency	Write Every Sub Step	Write Every Sub Step
Set Convergence Criteria		
	Zahdeh Building Model The existing situation	Zahdeh Building Model Added one floor
F (Ref. Value)	Calculated	Calculated
F (Tolerance)	0.05	0.05
F (Norm)	L2	L2
U (Ref. Value)	Calculated	Calculated
U (Tolerance)	0.05	0.05
U (Norm)	L2	L2

5.3.8 Solution output

The two forms of the solution output linked to the element are as follows:

- Nodal solution

- Element solution.

Both take into account nodal point stresses, forces, displacements, etc. Plot results also allows users to see the results' contour plot. In this section, the results were based on In contour plot to show the first principal stress 1, principal stress 3, and through Nadal obtained the deflection value, also, the support reaction (nodal load) fined in non-linear analysis.

The three main stresses are commonly identified as σ1, σ2 and σ3. σ1 represent the maximum (most tensile /positive value) principal stress, σ3 represent the minimum (most compressive/negative value) principal stress. So principal stress can be used to identify whether a material has failed or not.

Ultimate tensile strength $\sigma 1 \geq Su$t …safe OR Ultimate compression strength $\sigma 3 \geq Su$c…. Safe.

This research implemented nonlinear material behavior and solution process, macro-modeling is used, where the stonework is treated as a homogenous continuum, and the macro behavior is modeled by choosing particular properties for the composite materials. Zahdeh building is modeled as an isotropic material with homogenized properties. Multilinear isotropic hardening material is used to simulate the stone structure. With an isotropic work hardening assumption and a multilinear stress-strain curve as its description, such a kind of material (MISO) employs von Mises yield criterion. Willam and Warnke (1975) failure criteria have been adopted.

The structure was modeled by finite elements using solid 185 and solid 65, then nonlinear analysis was first carried out in order to check the safety of the walls and ceiling in the original conditions under its own weight.

In the first method of nonlinear analysis, modeling was performed *using Solid 185*, and the results are shown in Figures 5.20 to 5.31.

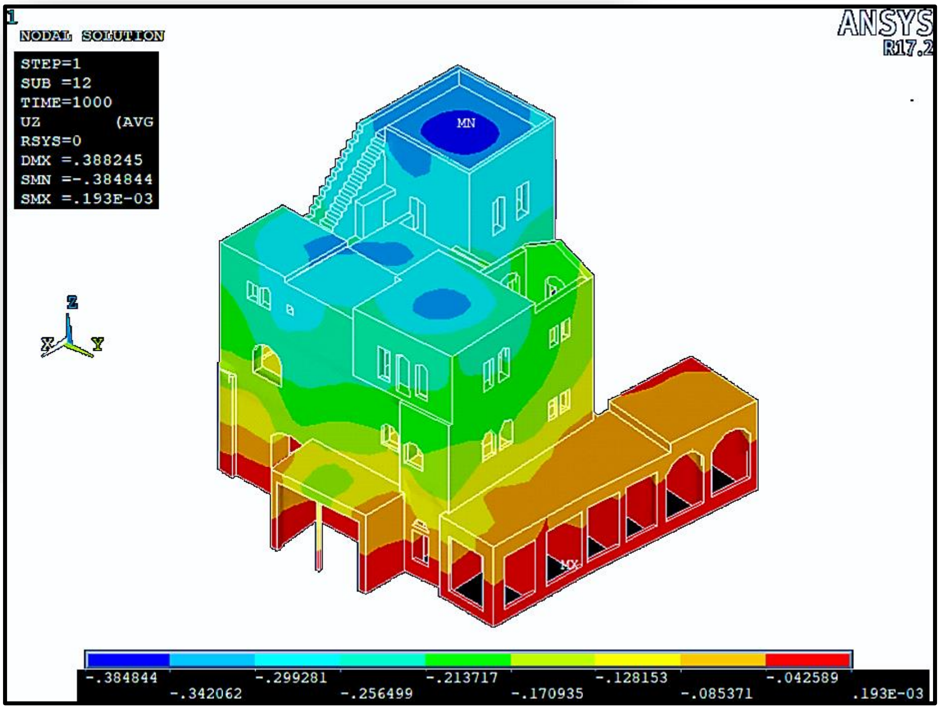

Figure 5.20: Deflection, Zadeh Building Model of the existing situation/Solid185.

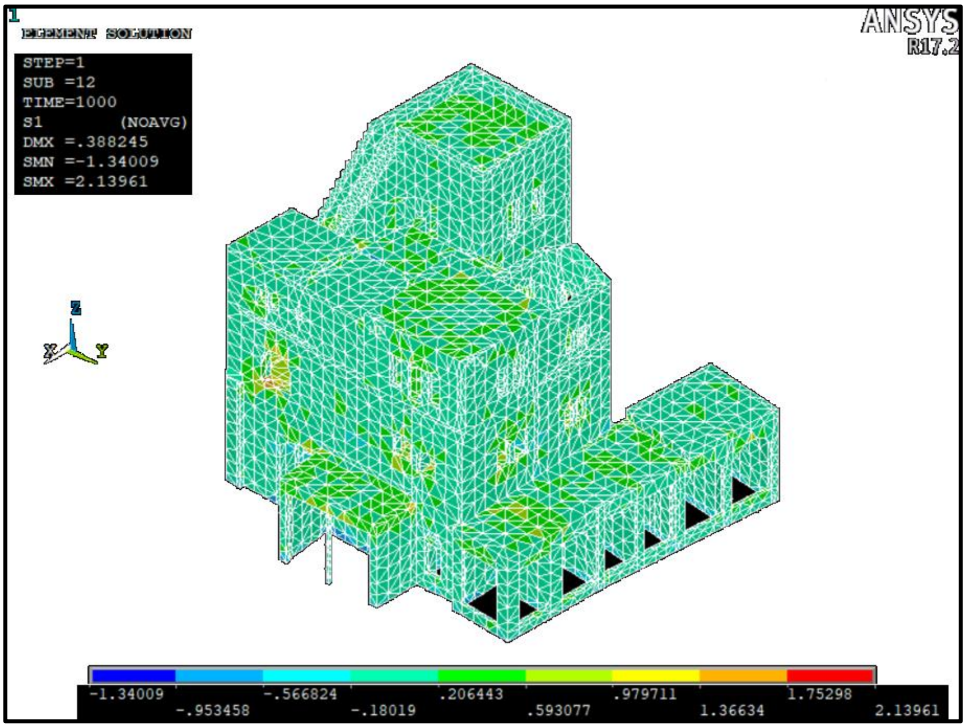

Figure 5.21: Principal stress σ1- Zadeh Building Model of the existing situation/Solid185.

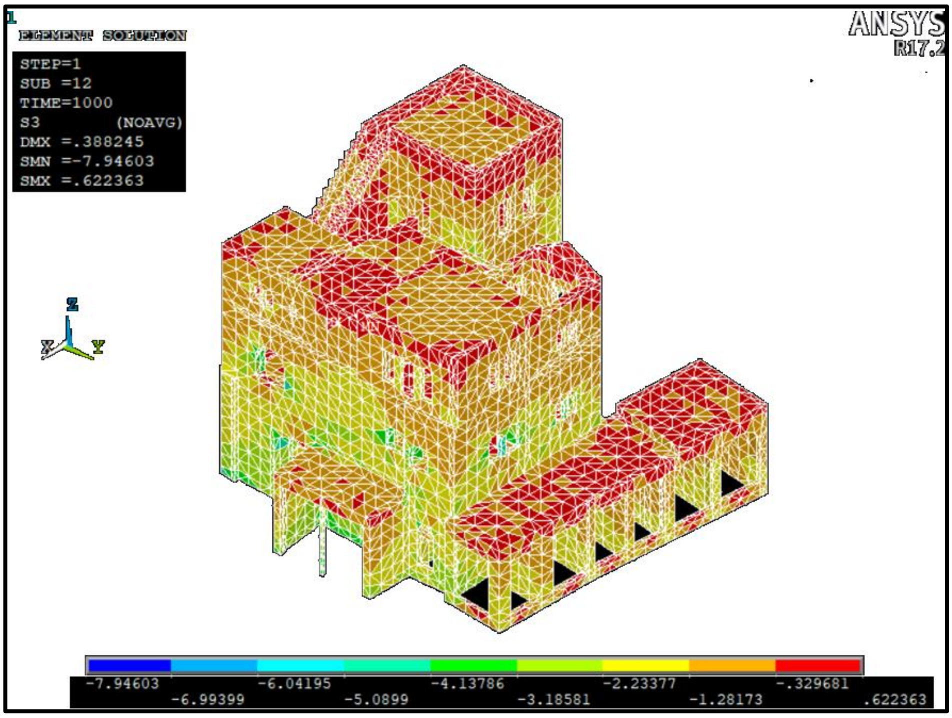

Figure 5.22: Principal stress σ3- Zadeh Building Model of the existing situation/Solid185.

