ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

DEVELOPING A GEODETIC-BASED BUILDING INFORMATION MODEL FOR DAMAGE ASSESSMENT AND REPAIR STRATEGIES FOR HISTORIC MASONRY STRUCTURES

Ph.D. THESIS

Esra TEKDAL

Department of Geomatics Engineering

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

TARİHİ YIĞMA KÜLTÜR VARLIKLARININ HASAR BELİRLEME VE ONARIM STRATEJİLERİ İÇİN JEODEZİK TABANLI YAPI BİLGİ MODELİ TASARIMI VE UYGULAMASI

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Esra TEKDAL, **a Ph.D.** student of ITU **Graduate School of Science Engineering and Technology,** student ID **501072602**, successfully defended the **dissertation** entitled "**DEVELOPING A GEODETIC-BASED BUILDING INFORMATION MODEL FOR DAMAGE ASSESSMENT AND REPAIR STRATEGIES FOR HISTORIC MASONRY STRUCTURES**" which she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my father Yılmaz TEKDAL,

FOREWORD

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ABBREVIATIONS

ADE : Application Domain Extension
BIM : Building Information Modelling
CityGML : City Geography Markup Language
FEM : Finite Element Method
FOV : Field of View
GML : Geography Markup Language
GPR : Ground Penetrating Radar
GPS : Global Positioning System
IAI : International Alliance for Interoperability
IE : Impact Echo
IFC : Industry Foundation Classes
IRT : Infrared Tomography
ISO : International Organization for Standardization
ITRF : International Terrestrial Reference Frame
ITU : Istanbul Technical University
KLM : Keystroke Level Model
LOD : Level of Detail
OGC : Open Geospatial Consortium
SG : South Gate
TPS : Tacheometrical Object Oriented Partly Automated Laser Surveying System
TUTGA : Turkish National Fundamental GPS Network
UML : Unified Modelling Language
UPV : Ultrasonic Pulse Velocity
VRML : Virtual Reality Modelling (Markup) Language
WGS84 : World Geodetic System 1984
XML : Extensible Markup Language
XRD : X-Ray Diffraction
X3D : Extensible 3D
2D : Two Dimensional
3D : Three Dimensional

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DEVELOPING A GEODETIC BASED BUILDING INFORMATION MODEL FOR DAMAGE ASSESSMENT AND REPAIR STRATEGIES FOR HISTORIC MASONRY STRUCTURES

SUMMARY

As our world is suffering from natural disasters, preservation of cultural heritage is becoming more important each day. The documentation of historical masonry structures is the first task that should be carried out for the preservation purposes. The geometric and semantic(explaining how the objects relate to real world) data required for documentation of the historical masonry structures can be obtained using different geodetic techniques(laser scanning, terrestrial survey and photogrammetric techniques) according to the current conditions and application needs.

The protection of cultural heritage in seismic areas is a very complex problem due to the wide variety of involved aspects such as the quality of the masonry, the structural properties and the economic factors. The whole assessment and protection procedure is a multidisciplinary work that includes historical, architectural, civil engineering and ecological aspects.Thereforethe objective of the assessment should be clearly specified in terms of its future performance in an agreement between the authorities (architects, civil engineers, etc.), who will be involved in the assessment process.

The scope of this thesis is the 3D semantic and finite element model of the North and South Towers of Seddülbahir Fortress using laser scanning data. Research is divided into four parts: laser scanning methodology and detection of stones, principles, applications and usage of City Geographic Markup Language (CityGML), design of a 3D model, finite element model (FEM) of the North and South Towers of Seddülbahir fortress and finally strengthening and repair recommendations will be proposed in the final part of the thesis.

Terrestrial laser scanning is one of the fastest and accurate data collection methods for visualization and documentation of 3D real world objects. It enables the user to produce point clouds of a huge working space in a very short time. The fortress of Seddülbahir and its surroundings cover a large area (nearly 24000 m^2). For this reason in order to speed up the documentation procedure terrestrial laser scanner was used.

Detailed point clouds of Seddülbahir fortress were registered using Leica Cyclone Register program and they were brought to a common coordinate system. As a part of my thesis, North Tower of Seddülbahir was chosen as the pilot region. With the help of the dense point cloud data, stones on the façades of the North Tower were individually traced using Kubit PointCloud in selected AutoCAD environment.

After the segmentation procedure, the detected stones were triangulated and exchanged into CityGMLreadable format. A special Application Domain Extension (ADE) called masonry was prepared for masonry buildings. This ADE includes materials and damages observed on the façades of the North Tower. Newly designed ADE is represented using Unified Modelling Language (UML) diagrams.

Finite element method is one of the most realistic modelling methods applied for designing, controlling and evaluating existing or new civil engineering structures. Point clouds of the North and South Towers are used for designing the 3D finite element model of both towers. The structures are observed under their own weight and earthquake loads.

Using and combining the results obtained from each step, recommendations for final strengthening and repair are given in the last part of the thesis.

Conservation of historic heritage and restoration of historic structures necessitates a great effort using different expertise. There are many challenges for understanding the behaviour of historical structures under their own weight and seismic loads, usually the ones with architectural importance. Historical structures have very complex load carrying behaviour due to the massive and continuous interaction of domes, vaults, arches and pillars. Typically, these structures are more massive than contemporary structures and that usually carry actions primarily in compression.

The restoration, renovation and intervention of these historical structures are vital in order to preserve them for future generations. For deciding necessary interventions an understanding of the structural behaviour and good engineering judgment with sufficient experience of the old construction techniques and concepts are essential for correct interpretations of the structural analyses.

TARİHİ YIĞMA KÜLTÜR VARLIKLARININ HASAR BELİRLEME VE ONARIM STRATEJİLERİ İÇİN JEODEZİK TABANLI YAPI BİLGİ MODELİ TASARIMI VE UYGULAMASI

ÖZET

Mevcut yapıların kullanımına, üzerine etkiyen yüklere ve bulunduğu çevre koşullarına bağlı olarak, yapının tasarlanan ömrünün belirlenmesi, yapıda ve yapı elemanlarında zamana ve çevre koşullarına bağlı olarak meydana gelen bozulmaların uygulanacak testlerle tespit edilmesi ve gerekli görüldüğü takdirde, yapının onarılması için gerekli işlem adımlarına karar verilmesi için yapıların detaylı olarak incelenmesi ve değerlendirilmesi gerekmektedir. Yapılan incelemeler ve değerlendirmeler sırasında, ekonomi göz önünde bulundurularak yapının yaşam ömrünün uzatılması amaçlanmaktadır.

Mevcut yapılara örnek olan tarihi taşınmazların da ayrıntılı olarak incelenmesi, tarihi mirasın korunması için çok büyük bir önem taşımaktadır. Tarihi taşınmazlarda meydana gelen hasarın belirlenmesi için malzeme özelliklerinin belirlenmesi ve yapı üzerinde çeşitli testlerin yapılması gereklidir. Hasar mekanizmasının belirlenmesi için yapının bulunduğu ortamın iklim özelliklerinin de diğer bilgilerle birlikte göz önünde bulundurulması gerekmektedir.

Mevcut yapıların, yapısal olarak değerlendirilmesi yapının mevcut durumu göz önünde bulundurularak, şu işlem basamakları izlenerek gerçekleştirilir.

a) Değerlendirme amacının belirlenmesi

b) Senaryo

c) Ön Değerlendirme:

1) Dokümanların ve diğer bilgilerin araştırılması; İncelenen yapıya ait tasarım ve kontrol dokümanları tam bir değerlendirme için büyük önem taşımaktadır. Ancak bu dokümanların doğruluğunun ve yapı üzerinde önceden yapılan müdahalelerin içeriğinin ve güncelliğinin tasdik edilmesi gereklidir. Çevresel ve sismik etkilerin, yapının bulunduğu zemindeki değişimlerin, yapının yanlış kullanımından kaynaklanan sorunların kayıt edilmesi ve belgelendirilmesi gereklidir.

2) Ön inceleme; Ön incelemenin amacı, yapısal sistemin belirlenmesi ve basit araçlarla gerçekleştirilecek görsel denetimle, yapıda meydana gelmiş hasarların belirlenmesidir. Görsel denetimle yüzey özelliklerinin yanı sıra gözle görülebilir deformasyonlar da (çatlak, korozyon, parçalanma, v.s) belirlenmektedir.

3) Ön kontroller; Ön kontrollerin amacı yapının güvenliğini etkileyebilecek kritik durumların belirlenmesidir. Ön kontrolün sonucuna bakarak başka incelemelerin gerekli olup olmadığına karar verilir.

4) Acil eylemler için karar verme; Ön inceleme ve kontroller sırasında yapının durumunun tehlikeli olduğuna karar verilirse, gerekli müdahale ve/veya müdahalelerin en kısa sürede yapılması gereklidir.

5) Detaylı değerlendirme için öneri: Ön incelemeler yapının güvenilir olup olmadığı konusunda yeterli bilgi vermektedir. Ancak yapının durumunda herhangi bir belirsizlik olduğu takdirde yapının detaylı olarak incelenmesi gereklidir.

d) Detaylı değerlendirme:

1) Detaylı doküman araştırması ve incelenmesi; Mevcut olduğu takdirde yapıya ait aşağıdaki dokümanların incelenmesi değerlendirme açısından çok büyük önem taşımaktadır.

- Çizimler, şartnameler, yapısal hesaplar, inşaat kayıtları, kontrol ve onarım kayıtları, yapı üzerinde gerçekleştirilen değişikliklerin detayları
- Mevzuatlar, tüzükler ve yapının inşaatı için kullanılan yönetmeliklerin tümü
- Bulunduğu arazinin topoğrafyası, zemin koşulları, ve yeraltı su seviyesi

2) Detaylı inceleme ve malzeme testleri; Yapının detayları, boyutları ve malzeme özellikleri mevcut dokümanlardan elde edilemediği takdirde, detaylı bir kontrolün ve malzeme testlerinin (hasarlı ve hasarsız) yapılması gereklidir. Yapıda kullanılan malzemelerin doğruluğu yapının davranışının belirlenmesi için büyük önem taşımaktadır.

3) Yapının davranışının belirlenmesi; Mevcut koşullar altında yapının davranışının belirlenmesi yapıda zamanla meydana gelebilecek bozulma ve deformasyonların belirlenmesi açısından çok önemlidir.

4) Yapı özelliklerinin belirlenmesi; Yapının özellikleriyle ilgili bilgiler oluşturulacak jeodezik tabanlı yapı bilgi modelinin altlığını oluşturmaktadır. Yapının yük taşıma kapasitesinin belirlenebilmesi ve yapısal analizin gerçekleştirilebilmesi için yapı özelliklerine ihtiyaç vardır.

5) Yapısal analiz; Seçilen yönetmeliğe bağlı olarak , yapı üzerine etkiyen yüklere, çevre koşullarına ve malzeme özelliklerine dayanarak yapısal analiz gerçekleştirilir.

6) Doğrulama: Analizler sonucunda söz konusu yapının hedeflenen yapısal güvenirliği sağlayıp sağlamadığının doğrulanması gerekmektedir. Doğrulama gerçekleştiği takdirde yapı üzerinde gerçekleştirilen analizlerin sonucu, yapıya yapılacak onarım ve rehabilitasyon müdahalelerin önerilmesi, ve yapının iyileştirilmesi için kullanılır.

e) Değerlendirmenin sonucu:

1) Rapor;

2) Yapılacak müdahalelerin kavramsal tasarımı; Analizler sonucunda yapının yetersiz olduğu belirlenirse, yapılan analizler doğrultusunda, yapılacak müdahaleler kavramsal olarak tasarlanır. Tasarım aşaması tamamlandıktan sonra gerekli müdahalelerin uygulanması işlemine geçilir.

3) Risk kontrolü.

f) Gerekirse işlem dizisi tekrarlanacak .

Araştırmanın temeli, tarihi taşınmazların yapısal değerlendirmesine dayanmaktadır. Yapının değerlendirilmesi için gerekli malzeme özellikleri hasarlı ve hasarsız deneyler kullanılarak belirlenmiştir. Malzeme özelliklerini yanı sıra, yapının kullanım durumu ve çevresel etkiler de göz önünde bulundurularak uygun koruma, restorasyon ve onarım stratejileri belirlenecektir..

Yapının bulunduğu çevre koşulları ve tarihi geçmişi de detaylı olarak incelenerek yapıya ait performans analizi gerçekleştirilmiştir. Performans analizi, yapıda meydana gelen bozulmaları inceleyerek belirlenecek bozulma mekanizmasını, yapının geçmiş performansını ve yapının izlenmesi işlemlerini içermektedir.

İşlem adımlarının tamamlanmasından sonra yapıya ait 3D jeodezik tabanlı yapı bilgi modelini oluşturmak amacıyla yersel lazer tarama işlemi sonucunda elde edilen nokta bulutları kullanılmıştır. Nokta bulutlarının kullanılabilir hale gelmesi için gerekli işlem adımlarından olan registrasyon, segmentasyon, üçgenleme ve semantik zenginleştirme işlemleri anlatılmıştır. Oluşturulan yapı bilgi modeli üzerinde, yapının değerlendirilmesi işlemi gerçekleştirilebilmektedir. Söz konusu yapı yığma yapı olmasından, tarihi ve kültürel bir değere sahip olmasından dolayı CityGML'e konu olan yapılardan farklılık göstermektedir. Çalışma amacına uygun verilerin model üzerinde kullanılabir hale gelebilmesi için uygulamaya özel "Masonry" adında bir uygulama etki alanı uzantısı geliştirilmiştir. Geliştirilen uzantı için bir diyagram çizme ve ilişkisel modelleme dili olan tümleşik modelle dili (UML) kullanılmıştır.Kullanılan modelleme dili ve geliştirilen uygulama etki uzantısına ait detaylar tez kapsamında verilmektedir.

Yapıların sonlu elemanlara ayrılarak modellenmesi prensibine dayanan sonlu elemanlar yöntemi günümüzde yaygın kullanıma sahiptir. Yapılar çeşitli yükleme koşulları altında farklı davranışlar sergilemektedirler. Özellikle tarihi yığma yapıların çeşitli yüklemeler altında göstereceği davranışların belirlenmesi oldukça detaylı ve uzun işlem adımları gerektirmektedir. SAP2000 sonlu elemanlar programıyla çalışma alanına ait nokta bulutları kullanılarak Kuzey ve Güney kuleleri sonlu elemanlara ayrılarak modellenmiştir. Oluşturulan model üzerinde yapıların deprem yükleri ve kendi ağırlıkları altında davranışları belirlenmiştir. Değerlendirme sonucunda yapının ihtiyacı olan onarımları da içeren müdahaleler, kritik kısımların bakımı ve yapılacak olan müdahalelere ait detaylar belirlenmiş ve anlatılmıştır. Yapı için karar verilen müdahalelerin tamamlanmasından sonra yapı izlenmeye devam edilmelidir.

1. INTRODUCTION

The continued use of existing structures is of great importance because the built environment is a huge economic and political asset, growing larger every year. The assessment of existing structures is a major engineering task. The structural engineer is increasingly called upon to devise ways for extending the life of structures whilst observing tight cost constraints.

The aim of this thesis is fourfold; first to detect individual stones in registered and triangulated point clouds obtained by using a terrestrial laser scanner; second to create a geodetic based 3D CityGML models of the existing remains of the North Tower of the Ottoman fortress of Seddülbahir which includes information that is generated about building damage and surface characterization using terrestrial laser scanning data; third to create the finite element model of the North and South towers of Seddülbahir Fortress in order to evaluate the behavior of the structures under earthquake loads; fourth to use these models to propose interventions [1].

The documentation project process began at Seddülbahir in 1997. Since 1997 research of the Seddülbahir fortress, the survey and documentation on site, archival research in various libraries, topographical and architectural drawings and modelling process in the office have continued [2].

Stone, mortar, metal and wood samples were taken from various parts of the fortress for laboratory analysis. These results along with archive data helped to determine the repair chronology of the fortress. Since 1999 the focus of the project at Seddülbahir moved from the documentation of the extant remains to the preparation of a preservation and restoration proposal for the fortress and adjoining buildings [3].

Located at the tip of Cape Hellas, the fortress and the coast where it is situated is also one of the most important sites of the Gallipoli campaign of World War One.

The historic records helped to determine the different periods of Ottoman repair to the fortress, the sources and nature of building supplies used by the Ottomans in this region and provided information about several repairs to the fortress. The archival records have also been useful as they often give the names and functions of different parts of the fortress. In summation, the repair records along with other types of documentation helped to understand which sections of the fortress were repaired or expanded at a particular time [3].

The assessment of existing structures is composed, in general, of the following steps, taking into account the actual conditions of the structures [4].

a) Specification of the assessment objectives.

b) Scenarios.

c) Preliminary assessment:

  1) preliminary checks;

  2) decisions on immediate actions;

  3) recommendation for detailed assessment.

d) Detailed assessment:

  1) detailed documentary search and review;

  2) detailed inspection and material testing;

  3) determination of actions;

  4) determination of properties of the structure;

  5) structural analysis;

  6) verification.

e) Results of assessment:

  1) report;

  2) conceptual design of construction interventions;

  3) control of risk.

f) The whole sequence is repeated when necessary.

The objective of the assessment of the structure should be clearly specified in terms of its future performance in an agreement between different stakeholders: the client, the authorities when relevant, and the assessing engineer. The required future performance shall be specified in the reusage plan and risk management plan.

Scenarios related to a change in structural conditions or actions should be specified in the risk management plan in order to identify possible critical situations for the structure. Each scenario is characterized by a predominant process or action and, when appropriate, by one or more accompanying processes or actions. The identification of scenarios represents the basis for the assessment and design of interventions to be taken to ensure structural safety and serviceability.

Design and inspection documents contain important information that is necessary for a thorough assessment of an existing structure. It shall be verified that the documents are correct, and that they are updated to include information of any previous intervention to the structure. Other evidence, such as the occurrence of significant environmental or seismic actions, large actions, changes in soil conditions, corrosion, and misuse of the structure, should be recorded and documented.

The aim of a preliminary inspection is to identify the structural system and possible damage to the structure by visual observation with simple tools. The information collected is related to aspects such as surface characteristics, visible deformations, cracks, spalling, corrosion. The results of the preliminary inspection are expressed in terms of a qualitative grading of structural conditions (e.g. none, minor, moderate, severe, destructive, unknown) for possible damage.

The purpose of the preliminary checks is to identify the critical deficiencies related to the future safety and serviceability of the structure with a view to focussing resources on these aspects in subsequent assessment campaign. Based on these results, it is then judged whether a further investigation is necessary or not.

When the preliminary inspections and/or checks clearly indicate that the structure is in a dangerous condition, it is necessary to report to the client that interventions should be taken immediately to reduce the danger with respect to public safety. If there is uncertainty, the critical deficiencies should be assessed immediately and actions taken, if necessary.

The preliminary checks may clearly show the specific deficiencies of the structure, or that the structure is reliable for its intended use. Where there is uncertainty in the actions, action effects or properties of the structure, a detailed assessment should be undertaken.

In order to carry out a detailed assessment the following documents, if available, should be reviewed [4]:

- drawings, specifications, structural calculations, construction records, inspection and maintenance records, details of modifications;

- regulations and by-laws, codes of practice which were used for constructing the structure;
- topography, subsoil conditions, groundwater level at the site.

The details and dimensions of the structure as well as characteristic values of material properties can be obtained from design documents, provided that the documents exist and there is no reason for doubt. In case of any doubts, the details and dimensions of components and properties of materials assumed for the analysis should be determined from a detailed inspection and material testing. The planning of such an inspection is based on information that is already available. The detailed quantitative inspection will result in a set of updated values or distributions for certain relevant parameters that affect the properties of the structure.

Testing of the structure is used to measure its properties and/or to predict the load-bearing capacity when other approaches such as detailed structural analysis or inspection alone do not provide clear indication or have failed to demonstrate adequate structural reliability.

Structural analysis in accordance with International Organization for Standardization (ISO) 2394 should be carried out to determine the effects of the actions on the structure. The capacity of structural components to resist action effects should also be determined. The deterioration of an existing structure should be taken into consideration. When deterioration of an existing structure is observed, the reliability assessment of the structure becomes a time-dependent deterioration problem as described in ISO 2394, and an appropriate analysis method should be used. In the case of deteriorated structures, it is essential to understand the causes for the observed damage or misbehaviour.

The verification of an existing structure should normally be carried out to ensure a targeted reliability level that represents the required level of structural performance. Current codes or codes equivalent to ISO 2394 which have produced sufficient reliability over a long period of application may be used. Former codes that were valid at the time of construction of an existing structure should be used as informative documents. Alternatively, verification may be based on satisfactory past performance.

If the structural safety or serviceability is shown to be inadequate, the results of the assessment should be used to recommend construction interventions for repair, rehabilitation, or upgrading of the structure to perform in accordance with the objective of the assessment for its remaining working life.

An alternative approach to construction interventions, which may be appropriate in some circumstances, is to control or modify the risk. Various measures to control the risk environment include imposing load restrictions, altering aspects of the use of the structure, and implementing some form of in-service monitoring and control regime.
Along with the laboratory analyses of stone, mortar, metal and wood samples taken from Seddülbahir it is hoped to be able to produce in the restoration proposal a sound chronology of the various phases of construction and repair of Seddülbahir's 350 year past [5].

Project History: In July 1997, a few months after Seddülbahir was vacated by the military, the Kaletakımı, a research group comprised of students and faculty members from the Department of History at Koç University and the Department of Geodesy and Photogrammetry Engineering at Istanbul Technical University (ITU), began an architectural survey and documentation project. As there had been no publications or comprehensive architectural plans made for the fortress of Seddülbahir the goal was to thoroughly document the site using the most recent surveying technologies available in Turkey and the existing Ottoman buildings that comprised the fortress and to produce architectural plans, elevations and a topographical map of the entire site [6].

Using the latest technology in laser scanning, along with total station and traditional measuring equipment when necessary, digital survey of entire fortress was conducted [7].

The aim of this thesis is to establish a geodetic-based CityGML model ofthe North Tower of Seddülbahir fortress. This process includes assesing information that is generated about building damage and surface characterisation in order to preserve the cultural heritage. Moreover a finite element model of the North and South Towers will also be evaluated under earthquake loads. Both models will be used to decide on necessary interventions for the rehabilitation of the structures [1]. The last part of the thesis will concentrate on the restoration, conservation and repair recommendations for the North and South towers of Seddülbahir Fortress.

2. GENERAL INFORMATION ABOUT SEDDÜLBAHİR FORTRESS

2.1 Location and History of the Fortress of Seddülbahir

The fortress of Seddülbahir is situated in the small village of Seddülbahir overlooking both the Aegean Sea and the entarance to the Dardanelles (Figure 2.1), on the site of Gallipoli battlefields of Cape Hellas and Ertuğrul Bay at the southern edge of the Gallipoli peninsula. It stands 110 kilometers from Gelibolu and 30 kilometers from Kilitbahir village [7].

The fortress of Seddülbahir, the "Dam of the Sea", was built in 1658 on the European shore by Hadice Turhan Sultan, the mother of the Ottoman Sultan, Mehmet IV [3].

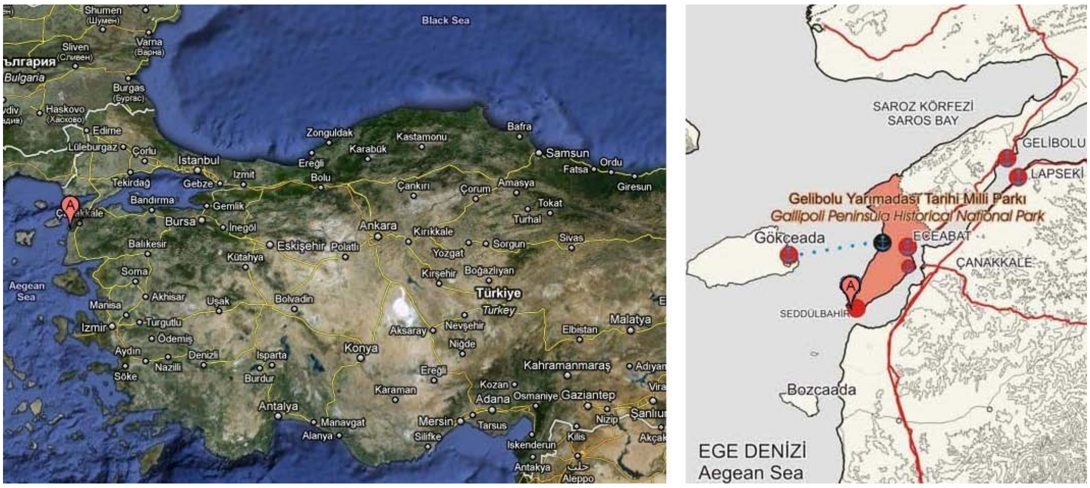

Figure 2.1 : Location of the Fortress of Seddülbahir.

Seddülbahir was built because during the long war over Crete the Ottomans had discovered that Kilitbahir and Kale-i Sultaniye, the two fortifications at the narrowest point of the Dardanelles built by Mehmed II, were not sufficient to keep naval invaders out of Ottoman waters. Therefore along with its sister fortress Kumkale, Seddülbahir was constructed and served as the first line of defense against Venetian naval attacks of the straits. Since that time Seddülbahir has protected the Ottoman and later Turkish lands, against threats to the Dardanelles, the strategic waterway which leads to Istanbul on the Bosporus [3].

2.2 Seismicity and Natural Conditions of the Region and Repairs

Seddülbahir fortress is located at the entrance to the Dardanelles at a critical site threatened by erosion from the sea, rain and windsas shown in Figure 2.2.

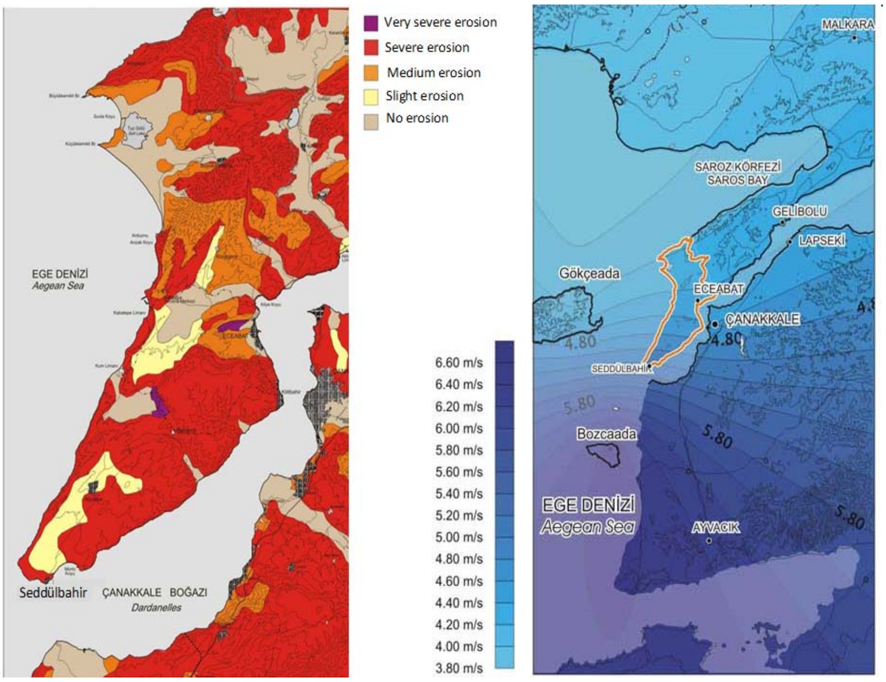

Figure 2.2 : a) Erosion map of region around the Fortress of Seddülbahir b)Wind speed map of region around the fortress of Seddülbahir [8].

In 18th and 19th centuries natural disasters such as earthquakes and rough climate conditions caused severe damages to the fortress. In these two centuries archival records of the Ottoman Empire are filled with orders to build protective walls against erosion which originated from harsh winds and waves [3]. In addition to that the fortress is located near the North Anatolian fault as shown in Figure 2.3.

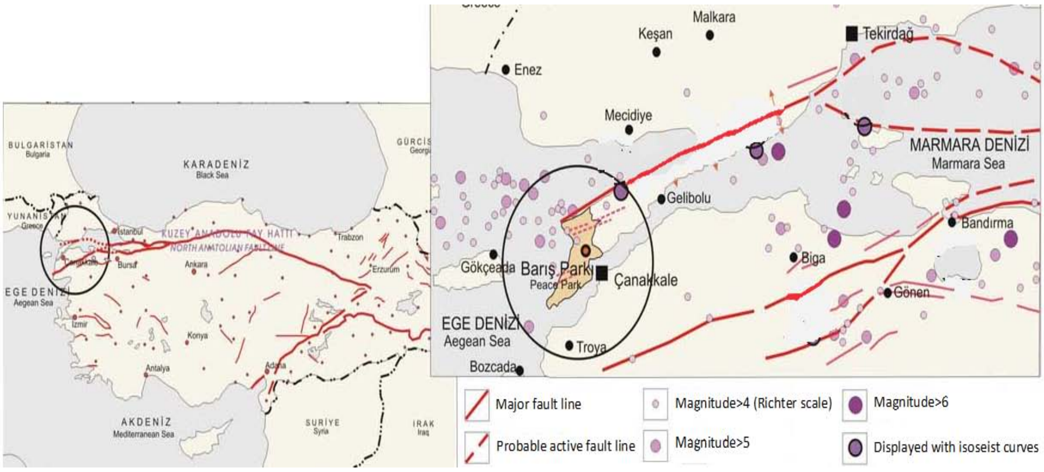

Figure 2.3 : Tectonic map of the region around the Fortress of Seddülbahir [8].

The earthquake records in the 19th century show four major earthquakes that affected the fortress of Seddülbahir [9]:

- The earthquake on the 1st of June 1707 caused the collapse of some non-structural parts of Seddülbahir fortress.
- The earthquake on 6th of March 1737 was a destructive earthquake in the Biga region and brought the castles of Kilitbahir, Seddülbahir, Çanakkale and Bozcaada close to collapse.
- The earthquake on the 5th of August 1766 there was a major earthquake in the western part of the Sea of Marmara, completed the destruction caused by the shock of 22 May 1766. The larger area was affected area at the west of Tekirdağ in the region of Gaziköy and Gelibolu with loss of life. Of the Dardanelles castles, Seddülbahir and Kilitbahir were extensively damaged, as well as the mosque at Kilitbahir and the mosque of Mehmed II in the castles of Kale-i Sultaniye in Çanakkale.
- An earthquake in the year (25th March 1773 and 13th March 1774) necessitated repairs to the governors’ house in the inner castle of Seddülbahir.

2.3 Archaeology of the Fortress

The excavation of the upper fortress which had commenced on the 27 June 2005 and continued to the end of July 2005, provided a more accurate picture of the original plan and parameters of the Abdülhamid II era military building that was built here in the late nineteenth century. Further it was important to determine whether there were any earlier levels at the barrack’s location. Seddülbahir is directly across the Dardanelles from Troy and 1.5 kilometers from the alleged site of Protosileus, one of the mythical warriors of the Trojan War. Historical sources indicate that there was a pre-Ottoman occupation era of this region of the Gallipoli peninsula but there have been no documented excavations at the site of Seddülbahir, and no excavations in the surrounding region since 1920’s. There is very little known about the archeological past of this side of the Dardanelles. [2].

The excavation of the north and northwest towers was conducted as part of the process of determining the levels and plan of the foundations as this is an advantage for more accurate restitution drawings and future restoration plans. Sondages were made in both the northwest and north towers [10].

Excavations in the northwest tower were particularly challenging as a concrete floor had been made during the military's occupation of the fortress. Since 1997 the tower interior had also been used for housing farm animals. After extensive cleaning of the existing floor the excavation proceeded to the depth of 2 meters. The foundations of the northwest tower appear to be deeper than the two meters depth but the probability of destabilizing the walls of the tower contributed to the decision to stop the excavation at 2 meters depth. Depending on the restitution needs, and the assessment of the structures stability it may be advisable to continue to excavate the foundations of this tower in the future for more accurate restoration work [10].

Two sondages in the north tower, seen in Figure 2.4, were made to the depth of 1.20 meters and 0.56 meters to determine the level of the foundations but again the risk of destabilizing this tower contributed to the decision to excavate a larger surface area of the tower interior rather than continue to excavate to a greater depth. Immediately below the surface of this tower's floor was a surface of inverted pine cones and brick. This surface and the central area of the tower revealed a thick layer of charcoal and located in this tower is an indication that there was a small foundry of some sort, perhaps the worksite of a metal smith [10].

Figure 2.4 : Two sondages opened in North Tower [10].

2.4 Architecture

A sound restoration proposal is imperative for the proper conservation of Seddülbahir. The fortress of Seddülbahir is a large site; encompassing a total landscape of nearly 24.000m^2 and containing a building mass of approximately 4200m^2(Figure 2.5).

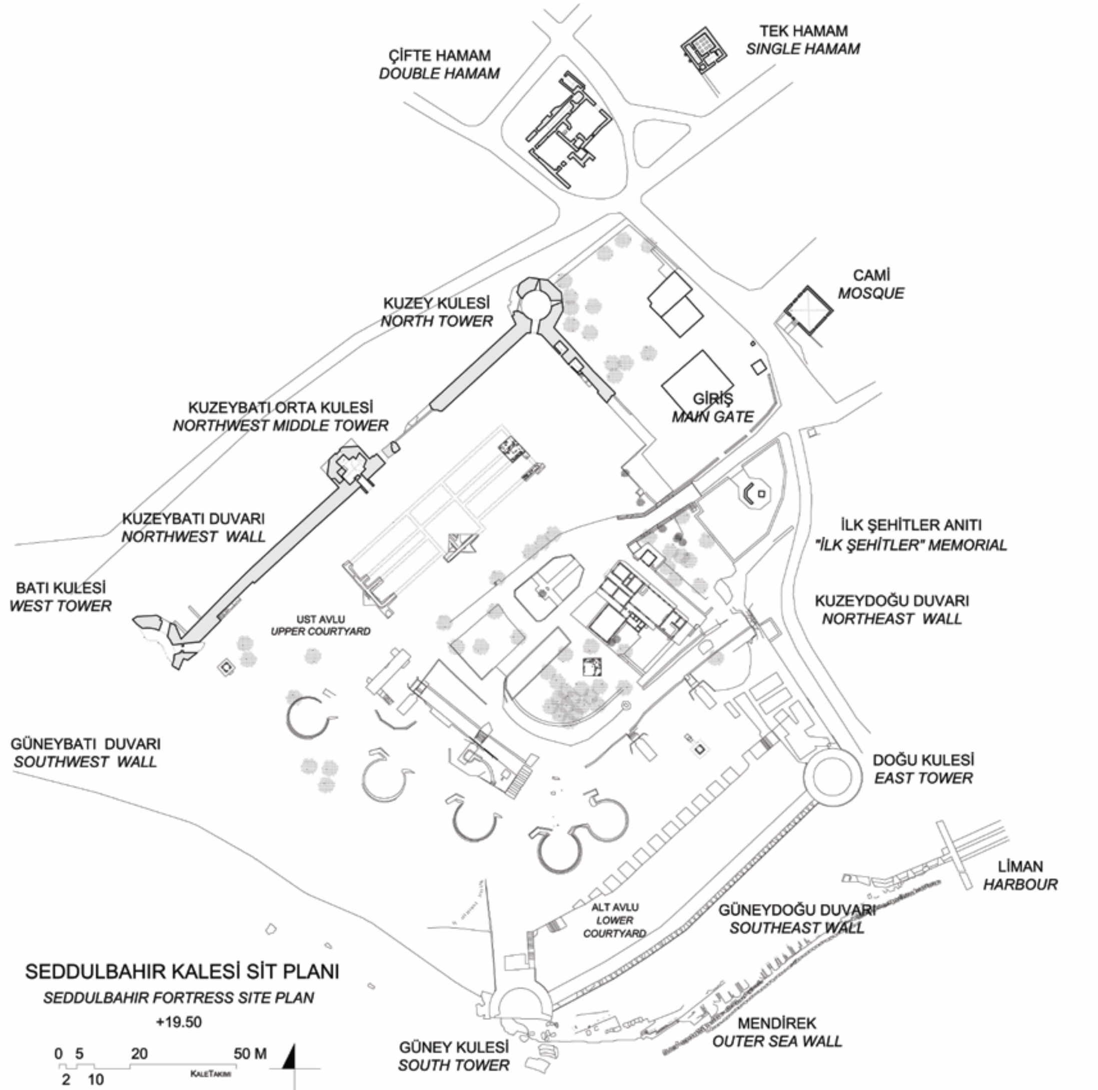

Figure 2.5 : The fortress of Seddülbahir site plan[10].

The octagonal North Tower of Seddülbahir fortress seen in Figure 2.6 is built up of wooden beams and rubble stones inside and with large cut stone blocks at the outside. It has 67.5 m^2 interior space area. The elevation of the tower is +16.80 m.

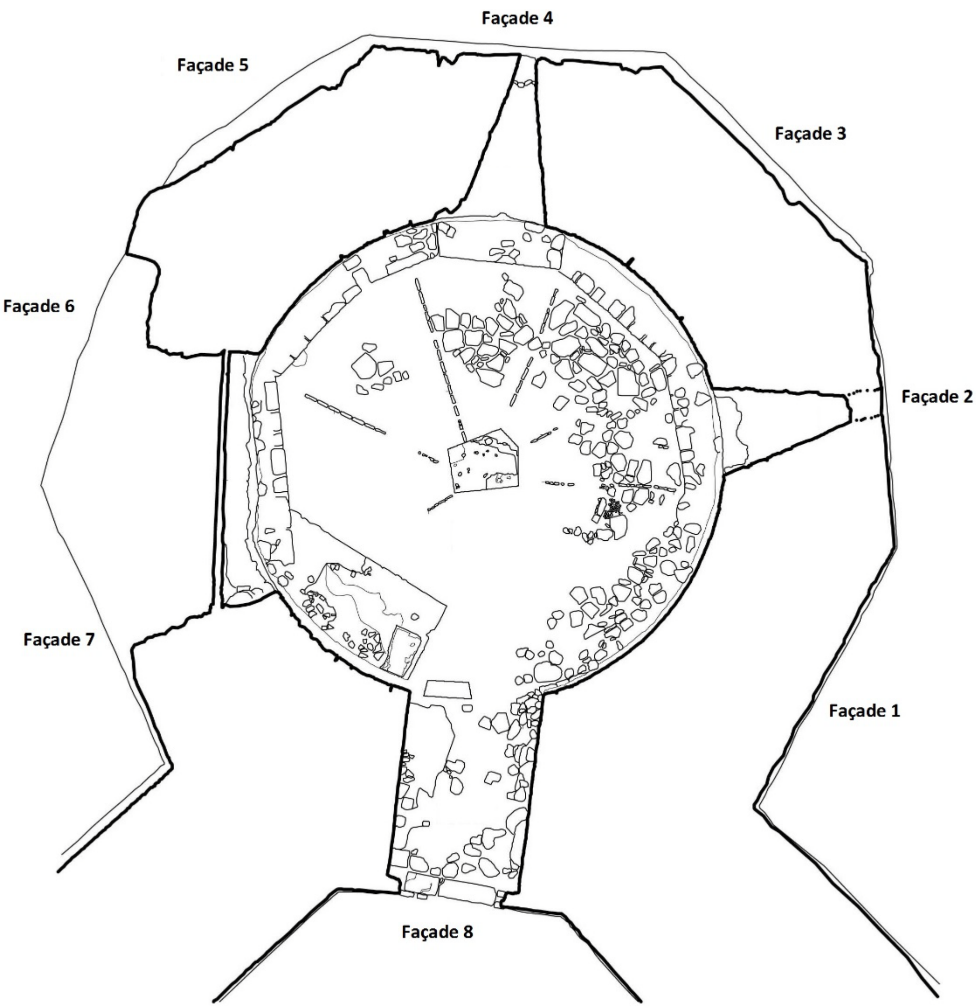

Figure 2.6 : Octagonal plan of the North Tower [10].

The northwest façade was largely destroyed by bombs during I. World War. The destroyed part is closed with perforated brick and concrete. Wooden beams can be observed in three distinct levels on the original part of the collapsed wall. The entrance to the tower is provided by arched, rough cut stone door on the south façade, opening to the upper courtyard.

The externally octagonal shaped tower has a circular interior plan. The diameter of the dome, which is built up of cut stone blocks and small stone rows between them, is 8.80 m.

There are three porthole windows in the interior part as seen in Figure 2.7. The east porthole is partially open, the north porthole is completely closed. On the west side of the tower, only the beginning part of the porthole can be observed [3].

Figure 2.7 : East porthole (left), north porthole (middle), west porthole (right)[10].

The South Tower of Seddülbahir fortress has a circular plan both inside and outside. The south half of the tower has completely collapsed and large pieces of rubble stone and mortar lie inside the sea as seen in Figure 2.8.

Figure 2.8 : General view of South Tower[10].

The elevation of the tower is +1.07m. the dome has a diameter of approximately 12 m. It has two doors South Gate 01 (SG01) and SG02 as seen in Figure 2.9.

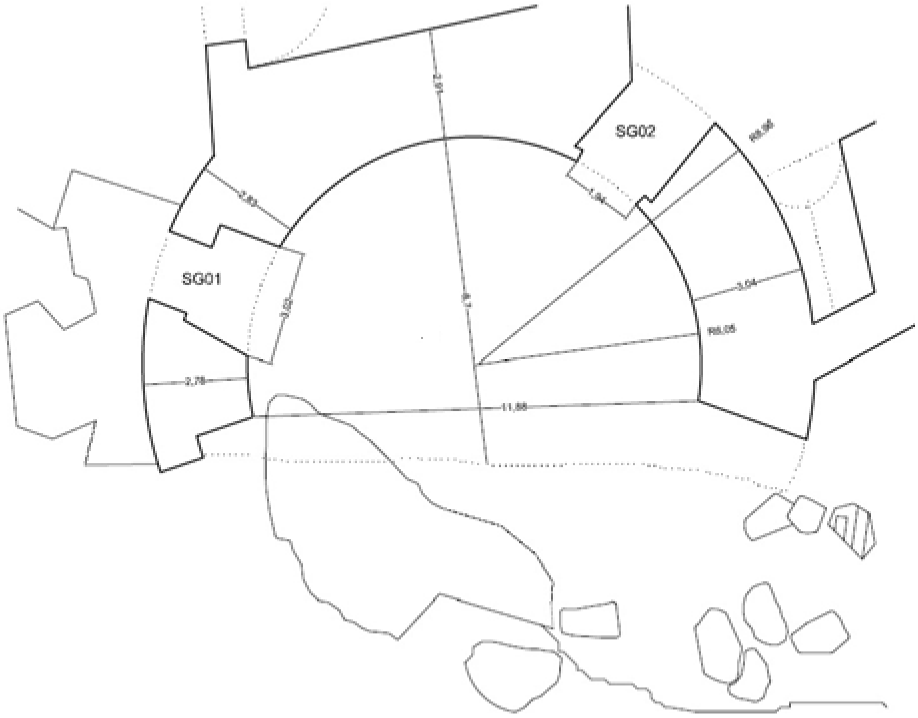

Figure 2.9 : Plan of the South Tower [10].

3. GEODETIC SYSTEM ESTABLISHMENT FOR SEDDÜLBAHİR FORTRESS

Geodetic surveys were one of the important components of documenting Seddülbahir Fortress. The main objective of the geodetic survey was to determine the present situation and topographic structure of Seddülbahir fortress and its surroundings.

3.1 Geodetic Infrastructure

In 1997, as the first step of the project a polygon network was established to be used as reference for geodetic measurements. The locations of these points were determined by Global Positioning System (GPS) measurements. At that time in Turkey there was an absence of a national network defined in global datum for GPS measurements. Because of that, based on the coordinate value of a network point measured in World Geodetic System 1984 (WGS84) coordinate values of other polygons in the network were determined in WGS84 datum.

In 2001, the 6 main control points in Seddülbahir were positioned with the GPS technique. The positions of the main control points were determined using GPS static survey. After processing these sets of data WGS84 coordinates of the main control points were obtained. In order to calculate the coordinates of previously measured (in local coordinate system) points in International Terrestrial Reference Frame 1996 (ITRF96) datum, 5 common points were used. The network of Seddülbahir was connected to the Turkish National Fundamental GPS Network (TUTGA) (Figure 3.1). With these surveys the geodetic infrastructure established in scope of the geodetic works was associated with TUTGA and thereby with the global ITRF96 datum. TUTGA is a network that consists of 594 points with 1-3 cm coordinate accuracy, in ITRF96 datum. It includes three dimensional coordinates (X, Y, and Z), time dependent change of coordinates (velocity;V_x, V_y, V_z) and the orthometric height (H) and geoid height (N) is also known [11]. As a result the coordinates of approximately 15,000 points were computed in Gauss-Krüger coordinates with central meridian 27° and zone with 3° in the datum of ITRF96 within the project.

The topographical maps, digital terrain models, architectural drawings and models, etc. were produced based on these grid coordinates.

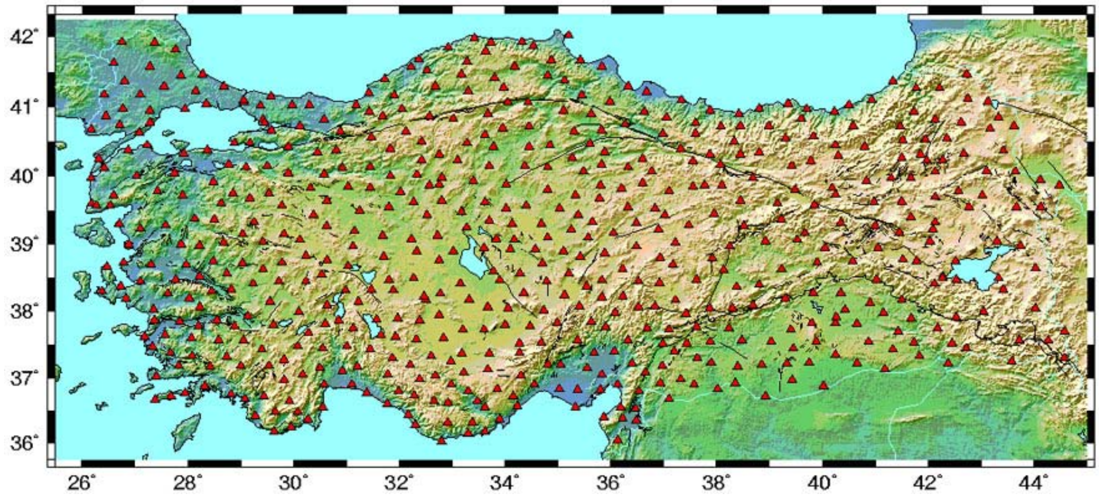

Figure 3.1 : Distribution of TUTGA stations [11].

In addition, during the work carried out in the same year (2001) with the help of a measurement carried out at a point at sea level, geoid heights (which means the difference between height from sea level and ellipsoidal height) (Figure 3.2) obtained from GPS measurement were calculated. This value is used in order to calculate the heights of points above sea level from the ellipsoidal heights obtained by GPS technique.

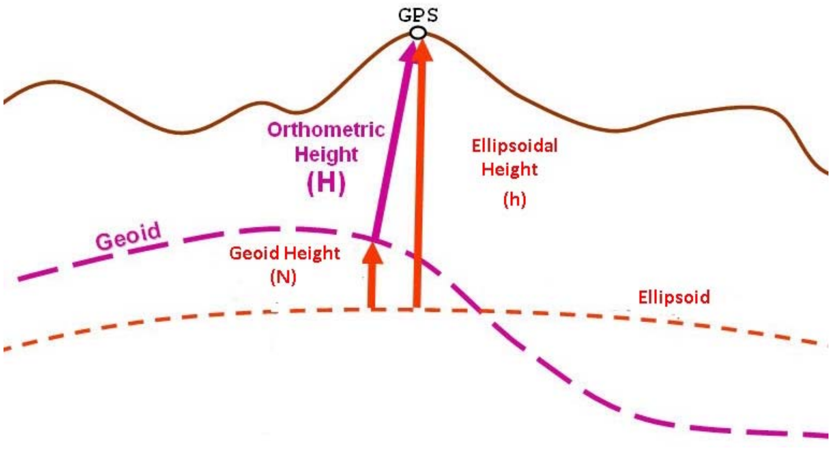

Figure 3.2 : Definition of different height systems [12].

3.2 Geodetic Measurements Carried Out

On-site surveying of the project began in the summer of 1997 in Seddülbahir shortly after the fortress was demilitarized. Reconnaissance sketches were made to decide which survey techniques would be used and what would be measured.

Using a total station, GPS and photogrammetric camera a survey of the remains of Seddülbahir on the European side of the Dardanelles began. Photogrammetric documentation was conducted on several sections of the fortress. All sections of the fortress were photographed. Measuring and documentation work concentrated on the lower southern section of the fortress and along the northern wall of the upper section of the fortress [13].

From the beginning of the project terrestrial geodetic measurements and photogrammetric documentation, as well as GPS were used. In order to create a base for architectural works additional measurements were made with a terrestrial laser scanner during the 2005 survey campaign [10].

3.2.1 GPS and conventional geodetic measurements

3D positions of traverse points in the control nets were determined using Real Time GPS surveys and Stop and Go method. Some traverse points within the towers, rooms and other structures were measured with TPS system (Tacheometrical Object Oriented Partly Automated Laser Surveying) with a total station [14]. 40 control points in Seddülbahir were positioned in this way. The borders of surveying areas were measured [15].

The object or detail points of the fortress were measured from the traverse points using the Total Station. More than two thousands points were measured at Seddülbahir with the Total Station to produce a geodetic map of the site and the architectural drawings of the present situation of the fortress. Approximately 8000 building detail points with TPS and 18000 points with GPS were measured[14].

The surveying work that was done in the project was conducted with what was then state of the art surveying instruments, such as GPS receivers, and Total Stations capable of measuring without reflectors. Data collection in the field was done using several different GPS techniques, including Static, Kinematic, and Real-Time Kinematic GPS as well as conventional techniques. By employing the most recent GPS technology and conventional measuring techniques, the degree of accuracy in the measurements for the fortress was significantly increased. At the beginning of the measurement campaign, a main triangulation frame was established and the points were positioned with GPS. The topographic details, which were going to be used to prepare the digital terrain model, were recorded with GPS in Kinematic mode. The first step was to determine the accuracy required for the project and then choose the suitable equipment. In the project, Leica GPS System 300 equipment was preferred whose baseline accuracy up to 3mm + 0.5ppm in the static survey mode with post processing and up 10 to 20mm + 1ppm in kinematic survey. The terrestrial measurement instrument used in the project was Leica TCRA 1105 total station.

Measurements necessary for architectural drawings were carried out using a reflectorless total station and during these measurements details of structures present in the area were measured. This procedure can be divided into two as: detailed measurements of fortress and details of surrounding buildings.

3.2.2 Photogrammetric techniques

Terrestrial photogrammetric work was conducted at Seddülbahir to collect additional information about the structures comprising the fortifications and to examine the various degrees of accuracy between measurements of buildings generated using photogrammetric techniques and those generated by conventional methods [6].

Between 1997 and 1998, in order to determine the current situation of the fortress using photogrammetric methods, all sections of the fortress were photographed. At the end of the work base data to create axonometric drawings was collected. Topographic maps and plans, including the heights of walls and towers, were produced.

3.2.3 Terrestrial laser scanning

The terrestrial laser scanning technique was employed in project in 2005. Using a Leica HDS 3000 laser scanner and Leica TCR407 reflectorless total station the façades and interior spaces of the fortress were scanned and measured. The fortress was analysed prior to 3D scanning work of the structures and objects to be analysed were assessed.The laser scanning works are described in Section 4.

4. TERRESTRIAL LASER SCANNINGAND DATA PROCESSING AT SEDDÜLBAHİR FORTRESS

Terrestrial laser scanning, when compared with other traditional measurement techniques, is one of the fastest ways to acquire measurements and obtain 3D point data.

Laser scanning is widely used in documentation, archival, virtual modelling and conservation of historical structures and cultural heritage. Using the laser scanning data, deformations on the model can be determined and the destroyed or damaged parts of the historic or cultural structures can be evaluated for restoration.

Laser scanners are now the most commonly used modern measurement tools especially for restoration and survey works. When compared with other conventional measurement techniques this technology provides fast data acquisition and reduces the cost of surveying.

3D point data of the measurement area can be measured with high accuracy in the form of strings of dots which are called point clouds. Terrestrial laser scanners are now widely used especially for the survey of historic buildings.

The basic entity measured during terrestrial laser scanning is the distance between the scanner and the measured point. Different techniques are used for laser distance measurement. These are: triangulation, phase difference measurement (phase based), time of flight measurement methods[16].

Triangulation laser scanners are mostly used for small objects and short distances. Phase-difference-measuring-laser scanners measure the distance by calculating the phase difference between the transmitted and received waves. Phase-difference-measuring-laser scanners are effective for short distances. A laser beam is sent to the object and the distance between the sender and the surface is measured using the signal travel time for a time of flight laser scanner. Typical standard deviation of distance measurements is a few milimeters. Due to the relatively short distances measured, the accuracy is almost the same for the entire object space.

Rapid advances in sensor technology and related software tools made terrestrial laser scanning an important method to obtain geometric data in engineering studies, historical and cultural monuments, documentation of urban areas for 3D modelling, mining works, deformation analysis and measurement of forest areas.

During the terrestrial laser scanning measurements Leica HDS 3000 (Figure 4.1) time-of-flight laser scanner with its 360^o horizontal field-of-view (FOV) and 270^o of vertical FOV was used. With its tripod and optical plummet it can be set on previously established points. This equipment has a built in camera which enables the user to capture panoramic images before scanning and allows for scanning of the desired area or the object separately. It has a 6mm 3D positional accuracy at 50m. The device is operated with a laptop and collected data is stored as point clouds on hard disk.

Figure 4.1 : Leica HDS 3000 terrestrial laser scanner[10].