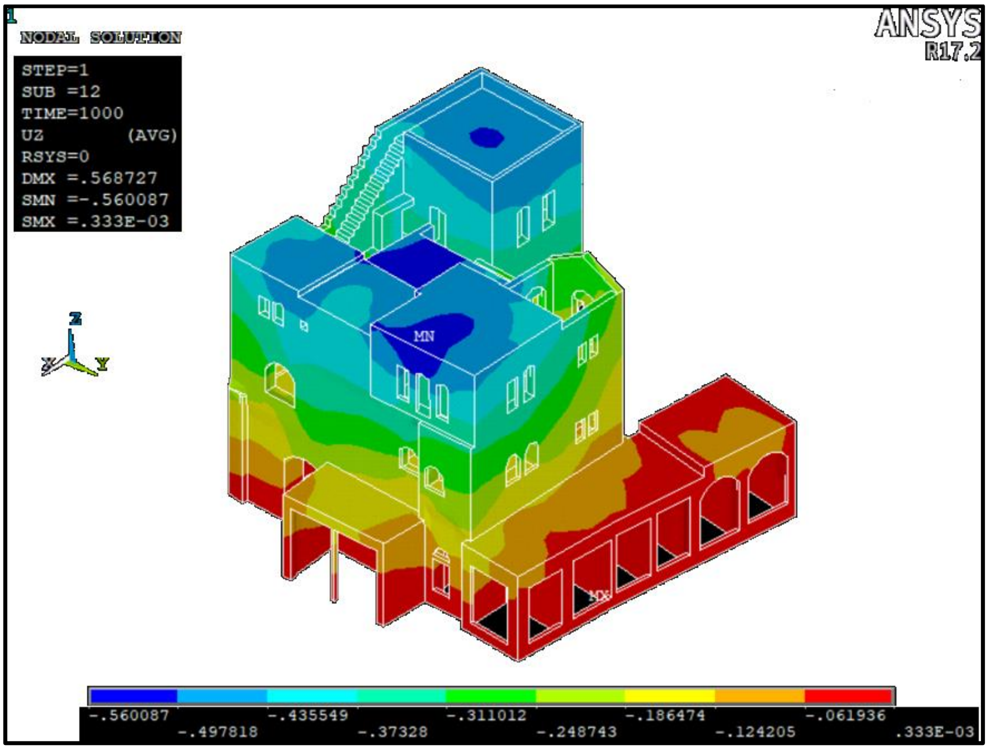

Figure 5.23: Deflection, Zadeh Building Model of added one story/Solid185.

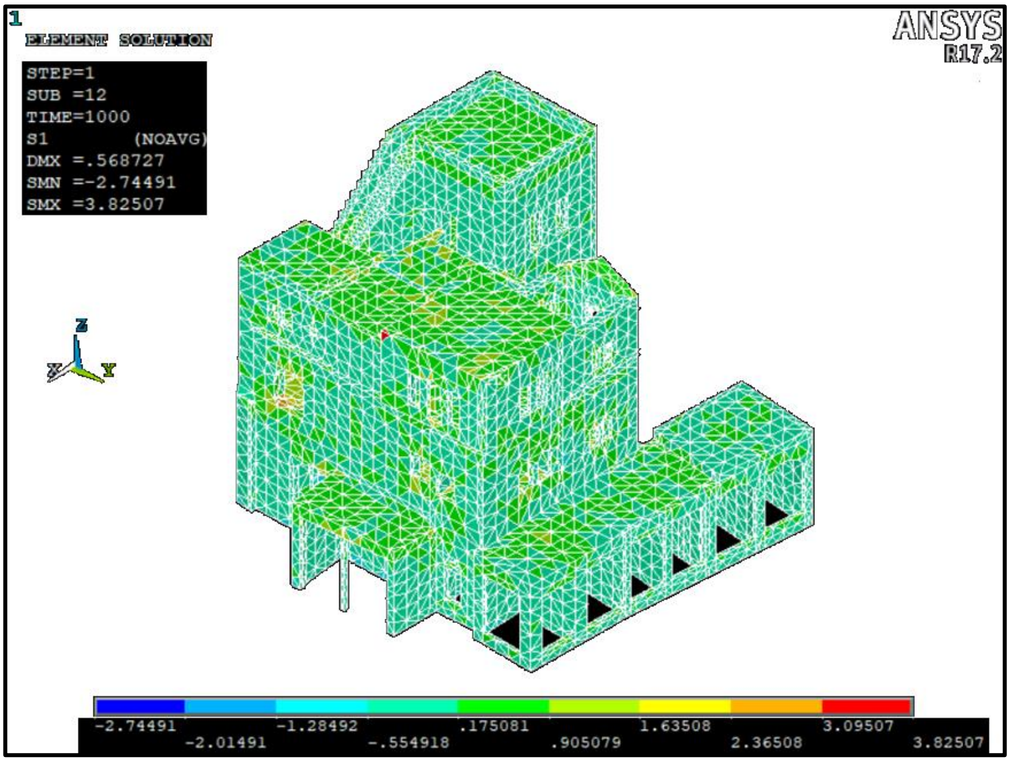

Figure 5.24: Principal stress σ1- Zadeh Building Model of added one story/Solid185.

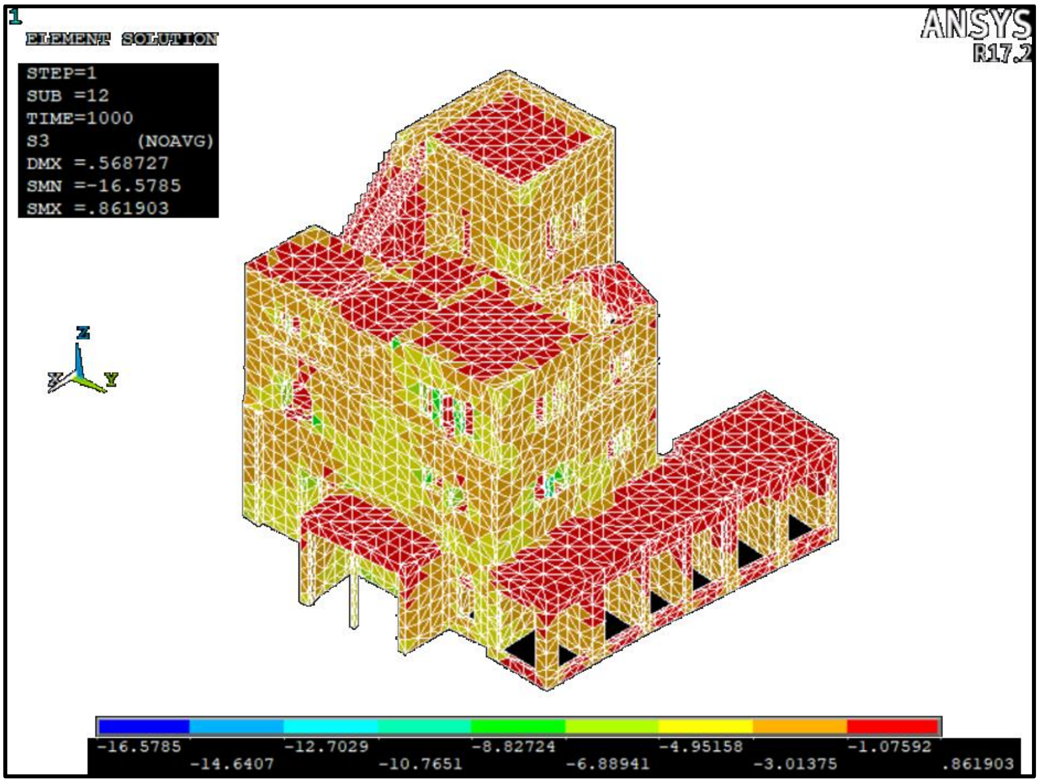

Figure 5.25: Principal stress σ3- Zadeh Building Model of added one story/Solid185.

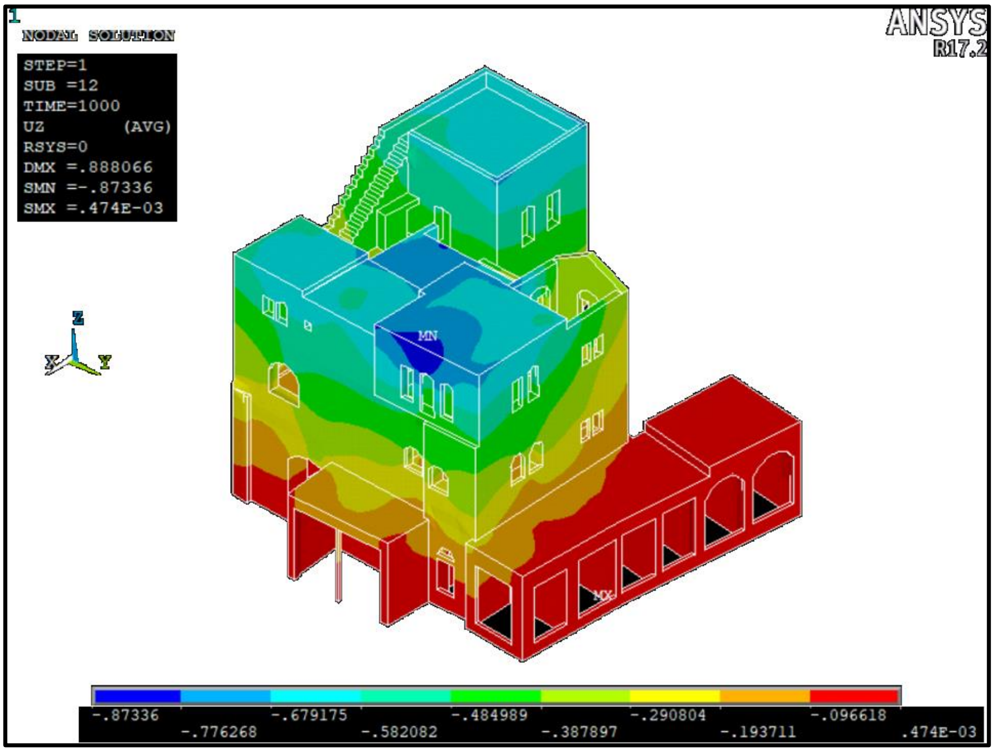

Figure 5.26: Deflection, Zadeh Building Model of added two story/Solid185.

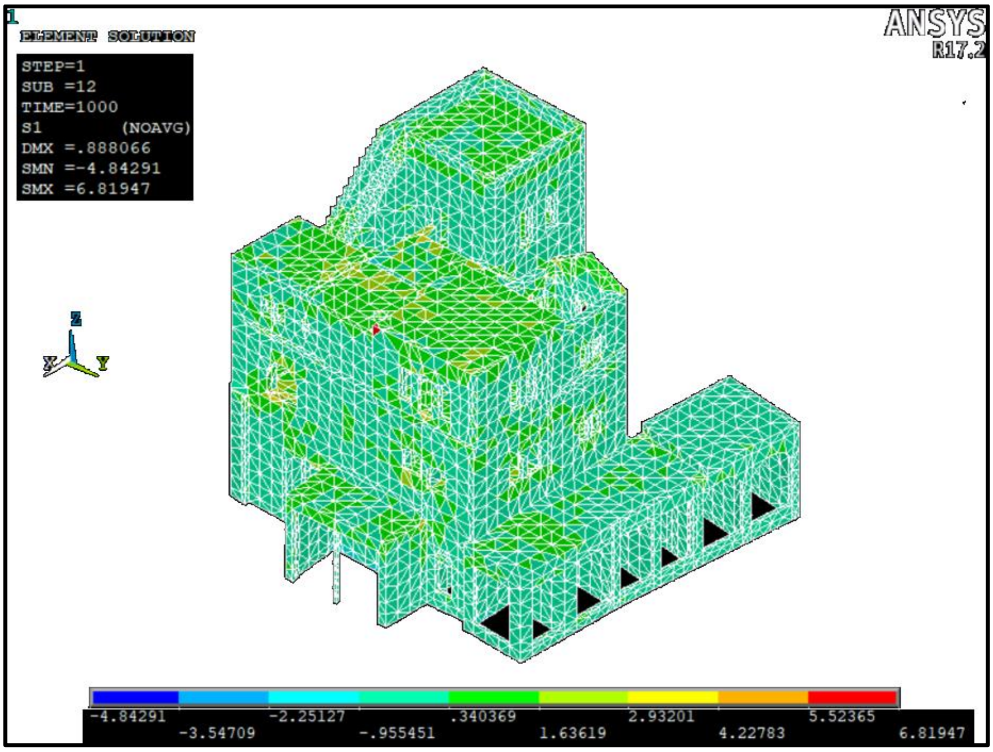

Figure 5.27: Principal stress σ1- Zadeh Building Model of added tow story/Solid185.

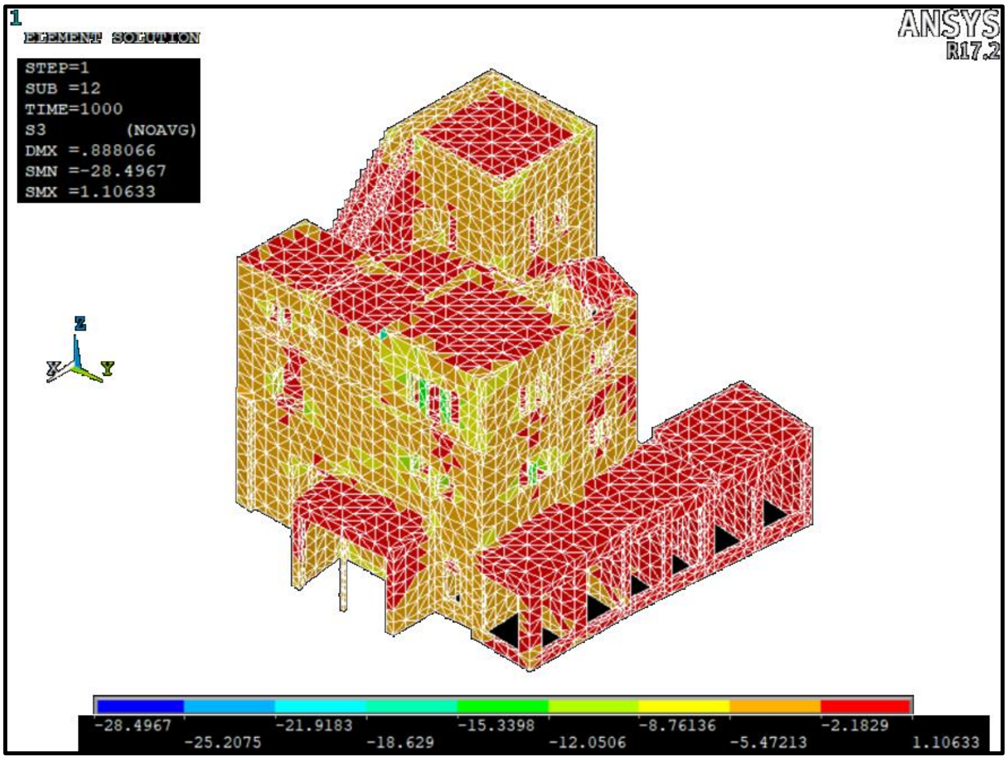

Figure 5.28: Principal stress σ3- Zadeh Building Model of added tow story/Solid185.

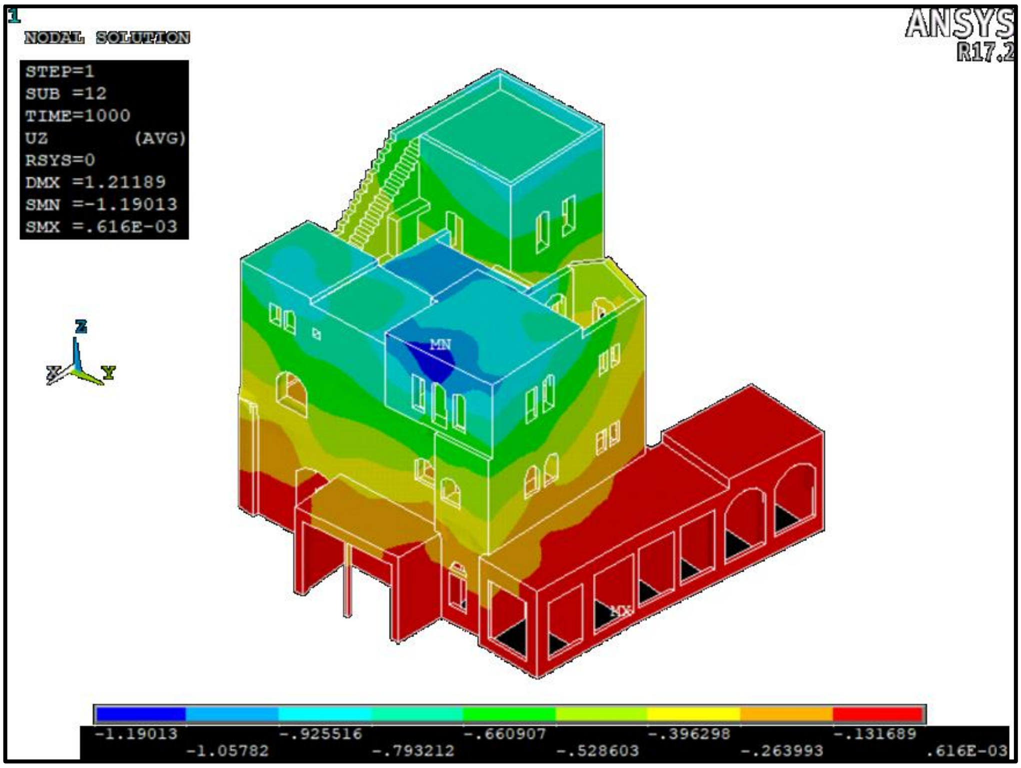

Figure 5.29: Deflection, Zadeh Building Model of added three story.

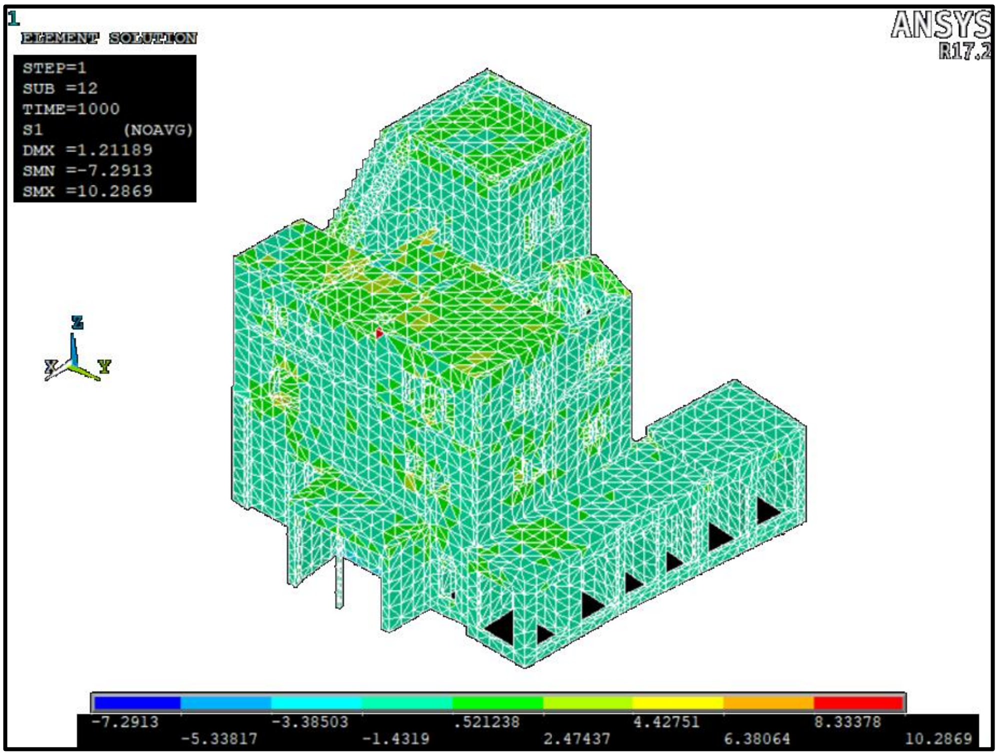

Figure 5.30: Principal stress σ1- Zadeh Building Model of added three story/Solid185.