Before the scanning procedure a detailed observation of the site was carried out. After the initial observation the scanning resolution was decided as 5mm. The resolution defined indicated the distance between the individual points of the point cloud.

During laser scanning measurements, previously established polygon points were used. With the help of this network, scans carried out at different times were registered on the same coordinate system with high accuracy.

The laser scanner was set at 45 different control points during the whole scanning procedure. 5 of these points were inside the towers.

For the registration of laser scanning data, blue and white colored targets with high reflectivity as seen in Figure 4.2 were used. These targets are established for every scanning process, and center point coordinates of these targets were determined using Leica TCR407 Power reflectorless total station.

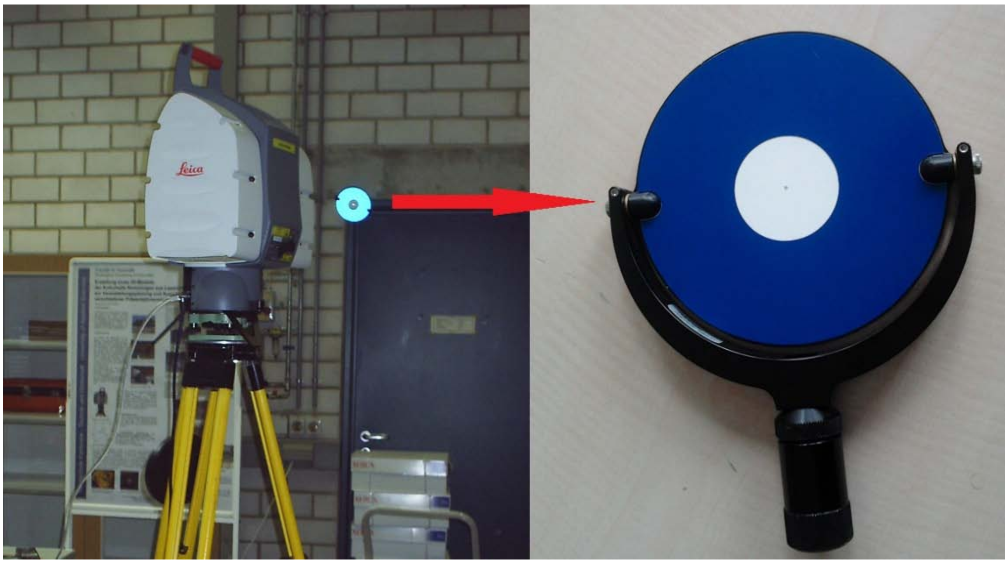

Figure 4.2 : High reflectivity targets necessary for registration.

During 3D laser scanning a witness sketch was prepared for every scan point and all the information related with the scanned area and targets was recorded. These sketches are helpful for the solution of problems that can be faced during the evaluation step.

At the end of scanning a point cloud that contained 350 million points was obtained. The resulting point cloud was used to create a 3D model of the fortress which closely represented the structure. This rich data can also be used as archive data for future works and is an important resource in case of future damage by natural or other events such as earthquakes or incorrect restoration work.

Terrestrial laser scanning technology is widely used in the world for many studies. Scanner and software are developed in line with developing technology and offers different solution methods.

Visualization of structures, the archiving of structures in digital environment, representation of buildings and historical, cultural relationships of building elements, creation of information systems, preparation of substrate for restoration and survey work, renewal of damaged structures according to the original plan are all among the application areas of laser scanners.

Three dimensional data obtained by laser scanning is widely used by architects. The wide field of view, high accuracy and possibility of combining with high resolution digital colored photographs makes this technology one of the best solutions for architectural measurements. Three dimensional data obtained as a result of laser scanning and wide variety of software offers various solutions for architectural applications and allows for the production of new data.

4.1 Registration

In the laser scanning process, the object has to be scanned from different viewpoints in order to model it as if it is in the real world. These sets of point clouds have their own local coordinate system and must be transformed into one common coordinate system. This process is known as registration.

In the registration process, object scanning is carried out on station points together with the scanning of high reflectivity targets seen in Figure 4.2 that give the user the opportunity to make an automatic registration of separate point clouds.

For automatic registration at least three high reflectivity targets are scanned in each scanning scene common with other scans. In this way point clouds obtained from different scanner positions are combined (registered) with the help of these targets.In the scope of the thesis several scans of the North Tower were registered using Leica Cyclone Register software in order to produce a single 3D point cloud of the tower seen in Figure 4.3.

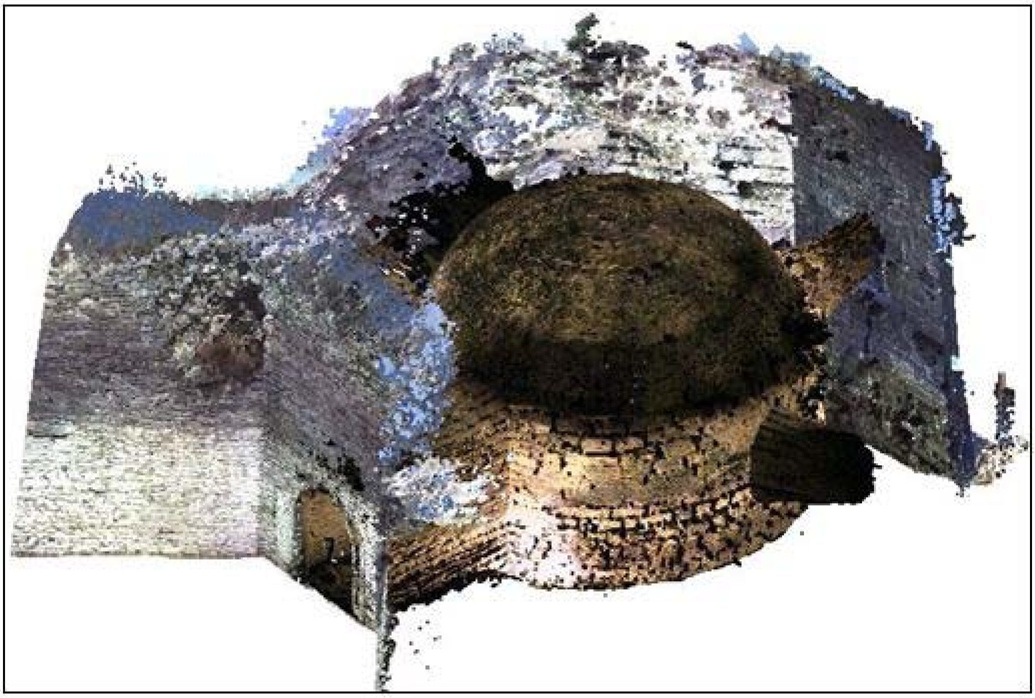

Figure 4.3 : Registered point clouds of North Tower.

4.2 Segmentation

Segmentation is the process of dividing a given point cloud into a number of disjointed subsets each of which is spatially connected. It is the preliminary step that needs to be carried out for object recognition and model fitting [17].

Many point cloud segmentation methods are developed to segment industrial installation scanning data whose real world equivalent usually have relatively regular and simple geometric shapes. But these geometrical derivatives based methods easily lead to over segmentation when they are used to segment point clouds of geometrically complex architectures. Although several algorithms have been developed to find planes in point clouds, it is not enough to segment points using constraints because geometrically complex parts of architectural structures (e.g. damaged stones in a masonry structure), often consist of many spatially connected planar patches which are not coplanar as a whole [18].

Point cloud data of the fortress used in this thesis is very rich in detail; however due to the irregularities (cracks, erosion, damage etc.) of the stones and mortar joints automatic segmentation methods do not produce satisfactory results. Since the resulting segmented data will be used for the architectural documentation of the tower, it is very important to trace the stones accurately.

Kubit PointCloud software that enables the user to work with the point clouds in AutoCAD environment using standard and special drawing tools to trace the appearance of each stone, without any automation was employed for the segmentation. The result of the manual segmentation process can be seen in Figure 4.4.

Figure 4.4 : Segmented stones on façade 4 of the North Tower.

4.3 Triangulation

Triangulation, converting the set of points into a logical and reliable polygonal model, is an important method of surface reconstruction. This operation organizes or divides the input data into simplexes and usually generates vertices, edges and faces that meet only at shared edges [1], [19]. 3DReshaper software is used for triangulation of point clouds as seen in Figure 4.5.

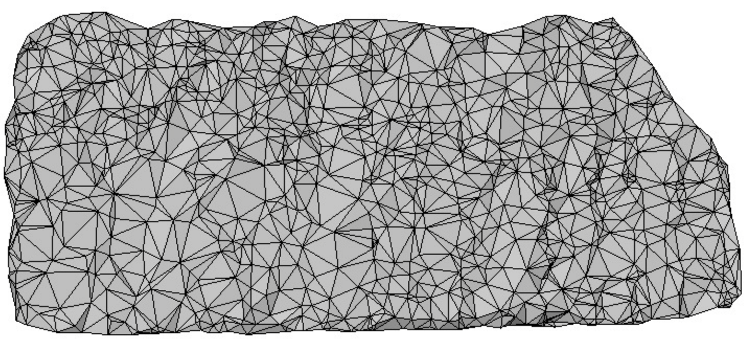

Figure 4.5 : Triangulated single stone of North Tower.

5. DETAILED DEFINITION AND ANALYSES OF MASONRY STONE WALLS

In order to define an object as detailed as desired, it should be well modelled. A model is a simplification of reality. While modelling, the system is visualized as it is or in a desired form, system behaviour of the structure can be determined, templates that are going to guide while constructing a system can be prepared, the decisions taken are documented. A good model contains components that have a major influence and ignores irrelevant details or components at the desired abstraction level [20].

5.1 Obtaining the Best Implementation Modelling Processes

As a result of research and studies conducted on 3D modelling formats such as Virtual reality modelling language (VRML), Extensible 3D (X3D), Keystroke Level Model (KLM), Industry Foundation Classes (IFC) and CityGML were developed [21].

IFC is the ISO standard which has been developed by the International Alliance for Interoperability (IAI) and supports model-based construction objects and activities. Classes are defined to describe a range of object variables that have common characteristics and the standards from an open communication platform operating across the design and construction sectors. The principal advantage of the IFC is that the format supports multi-material objects at all stages of the building and construction processes, resulting in the transfer of rich building information [22].

CityGML model is a standard XML (Extensible Markup Language) based information model that facilitates data sharing [21]. CityGML is an international Open Geospatial Consortium (OGC) standard and an open data model for storage and exchange of three dimensional virtual city models. With the help of this model physical environments, lands, buildings, vegetation, rivers, transportation systems such as highways and railroads, etc., with different spatial information would be merged in the same environment and virtualized [23]. Spatial objects, such as trees, vegetation, etc. with different details can be modelled as prototypes and be used in various parts of the city model [24]. As the North and South towers are single storey structures, CityGML was preferred for modelling.

CityGML allows the exchange, storage and transformation of data using GML language and aims to combine the relationships of objects with each other in a general environment. CityGML has multiple components for different Levels of Detail (LoD) [25].

CityGML is also successful to discriminate between the geometric and semantic information of the object. This means that a virtual city model will not only offer geometric information but also thematic information [26]. CityGML also provides an extension mechanism to enrich the data with special domain areas and semantic associations. This extension mechanism is the base fact for the application of CityGML in various applications (e.g. flood simulation, energy management).

CityGML can also gather special information other than 3D model and use it for various applications. CityGML is a standardized information model that does not only focus on the geometry of the objects but also on their meanings (semantics), topologies and appearance at the same time.

Semantic modelling: The semantic defines the objects and its attributes (name, date of construction, owner, value, etc.) and its parts (wall, roof, window, door, etc.) as seen in Figure 5.1 [27]. Cultural and historic importance of the structure can also be considered within the scope of semantic interest [28].

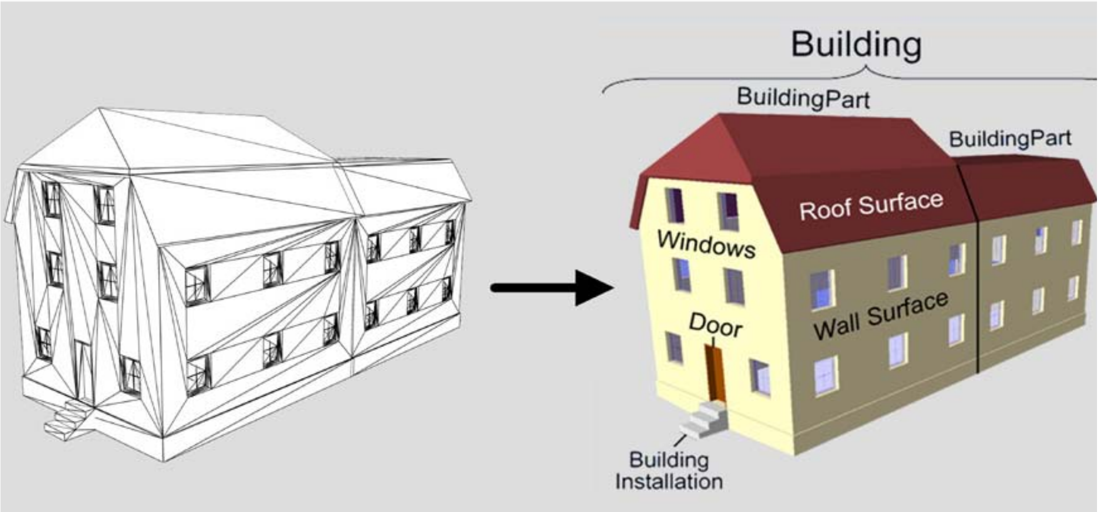

Figure 5.1 : The semantic of a building [29].

LoD concept: The concept of scale for 3D buildings is expressed as LoDs (Level of Detail). Each LoD indicates a specific level of generalization. As stated in [30] CityGML files can contain, but do not have to contain, multiple representations and geometries for each object in different LoD.

CityGML language is developed to bring a standard to the Level of Detail concept [31]. LoD also enables the storage of independently collected data in the same database. With LoD, data analysis and the visualization process become easier. CityGML allocates detail into 5 levels (LoD0-LoD4). Each LoD is associated with a certain accuracy and complexity in geometric and semantic representation. Models are semantically enriched and more detailed with increasing LoD [23], as shown in Figure 5.2.

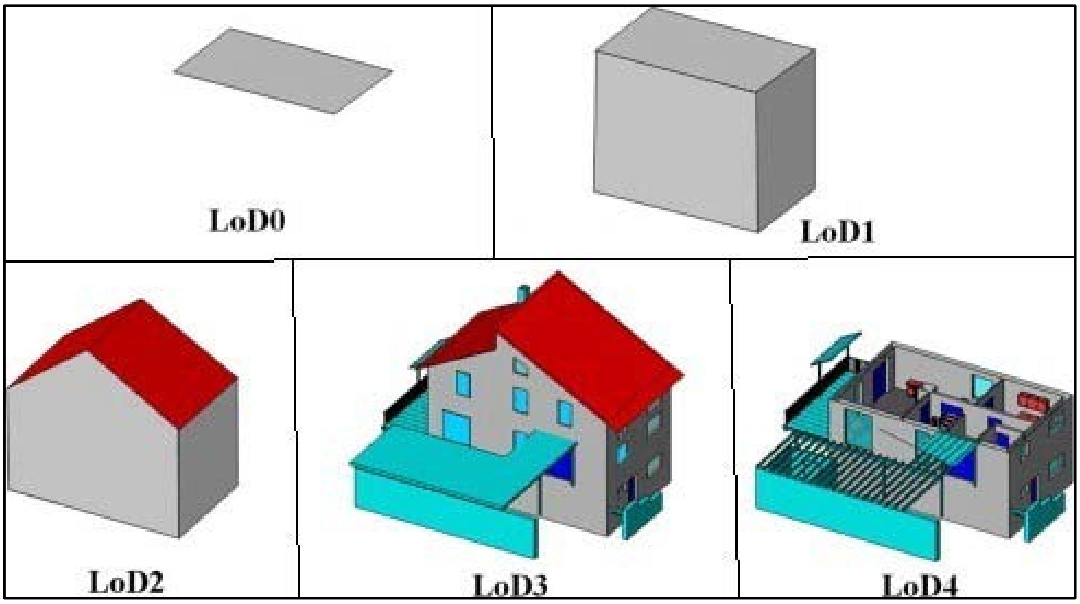

Figure 5.2 : Five Levels-of-Detail provided by CityGML [32], [30].

LoD0 represents topography in a 2.5 dimensional terrain model. At the first level (LoD1) block models of buildings are geometrically upgraded to 3 dimensions. With this block model, representations related to roof structures and façade cladding do not take place. At LoD2 roof structures and façade cladding are modelled as well as city vegetation. At LoD3 detailed architectural models are created. Balconies and façade operations are also included in the model [21]. The outer shell containing the door and windows has the highest level of accuracy [23]. At the last level (LoD4) the 3D model is completed with inner space structures [21]. In Table 5.1 different LoDs of CityGML with their accuracy requirements can be seen.

Table 5.1 : LoD 0-4 of CityGML with its accuracy requirements [30], [33].

	LoD0	LoD1	LoD2	LoD3	LoD4
Model scale description	regional, landscape	city, region	city districts, projects	architectural models (out-side), landmark	architectural models (interior)
Class of accuracy	lowest	low	middle	high	very high
Absolute 3D point accuracy (position / height)	lower than LOD1	5/5m	2/2m	0.5/0.5m	0.2/0.2m
Generalisation	maximal generalisation (classification of land use)	object blocks as generalised features; > 6*6m/3m	objects as generalised features; > 4*4m/2m	object as real features; > 2*2m/1m	constructive elements and openings are represented
Building installations	-	-	-	representative exterior effects	real object form
Roof form/structure	no	flat	roof type and orientation	real object form	real object form
Roof overhanging parts	-	-	n.a.	n.a.	Yes
CityFurniture	-	important objects	prototypes	real object form	real object form
SolitaryVegetationObject	-	important objects	prototypes, higher 6m	prototypes, higher 2m	prototypes, real object form
PlantCover	-	>50*50m	>5*5m	< LoD2	< LoD2

5.2 Creating Application Domain Extension for Masonry with UML

Unified Modelling Language (UML) is a general purpose visual modelling language used for determination, visualization and documentation of system components [34]. Today UML is the most widely used object-based conceptual modelling language especially for software engineering and spatial data modelling [35].

UML contains use case, class, object, sequence, collaboration, state, activity and deployment drawings. Use case and class drawings are used to describe the static structure where object, state, activity, sequence and collaboration drawings are used to describe the dynamic structure of the system. Component and expansion drawings are used to determine the physical state.

Using diagram elements defined (Table 5.2), a new Application Domain Extension (ADE) for evaluation of damaged historic masonry structures is proposed. ADE offers a practical extension mechanism to augment the CityGML data model with application specific data. These application specific extensions are formally specified in their own ADE XML scahema file and can comprise additional property elements for existing CityGML objects as well as newly defined feature types. ADEs are associated with their own XML namespace which allows for integrating ADE data into CityGML instance documents.

Table 5.2 : UML diagram elements and definitions [36].

Parameter Name	**Diagram Element**	**Meaning**
Class	Class Attribute Operation()	Class defines set of objects that share the same attributes, operations, relationships and semantics.
Inheritage	A △ │ B	B inherits from A
Association	A ———— B	A and B call and access each other's elements
Association (one way)	A ————> B	A can call and access B's elements, but not vice versa
Aggregation	A ◇———— B	A has a B, and B can outlive A.
Composition	A ◆———— B	A has a B and B depends A.
Multiplicity	(1) one instance (0..1) zero or one (0..*) or (*) zero or more instances (1..*) one or more instances	States how many objects may be connected across an instance of an association

This ADE contains information about possible damages and material properties that can be observed on historical masonry structures. Draft UML diagram of the ADE which is named as "Masonry" can be seen in Figure 5.3. This diagram only contains newly added objects, classes, etc. Others are inherited from CityGML's main model shown in Appendix A.

Newly defined AbstractCityObjectType damage, which is divided into sub classes such as efflorescence, surface erosion, spalling and cracks, is added in order to represent the damages observed on North Tower. Moreover basic building components of the North Tower such as stones, clamps and mortar, are also added to the Masonry ADE.

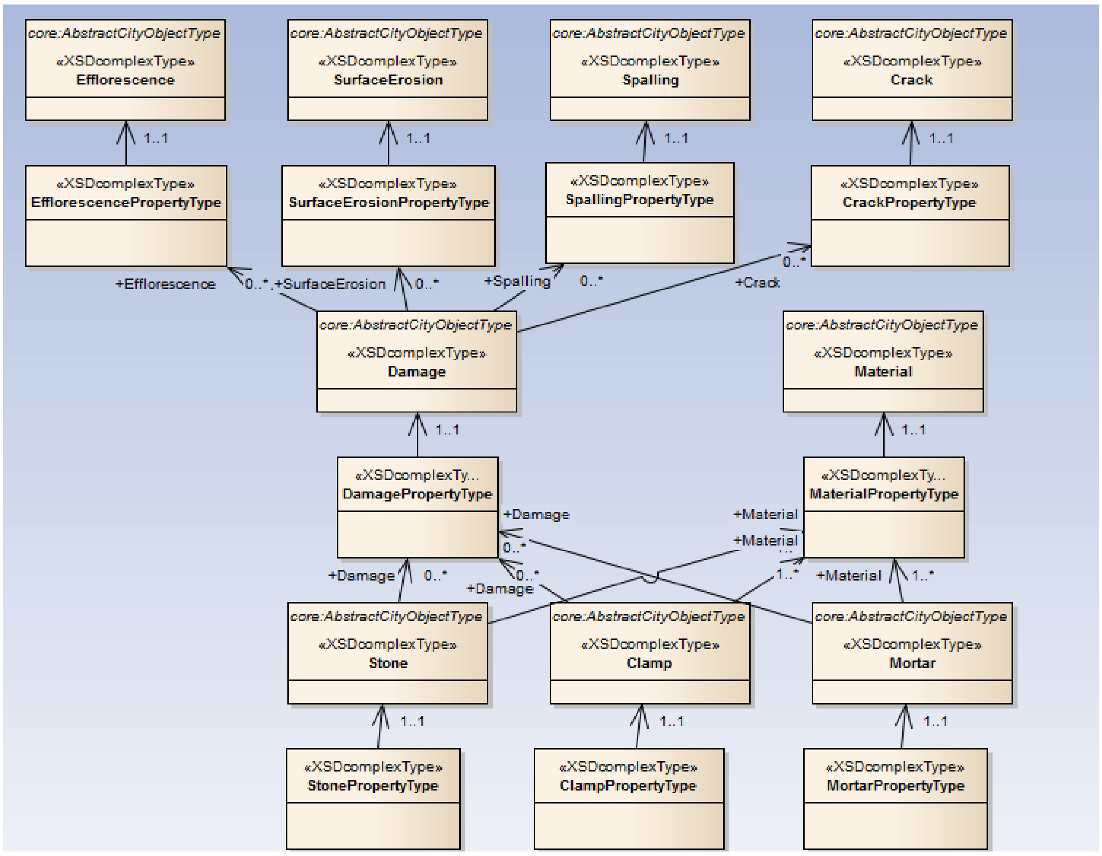

Figure 5.3 : UML diagram of masonry ADE.

XML Schema Definition (XSD) seen in Figure 5.3 is a language that contains definitions and standards for defining the number, order of elements in a XML document, sub elements, data type of elements, constraints on the data held and etc. With XSD several definitions such as elements, attributes, child elements and order of them, number of elements, data type and attributes of elements can be made.Detailed source text of the Masonry ADE can be seen in Appendix B.

5.3 Visualization of Final Model

The North Tower of the Seddülbahir fortress was chosen as a pilot region for visualization. During the design of a spatial object, symbols and styles that human mind can perceive are arranged in two or three dimensional models; this process is referred to as visualization [37]. Visualization is the representation of a phenomenon in a graphical way, for effective communication, in making decisions and facilitating understanding. For more efficient provision of information visualization is necessary.

As the real world is three dimensional, there is a tendency to represent the world in three dimensions. Due to this growing trend, cities in a certain geographical area can be investigated in three dimension without risk and effort with the help of visualization.In order to visualize and evaluate the North Tower of Seddülbahir fortress CityGML tools are used and the steps seen in Figure 5.4 are followed.

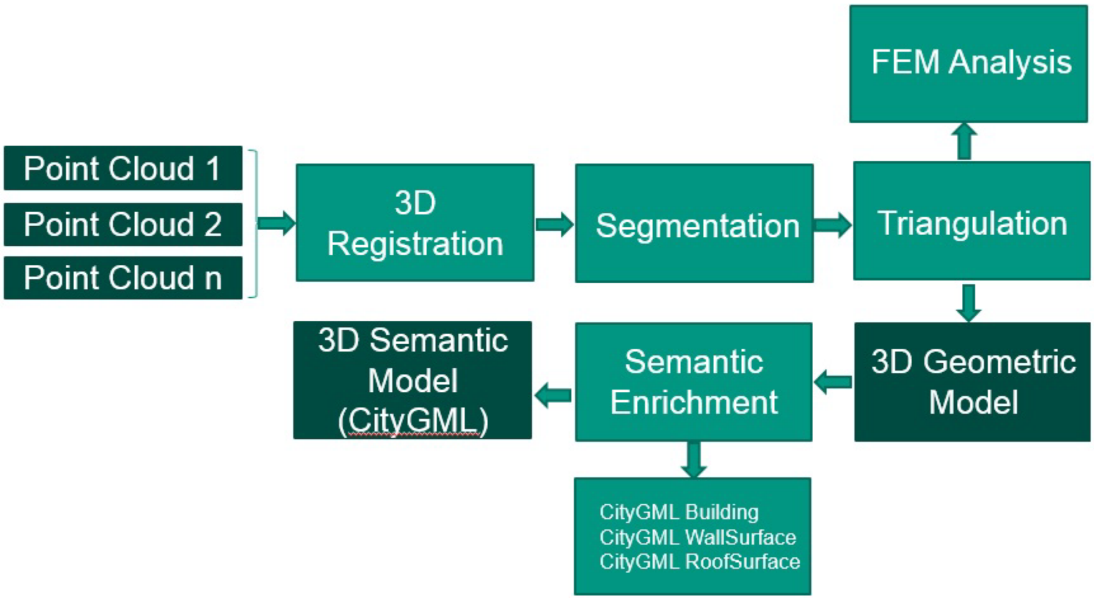

Figure 5.4 : The workflow of the evaluation procedure.

The final model is comprised of individually segmented stones which enables the user to detect the current surface condition of the stones comprising the tower as seen in Figure 5.5.

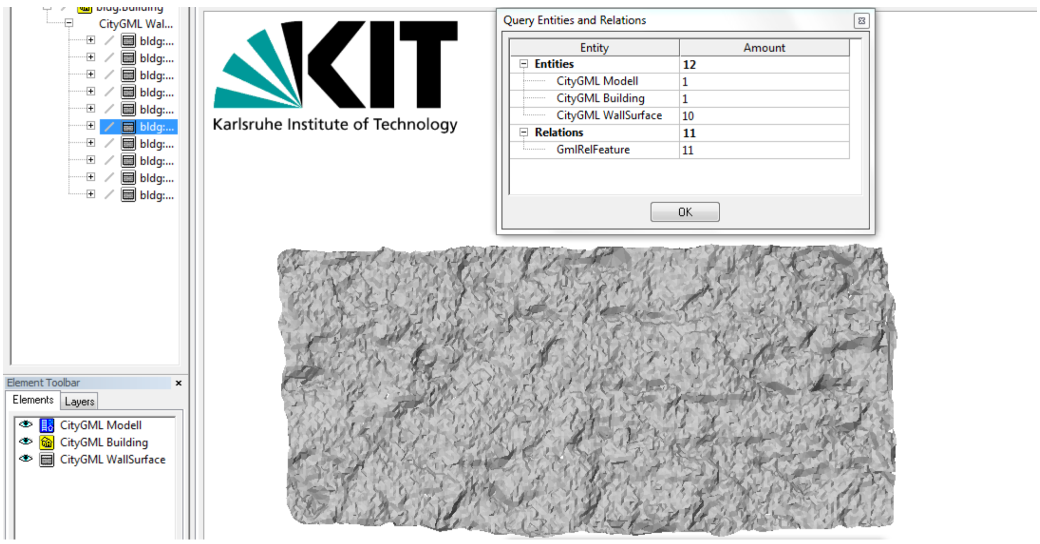

Figure 5.5 : Detailed view of a segmented stone [1].

A detailed view of a façade of North Tower visualized by using IfcExplorer, a software developed by the members of Karlsruhe Institute of Technology, Institute for Applied Computer Science, can be seen in Figure 5.6.

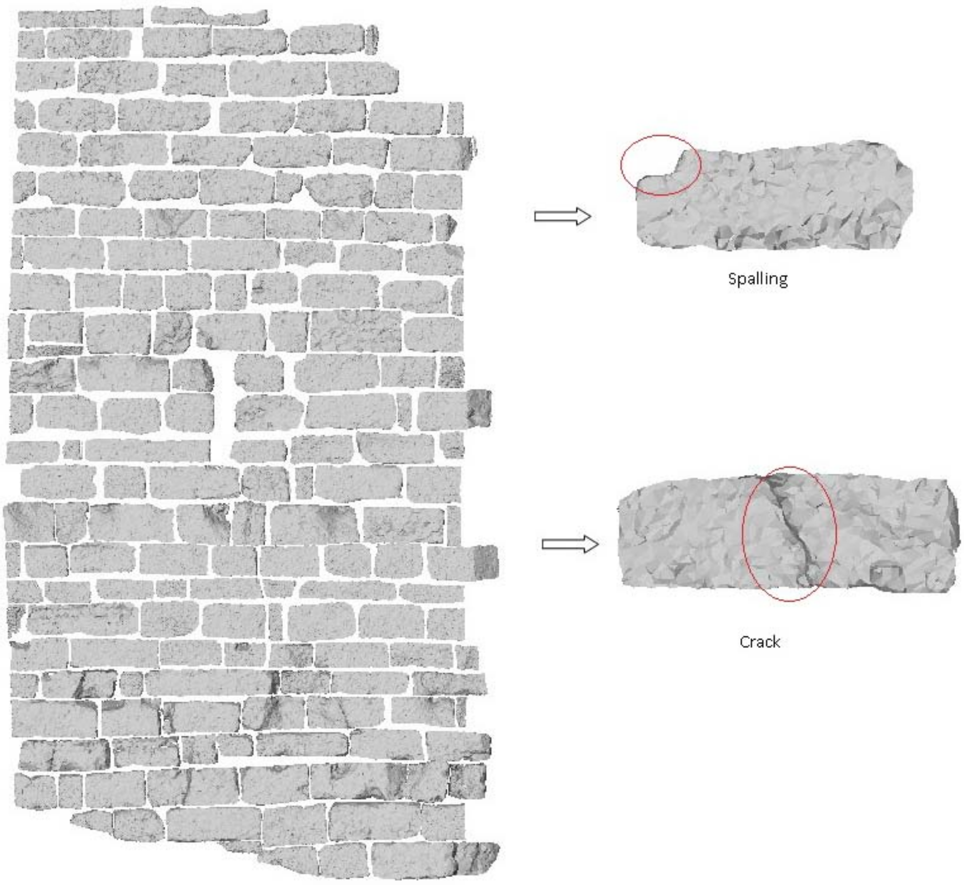

Figure 5.6 : Detailed view from a façade of North Tower segmented into stones [7].

The quality of the geometric input is one of the important factors affecting the quality of the 3D model. Since the preliminary purpose of our end product is to serve as a data model for architectural renovation and restoration projects, it is very important to detect the current surface condition of the stones in the final model to make decisions for restoration. In Figure 5.7 outer façade of the North Tower can be seen.

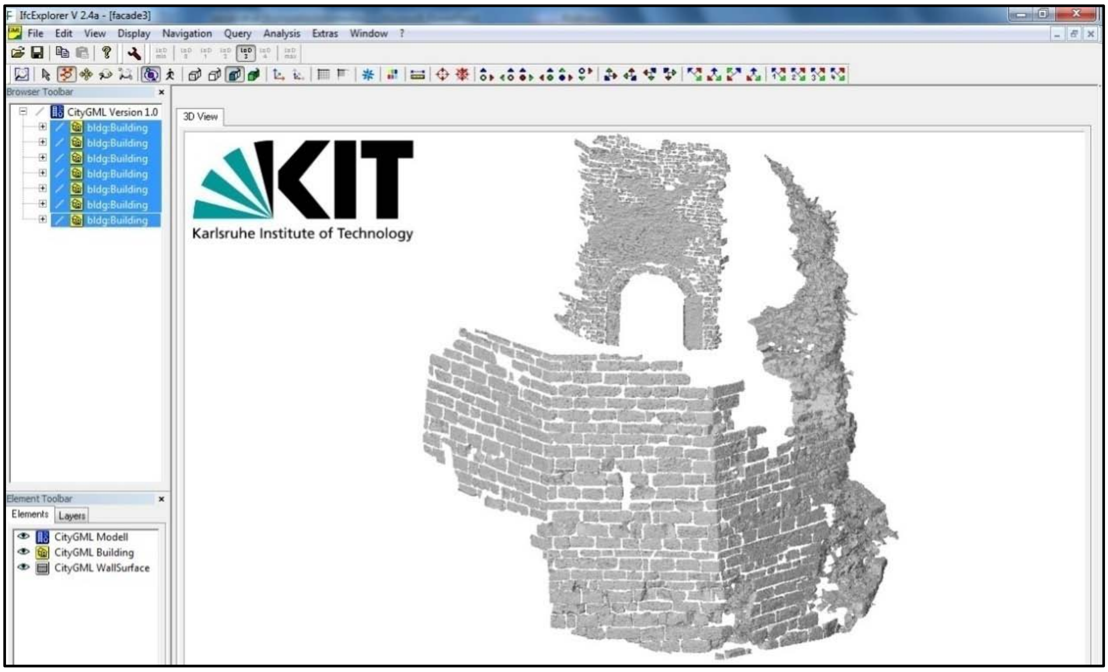

Figure 5.7 : Outer façade of the North Tower.

In Figure 5.8 part of the tower indicated by red color is the dome of the tower.In the element toolbar seen on the left part of the Figure 5.8, roof surface is indicated as CityGML RoofSurface.

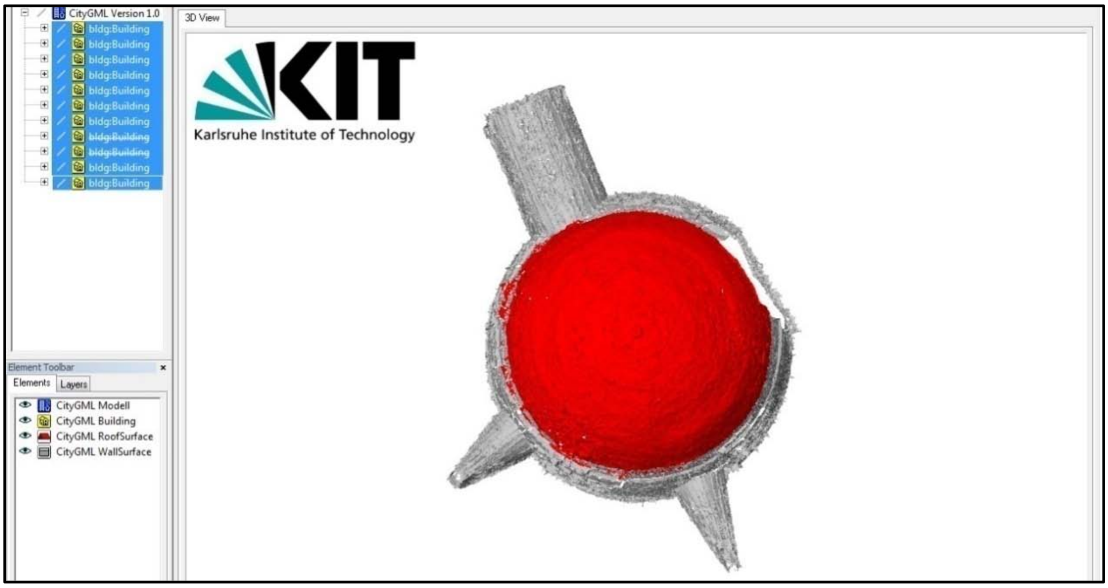

Figure 5.8 : Dome of the North Tower.

In Figure 5.9 inner façade of the North Tower can be seen from two different viewpoints.

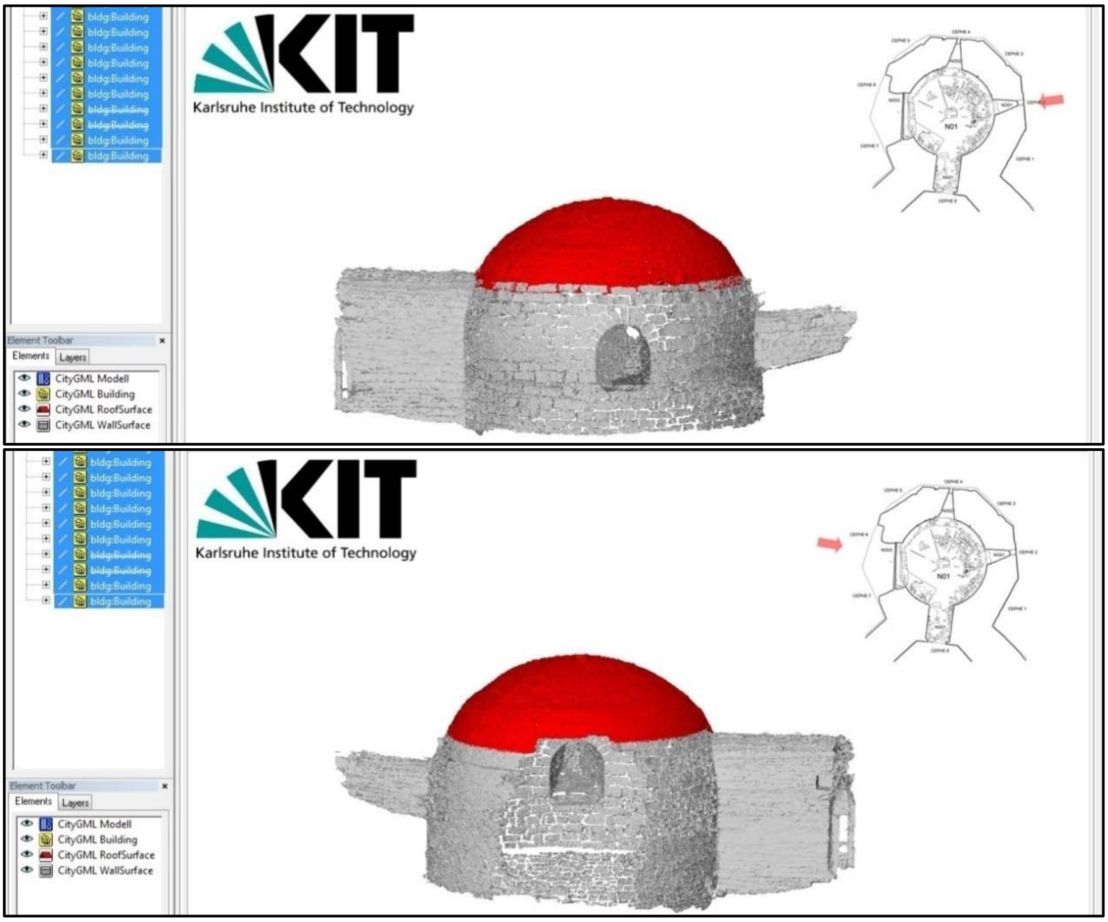

Figure 5.9 : Inner façade of North Tower.

6. INVESTIGATION MODELLING AND EVALUATION OF NORTH AND SOUTH TOWERS OF SEDDÜLBAHİR FORTRESS

6.1 Methods for Historic Masonry Structures

Before modeling and analyzing, some experimental study and investigation on the structure should be performed.

These steps can be listed as follows;

-Detailed inspection of architectural plans showing the original state of a structure

-Investigation of load bearing system of the structure

-Determination of damages on the structure

-Determination of material properties

-Determination of ground conditions where the structure is founded.

6.1.1 Sample collection

The material samples that are going to be investigated in historical structures should be carefully chosen and collected. Sample size must meet the requirements of experiments that are planned [38], [39].

Within the framework of this procedure detailed observations were made inside and outside the towers façades and walls in order to choose the most appropriate stone and mortar samples. In the field during the collection of samples, materials that can be easily removed from the façades and walls and not lead to deformation were chosen. Samples were collected by hand or with a hammer and chisel when necessary as seen in Figure 6.1.

Figure 6.1 : Sample collection for analyses [10].

Material samples were coded during the sample collection process and placed in bags with individual code numbers. During sample collection, the locations of samples were recorded using drawings and photos, both which are necessary for documentation [39], [37], [40].

6.1.2 Materials used in North and South Towers

Natural Stone: Stone is one of the materials most commonly used in the construction of historical buildings. Stone is known to be good in compression but weak in tension. In the construction of historical buildings metamorphic and sedimentary stones are widely used because of their ease of workability. In Table 6.1 compressive, shear, tensile strength and modulus of elasticity values of some stones can be seen.

Table 6.1 : Average physical properties of natural building stones [41].

Type of Stone	Compressive Strength (KPa)	Shear Strength (KPa)	Tensile Strength (KPa)	Modulus of Elasticity (KPa)
Granite	30.000-70.000	14.000-33.000	4.000-7.000	$30x10^6$-$55x10^6$
Marble	25.000-65.000	9.000-45.000	1.000-15.000	$25x10^6$-$70x10^6$
Limestone	18.000-35.000	6.000-20.000	2.000-6.000	$10x10^6$-$55x10^6$
Sandstone	5.000-30.000	2.000-10.000	2.000-4.000	$13x10^6$-$50x10^6$
Quartz	10.000-30.000	3.000-10.000	3.000-4.000	$15x10^6$-$55x10^6$
Serpentine	7.000-30.000	2.000-10.000	6.000-11.000	$23x10^6$-$45x10^6$

Stone is also used in the construction of walls and pillars for carrying compression loads of arches, vaults and domes.

Lime Mortar*:* Plaster and mortar mixed with lime is used for construction in ancient Greek, Roman, Ottoman and subsequent periods. Lime can be used as binder and for lime mortar or plaster filling material by mixing it with aggregates. In order to improve the properties of lime and lime mortar, organic and inorganic substances can be added to the mixture [42].

Raw material for lime is limestone composed of calcium carbonate ($CaCO_3$) minerals. These stones are calcinated by heat and transformed into calcium oxide (CaO) as a result of the separation of carbon dioxide (CO_2). The obtained product is called quicklime. Quicklime (CaO) is obtained when calcination turns into calcium hydroxide (Ca(OH)2) by reacting with water or moisture in the air. This product is referred as hydrated lime.

There are many factors that affect the quality of lime. The lump size of limestone, porosity and size of calcium carbonate crystals are the main factors that affect the reactivity of quicklime. Water/lime proportion, the purity of quicklime, particle size and purity of water used to mix and slake lime also affect the porosity of lime [43]. The lime cycle can be seen in Figure 6.2 in detail.

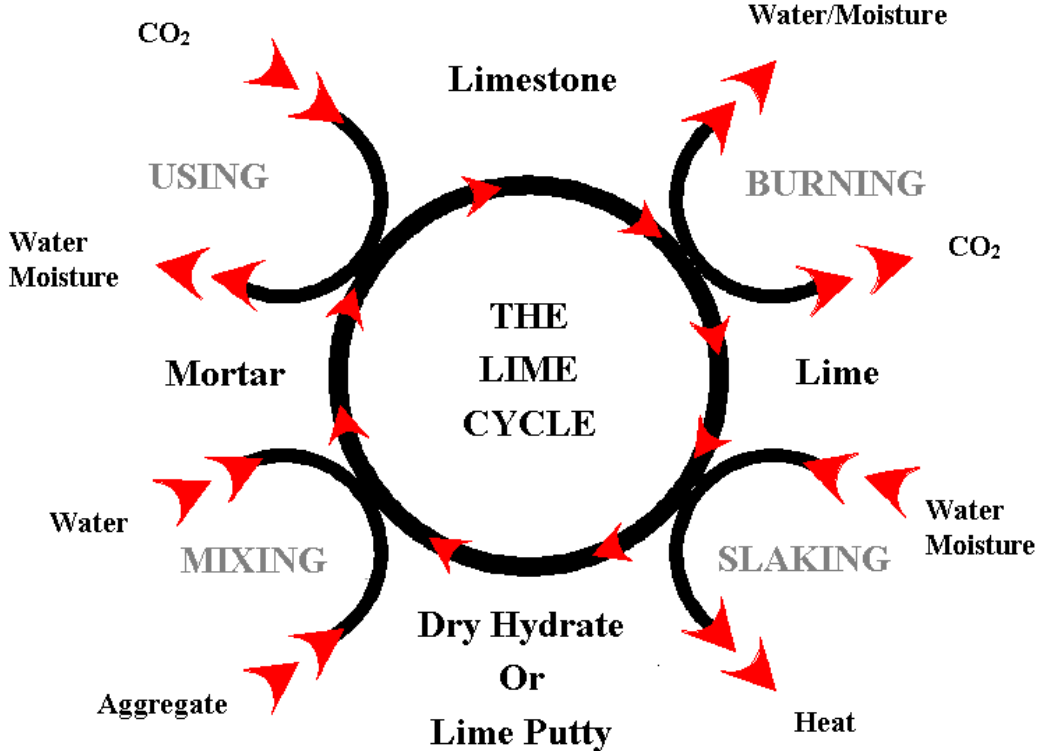

Figure 6.2 : Lime cycle between limestone and mortar [44].

Aggregates used as fill material in the production of lime mortar and plaster, can be classified as non-reacting with lime and reacting with lime (pozzolan) aggregates. Non-reacting aggregates are quarried from streams and seas. Pozzolans can be classified natural and artificial. Natural pozzolans (tuff, trass, opal, etc.) are mostly composed of volcanic ash. Artificial pozzolan materials such as bricks, tiles, etc. are used in many historic buildings [45].

In order to accelerate carbonation or improve physical properties of lime during preparation of lime mortar, organic and inorganic substances can be used. Some of them are blood, egg, cheese, fertilizer, Arabic gum, animal glue, vegetable juices and casein [46].

Wood: Wood is one of the most widely used elements in historic structures because of its ease of handling features. The life of wood is short compared to stone but its lightness and tensile strength is better than stone. By considering the properties mentioned above, large openings which cannot be permeated by stone are permeated with wooden elements.

Metal Clamps*:* Unreinforced masonry walls are good in compression but weak in tension. Tensile elements such as iron clamps are used to bind masonry stone in order to make them work together and enable walls to transfer load equally to the foundation. They also provide physical binding and protect the structure against seismic forces.

6.1.3 Determination of mortar and stone characteristics

The most commonly used materials in masonry structures are natural stone, brick, mortar, wood and iron. Because of this composite formation, determination of load bearing elements and capacity of historic structures by laboratory tests is quite difficult.

Physical, chemical and mechanical properties of materials affect the load bearing performance of masonry structures. These are: strength, water absorption coefficient, compressive strength, shear strength, tensile strength and thermal expansion properties. Material strength is affected by air pollution, erosion caused by wind and excessive heat, freeze and thaw cycles, compressive strength and water absorption capacity of the material.

Macroscopic Inspections: In order to determine the texture and aggregate distribution of samples, visual inspection and detailed analysis were made and the scaled photos of samples are given as seen in Figure 6.3.

Figure 6.3 : Stone sample taken from the Fortress of Seddülbahir [10].

Determination of Chemical Properties: In order to determine the chemical properties, material compositions, carbonate content and aggregate morphology of samples taken from the structure, acid loss analysis, after acid loss analysis, sieve analysis and loss on ignition analysis on left aggregates were made.

Acid Loss Analysis: Acid loss analysis is made in order to calculate lime content, separate binder, fine aggregate, and coarse aggregate. This analysis should be evaluated with microscopic and mineralogical analyses.

Aggregate and lime which are components of mortar cannot be easily separated from each other. In order to separate binder and aggregate by reaction, diluted hydrochloric acid (HCl) is used. The most important result of acid loss analysis is; while the binder is dissolved in acid, siliceous aggregates are not affected by the acid. The results of the analysis can be seen in Table 6.2.

Table 6.2 : Results of calcination, acid loss and sieve analyses [10].

Sample	Calcination (%)			Acid Loss (%)		Left on Sieve (%)				
Number	**Moisture**	**550°C**	**$CaCO_3$**	**Lost**	**Remain**	**1000µ**	**500µ**	**250µ**	**125µ**	**<125µ**
MSP01	-	-	-	87.61	12.39	13.59	0.00	33.01	6.07	47.33
MSP02	2.97	6.20	85.98	93.65	6.35	1.39	0.00	37.95	6.65	54.02
MSP13	4.33	6.25	52.10	75.76	24.24	28.81	9.70	51.39	2.77	7.34
MSS03	-	-	-	51.05	48.95	-	-	-	-	-
MSS12	-	-	-	77.15	22.85	-	-	-	-	-
MSS13	-	-	-	83.88	16.12	-	-	-	-	-

Loss on Ignition analysis: In order to determine the composition, moisture and carbonate content of mortar samples loss of ignition analysis has been used. The samples are heated up to 105°C, 550°C and 1050°C, and after cooling down they are weigh each time.

The moisture content of samples was measured by weighing them before and after drying in an oven until a constant weight was reached. The weight loss corresponds to the moisture content and is expressed as a percentage of the dry mass of the sample. The moisture and calcium carbonate ($CaCO_3$) content of sample as a percentage can be seen in Table 6.2.

Sieve Analysis*:* After dissolving the mortar samples in HCl solution, in order to determine the grain size (granulometry) of insoluble aggregates (part of the mortar left undissolved), sieves with sizes ranging between 1000µ and 125µ were used. The results can be seen in Table 6.2.

In the preparation of repair mortar, results of sieve analysis were used. After completion of sieve analysis aggregates were examined with stereomicroscope in order to give detailed information about aggregates [47].

Soluble Salt analysis*:* Salt activity is usually noticed when there is efflorescence on the surface of materials (stone, mortar, etc.) occur. The hygroscopic nature of salt is an important factor in determining the destruction potential. This nature causes the salts to absorb water present in moist air and finally start to hydrate and dissolve in the water they absorbed. The resulting salt solution is redistributed in the porous system by capillarity and diffusion mechanisms. Its effect depends on the pore type and structure of the material. During dry periods water evaporates from the salt solution and mechanical damages occur on the porous material because of salt crystallization. The names, symbols and sources of most common salts found in historic masonry structures can be seen on Table 6.3.

Knowledge of the composition of the salt system and the behavior of the air surrounding it helps in the calculation of the power of destruction. This information is essential in determining the appropriate environmental conditions and provides long term conservation of salt-loaded stone, mortar and wall paintings. Thus, the quantitative analysis of salt gives basic information to determine the appropriate environmental conditions. Quantitative analysis of salt is required also for comparing different conservation methods and to check salt reduction work. In addition it is also used for determining the water soluble salt content of materials to decide whether it is within the framework of historical building conservation [48].

Table 6.3 : Most common salts in historical masonry structures [48], [49].

Type	Symbol	Source
Calcium	Ca	Limestone, gypsum and fluoride
Sodium	Na	Sea spray and other natural water
Chloride	Cl^-	Sea spray, de-icing salts spread on roads in winter, emissions of hydrochloric acid into the atmosphere from industrial activity
Nitrates	NO_3^-	Agricultural land(fertilizers), photochemical smog, microorganisms, sewage water
Carbonates	CO_3^-	Calcite
Sulphates	SO_4^{2-}	Atmospheric pollution, agricultural land(fertilizers), original or added materials, sea spray, microorganisms

Quantitative analysis of salt is required to calculate equilibrium relative humidity of the structure contaminated with salt, salt crystallization cycles and to prevent the damage.

Most of the structures and repair materials contain a certain amount of soluble salts. Therefore, in the salt sensitive environments during repair works, repair material containing small amounts of salt should be selected.

As a part of the work, the amount of soluble salts is found by conductivity measurement and the type of salts (chloride, sulfate, nitrate, carbonate) were determined by spot analysis. The results of the analyses can be seen in Table 6.4.

Table 6.4 : Qualitative and semi-quantitative analysis of water soluble salts [10].

Sample Number	**$Cℓ^-$**	**SO_4^{-2}**	**CO_3^{-2}**	**NO_3^-**	**Conductivity µs**	**Salt %**
MSP01	++++	-	-	+	455	3.27
MSP02	++++	-	-	+	351	2.52
MSP13	+	+	-	+	136	0.87
MSS03	++	-	-	+	150	0.98
MSS12	++	-	-	+	113	0.74
MSS13	++	+++	±	+	599	4.21

(-) indicates the absence of an ion

(±) indicates the presence of an ion at the limit of perceptibility

(+) indicates the presence of an ion

(++…) indicates the presence of an ion in relative abundance

Further Technical Analysis*:* Detailed determination of the microstructure of masonry components requires an initial mineralogical identification of various masonry minerals present in the component. Two common methods of quick identification of diverse masonry minerals involve: (a) examination of masonry minerals by a petrographic microscope, where various minerals are identified by their characteristic refractive indices, and (b) X-ray diffraction (XRD) [50].

The petrographic and X-ray diffraction information is necessary for interpretations in calculating mortar composition [51].

Petrographic analyses supply detailed and accurate information about the composition of the material besides its texture, microstructure and other properties. Thin sections are observed under a polarizing microscope and by using the optical properties of minerals; mineral compositions of observed samples are then determined.

X-Ray diffraction is one of the few methods that enables one to directly identify the numerical features and identity of crystalline phases present in samples. It is widely used in material science, engineering, geology, environmental science and biology [52].

X-ray diffraction analysis is used in the diagnosis of dissolved salts and clay minerals in rocks, mortar, flowering products and mineralogical examination of black and dirty shell. Mineralogical composition of the samples obtained by XRD analysis can be seen in Table 6.5.

Table 6.5 : Mineralogical composition of samples obtained by XRD analysis [10].