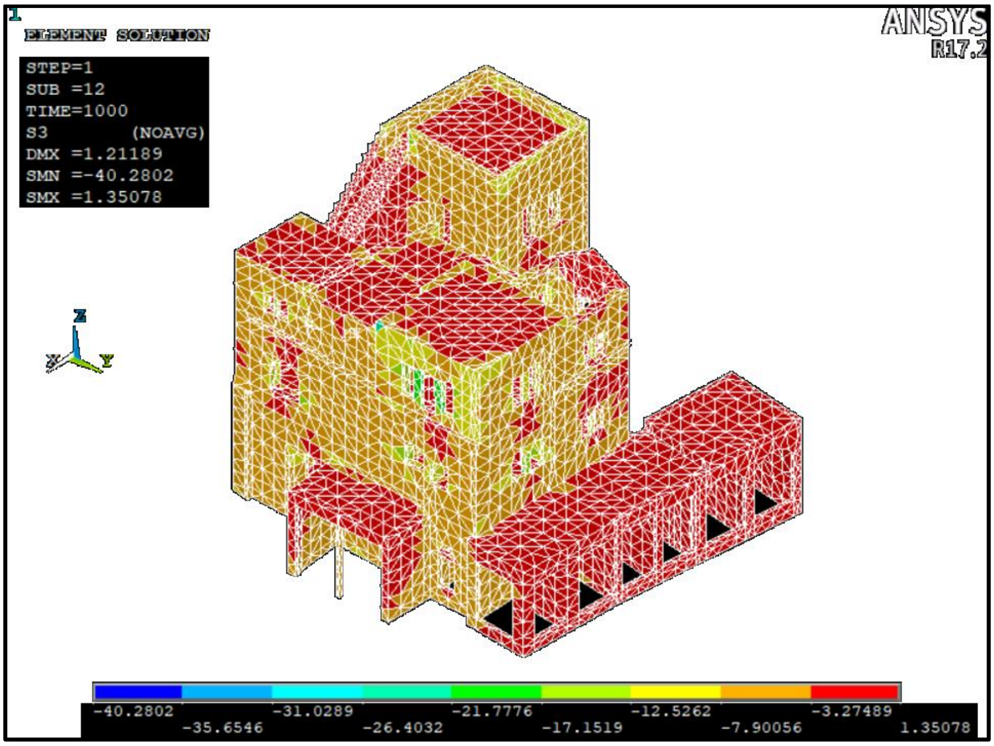

Figure 5.31: Principal stress σ3- Zadeh Building Model of added three story/Solid185.

Table 5.10: Solution output of solid185 for existing situation & additional load

Nonlinear analysis	existing situation	Added one Concrete Story	Added two Concrete Story	Added three Concrete Story
Principal stress σ1 (kg/cm^2)	< 2.13	< 3.82	< 6.82	>10.3 failure
Principal stress σ3 (kg/cm^2)	< 7.9	< 16.6	< 25.1	< 35.6
Deflection at Failure (ANSYS) mm	3.9	5.7	8.8	12.1

In the Second method of nonlinear analysis, modeling was performed *using Solid 65*, and the results are shown in Figures 5.32 to 5.42.

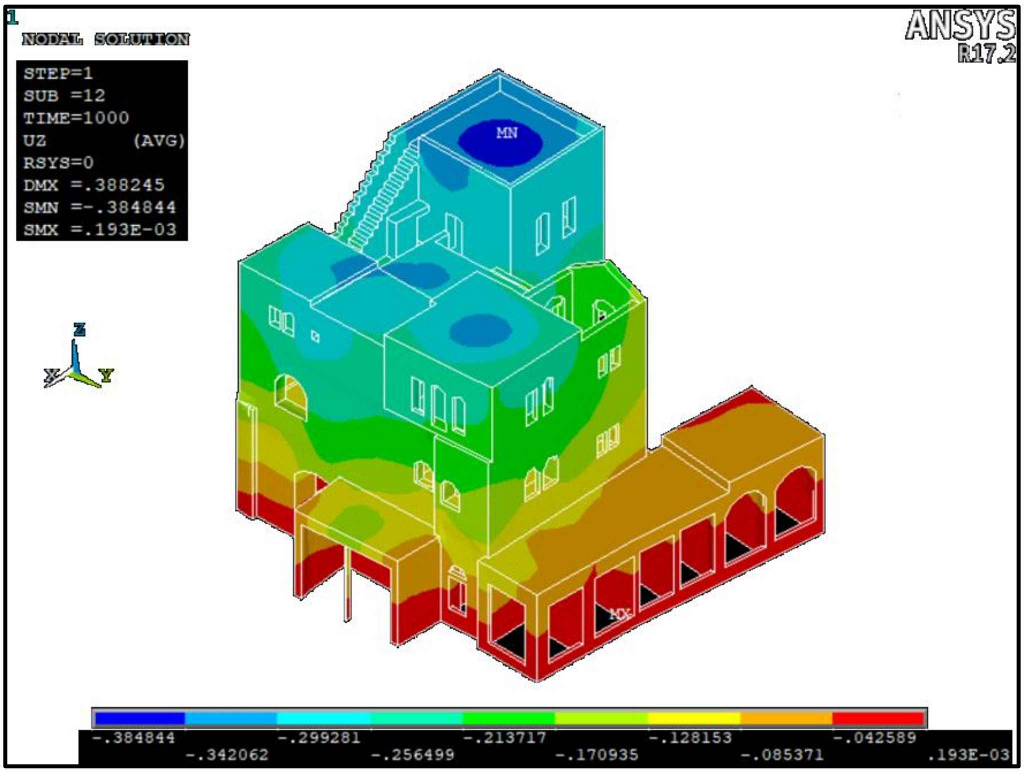

Figure 5.32: Deflection, Zadeh Building Model of the existing situation/solid65.

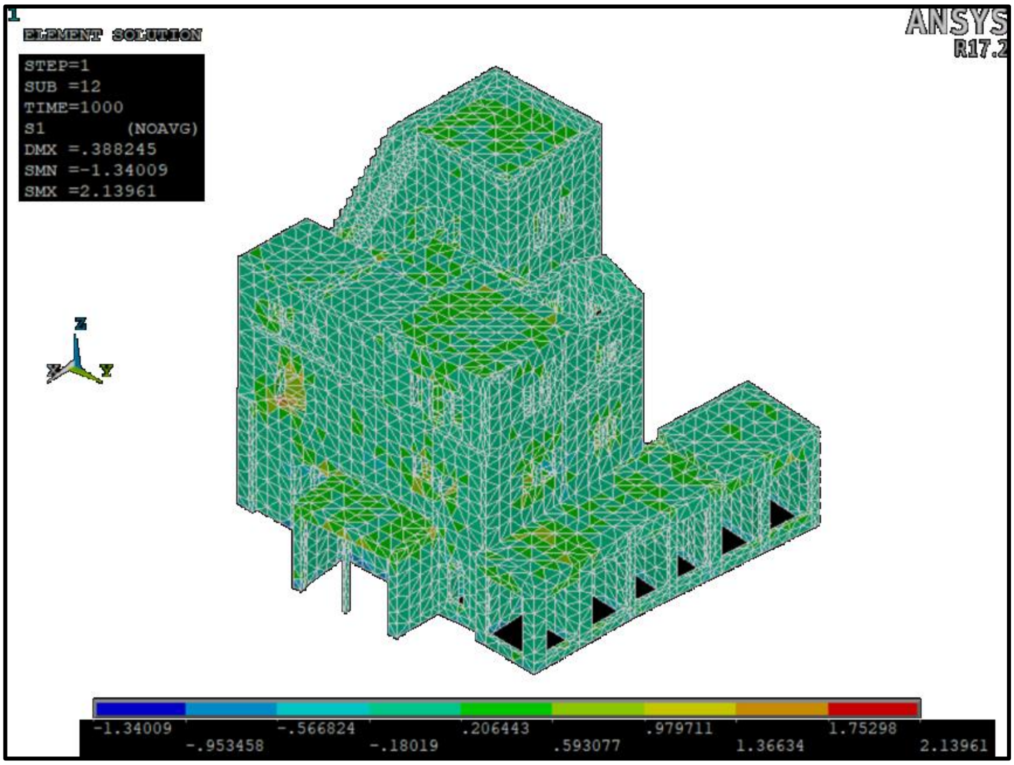

Figure 5.33: Principal stress σ1- Zadeh Building Model of the existing situation/solid65.

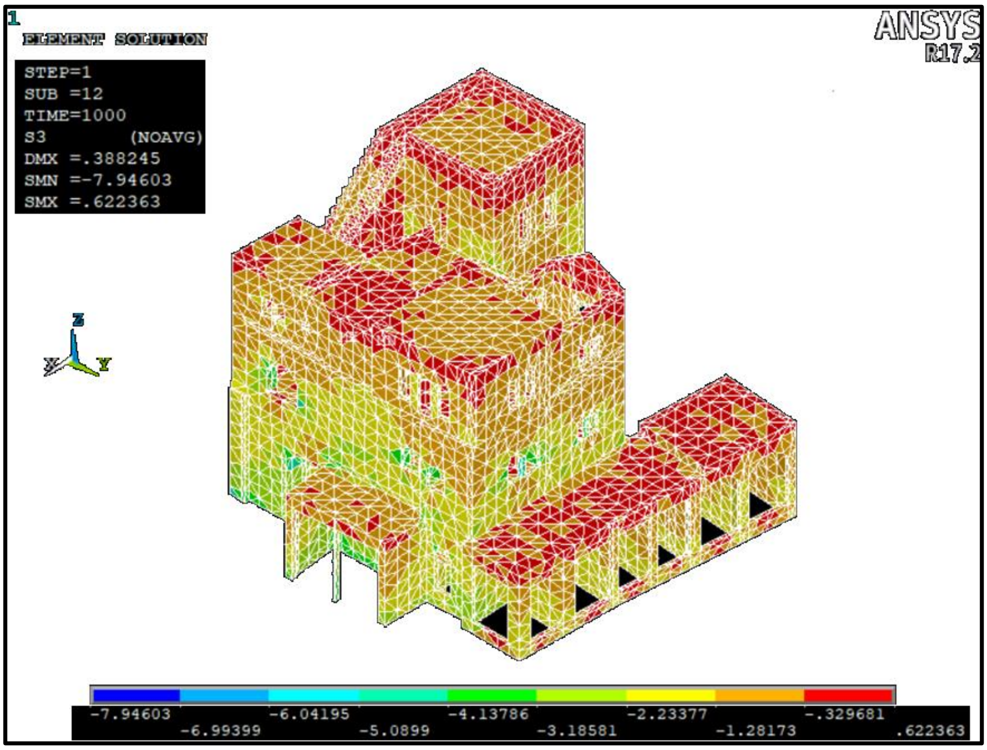

Figure 5.34: Principal stress σ3- Zadeh Building Model of the existing situation/solid65.