Sample Number	Calcite %	Quartz %	Clay %	Dolomite %	Feldspar %	Mica %	Plagioclase %
MSP02	95	5	-	-	-	-	-
MSP13	75	20	-	-	-	-	5
MSS03	46	37	-	10	-	-	7
MSS12	40	10	-	45	5	-	-

Determination of Mechanical Properties: In historic masonry structures, in order to determine the level of compressive stress, shear stress brick, stone or concrete blocks with mortar, modulus of elasticity and properties of materials, non-destructive test methods are widely used. In some parts of the masonry where non-destructive tests are performed, core samples are collected. Results obtained from core samples are evaluated together with non-destructive test results, material and structure performance is determined [53].

Non-destructive tests applied on masonry structures can be as follows [54]:

Ground Penetrating Radar (GPR): Subsurface voids and embedded items.

Ultrasonic Pulse Velocity (UPV): Crack and deterioration location

Impact Echo (IE): Crack and debond location.

Rebound Hammer (Schmidt Hammer): Surface hardness

Metal detection (Induction): Location of reinforcing or other embedded materials in subsurface.

Infrared Thermography (IRT): Surface temperature differences suggesting voids or delamination.

Flatjack Deformability Test: Compressive strength and/or stiffness of brick/stone assembly.

Flatjack Stress Test: Determination of in-situ compressive stress in masonry.

In order to obtain reliable results, suitable instruments should be used, adequate measurements must be taken and the measurement or/and test results should be evaluated by experts.

6.1.4 Determination of common material properties

Unit elements forming the masonry structural element and the binder mortar usually have different material properties. Due to these properties, masonry structure elements are regarded as comprised of homogeneous material based on the dimensions of the unit element and binding pattern with each other. The binding pattern of the unit element is very important in masonry structures for calculating its load bearing capacity [55].

Determination of common material which will represent the two materials with different properties provides greater convenience for the analysis. Common material parameters are obtained by two methods. The first method, brings the experimental data used in analysis together. The second method, is the basic approach called the homogenization technique [56].

As seen in Figure 6.4 a simple cell taken from the brick wall is inspected and the participation rates of mortar and brick are taken into account for calculation of material parameters and considered as a single material.

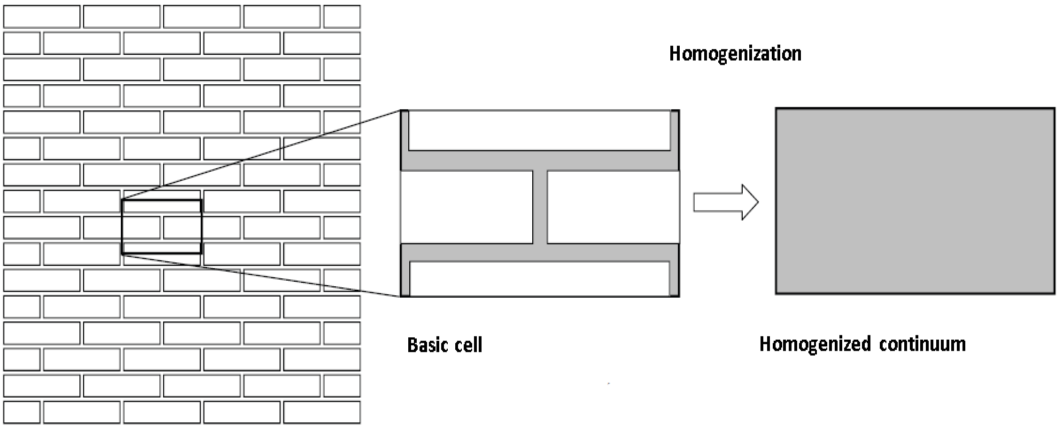

Figure 6.4 : Common material parameter determination method [57].

6.2 Load Bearing Elements of North and South Towers

Masonry structures are made up of stone brick or adobe materials which stand either by their own weight with or without mortar. In masonry structures walls both separate the spaces and have a load bearing function. They transfer the loads of the dome and other structural elements to the foundation. Before modeling and analyzing, some experimental study and investigation on the structure should be performed. Some preliminary tests were conducted on the North and South Towers, as mentioned in previous parts of this chapter.

6.2.1 Foundation

Foundations are load bearing elements that transfer the weight of the structure, usage loads, snow, wind and earthquake loads to the earth [58]. In historic buildings the foundation is the most important part of the structure for load bearing analyses.

The foundations of historic buildings remain very primitive compared to today's conditions and do not exceed a few number of types [59].

6.2.2 Dome

A dome is obtained by rotating an arch around its symmetry axis. They are shell elements which carry loads on positive double curvature surfaces [60]. In historic masonry structures domes were usually built as spheres. The weakness of masonry under tensile forces, and the tensile forces caused by the windows built inside the dome causes formation of cracks at dome points where the windows are located [61].

The most important precaution that can be taken against the formation of tensile stresses at the base of dome is to surround the region with a circle made of a material resistant to tensile stresses. The wall section on which domes are resting on is called drum. Drums at the large domed structure neutralize tensile forces occurring in the region with their massive and heavy structure [41]. Compression and tension regions of dome can be seen in Figure 6.5.

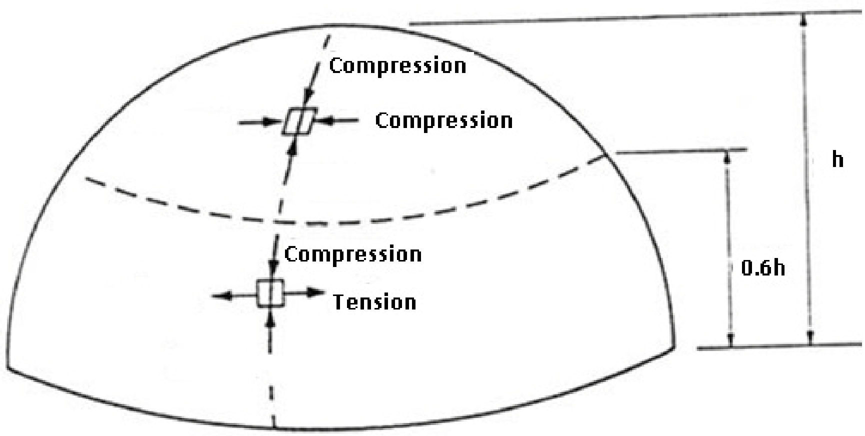

Figure 6.5 : Compression and tension regions at dome [62].

6.2.3 Load bearing wall

Load bearing walls are structural elements that transfer vertical and horizontal loads to the foundation [59]. In masonry structures wall thickness increases or decreases depending on the loads and weight of the elements that a structure carries.

Vertical loads originated from the own weight of the structure, weight of roof or slab; external horizontal loads generated by wind, earthquake, etc., loads coming from the curvilinear coating elements like: arch, vault, etc. affect the thickness of the walls. On the other hand, door and window openings reduce the strength of the load bearing walls.

Loss of material rates of load bearing walls should be considered in order to maintain enough and continuous bearing capacity. At critical points like corners loss of material rates should be continuously monitored and minimized.

6.3 Finite Element Modelling with SAP2000

Finite Element Method (FEM) is a numerical method that can be used for static and dynamic analysis of three dimensional linear or non-linear structures. The results can be obtained in numerical and graphical formats [63].

Advantages of the finite element method can be as follows;

-Material properties of adjacent elements might not be the same. This property allows the application of FEM for the analysis of the objects composed of different materials.

-Shapes with non-uniform borders can be analyzed using curve edged elements.

-Element size can be changed by the user. Thus in areas where significant changes are expected they can be divided into smaller elements for precise calculations. The speed of the process can be increased when necessary for the same area by dividing into large elements.

-Boundary conditions can easily be applied.

-Versatility and flexibility of the FEM can be effectively used for complex structures, continuous environment and computation of cause and effect relations in other problems [64].

The main steps of the finite element method can be summarized as follows.

-Load bearing system is divided into small pieces (finite elements).

-Finite element shape functions are defined.

-Element matrices are determined.

-System matrices are obtained by merging element matrices.

-The boundary conditions are applied.

-System balance equation is solved.

-Advanced calculations of solutions and desired values are done [65].

The most important step in FEM is to define the area given by elements. Selection of the element type, number and density for problem analysis and desired degree of accuracy depends on the geometry of the area.

If the location of a system in motion is estimated by a single parameter, such a system is called as a single degree of freedom system. If estimated by more than one parameter called as multi degrees of freedom system [66].

The first step for examination of the building under ground motion is, representing it with a simple model. The number of parameters necessary for determination of the location of a structure under vibrational state is called the “degrees of freedom”. For the solution the system is discretized and defined as a system with multi degrees of freedom. In addition most of the systems with multi degrees of freedom are solved by a simple approach assuming as a single degree of freedom system.

Evaluation of historical masonry structures requires some detailed technical preliminary preparation. Before modelling and analyzing, some experimental study and investigation on the structure should be performed.

These steps can be listed as follows:

-Detailed inspection of architectural plans showing the original state of a structure

-Investigation of load bearing system of the structure

-Determination of damages on the structure

-Determination of material properties

-Determination of ground conditions where the structure is founded.

SAP2000 Analyses: Modelling of the North and South Towers of Seddülbahir fortress have been made by the finite element modelling method using point cloud data of the towers. SAP2000 software was used for modelling. As mentioned before in finite element analysis the geometry of the structure and its elements are determined by finite number of nodes.

In order to determine the behavior of the North Tower in an accurate way, 4679 shell elements and 2449 node points are used. For South Tower 2378 shell elements and 1248 node points are used. The stresses (S11, S22, S12, S13, S23 and S33) acting on the shell elements,which have same definition as forces (Fij) are schematically shown in Figure 6.6.

The modulus of elasticity, weight per unit volume and poisons ratio of structural elements of North and South Towers are 9.000.000 kN/m^2, 25 kN/m^3, 0.3 respectively. Since no mechanical tests were conducted on both towers these values are obtained as a result of material tests and a literature search.

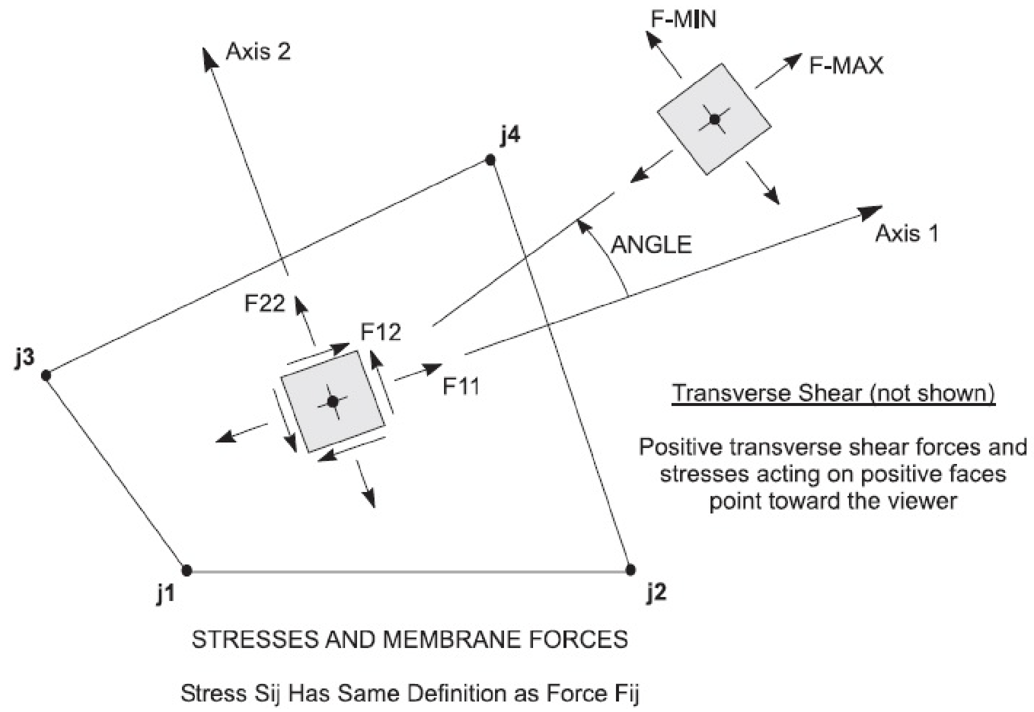

Figure 6.6 : Shell element stresses and internal forces defined in SAP2000 [67].

By using equivalent seismic load method defined in Turkish Earthquake code [68], earthquake calculations have been done. In this method total equivalent seismic load (base shear), V_t acting on the entire building in the earthquake direction is determined by (6.1).

$$V_t = W.A(T_1)/R_a \tag{6.1}$$

W in equation (6.1) is the total weight of the structure and calculated by adding the W_i floor weights of the structure as in (6.2).

$$W = \sum_{i=1}^{N} W_i \tag{6.2}$$

Weights of each floor are obtained by adding the live loads multiplied by a pre-defined coefficient (n) to the static loads by using (6.3). The reason for reducing the live loads, is the low probability of having all live loads at the same time on the structure during an earthquake.

$$W_i = G_i + n.Q_i \tag{6.3}$$

$A(T_1)$ is the spectral acceleration coefficient that corresponds to the first natural vibration period T_1 and is calculated as in equation (6.4)

$$A(T_1)=A_0.I.S(T_1) \tag{6.4}$$

A_0 is the effective ground acceleration coefficient and as Seddülbahir fortress is located at a first degree earthquake zone its value is 0.40.

I is the building importance factor whose value is 1.4 (for museum), S(T) is the spectrum coefficient and is calculated according to local ground conditions and the natural period (T) of the structure as in equation(6.5).

$$\begin{aligned} &S(T)=1+1.5.T/T_A && (0\leq T\leq T_A) \\ &S(T)=2.50 && (T_A\leq T\leq T_B) \\ &S(T)=2.5.(T_B/T)^{0.8} && (T_B<T) \end{aligned} \tag{6.5}$$

Spectrum coefficient (S(T)) diagram with respect to natural period can be seen in Figure 6.7.

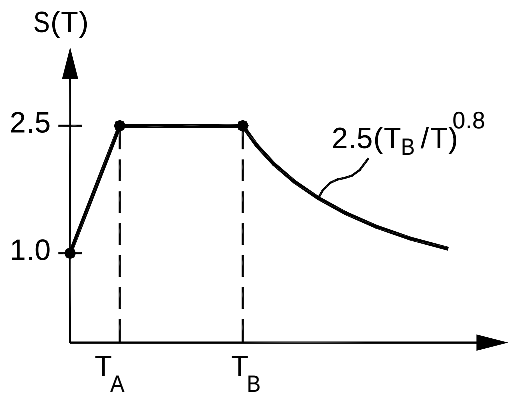

Figure 6.7 : Spectrum coefficient diagram with respect to natural period [69].

Spectrum characteristic periods T_A and T_B are obtained from Table6.6 according to local site class type. Local site class of Seddülbahir Fortress is Çanakkale formation which corresponds to Z3 on Table 6.6.

Table 6.6 : Local site classes and spectrum characteristic periods (T_A,T_B) [68].

Local Site Class	**T_A (sn)**	**T_B (sn)**
Z1	0.10	0.30
Z2	0.15	0.40
Z3	0.15	0.60
Z4	0.20	0.90

R_a is the seismic load reduction factor and is calculated according to structural behavior factor

R_a and natural vibration period T as in (6.6).

$$R_a = 1.5 + (R - 1.5)\frac{T}{T_A} \qquad (0 \le T \le T_A)$$
$$R_a = R \qquad (T_A < T) \qquad \textbf{(6.6)}$$

The spectrum is applied to both towers in two different directions as EQ_x (earthquake loading in X direction), EQ_y (earthquake loading in Y direction) and the load combinations are made accordingly. Allowable compressive stress provided by the current Turkish Earthquake Design code for stone masonry (fc=0.3MPa) is increased by 3. During the evaluation of the results, there hasn't been any reduction (R=1) at the effect of earthquake loads or dead loads in order to compare the results with the capacity. The allowable tension is assumed as 15% of the compressive strength as 0.135MPa. The allowable shear stress of the wall is calculated through the formula τm = τo+μσ where τo, allowable stress for cracking (0.3 MPa), μ, the coefficient of friction (0.5) and σ vertical stress (0.45 MPa), thus, obtained the value 0.53 MPa for the allowable shear stress of the stone.

In order to find the most unsuitable loading conditions of the North and South towers, 13 different combinations are made with EQ_x, EQ_y and G (dead loads, in this case weight of the tower).

Table 6.7 : Load combinations applied to North and South Towers.

Load Combination Name	**Load Combination Definition**
Comb1	G
Comb2	$G+EQ_X+0.3EQ_Y$
Comb3	$G+EQ_X-0.3EQ_Y$
Comb4	$G-EQ_X+0.3EQ_Y$
Comb5	$G+0.3EQ_X+EQ_Y$
Comb6	$G-0.3EQ_X+EQ_Y$
Comb7	$G+0.3EQ_X-EQ_Y$
Comb8	$0.9G+EQ_X+0.3EQ_Y$
Comb9	$0.9G+EQ_X-0.3EQ_Y$
Comb10	$0.9G-EQ_X+0.3EQ_Y$
Comb11	$0.9G+0.3EQ_X+EQ_Y$
Comb12	$0.9G-0.3EQ_X+EQ_Y$
Comb13	$0.9G+0.3EQ_X-EQ_Y$

All geometric dimensions and measurements necessary for mathematical model of the structure were obtained using the point cloud of the North and South Tower. Triangulated point clouds of towers were converted into SAP2000 readable format and necessary joints defining the foundations were installed as seen in Figure 6.8.

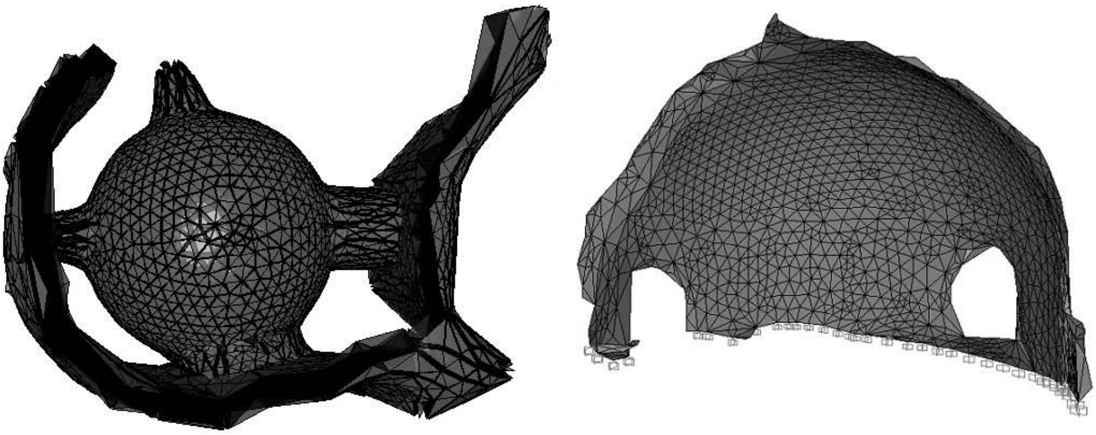

Figure 6.8 : SAP2000 models of North (left) and South (right) Towers.

In historic structures tensile and shear stresses acting on the structure play an important role in the structural survival. Tensile stress is the resistance ability of the material against tension. Shear stress is a stress state caused by the component of the resultant force acting on the material in the parallel direction of the surface. The schematic representation of tensile and sheer stress acting on structures can be seen in Figure 6.9.

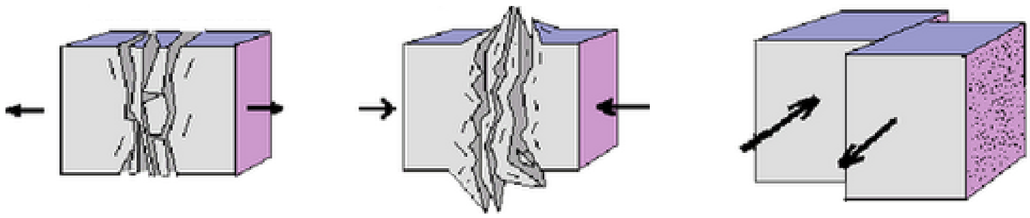

Figure 6.9 : Tensional (left), compressional (middle) and shear stress (right) acting on a structure [70].

As a result of loading combinations applied to the North and South tower, stress and displacement values are obtained for each case. S22 (in-plane direct stress) values seen in Table 6.8 for North Tower and Table 6.9 for South Tower indicate tensile stress and S12 (in-plane shear stress) values indicate shear stress. + sign indicates tension and – indicates compression. Masonry structures are good in compression however weak in tension as seen in Figure 6.10.

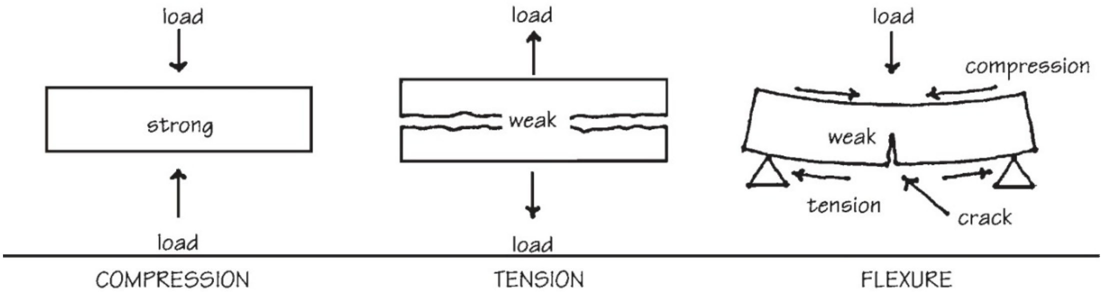

Figure 6.10 : Behavior of masonry under compression and tension [71].

S22 and S12 stress values obtained as a result of FEM of North and South towers for determining the critical conditions under earthquake loads using shell elements gives explanatory information about the earthquake resistance of the structure.

Numeric values of the most unsuitable stresses obtained for North tower and the loading combination can be seen in Table 6.8.

Table 6.8 : Maximum and minimum stress values obtained for North Tower.

Loading Combination	**Stress (kN/m^2)**	**Max/Min**	**Location**	**Stress Type**
Comb11	3228.03	Max	Top	S22
Comb5	3215.37	Max	Top	S22
Comb13	-2669.01	Min	Top	S22
Comb7	-2681.66	Min	Top	S22
Comb6	1513.3	Max	Bottom	S22
Comb4	1458.15	Max	Bottom	S22
Comb8	-2722.75	Min	Bottom	S22
Comb2	-2783.47	Min	Bottom	S22
Comb2	752.41	Max	Top	S12
Comb5	749.05	Max	Top	S12
Comb4	-1053.49	Min	Top	S12
Comb10	-983.97	Min	Top	S12
Comb4	994.55	Max	Bottom	S12
Comb10	930.82	Max	Bottom	S12
Comb2	-737.14	Min	Bottom	S12
Comb8	-712.94	Min	Bottom	S12

The most unsuitable stresses obtained for South Tower and the loading combination can be seen in Table 6.9.

Table 6.9 : Maximum and minimum stress values obtained for South Tower.

Loading Combination	Stress (kN/m^2)	Max/Min	Location	Stress Type
envelope	598.40	Max	Top	S22
envelope	507.23	Max	Top	S22
Comb7	-1609.11	Min	Top	S22
Comb4	-1650.04	Min	Top	S22
Comb4	902.4	Max	Bottom	S22
Comb4	898.76	Max	Bottom	S22
Comb7	-1408.59	Min	Bottom	S22
Comb13	-1314.26	Min	Bottom	S22
Comb7	393.12	Max	Top	S12
Comb7	388.47	Max	Top	S12
Comb4	-394.27	Min	Top	S12
Comb7	-367.5	Min	Top	S12
Comb7	476.14	Max	Bottom	S12
Comb4	447.30	Max	Bottom	S12
Comb4	-553.5	Min	Bottom	S12
Comb10	-525.19	Min	Bottom	S12

Graphical representation of S22 and S12 values for North and South Tower can be seen in Appendix C and D respectively. The most unsuitable stress values are observed around door and window openings together with the foundation support, as expected.

As a result of forces applied on tower U1, U2 and U3 displacement values given in Table 6.10 and Table 6.11 are observed.

Table 6.10 : Joint displacements for North Tower.

Joint No	U1 (m)	U2 (m)	U3 (m)
162	0,002	0,005	-0,002
214	0,003	0,005	-0,001
162	0,002	0,005	-0,002
214	0,003	0,004	-0,001
258	0,003	0,004	0,000
162	0,002	0,004	-0,002

For North Tower maximum displacements are observed on façade 8 because missing façades 2 and 1 effect the stability of the neighbouring façade.

Table 6.11 : Joint displacements for South Tower.

Joint No	U1 (m)	U2 (m)	U3 (m)
305	-0,001	-0,001	-0,001
255	-0,001	-0,001	-0,001
362	0,000	-0,001	-0,001
254	0,000	-0,001	-0,001
304	0,000	-0,001	-0,001
256	-0,001	-0,001	-0,001

For South Tower maximum displacements are observed at the peak part of the dome. Graphical representation of displacements observed for North and South towers under different loading conditions can be seen in Appendix E and F respectively. In figures Pt obj represents node numbers, U1, U2, U3 indicate displacements in metres and R1, R2 and R3 indicate rotations in radians.

7. RESTORATION AND CONSERVATION RECOMMENDATIONS

Seddülbahir fortress area was changed to first degree archeological site in 2006 [72]. During the excavations carried out at the archaeological site, both existing and sites which will be excavated in the future at the fortress of Seddülbahir should be protected against destruction. For this reason the restoration project should contain a conservation stage. At this stage all structural and architectural elements of the fortress that are in danger and require immediate repair should be preserved as a whole.

7.1 Causes of Damage and Deterioration in Historic Masonry Structures

Damages seen on masonry structures show differences depending on the material structure, shape of the construction, direction of the forces acting on the structure [72]. Deterioration is a process that causes reduction in strength, brittleness of material, and change in material properties, leading to loss of material in structural elements most of the time starting from the outer surface and processing inward. Damage is partial or complete loss of bearing capacity of structural elements or materials by deterioration of external factors.

Deterioration of masonry building materials usually begins on the surface of structural elements exposed to climatic conditions. On the surfaces whose physical and chemical properties are changed, crusting, surface erosion and material loss occurs. The increase of water in masonry material influences the physical and mechanical properties and accelerates the separation of masonry materials[73].

When investigating the causes of damage property of the load bearing elements, material type, structural weaknesses, foundation and environmental conditions and other negative factors affecting the structure should be considered. In some cases similar looking damage arising from different factors may be encountered.

While assessing damage, the primary causes of deterioration should be searched and the level of deterioration should be determined and after that damage processes should be determined. The level of deterioration and damage depends on the physical properties of materials and conditions of conservation provided as well as maintenance of the structure. Deterioration and damage that occurs can be determined by simple observation on the surface but sometimes requires more detailed research and tests [74].

The formation of deterioration and damage to the monumental historic buildings is an important factor that threatens the safety of life because these structures are visited by numerous people at the same time. In addition to that, loss of historical and cultural values is an irreversible phenomenon.

When determining deterioration and damage to the historical monumental buildings, the structure should be evaluated as a whole by a multidisciplinary team of experts. According to the damage type and level of interventions such as improvement, maintenance, repair or restoration of loses in load bearing system should be decided.

7.1.1 Natural factors

Structures are always under threat of natural disasters, climate effects, impacts of living organisms and natural formations which cannot be avoided. But the impact of natural events and formations can be significantly reduced by investigating the format, cause and speed of the negative effects and taking precautions. When the necessary precautions are not taken or natural disasters are experienced structures can be damaged.

Natural disasters: cause very serious damage because their size and effect cannot be predicted or eliminated. Based on the post disaster findings and studies some precaution can be taken for the next disaster. Earthquake is often the most important natural disaster that threatens historic buildings.

Earthquake motion is the sudden release of energy accumulated in earth by sudden fracture of layers. These fractures are formed as a result of movements in deep layers of the earth, and transmit the energy as wave motion to the earth crust. The structure of the earthquake waves differs with the structure of the earth crust and the distance of earthquake center to the earth crust. The shock formed in the depths of earth that causes earthquake is transmitted to the structure depending on the ground type by foundations [72].

Damage that will form on historical masonry structures depends on the type and structure of ground as well as size and shape of building components. Repeated loads acting on structures that stand for centuries cause material fatigue in time and cause damages to structures.

Effect of water and humidity: One of the leading causes of deterioration of masonry structures is water and humidity which penetrates into the material. Temperature differences, freeze thaw cycles, penetration of capillary water into the structure, flowering and such effects cause fatigue in materials. Rain water, ground water, or water from the air in humidy form, start the deterioration or speed up the deterioration [75].

Water that enters the building structure by capillary action starts freeze thaw cycle because of temperature changes resulting from climatic heat exchange. Depending on the porosity of the material, the water present in the structure freezes, expands and causes cracking of material. When the temperature increases, release of salts with dissolving water may cause mortar joint discharges. Joints discharges may also be seen due to shift between blocks because of loads. Therefore deterioration and damage to the structure should be evaluated as a whole and the relationship and interactions between factors affecting the structure should be taken into consideration in the investigation.

The presence of water and humidity in masonry structure causes formation of algea, shallow molds, discoloration, and decay, prepare a suitable environment for biological species which lead to deteriorations (Figure 7.1).

Figure 7.1 : Biological species formation observed on walls [10].

In structures whose drainage system has not been set or damaged, groundwater is absorbed by capillarity within the masonry material and salts dissolved in water reveals to material deterioration (Figure 7.2).

Figure 7.2 : Efflorescence observed on stone surface [10].

Metal materials such as iron and steel rust because of contact with moisture present in the air. In stone, brick masonry structures metal elements such as clamps, tie rods, column circles, etc. are used. These metal components of the masonry structures oxidize in time because of water penetrating the structure and humidity. Oxidized elements cross section grows and cause cracks which can cause decrease in the load bearing capacity of the structure (Figure 7.3).

Figure 7.3 : Corroded metal clamps observed on façades [10].

Timber elements as well as metal elements used in masonry structural systems are threatened by insects and other species. Water and humidity creates a suitable habitat for insects and species. Insects impair the structure of wooden material by leaving their eggs into the structure. Wood swells by the effect of water, dries and cracks by the effect of wind which causes moisture to penetrate into the structure and prepare suitable conditions for fungal growth (Figure 7.4).

Figure 7.4 : Deteriorated wooden beams [10].

Biological effects: The most important factors that cause deteriorations in the structure are insects, plants and etc. living in components of the structure. These living creatures cause the material to lose its properties and load bearing capacity, especially weakens wood elements used in the masonry structure and cause loss in load bearing capacity. If there is also moisture effect in wooden elements, different types of harmful fungi and algae can thrive.

Wind borne seeds and spores set in the empty joints on the surface of the structure and cause growth of plants. Creepers and other plants acquire a living environment by clinging on elements such as walls. Plant and tree roots enter the wall structure causing disintegration and even integrate with the structural element (Figure 7.5).

Figure 7.5 : Plants and tree roots observed [10].

Suberization occurs on moist surfaces of the masonry structure. Easy and rapid growing fungi cling to the surface of the structural elements when they find suitable living environment and disrupt the structure of the material.

Algae, mosses and lichens find suitable living environment on masonry materials and prepare a suitable environment for other living organisms. Algae create dirt and stains on building component as well as secreting oxalic acid from its roots and this lead to deterioration. However algae which do not produce acid and do not lead to chemical reactions form a natural protective layer by covering the surface of the structure and alleviates the corrosive effects of wind [73].

Soil type and soil structure: The soil type and structure that the structure is founded, ground movements, ground water, soil-foundation relation affect the damages caused by ground. Low resistance of ground or occurrence of different layers may cause settlements or rotations and can lead to cracking over time. As historic buildings are often built hundreds of years ago, location and soil type might not be suitable and this may cause damage during disasters. Ground based damages in historic structures which have survived for centuries are caused by phenomenon which will affect the ground water flow direction such as seasonal drought, degradation of drainage system, water well near the structure, new structure foundation excavation.

The samples that are going to be investigated in historic structures, should be carefully chosen and collected. Sample size must meet the requirements of experiments that are planned [38], [39].

7.1.2 Man made factors

Humans as well as natural phenomena cause damage to many buildings. Human based factors such as air pollution, fire, improper material selection in restoration, lack of proper care and repairs, improper interventions, legal restrictions, budget problems, abandonment of the structure endanger the safety of historic structures.

Improper interventions: In historic monumental buildings during change of function or maintenance and repair, improper interventions can be made and this can lead to partial or complete damage to the load bearing system.

New functions given without regard to the original use can bring extra load to the structure or disrupt the balance of the load bearing system and can cause stresses or damage.

Vibration effects: Historic buildings built hundreds of years ago and still standing are under the effect of changing life, environmental conditions and technological developments. The growth of cities and population, increase in traffic density, especially rail transport system creates long term vibration effect on structures and is difficult to measure or determine.

Environmental pollution: Increase in industrial production and widespread use of technological products in everyday life caused environmental damage. Release of untreated hazardous waste into the nature, air pollution resulting from various gases and environmental pollution, directly or indirectly causes deterioration of structures. Harmful gases by directly acting on the surface, increasing temperature and harmful sun rays cause damage on structure and materials.

Lack of good care and maintenance: Sometimes historic structures are left to their own destiny because of property issues, economic or legal reasons. These structures are sometimes used by homeless people or animals as shelter and serious deteriorations occur.

Vandalism: Number of people living in cities increasesby migration to cities. Social and cultural change as a result of urbanization directly affects the human behavior. One of the negative effects threatening historic structures is the tendency to be areas of vandalism.

Vandalism is defined as performing deliberately bad actions. People with tendency to vandalism give serious harm to historical structures such as; writing on the walls, use the structure as shelter at night, theft, break structure elements, etc. (Figure 7.6).

Figure 7.6 : Graffitis and paints observed on walls [10].

7.2 General Conservation Decisions

Basic building materials of the fortress of Seddülbahir are; stone, mortar-plaster, wood, metal (wrought iron, lead) and brick. This section will concentrate on the research results and recommendations for the conservation and reusage of these materials.

According to Ahunbay [76] principles collected under “Conservation” are:

-The basic aim of the protection of the monuments is to provide permanent protection and to ensure continuity.

-Conservation of monuments can be made easier by using them for any useful social purpose but therefore the plan of the building or decorations should not be changed. However within these limits changes required by the new function can be designed and allowed.

-The conservation of monument should also include the maintenance of the environment without moving out the scale. If there is traditional media, it should be left as it is. No new substitute which will change the relations of mass and color, destruction or change should be allowed.

-A monument is an integral part of the history and environment attested. The whole monument or a part of it should not be allowed to be moved to another location except in required cases for protection and national or international benefits.

-Decorations such as sculpture, painting which are considered as complementary elements of monuments can be removed to other spots if there is no other choice.

Conservation of a structure should include the entire plan, cross-section properties, material, building system, load bearing system and residential properties. Any irreversible intervention made to one of the components stated above will not be called “conservation” [77].

7.3 General Restoration Decisions

Historic structures with significant importance should be conserved, repaired and processed. According to [76] principles collected under “Restoration” are;

-Entire process related with restoration should follow a detailed archeological and historical research. During the historical research of the structure following answers should be searched; date of construction, whether the construction was interrupted or not, sketch and drawings showing the location and dimension of damages, what are the repair and strengthening processes carried out for the structure, if there were any changes at the usage purpose for the structure and surrounding.

-During the repair and strengthening of the structure contemporary methods whose adequacy is provided by scientific information and experiments can be used where traditional methods are inadequate. A restoration method whose appropriateness is not fully tested should not be used. The procedure is recommended to be reversible (in order to be removed when necessary). For restoration always the original building methods and materials should be preferred.

-Different period of contributions to the structure should be protected. The purpose of restoration is not to convert the shape of the structure to its first style.

-Missing parts and partitions can be merged in a manner which will not lead to misunderstanding but at the same time should be distinguishable from the original.

-All the process and techniques applied during the restoration process should be documented in detail.

During the repair and strengthening of historic structures the main principle is to “keep interventions at minimum”. It is essential to keep the originality of an old monument during interventions [77].

7.3.1 Cleaning

-All kinds of plants and trees that are formed in interior and exterior parts of the fortress should be cleaned and removed by chemical methods. The façade cleaning can be done by micro sandblasting when necessary, in order to protect the patina of the original walls.

-While preserving the original plaster on the walls and joints all the cement fills should be removed.

-Unskilled additional buildings and animal shelters outside the fortress plot and adverse effects of animal wastes should be removed.

-If an excavation of the area of the upper fortress is to be conducted the reinforced concrete structures and cement platforms in the courtyard should be removed and the septic system connected with those structures should be dried.

7.3.2 Excavations and research

-For areas that do not have sufficient data for restoration and reusage, non invasive investigation, archeological excavation should be performed to reveal the layers of the original buildings.

-In order to detect the structural voids seen on façades and core of the structure, endoscopic research should be made.

- In order to determine the relationship of the building walls with the ground and drainage mechanism additional excavation needs to be conducted.

7.3.3 Reinforcement

-The load bearing system of the structures that are no longer stable due to war time damage or natural effects and is no longer stable should be stabilised and reinforced.

-Parts of the fortress can be restored using the existing stones together with original materials. The stones should be numbered prior to dismantling.

-Voids that are formed by the decay of stones and wooden beams, on the walls of the tower and body sections should be repaired with materials that are close to those of the original structure first quality oak beams and mortar as seen in Figure 7.7.

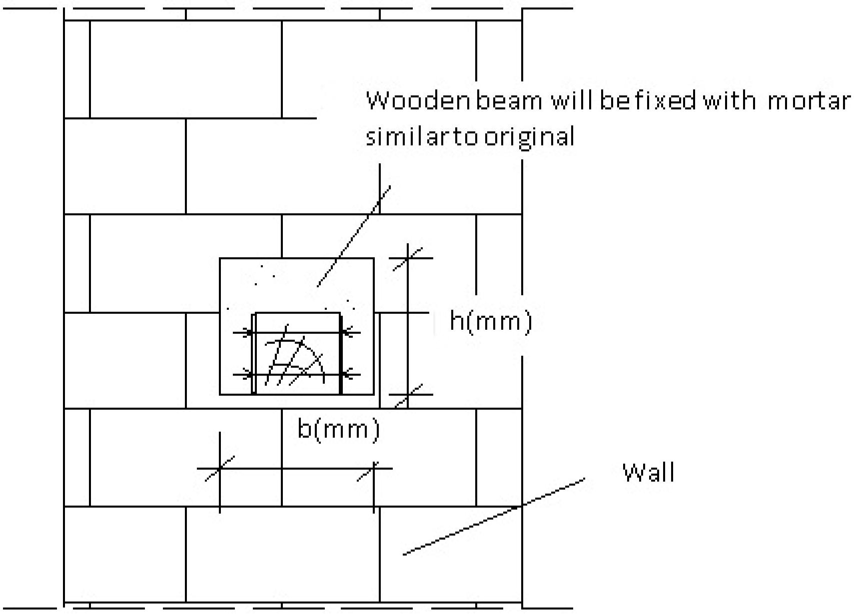

Figure 7.7 : Wooden beam detail[10].

-Capillary cracks on the structures should be filled with original mortar by injection as seen in Figure 7.8.

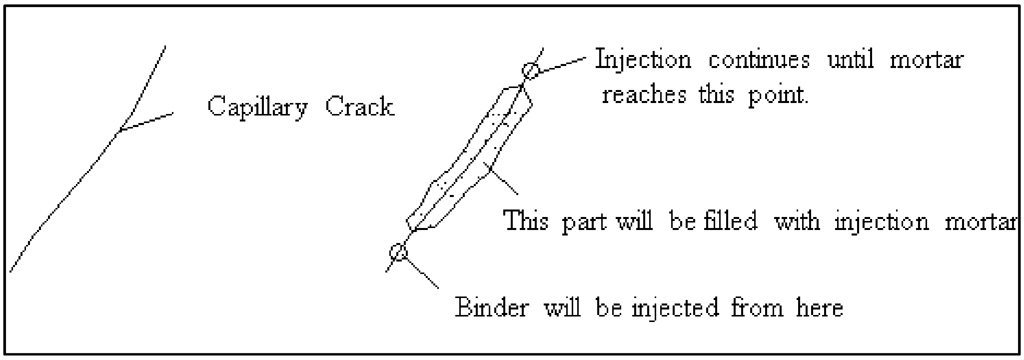

Figure 7.8 : A repair of capillary cracks with original injection material[78].

-The sections of the fortress that contain structural cracks should be secured (by suspending). The contour of the cracks up to 4 cm should be opened and completed with original stone/brick and mortar as seen in Figure 7.9.

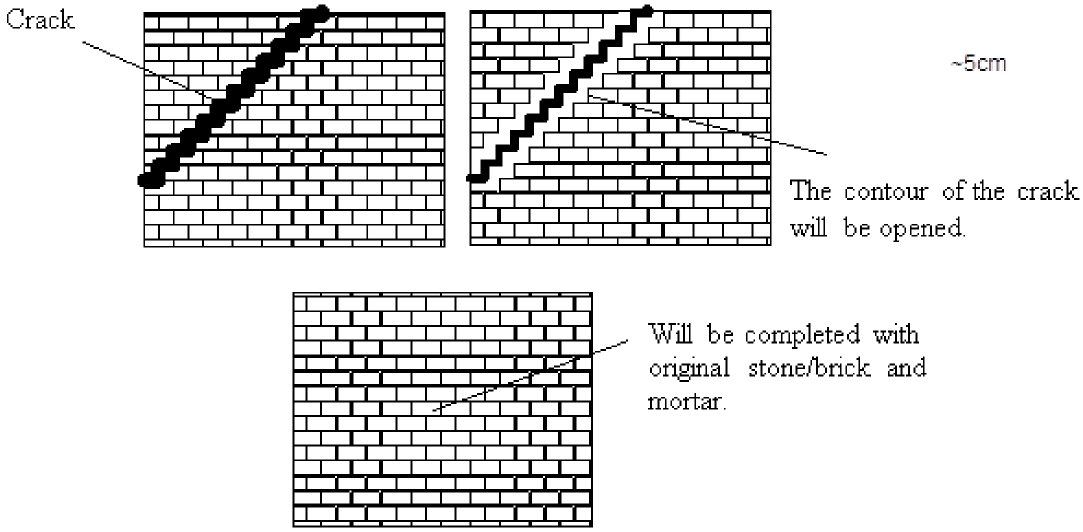

Figure 7.9 : Repair of large cracks [10].

-Loose parts of the structure should be stabilized.

-Open surfaces and sections of the structures should be reinforced and isolated against external factors and natural conditions using acrylic or ethyl silicate resins.

-Corroded iron clamps that caused cracking and spalling of stones should be mechanically cleaned and protected. In cases where iron clamps are not sufficient they should be replaced with new stainless steel clamps and they should be connected to the stones by lead.

-Dismantled or loose mortar should be reinforced with mortars that are prescribed as the result of material analysis.

7.3.4 Completion

-Regional loss of material observed at the bottom parts of the wall should be completed with original mortar and stone

-When structurally necessary missing parts of the structures should be completed with original material according to the restoration proposal.

-For the stones that are going to be used for intervention, material decision should be made. After the decision stone quarries should be searched for suitable material and the continuity (sustainability) of the material during restoration should be ensured while considering budget at the same time.

7.4 Strengthening and Repair Recommendations

7.4.1 North tower

The North Tower can be preserved in the current state as seen in Figure 7.10 and restoration measures can be taken according to the research that has been done and approved by the Kaletakımı and the Çanakkale Conservation Council.

Figure 7.10 : View from the North Tower [10].

A primary intervention that can be recommended for this tower is to renew damaged or removed wooden beams at the walls. During renewal original size wood that has reached equilibrium moisture content should be used. The deteriorated remaining beams should be cleaned. Wooden elements that are going to be placed in the beams should be fixed with mortar that is similar to the mortar used in the construction of tower as seen in Figure 7.7 and galvanized bolts should be used for joining beams together.

The brick wall that was built to the window cavity seen in Figure 7.11 should be removed. The damaged area around window cavity should be repaired with original material and loose stones should be stabilized.

Figure 7.11 : Brick wall built to the window cavity of North Tower [10].

Cladding stones forming the outer wall can be completed in accordance with the restoration decisions or kept as they are.

It is recommended to complete the cladding stones whose deterioration exceeds 15 cm depth from the lower face of the stone using a material with similar petrographic and physical properties.Vegetation observed on the façades should be cleaned (Figure 7.5).

7.4.2 South Tower

As seen in figure 7.12 half of the tower is damaged but the peak of the tower stands. FEM analysis carried out on the tower showed that maximum deformations are observed on the peak of the tower as seen in Appendix F.

Figure 7.12 : View from the South Tower [10].

In order to protect the current status of South Tower, standing parts of the tower should be stabilized urgently and temporarily by a steel frame arch seen in Figure 7.13.

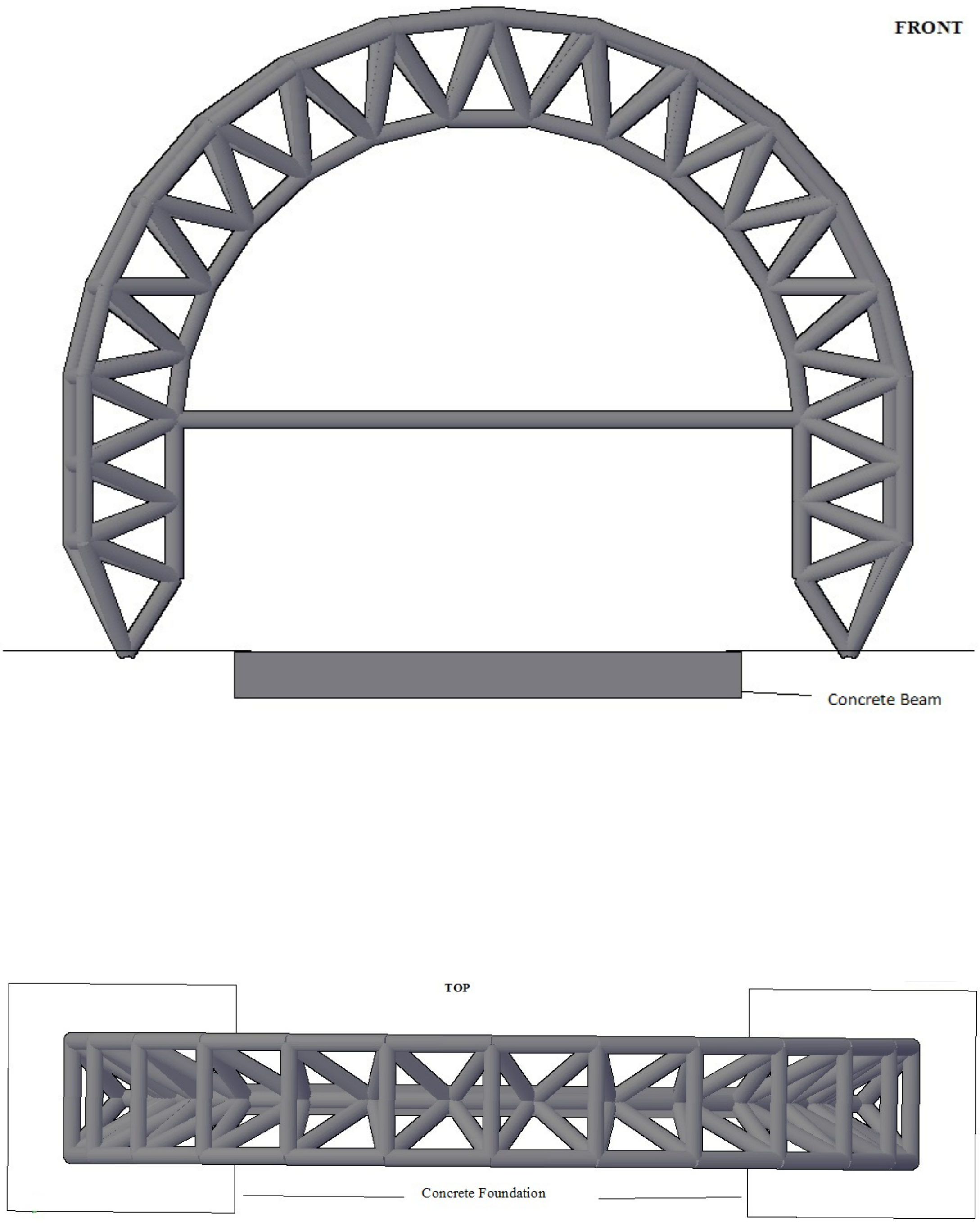

Figure 7.13 : Front and top view of steel frame arch that can be applied to South Tower for strengthening.

Prior to application dimensions and composition of steel frame arch should be calculated and detailed by an expert. The final steel frame arch merged to the point cloud of South Tower can be seen in Figure 7.14.

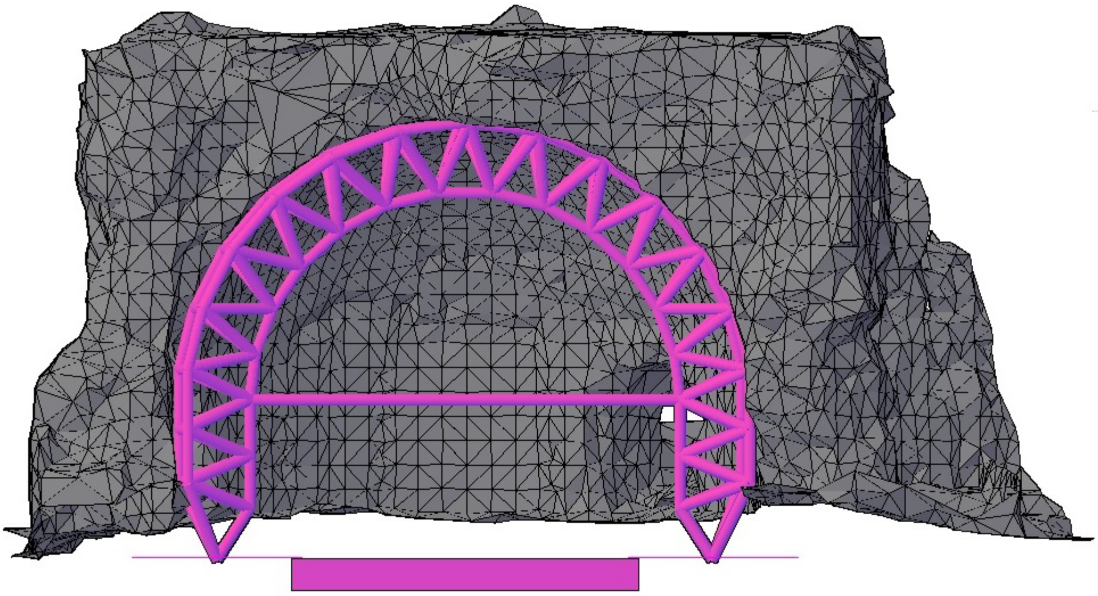

Figure 7.14 : Steel frame arch applied to South Tower.

There are two vertical cracks with 3-6 cm (on the left) and 1.5-2 cm (on the right) width as seen in Figure 7.15. Width of the cracks are measured from the point cloud data of South Tower. Large, and capillary cracks seen in figure 7.15 can be repaired with techniques recommended in Figure 7.9 and 7.8 respectively.

Figure 7.15 : Large crack (left) and capillary crack (right) observed on South Tower [10].

8. CONCLUSIONS AND RECOMMENDATIONS

Historic buildings should be elaborately evaluated in order to preserve cultural heritage and repair historic structures. This procedure is an interdisciplinary work which involves contribution of different disciplines.

Geomatics engineering tools are used in order to model the parts of the fortress on a geodetic based 3D CityGML model to determine the degree of damage to the building surface to characterize the damage mechanism stone by stone. Civil engineering tools are used to determine the behavior of the structure under its own weight and earthquake loads. An architect’s vision is used to evaluate the structure and propose interventions without touching to its authenticity. An art historians knowledge is used in order to evaluate the history of the structures. Conservation experts must be invited to study the materials used in the structure.

There are a wide variety of reasons for masonry damages, the most common reasons can be listed as follows;

-Load bearing system of masonry structures are composed of natural and artificial materials and therefore the weight of the structure is huge. This property increases the seismic loads acting on the structure.

-Due to the insufficient strength (bending, shear, etc.) of materials (stone, brick, etc.) forming the masonry structure, the structure cannot bear the stresses acting on them.

-Low strength of masonry mortar used to connect structural elements to each other, cannot bear the effects of shear.

-When window and door openings left on the wall exceed the limit values, stresses are accumulated around the gaps and these areas are damaged.

-Improper use of the building and attachments made to the structure without planning can cause damages. Changing the location of structural elements during restoration and usage of improper materials also cause damages.

-Low ductility of masonry is one of the most important factors that affect the damage mechanism. Ductility is the ability of the structure to change the shape without collapsing. As masonry structures are built with brittle materials, they show vulnerable behavior against the impacts.

-Sudden changes occurring in the foundation of the structure, excavations around structure, earthquakes, settlement, liquefaction, shear, etc. cause additional loads on the structure and cause damage.

-Lack of beams cause formation of vertical cracks on the wall joints, intersections and cause out of plane bending of the wall.

-Capillary cracks get deeper in time and cause serious damage to the structure and material. Materials lose their properties in time due to external forces (temperature, weather, rainfall, humidity, freeze-thaw cycles, environmental pollution, etc.) and cause damage.

The walls composing the body and towers of the fortress are buildup of ashlar and rough stone at the surface and core with rubble stone and white lime mortar as fill material. By the help of the walls that are damaged and not repaired over years, the layers of the structure can easily be observed. Wooden beams that reinforce the masonry walls and towers are placed in various levels of the structures.

Big stones on the surface especially the ones at the drum level are joined with iron clamps. Some of the structural elements such as chimneys are made up of bricks that are brought from Eceabat and nearby locations [14].