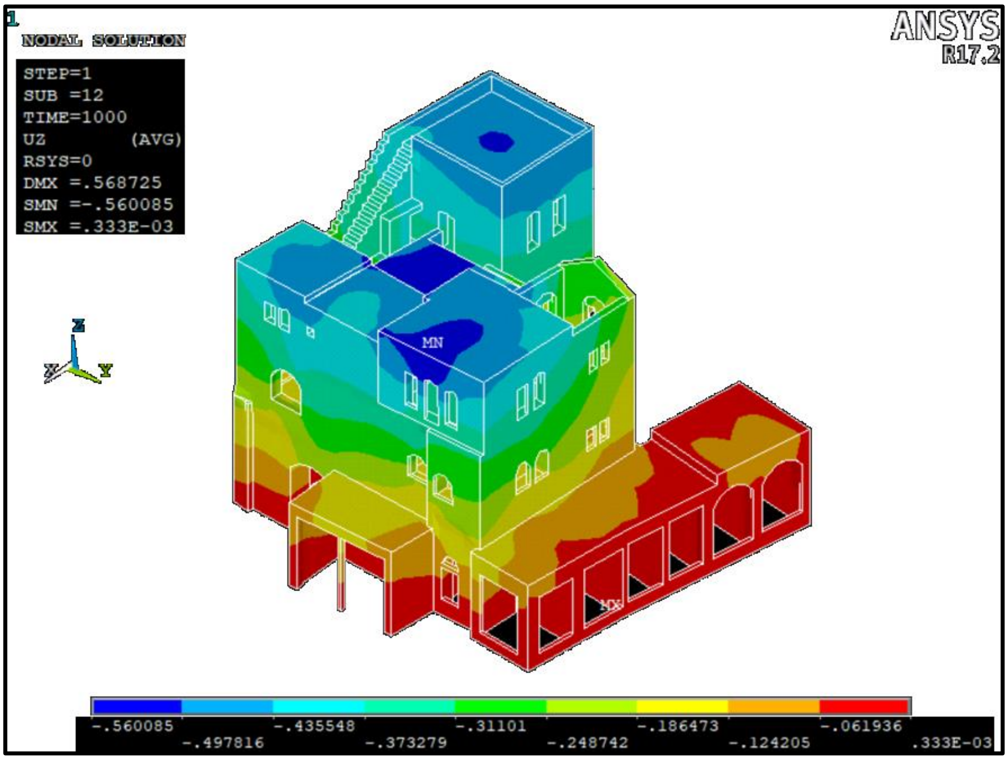

Figure 5.35: Deflection, Zadeh Building Model of added one story/solid65.

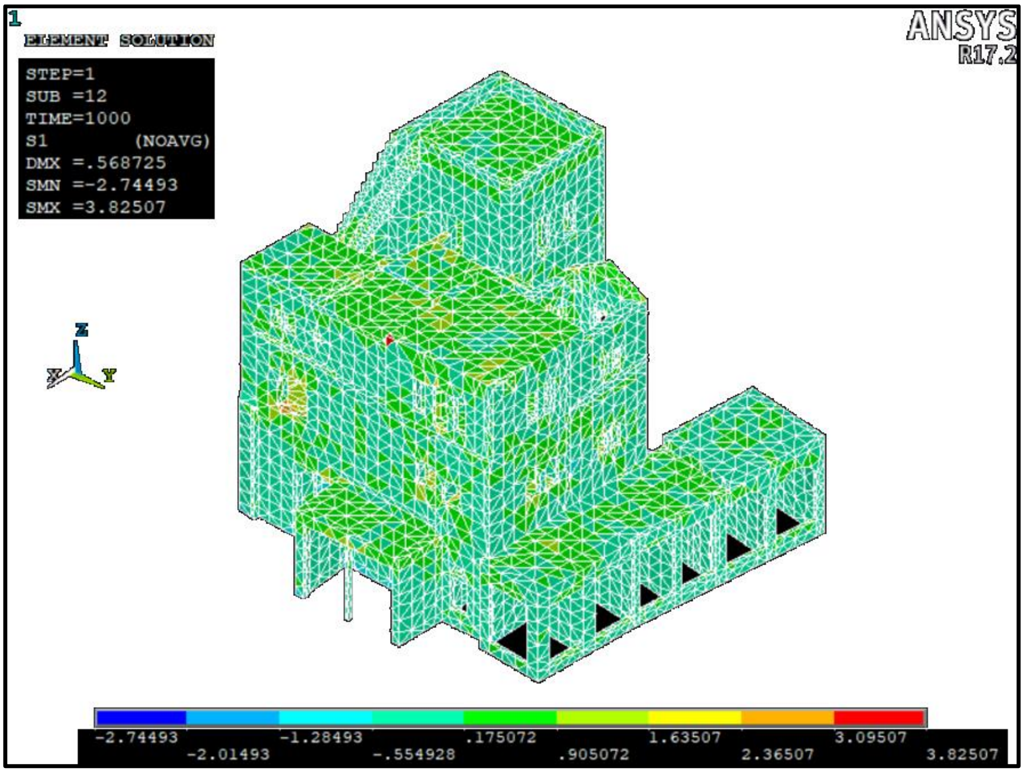

Figure 5.36: Principal stress σ1- Zadeh Building Model of added one story/solid65

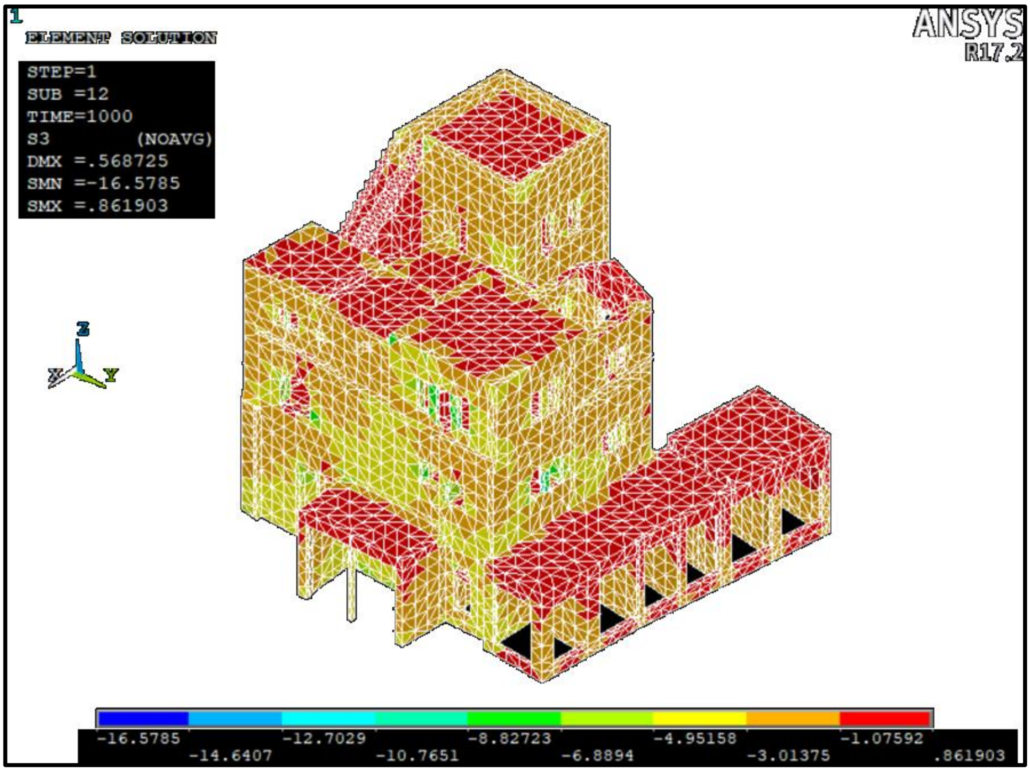

Figure 5.37: Principal stress σ3- Zadeh Building Model of added one story/solid65.

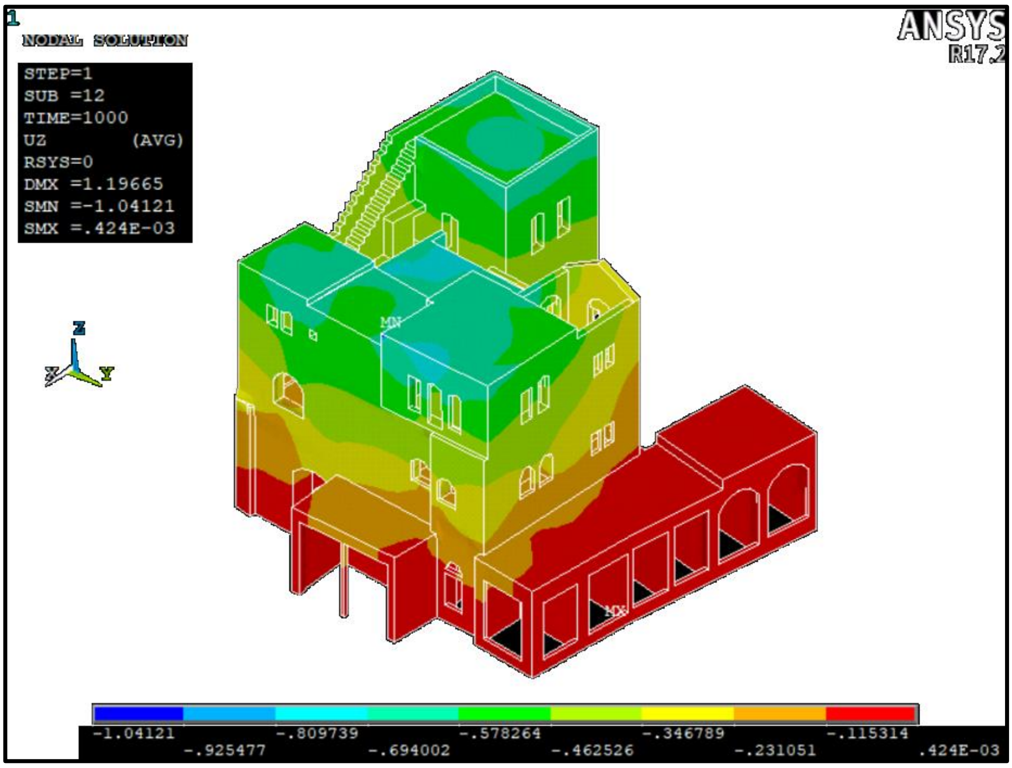

Figure 5.38: Deflection, Zadeh Building Model of added two story/solid65.

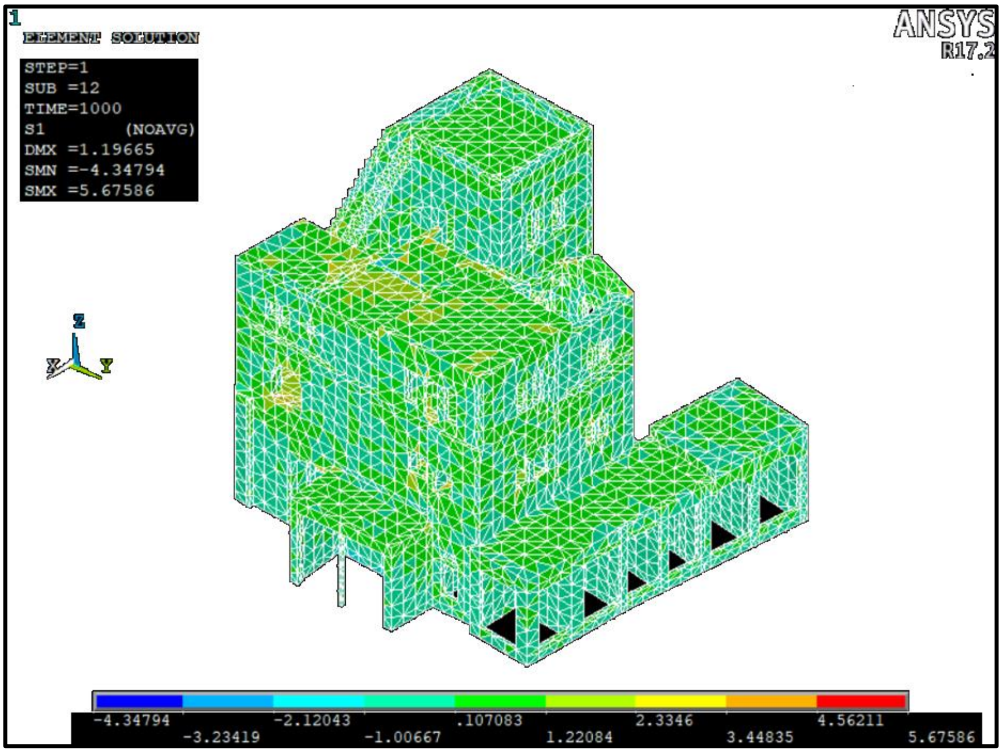

Figure 5.39: Principal stress σ1- Zadeh Building Model of added two story/solid65.

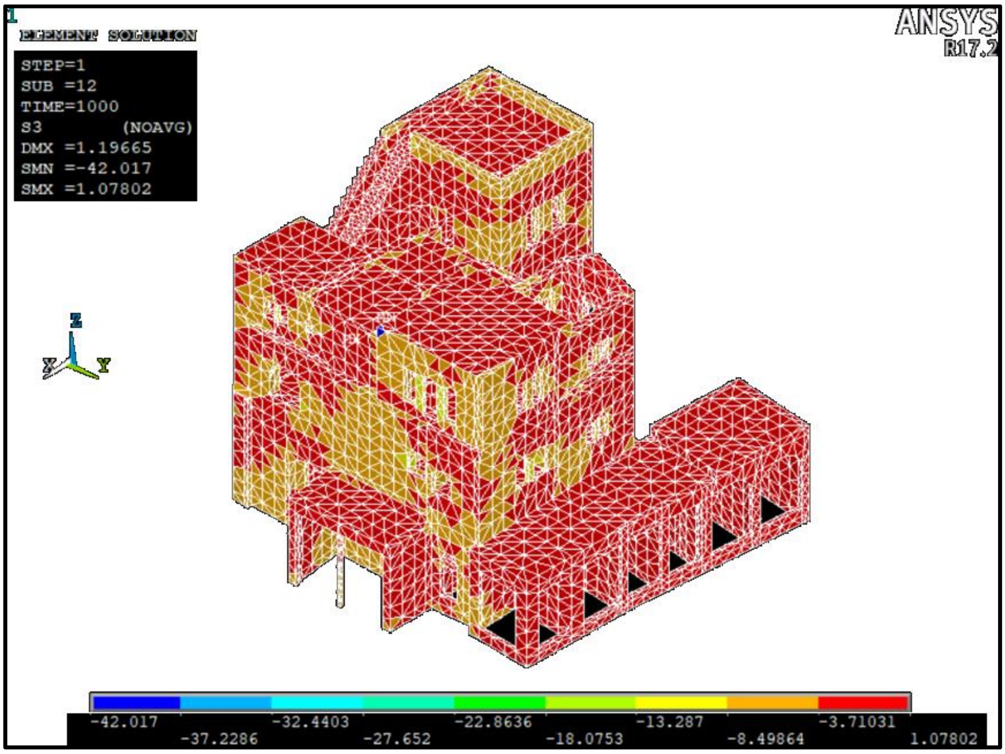

Figure 5.40: Principal stress σ3- Zadeh Building Model of added two story/solid65.

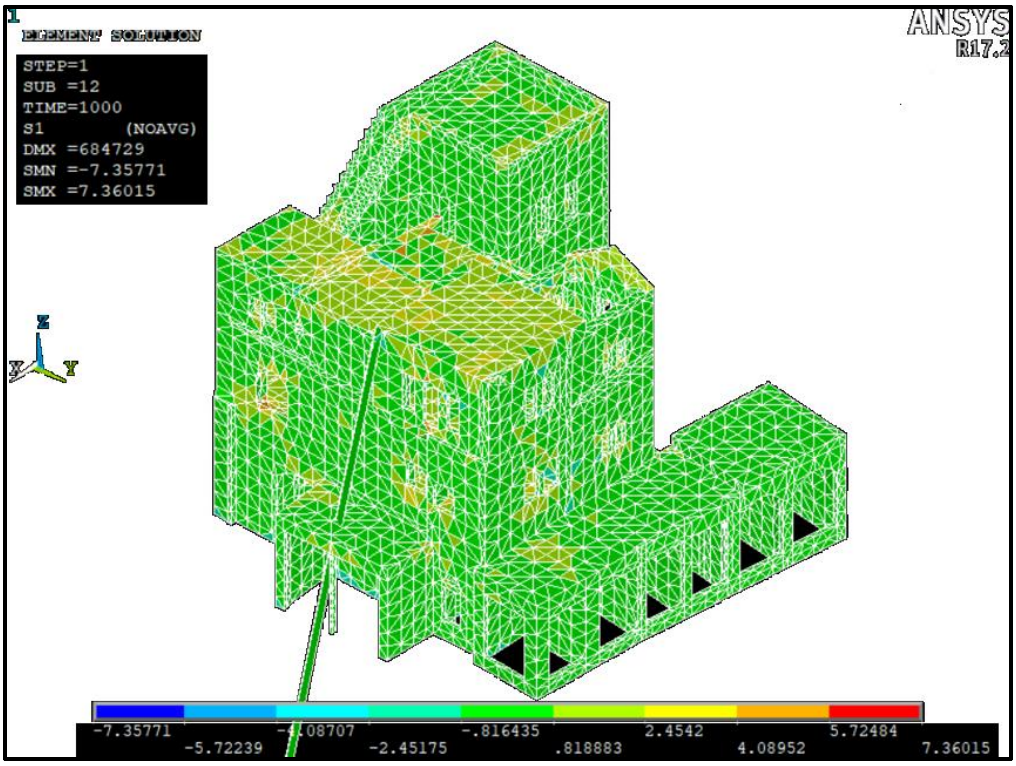

Figure 5.41: Principal stress σ1- Zadeh Building Model of added three story/solid65.

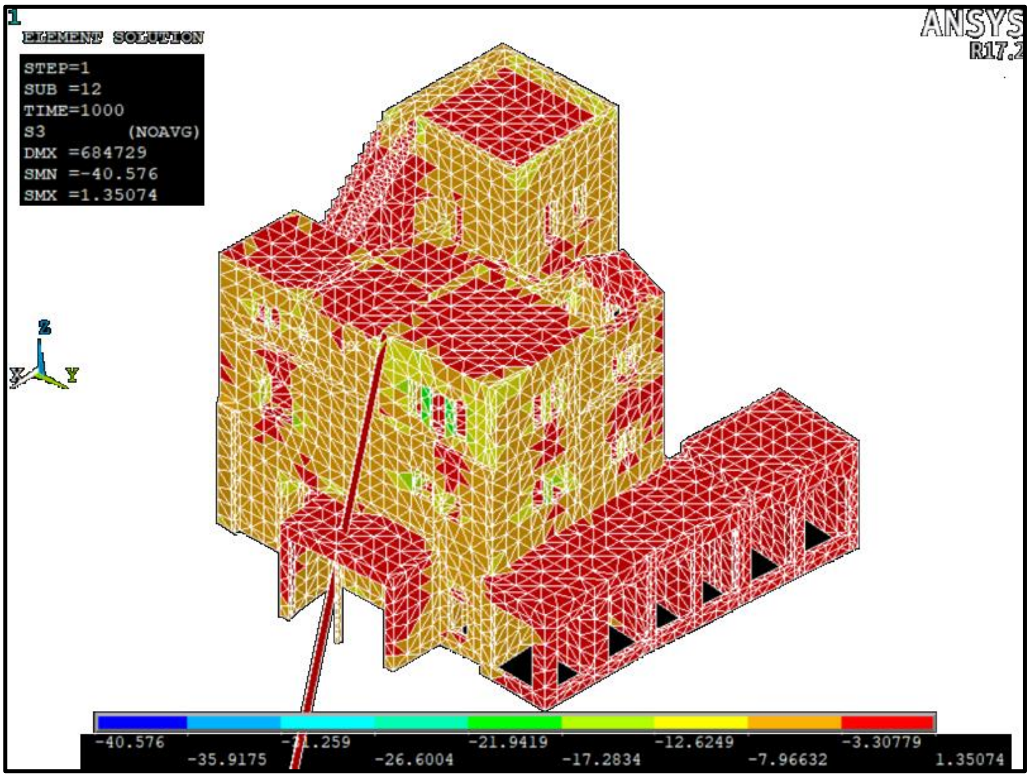

Figure 5.42: Principal stress σ3- Zadeh Building Model of added three story/solid65.