Materials (stone, mortar-plaster, wood, metal and brick) that make up the architectural elements of the castle show different decay (deterioration) patterns depending on the composition and where they are used.

Damages to the fortress of Seddülbahir can be classified as; First World War damage, weather, erosion damages caused by earthquakes and manmade damages. The damaged sections remained open to external influences for a long time so the deterioration increased.

The deteriorations observed on surfaces of rocks were caused by sea salt, wind, humidity, natural conditions and petrographic features of the stones.

Rupture and separation of stones in many places were caused by the corrosion of metal clamps. This can be observed easily on walls and drum.

Wooden beams that are widely used in walls and structures are decayed and deteriorated. Many beam slots are empty. At the walls and towers of the lower fortress the effect of sea and groundwater is observed as salinity and humidity.

Seddülbahir Fortress should be repaired and reinforced prior to reusage. First of all parts of the castle that are in danger should be structurally reinforced.

Stones at Seddülbahir show different deterioration patterns according to the location they are placed and conditions (sea salt, wind, humidity, etc.) exposed. Fracture, spalling and separation seen on stones are caused by structural damages, manmade factors and corrosion of metal clamps.

The most common problems are; capillary corrosion, differential decay, erosion, fracture, cavities, and disintegration. In most of the parts decay causes the loss of whole stone blocks. It is observed that stones are divided into layers in many parts. Capillary and wider cracks are due to deterioration of material or structural deformations. The façades that are near the sea and exposed to ground water are covered with moss and lichen. Algae growth seen on an area that is exposed to intense sun indicates the presence of ground water.

Detailed observations should be carried out on parts of the fortress which contain salts in order to determine the wearing out effect of rain together with salts. Priority should be given to the parts that are exposed to heavy rain or sun.

In order to protect existing structures against earthquakes the behavior of the structure under earthquake loads should be understood and determined carefully.

Large earthquakes have the potential to cause dangerous actions. The most important of these is the movement of the earth's crust tangent to the surface in back and forth, up and down directions. The first movement directly affects the structure. However the secondary effects caused by the earthquake damage buildings and environment significantly.

Earthquake loads occur due to the own weight of the structure. During an earthquake, when the seismic waves generated in the earth's crust reach the structure on the surface they cause vibration on the structure. This response caused by the vibrations is a dynamic behavior.

The factors disrupting the structural system of historic buildings are ground parameters and earthquakes. Earthquakes are very dangerous for heavy masonry (stone or brick) structures.

Strength and load bearing capacity of the structure against earthquake should be calculated. However materials such as stone, brick and mortar show non-linear mechanical properties which make the calculation of bearing capacity very difficult. Stone and brick structures are more prone to damages caused by earthquakes. The most important reason is the heavy mass of such structure, caused by their dimensions, materials and forms.

The three dimensional elements such as dome, vault and pendant work structurally as shell elements under vertical loads and loads caused by external influences. Because the masonry structures are weak in tension under the effect of tensile forces, shell elements theoretically crack. However due to the geometric form of the structure they don’t collapse immediately. Many domes and vaults, which should collapse according to the shell theory, still stand for centuries.

When determining the bearing capacity in addition to the axial force and bending moment, shear force and torsional moment should also be considered. Taking into account large sizes of elements of historic masonry structures, except for the effects of unexpected load, level of security can be considered as adequate against shear stress and torsional moment [41].

In order to evaluate the load bearing system of the structure from the structural engineers point of view mechanical properties such as unit weight, modulus of elasticity, compressive and tensile strength should be known. For determining the strength and modulus of elasticity of walls, large samples might be necessary. In this case damaged components of the structure can be used or non-destructive tests like ultrasonic methods, Schmidt hammer, etc. can be applied to the whole structure in the field.

Excavations conducted on North Tower do not give sufficient information about depth and condition of the foundation. For modelling the foundations of both towers, original depth of them should be determined. In the absence of enough information about foundation conditions, a sufficient number of ground observation pits and boreholes should be observed. The number and depth of boreholes are directly proportional with construction area and foundation width.

For each of the layers forming the foundation area, grain size, unit volume weight, water content and porosity should be determined by laboratory tests. In case of uncertainty standard penetration, bearing capacity and other necessary measurements will be helpful.

In historic structures foundation problems generally arise immediately after construction or after a short while. Without significant and sudden change in the structure and environment, such structures do not cause any problem because probable settlements in the foundation are completed years ago.

In order to determine the behavior of structure under seismic loads, period of elastic vibration, damping rate and mode shapes must be specified. These quantities can be specified numerically by micro vibration method in a non-destructive way or by the help of mechanical properties obtained by experiments.

FEM is the most suitable method for determining the seismic performance of historic structures. In order to obtain reliable results in FEM calculations dimensions and material properties of structural elements should be correctly modelled in the analytical model. However numerical values for defining the material properties of structural elements are determined as a result of literature search. In this case, deteriorations in specific locations of the structure or loss of material in the load bearing system of the structure can be said to affect the behavior of the structure.

Results of the finite element analysis showed that both normal and tensile stresses observed on North and South Tower exceed the allowable limit given in Chapter 7**.** Improper loading conditions are observed under different loading combinations as seen on Table 6.8 and Table 6.9. According to the results of the analysis it can be said that both North, South Towers are in need of urgent stabilization and restoration measures.

A new application domain extension (ADE) is proposed for the evaluation of historical masonry structures using a diagram seen in Figure 5.3. This ADE can be used for developing CityGML models for historic masonry structure.

As the Kaletakımı is comprised of experts from different disciplines: Preservation architects, archeologists, geodesy engineers and art historians/archivists/cultural heritage specialists this model will provide interoperability.

To sum up, the restoration, conservation and reusage decisions taken for the North Tower will be a reference guide for the protection and restoration decisions of other parts of the fortress including the South Tower. During the restoration process stabilisation and restoration works should be carried out by a team specialized in historic masonry structures.

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APPENDICES

APPENDIX A: UML diagrams

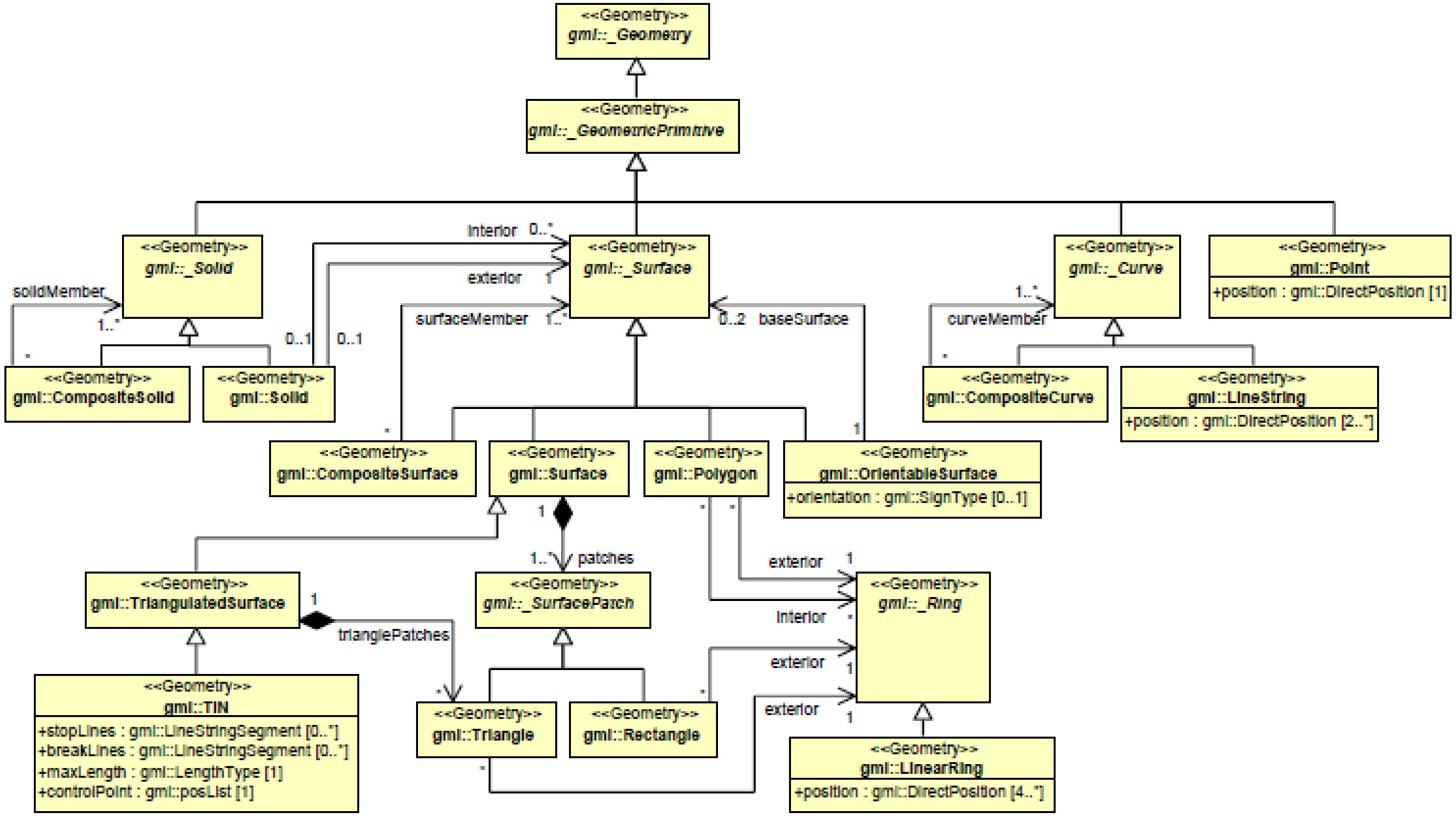

Figure A.1: UML diagram of CityGML's geometry model (subset and profile of GML3): Primitives and Composites [30].

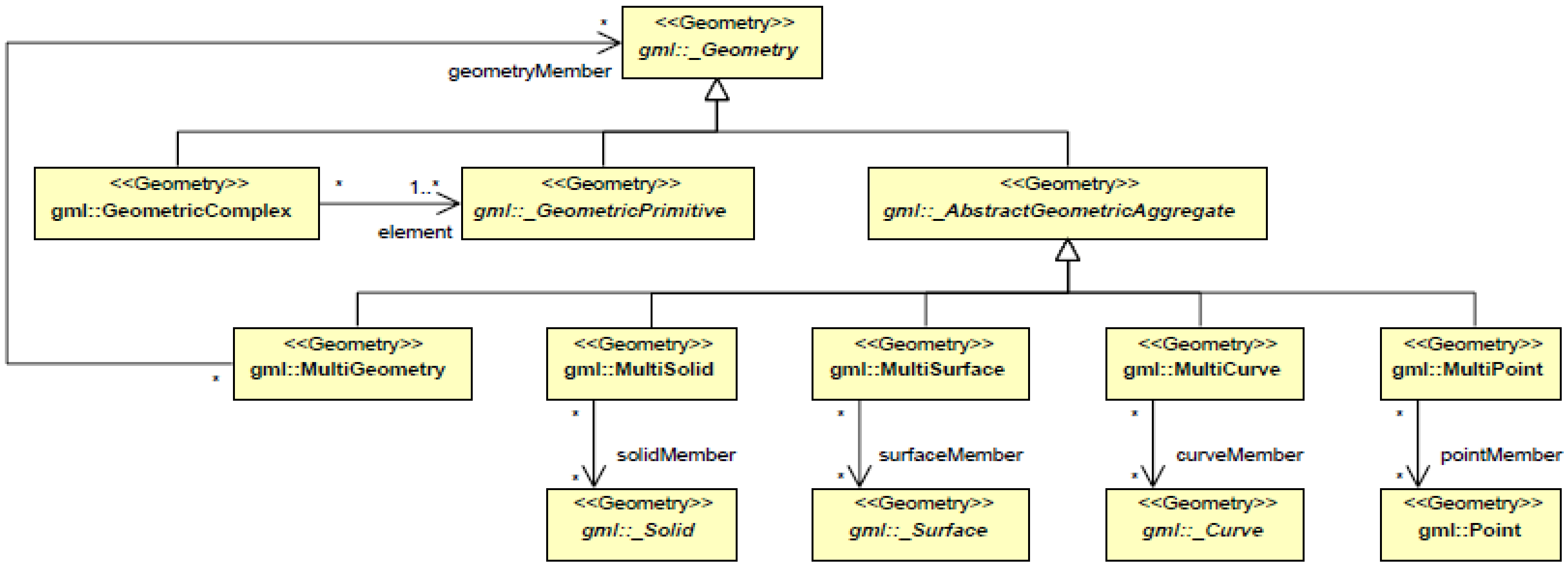

Figure A.2: UML diagram of CityGML's geometry model: Complexes and Aggregates[30].

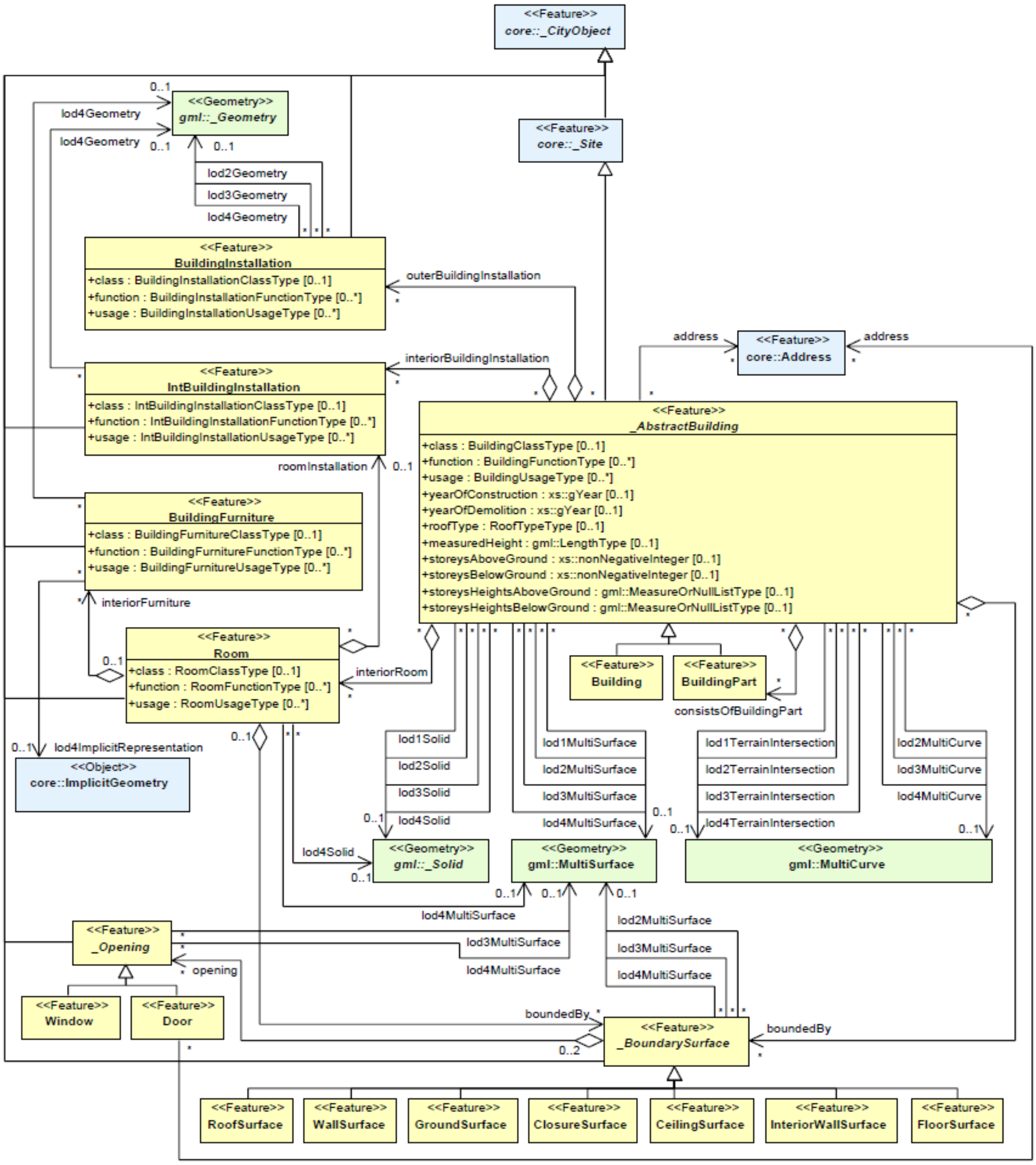

Figure A.3: UML diagram of CityGML's building model[30].