Table 5.11: Solution output of solid 65 element for existing situation & additional load.

Case	existing situation	Added one Concrete Story	Added not repeated two Concrete Story	Added repeated two Concrete Story	Added three Concrete Story
Principal stress σ1 (kg/cm^2)	< 2.13	< 3.83	< 5.7	failure	failure
Principal stress σ3 (kg/cm^2)	< 7.9	< 16.6	< 42	failure	failure
Deflection at Failure (ANSYS) mm	3.9	5.7	11.97	14.2	16.9

Solid 185 was used, for material non-linear properties, it is the general-purpose 3D solid element, the results listed in Table 5.10 were obtained, so that Principal stress σ1 was compared with ft, and that Principal stress 3 with fc, the comparison showed the following results:

In the case of adding one floor or two floors (design loads), the failure criterion was not satisfied, that is, cracking or crushing did not occur anywhere. The failure occurred when adding the design loads for the third floor, based on the fact that Principal stress σ1 ($10.3Kg/cm^2$) is greater than ft($8.1Kg/cm^2$), based on Figures 5.13-5.24 it appears that the value of Principal stress σ1 appears as large as possible in the area around the windows, i.e. the weakest area.

In this study when using Solid 185, the principal tensile stress values were determined and compared with the tensile strength, in all cases of addition, as follows:

Current status: principal tensile stress (0.213 MPa), tensile strength (0.81MPa). The condition of the current building with loads of three floors is good.

Added one concrete story: principal tensile stress (0.382 MPa), tensile strength (0.81MPa). The condition of the current building with loads of three floors is good. Based on a comparison of σ1 result values with Ft, it has the capacity and allows it to bear loads equivalent to the load of one floor.

Added two concrete story: principal tensile stress (0.682 MPa), tensile strength (0.81MPa). The condition of the current building with loads of three floors is good.

Based on a comparison of σ1 result values with Ft, it has the capacity and allows it to bear loads equivalent to the load of two floor.

Added three concrete story: principal tensile stress (1.03 MPa), tensile strength (0.81MPa). The condition of the current building with loads of three floors is good. Based on a comparison of σ1 result values with Ft, it does not have the capacity that allows it to bear loads equivalent to the load of three floor.

Solid 65 element is used for concrete, which is typically used for 3D solids, and also is ideal for modeling the failure of brittle materials like stone buildings, the results listed in Table 5.11 were obtained. In the case of adding one floor or two floors where one of them is not repeated (design loads), the failure criterion was not satisfied, that is, cracking or crushing did not occur anywhere. the building bears these loads. but when adding two repeated floors or three repeated floors, the failure occurred when putting additional loading with design loads, where the failure occurred due to divergences in the solution, meaning that the building is unstable.

Another method using solid 65 was used to determine the additional loads that the building can allow to bear, where Table 5.12 shows the support reaction values for all loads, considering that the loads are services, using the general post pro, then list results, reactions solu commands, all the support reactions of the building was found and recorded as follows:

The added load of the building = the Total load on the building when the failure occurred - the original load of the building.

The allowed load to be added = the added load of the building/factor of safety.

The number of floors allowed = thez allowed load to be added / the load of one floor added.

Table 5.12: Support reaction of solution output of solid 65 element for existing situation & additional load

case	existing situation	Added one Concrete Story	Added repeated two Concrete Story	Added repeated three Concrete Story
condition	safe	safe	safe	failure
support reactions (t)	2574.5	2989.3	3440.9	3877.8

The value of the support reactions was adopted when adding 3 floors, and it was considered the total load =3877.8t, factor of safety is 1.3, the original load of the building =2574.5t, the load for one added floor is 440 tons, through the application of the previous equations, it was found that the value of the permissible load is 1002 t, and the number of floors is 2 floors.

In the end, based on the results obtained from the Solid 185 and Solid 65 methods, the number of floors allowed is two floors.

CHAPTER 6

Conclusions and Recommendation

6.1 Introduction

The stone building is the oldest that represents an essential part of structural systems, where stone units and mortar join to form stone building systems. Since the historic buildings have heritage significance as they are a living symbol of the rich cultural heritage of Hebron, their preservation is a necessary foundation, and until this is done, there is a need for periodic evaluation of the structural performance. Evaluation of the structural behavior of historical structures is an issue of great interest and a difficult task, mainly due to the inelastic and inhomogeneous mechanical response of the material. Hebron is rich in ancient stone structures. The necessity of preserving this heritage is invaluable in order to pass it on to future generations, as the building system (wall construction) has numerous advantages such as economy, durability, and sustainability. Also, buildings are subjected to natural and human-caused trouble during their lives, which weakens their bearing capacity and causes partial or entire collapse. As a result, the structural assessment method is critical for determining the strength of their bearings and performing periodic maintenance and restoration.

Based on the importance of the study stemming from the need to preserve the historical buildings, and the possibility of adding floors to the old ones, especially since most of these additions are made in random ways without a scientific study, this study gave several results related to safety in these buildings and their ability to bear loads in their current condition and in the case of additional loads.

The results of the experimental section gave that it is possible to obtain the values of mechanical properties of old stones and mortars similar to old mortar, and different models of composite material of mortar and stone in several ways, and the results of the numerical analysis section demonstrated the ability to analyze historical buildings from a structural point of view, and it also gave the buildings bearing capacity for self-loading and additional loads. The study proved that the results of the experiments can be adopted on the same old materials of stone and mortar, in addition to that the numerical analysis can be applied in modeling similar historical building materials.

6.2 Conclusions

This study includes both experimental investigation and Numerical Analysis of the nonlinear behavior of stone buildings.

The study presented in Chapter 4 includes an experimental program that was established to characterize and analyze the mechanical properties and parameters of old stone walls that are used in old existing buildings in Hebron, where the main mechanical properties include: compressive strength, tensile strength, modulus of elasticity, Poisson's ratio, and stress-strain curve, where these parameters considered very important in structural analysis, and they are the preparatory step for numerical analysis and modeling, these parameters can be found in more than one method.

In this study, the first method to find the parameters of the physical and mechanical properties of stone buildings through experiments in method of non-destructive test, where these experiments are divided into five main sections, which is:

1) Experiments were carried out on three models of stone and mortar composite of different dimensions and shapes, under axial compression, Wallette & Prismatic models were constructed according to the configuration of typical ancient buildings Walls, which include: double-leafed stone and an inner core of low-strength mortar, 1/6 scale was chosen of the real scale in site. where the average values of the main parameters are shown in Table 6.1, for the three models.

Table 6.1: Average results of mechanical and physical properties of wallets and prisms

No. & Type models	**density**	**Compressive Strength**	**Modulus of elasticity at (30%-60%) fc´**	**Poisons ratio**
unit	gm/cm³	Mpa	Mpa	%
Exp avg W30	2.44	15.31	900-1100	0.14-0.25
Exp avg W 40	2.14	12.9	500-1160	0.19-0.27
Exp1 avg P 20	2.1	12.7	600-1230	0.17-0.35
Exp3 avg P 20	2.15	16.40	700-1300	0.24

2) Experiments were carried out on different type of old stone, where the average values of the compressive strength are 88.7Mpa, and the average values of density is 2.4 gm/cm³, also its water absorption rate is within the Palestinian specifications for hard limestone.

3) Experiments were carried out on two type of lime mortar, 6 cube (5×5×5) cm samples of lime mortar and 6cube samples of lime mixtures of were tested, under axial compression, also the same number of previous samples were tested under tensile, the lime mortar samples were prepared in a manner and proportions of materials similar to the old mortar, according to what is used in the Hebron Rehabilitation Committee. where the average values of the main parameters are shown in Table 6.2.

Table 6.2: Average results of mechanical and physical properties of two types of lime mortar.

No. & Type mortar	**density**	**Compressive Strength**	**Tensile Strength**
unit	gm/cm³	Mpa	Mpa
avg L.M	1.73	3.86	1.16
avg L.M.M.	2.02	4.82	1.00

4) Experiments were carried out of zahedah building site of stone and mortar and composite of it, by using Schmidt hammer, where the average values of the compressive strength are 9.0Mpa, 2Mpa, 44Mpa of composite, mortar, stone respectively. A core test was carried out to take cylindrical core samples from the site, in order to find the compressive strength, but all attempts failed to obtain correct and valid samples, in other words, the samples crumbled, so the result of Schmidt-Hammer was adopted
5) Experiments of flexural Strength carried out of two types of samples, the first type includes three double leaf beams with 2 steel barϕ6, the second type includes three double leaf beams without steel, this test was done for two purposes, the first is to find the flexural Strength of the samples without steel, and the second is to perform the verification of the numerical analysis section of the samples with bar steel. The mean value of flexural Strength is equal to 0.22Mpa.

The second method to find the parameters of the physical and mechanical properties of stone buildings by uses analytical predictions of equations, that include the strength of stone and the strength of mortar, according to the Eurocode and previous studies.

Table 6.3: Summery comparison of Experimental Results & Analytical Predictions with Literature Review on sample Prisms for mechanical properties.

			Compressive Strength MPa	**Modulus of elasticity MPa**	**Poisons ratio**
Experimental values	Exp of models W30 avg	f 1/6 Scale	8.2	900-1100	1.3
	Exp of models W40 avg		6.9	500-1160	1.6
	Exp of models P20 avg		7.6	700-1300	0.935
	Schmidt hammer	composite of stone &mortar	9.0	1.87	1.87
Analytical Predictions values	Common models		***fs = 88Mpa, fm=2Mpa***	***102 fc***	
	Eurocode6 2005		14.1	-----	-----
	Hendry and Malek(1986)		3.95	-----	-----
	Dayaratnam 1987		3.65	----	----
	Kaushik 2007		7.1	1.44	
	Adrian Costigan 2015		6.1	0.323	
Literature Review based on Experimental	(Wang, et al., 2021). Tibetan rubble stone (SPB)		2.6	72.9	-----
	(Gonen & Soyoz, 2021) Clayey-Limestone/ turkey		12.34	5490	-----
	(Shrestha & Bhandari, 2020) Three-leaf stone		6 -7.34	534 –1570	-----
	(Garcia, et al., 2012) Double leaf of stone/ ashlar		8.07	446	-----
	(Magenes, et al., 2010) Irregular stones and lime mortar/ Italy		3.28	2550	0.19

From the experimental studies, the following main conclusions may be presented:

- Table 6.3 shows a summary of the results of the compressive strength and modulus of elasticity, depending on two methods, which are of Experimental Results & Analytical Predictions and their comparison with previous studies. The results are considered close and almost compatible with each other, and the results of the previous studies themselves have differences, but the reason for the existence of differences is attributed to several reasons:
  - The type of stone varied from one region to another.
  - Mortar components, proportions, and thickness.
  - The dimensions of the samples and the method of arranging and constructing them.
  - Use single leaf or double leaf.

Therefore, the results of the experiments obtained, whether in the laboratory or using Schmidt-Hammer, are considered acceptable, as they are in good agreement with experimental and analytical studies as (Garcia, et al., 2012), (Magenes & Penna, 2009).

Through the results of the experiments, it was found that the stone has great strength and is considered hard material, where a higher compressive strength of old stone that the values range between 68.8Mpa to 165.8Mpa indicates that the stone can withstand a higher crushing load, also, the absorption rate of the stone ranged from 1.1% to 2.8%. So, it means that testing stone after using it for long periods of time, maintains its strength and is considered a sustainable material, this gives a good indication that the old buildings have the ability to withstand and bear.

- The average value of compressive strength was 20.3Mpa, and the average absorption rate was 12.0%, for one type of stone sample that was tested, as it is used for stone formation and decoration purposes.
- Stone has poor tensile strength, and the tensile strength of stone and composite mortar is about 10% of the compressive strength.
- In stone buildings, an example of the presence and availability of tensile forces is in the area of a stone lintel above a large door and window. Thus, these areas are considered critical and weak in tensile strength.
- Since the stone is hard and has the property of stuffiness, and the mortar is soft and has the property of flexibility, the equivalent component of the two materials possesses strength with elasticity, this is shown through the stress-strain curve.
- When comparing the results of mortar with stone, it was found that the mortar is weak, but it has the characteristic of flexibility and gives the property of permeability, allowing the building to breathe. Previous research also emphasizes on historic stone buildings found that ancient mortars are lime-based, with very poor compression strength and obviously influenced by deterioration processes at various levels. Because of the slow progress of lime mortars, which take ages to develop and grow up.

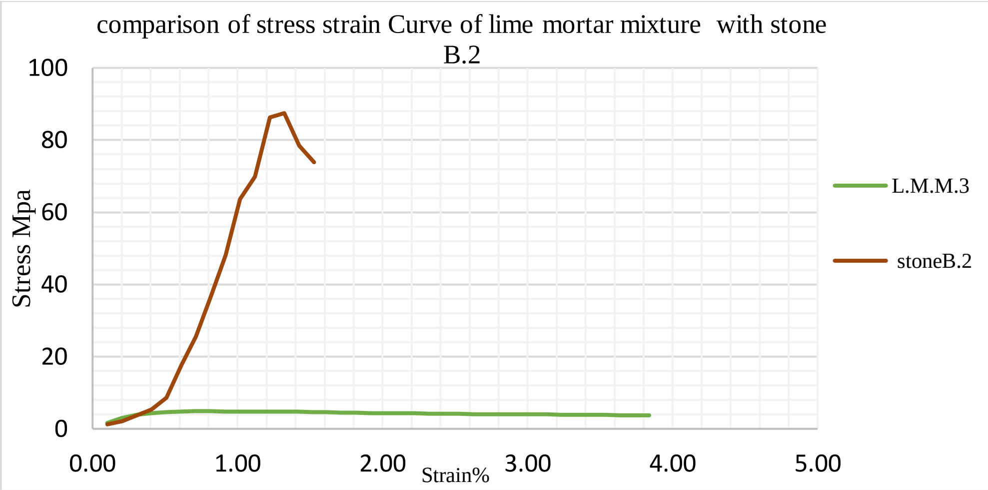

Figure 6.1: Comparison of stress strain Curve of lime mortar mixture with stone B.2

- The Schmidt Hammer tests provided an average compressive strength equal to 9 MPa. This value was approximately close to those proposed by Analytical Predictions for, Kaushik 2007, Adrian Costigan 2015, but higher than those suggested for Hendry and Malek, Dayaratnamnry, and lower than those suggested for Eurocode6. The value provided by Schmidt Hammer test was compared with those of laboratory results available in the study experimental. The comparison was complicated because three types of models of laboratory tests were linked to models made of stone and mortars. Schmidt's results were somewhat similar to the results of laboratory experiments.Therefore, it is possible to use the Schmidt-Hammer method to determine the compressive strength of old building materials.
- The results obtained from the Schmidt Hammer tests were used, with the rest of the parameters supported by analytical predictions of equations, to perform the numerical analysis of the case study modeling in the ANSYS program. While the results obtained from the laboratory tests were used to carry out the validation.

The study presented in Chapter 5 includes a numerical analysis and modeling that was divided into two main parts, the first to conduct verification and the second to make modeling using numerical analysis of the case study to evaluate it from a structural point of view.

The first step in the numerical analysis is to verify the analysis method and assumptions, where the results of the numerical analysis of the flexural beam model and the wall model under axial compression, were compared with the experimental tests that were conducted in the laboratory. The numerical results were in satisfactory agreement with the experimental results. This step is always necessary to confer reliability on models and their ability to predict structural response. Thus, it appears that it is possible to model historic stone buildings with multi-leaf walls with adequate accuracy.

In response to the research objectives, this thesis aimed to evaluate the performance and load-carrying capability of the Zahdeh building, so nonlinear analysis was performed using the FE computer code ANSYS, where the material parameters adopted from an experimental Schmidt test. In this study the following inputs, assumptions, and parameters were adopted in the numerical analysis modeling of the case study:

- A macro-structure strategy of modeling was used in finite element analysis, due to adopting the concept of homogeneous materials.
- The building was represented by SOLID185, which has six nodes and three degrees of freedom at each node, also it is appropriate for modeling general 3-D solid structures.
- The building is also represented by SOLID65, which contains six nodes and three degrees of freedom in each node and is also suitable for modeling concrete and brittle solid structures such as masonry buildings.
- The Willam-Warnke model was used as the appropriate failure criterion that is determined by the two material parameters ft (uniaxial tensile strength) and fc (uniaxial compressive strength) has been used to represent the brittle behavior of the structure.

To represent building materials, the materials properties of composite stone& mortar were adopted in the numerical model as the following: Specific weight 22KN/m3, Modulus of Elasticity 834.0MPa, Poisson's ratio 0.2, Multilinear isotropic hardening material is used, Compressive strength 8.1MPa, Tensile strength 0.81MPa, Shear transfer coefficient along opening cracks = 0.2, Shear transfer coefficient along closed cracks = 0.8.

From the numerical studies, the main conclusion may be presented that the results of the finite element model indicate the good structural state of the current building since no tensile stress exceeded the allowable values, then loads were gradually increased in the numerical model, and the Newton-Raphson iteration method was adopted to verify the convergence in each step. At first, the building was evaluated with its own loads with the live load. Depending on the results, the building is well positioned to withstand the current loads of three floors. In the second stage, loads including dead and live loads were added, where calculations of slab weight self, super dead loads, live loads, and wall weights were made, giving the loads of one floor that were loaded on the walls of the existing building, depending on the results of adding a floor, it is allowed to add one floor to the existing building, and in the same way, floors were added until the existing building reached additional loads with 3 floors, and the result was that the structure failed when the loads were increased by 3 floors. So, based on the results obtained from the Solid 185 and Solid 65 methods, the number of floors allowed is two floors are allowed to add to the existing building.

To answer the study questions, the following were summarized:

The stone buildings are strong and durable, but they need regular evaluation and maintenance.

The process of structural assessment of historical buildings is important, as it is considered the first key to selecting appropriate methods and materials for the restoration process. Through structural analysis, areas of weakness are detected, and accordingly, this leads to the preservation of ancient historical buildings, whose facades reflect centuries of history.

The structural analysis of old buildings differs from modern buildings, as the materials, construction methods and structural elements are different.

Preserving historical buildings has several goals:

- Preserve buildings of which few surviving examples are likely.
- Save resources by repairing and reusing existing buildings instead of demolishing them and building new ones.
- Reducing waste and carbon emissions resulting from modern construction.
- Reducing energy consumption, so that the old buildings through the nature of the distribution of internal spaces and materials used.
- Saving Money.
- Delivering the heritage of ancient buildings to future generations.

6.3 Recommendation

The following recommendations are made for future works:

1) Conducting a study of the effect of seismic loads on buildings consisting of several floors.
2) Studying strengthening and restoring buildings containing problems.
3) Methods of strengthening buildings to bear the additional loads resulting from new floors using lightweight materials.
4) Use of criterion fillers such as Drucker–Prager and Mohr-Columb using a non-linear analysis method to determine failure.
5) Carrying out a number of tests on relatively large models of stone walls or panels.
6) Monitoring the construction during and after the addition process, because the behavior of the building gives important information and a noticeable warning in the form of subsidence and cracking before the collapse occurs.
7) Sometimes, when the buildings are already in use and the entire overhead load has been completed, dwelling users need to reposition the hydraulic, gas or electrical installation in the stone walls and cut out the structural elements. This is the most serious problem of building safety, so we recommend that the Hebron Rehabilitation Committee, in cooperation with the Hebron Municipality, conduct a periodic assessment of the buildings to determine their bearing capacity.

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