APPENDIX B: XML source code for Masonry ADE

```
<?xmlversion="1.0"encoding="ISO-8859-1"?>
<xs:schematargetNamespace="http://www.opengis.net/citygml/ade/masonry/1.0"
xmlns:xs="http://www.w3.org/2001/XMLSchema"xmlns:mas="http://www.opengis.n
et/citygml/ade/masonry/1.0"elementFormDefault="qualified">
	<xs:elementname="Stone"type="mas:Stone"/>
	<xs:complexTypename="Stone">
		<xs:complexContent>
			<xs:extensionbase="core:AbstractCityObjectType">
				<xs:sequence>

	<xs:elementname="Material"type="mas:MaterialPropertyType"minOccurs="
1"maxOccurs="unbounded"/>

	<xs:elementname="Damage"type="mas:DamagePropertyType"minOccurs="0"ma
xOccurs="unbounded"/>
				</xs:sequence>
			</xs:extension>
		</xs:complexContent>
	</xs:complexType>
	<xs:elementname="StonePropertyType"type="mas:StonePropertyType"/>
	<xs:complexTypename="StonePropertyType">
		<xs:sequence>
			<xs:elementref="mas:Stone"minOccurs="1"maxOccurs="1"/>
		</xs:sequence>
	</xs:complexType>
	<xs:elementname="Material"type="mas:Material"/>
	<xs:complexTypename="Material">
		<xs:complexContent>
			<xs:extensionbase="core:AbstractCityObjectType">
				<xs:sequence/>
			</xs:extension>
		</xs:complexContent>
	</xs:complexType>
	<xs:elementname="MaterialPropertyType"type="mas:MaterialPropertyType
"/>
	<xs:complexTypename="MaterialPropertyType">
		<xs:sequence>

	<xs:elementref="mas:Material"minOccurs="1"maxOccurs="1"/>
		</xs:sequence>
	</xs:complexType>
	<xs:elementname="Damage"type="mas:Damage"/>
	<xs:complexTypename="Damage">
		<xs:complexContent>
			<xs:extensionbase="core:AbstractCityObjectType">
				<xs:sequence>

	<xs:elementname="Crack"type="mas:CrackPropertyType"minOccurs="0"maxO
ccurs="unbounded"/>

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APPENDIX C: Maximum and minimum stress diagrams for North Tower

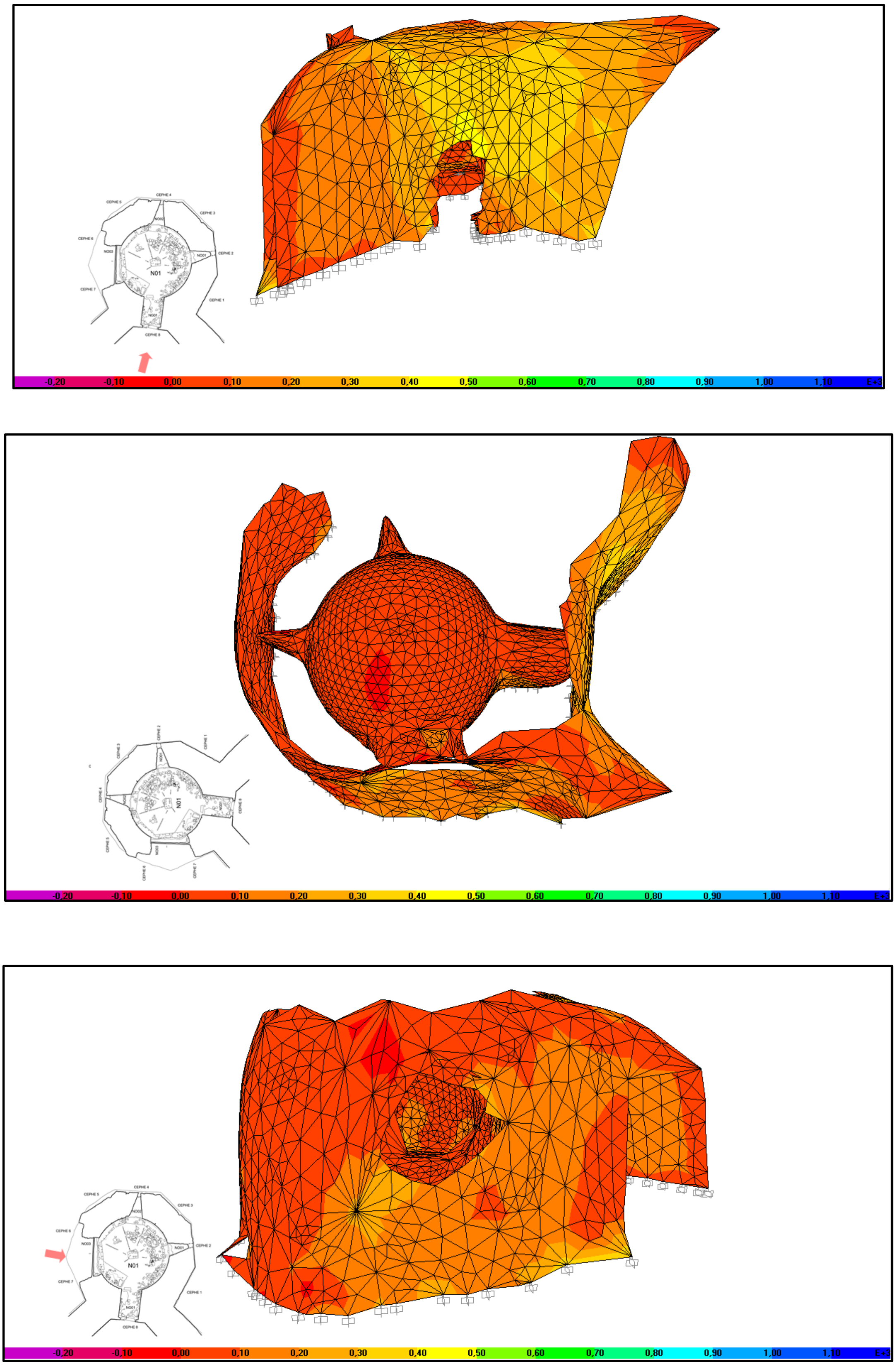


Figure C.1: S12 maximum values observed on North Tower (MPa).

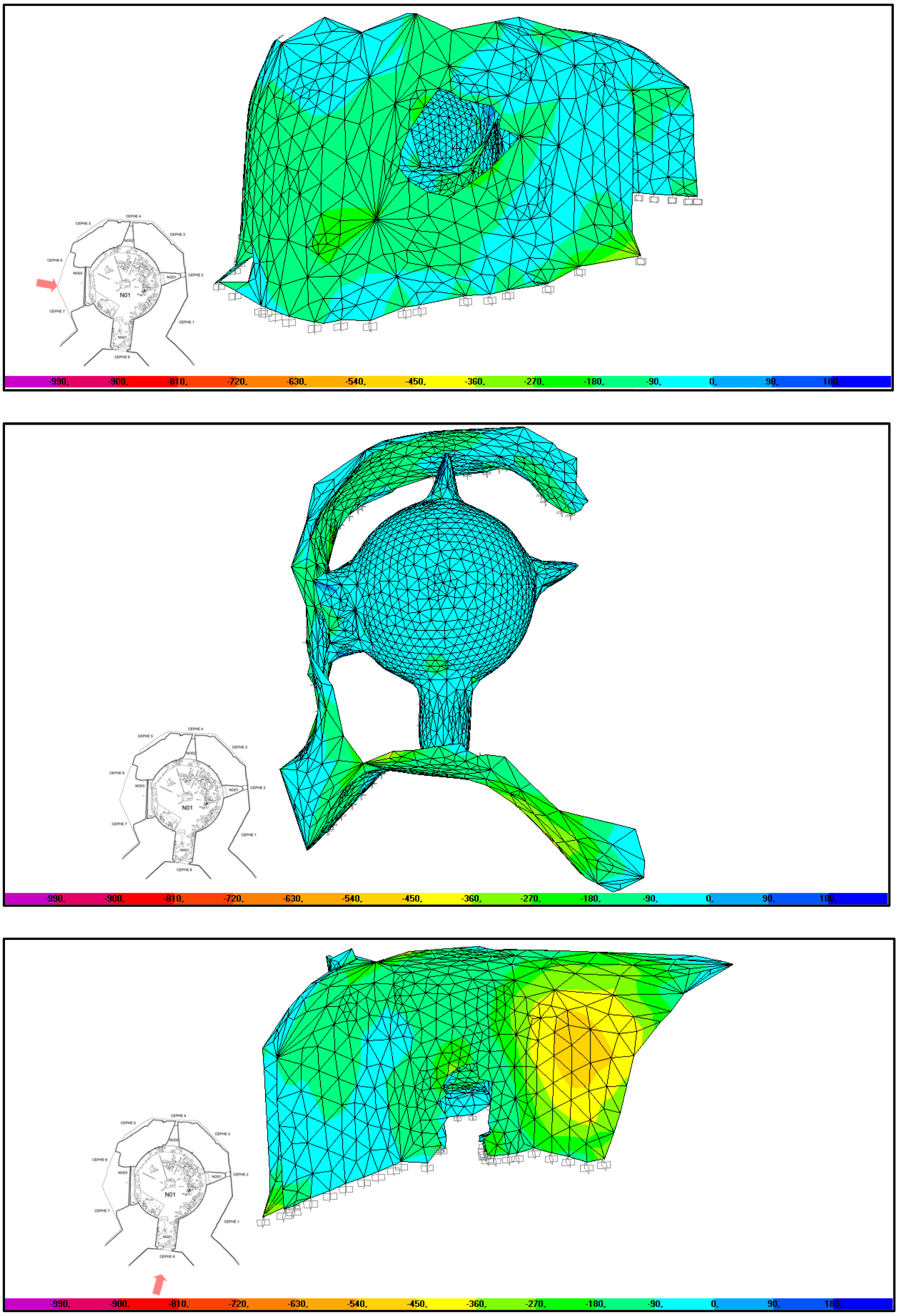


Figure C.2: S12 minimum values observed on North Tower (kN/m^2).

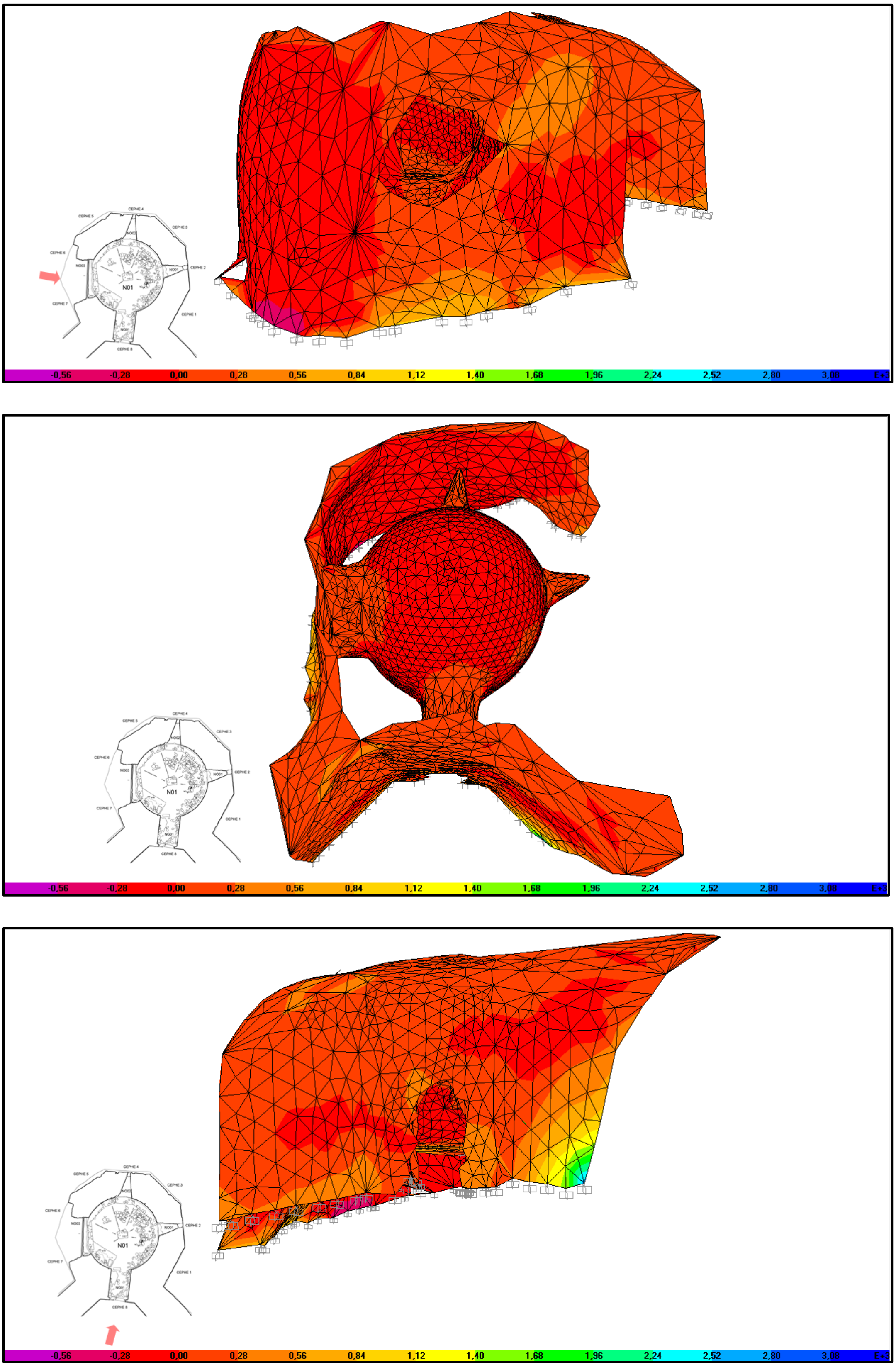


Figure C.3: S22 maximum values observed on North Tower (MPa).

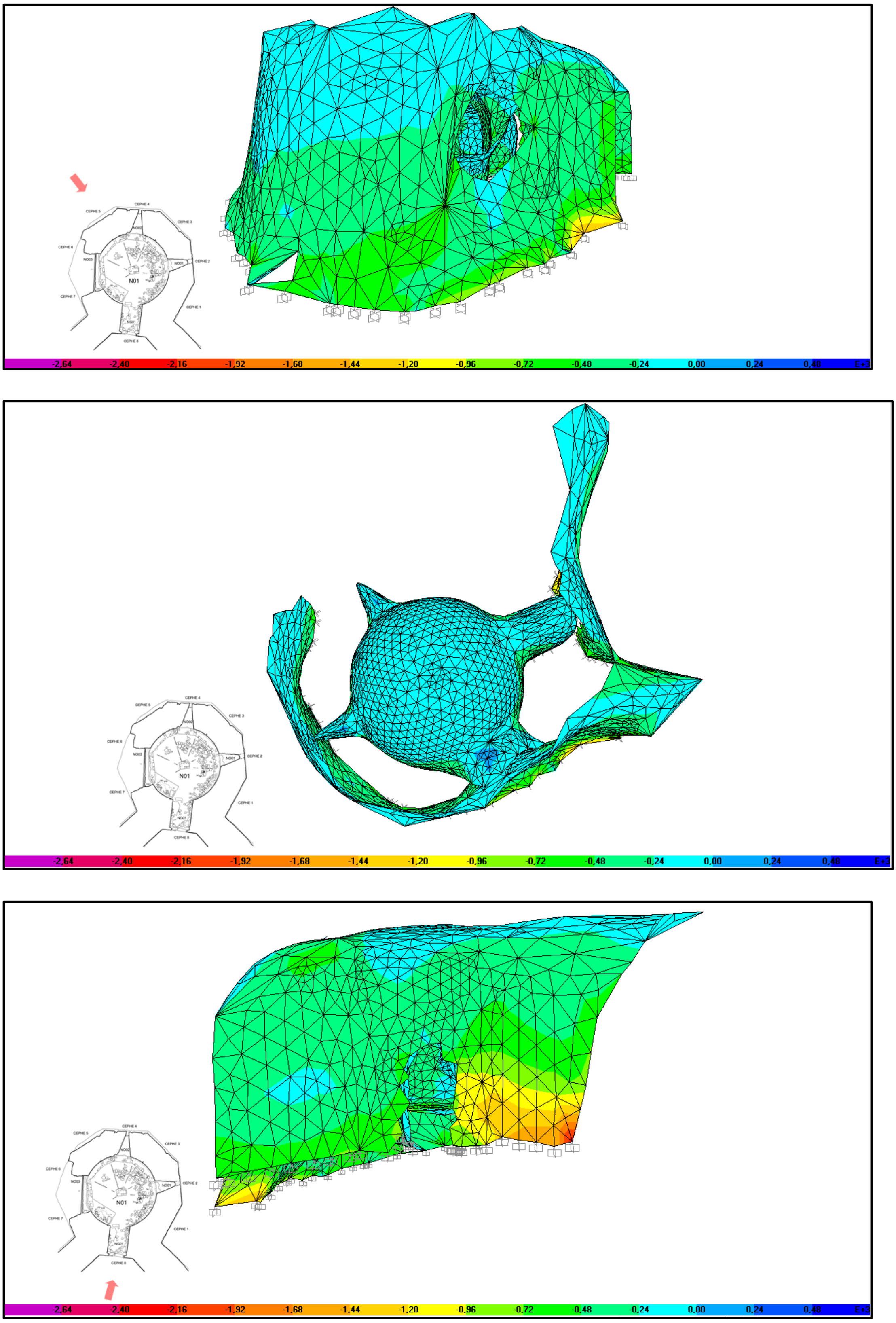


Figure C.4: S22 minimum values observed on North Tower (MPa).

APPENDIX D: Maximum and minimum stress diagrams for South Tower

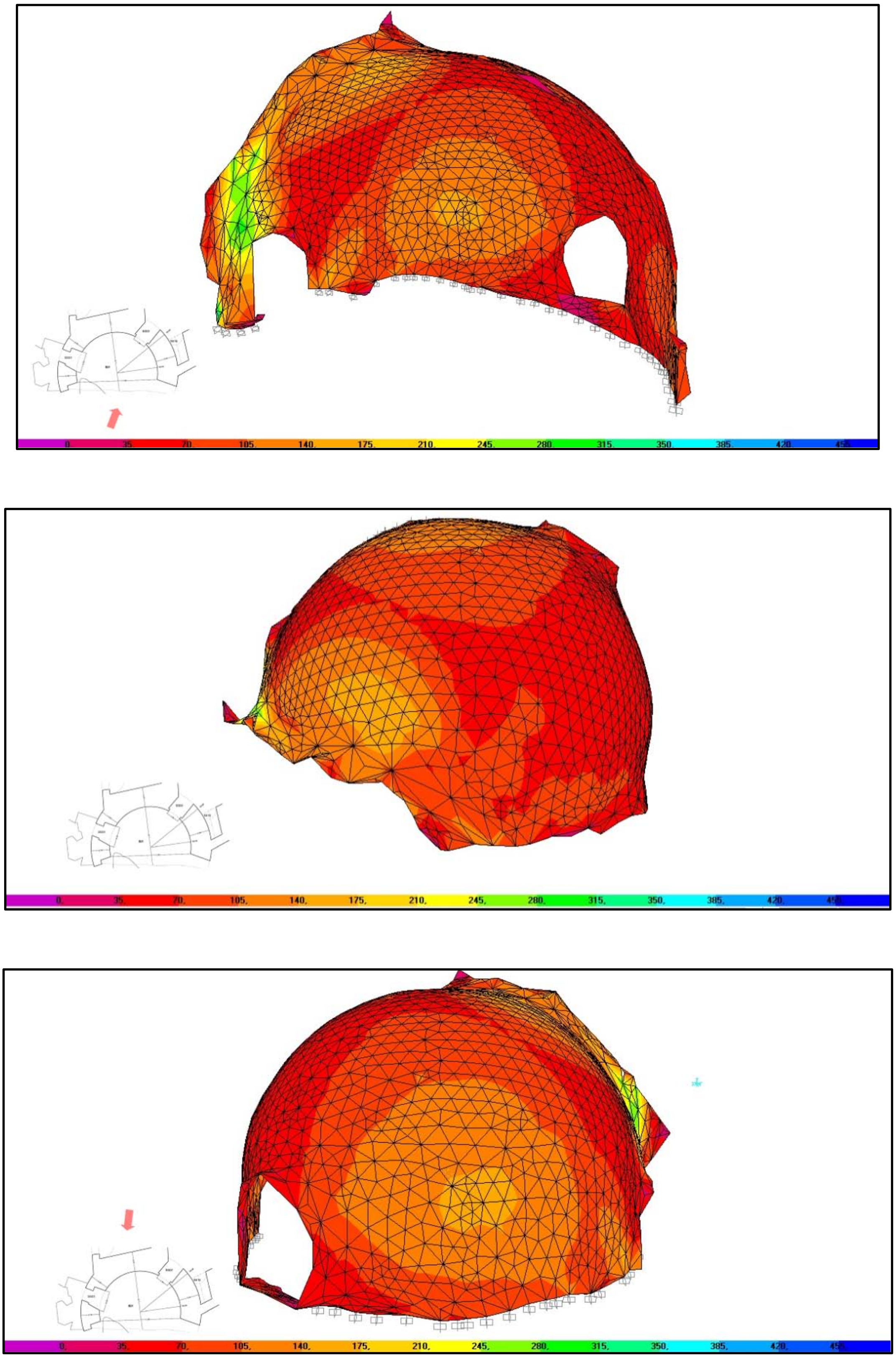


Figure D.1 : S12 maximum values observed on South Tower (kN/m^2).

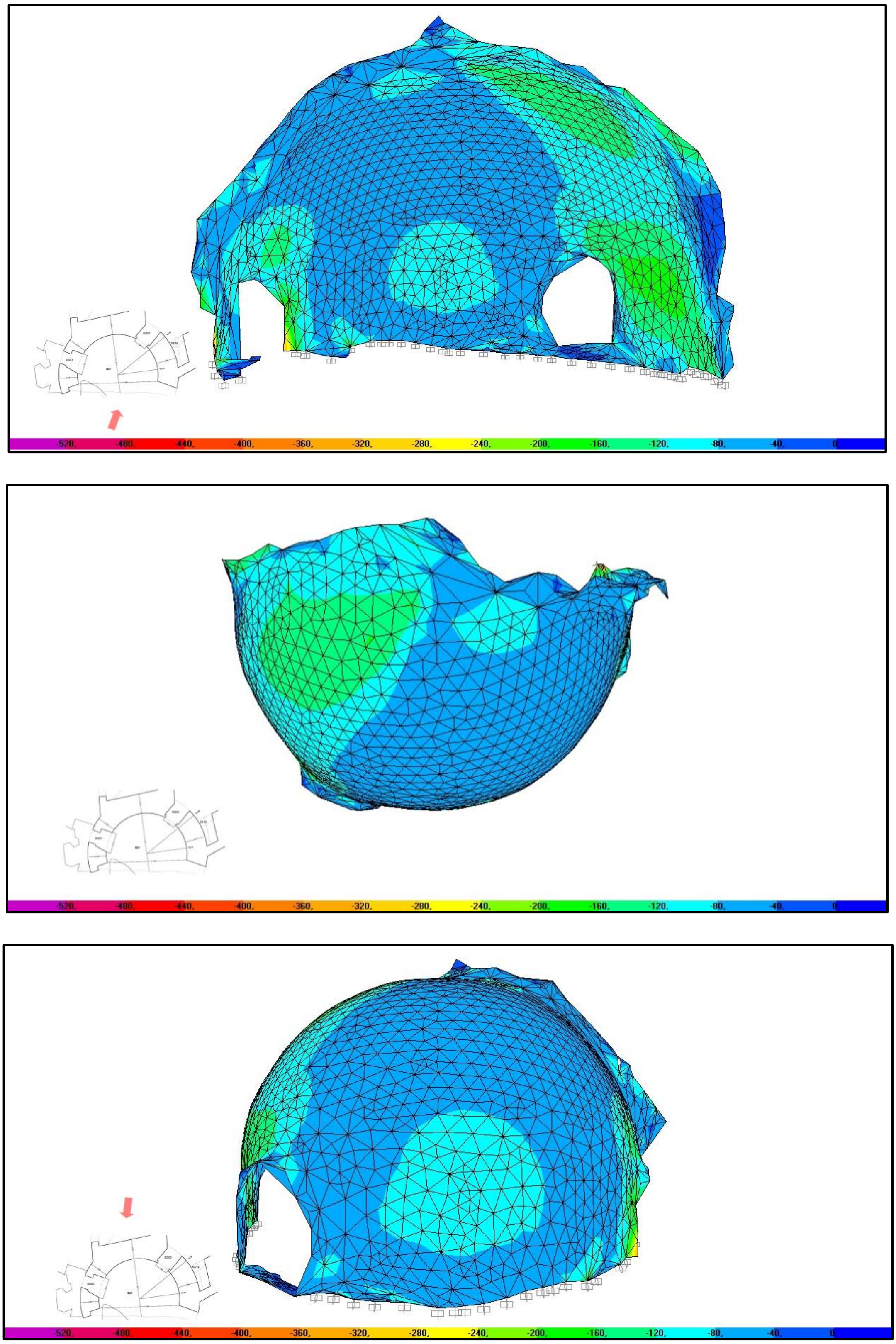


Figure D.2 : S12 minimum values observed on South Tower (kN/m^2).

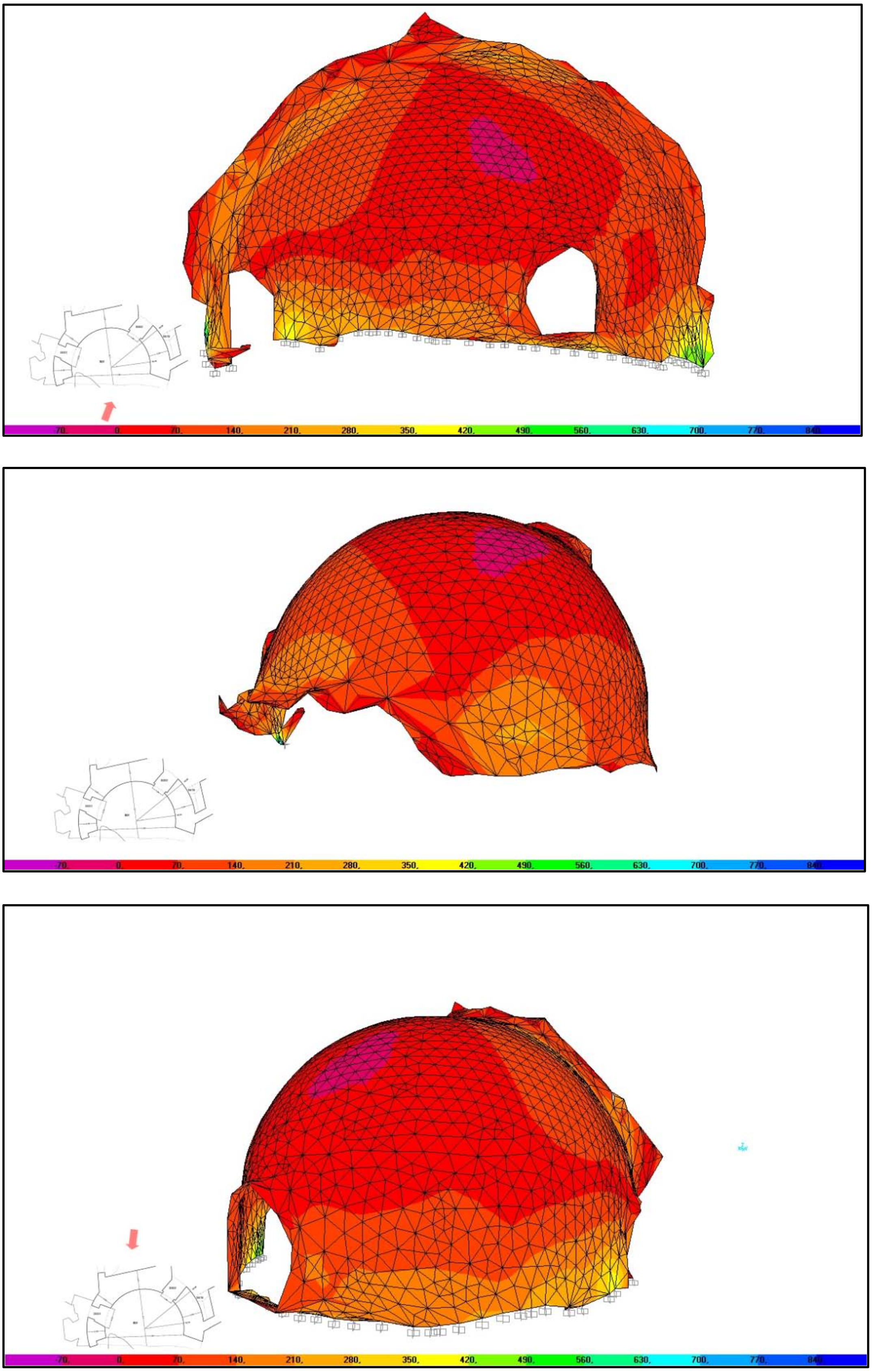


Figure D.3 : S22 maximum values observed on South Tower (kN/m^2).

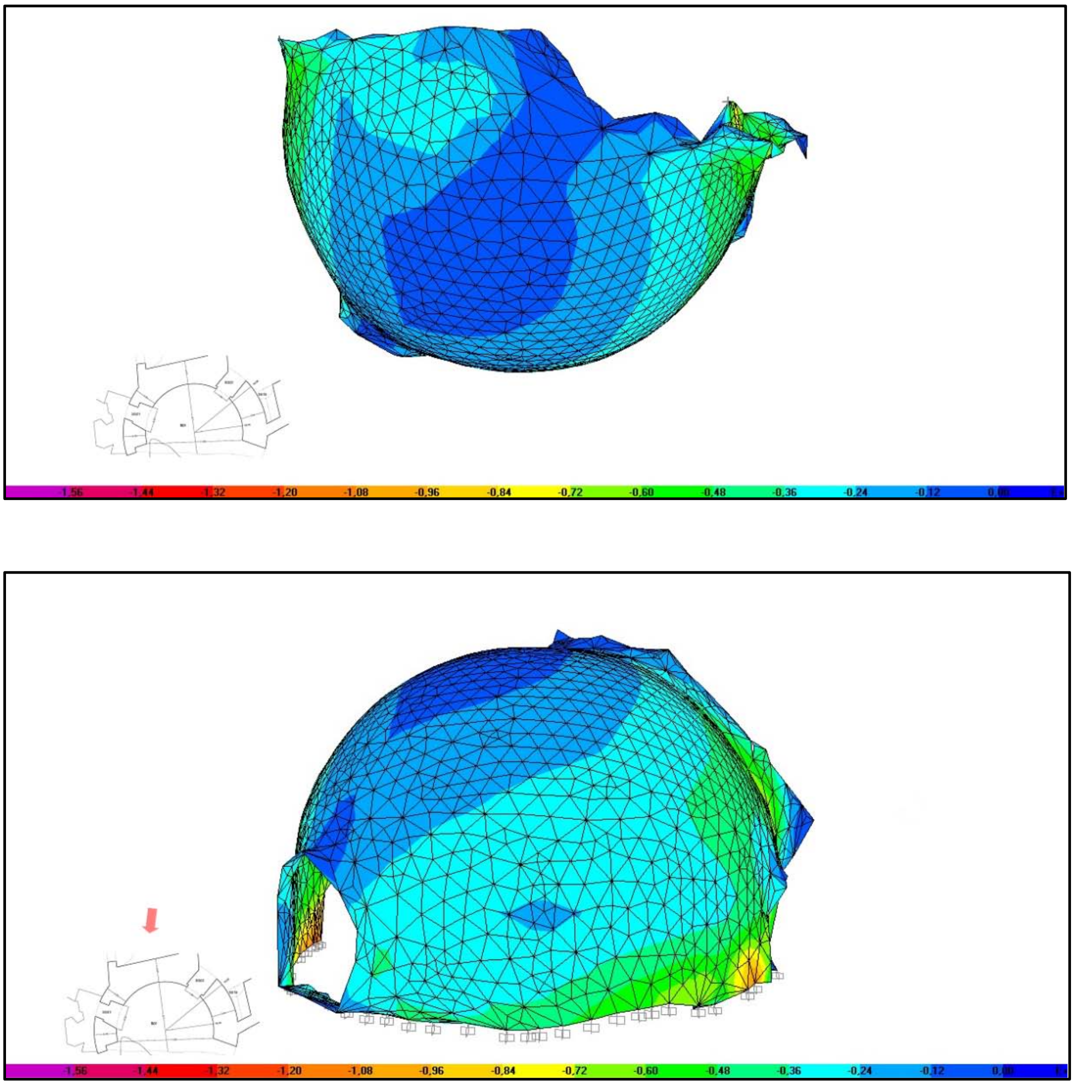
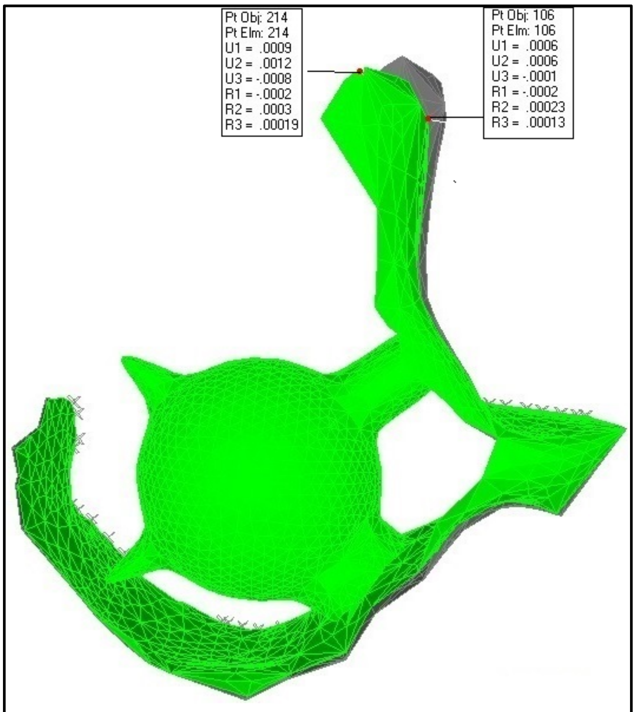
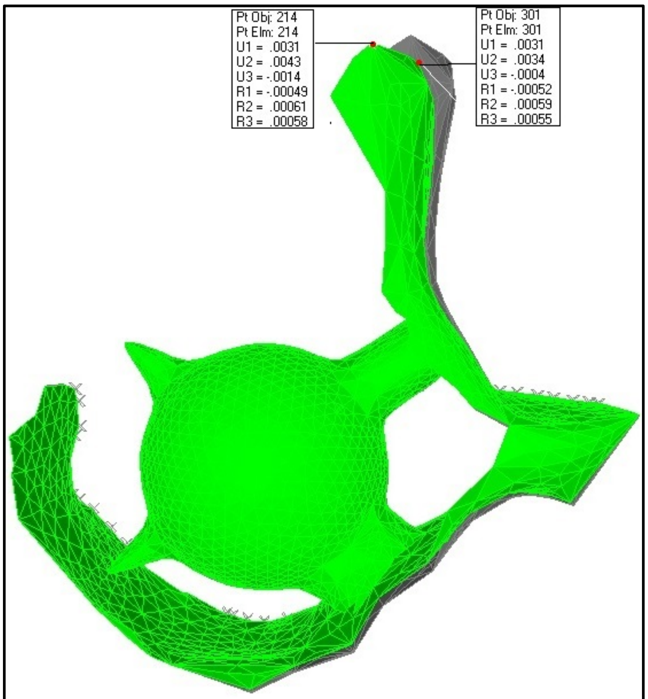


Figure D.4 : S22 minimum values observed on South Tower (MPa).

APPENDIX E: Displacements of North Tower observed for different loading combinations

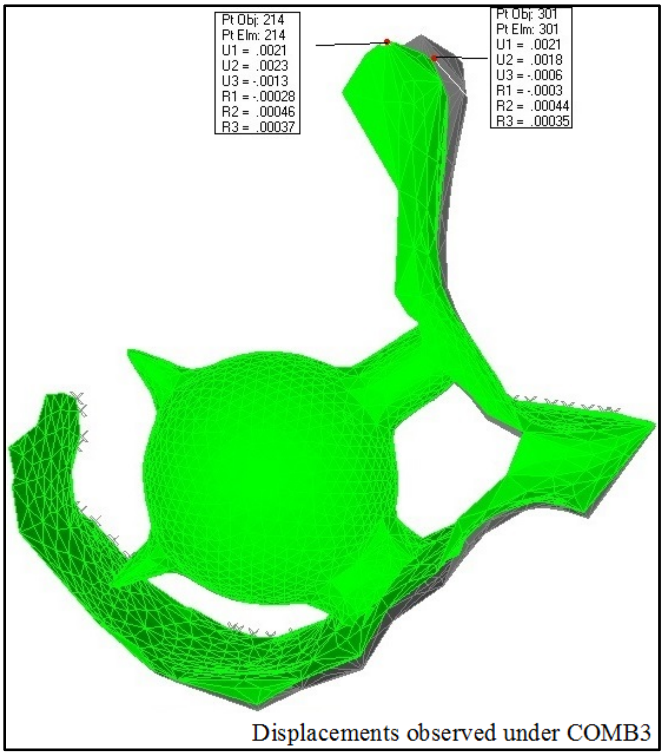


Displacements observed under COMB1



Displacements observed under COMB2

Figure E.1 : Displacements of North Tower observed for different loading combinations.



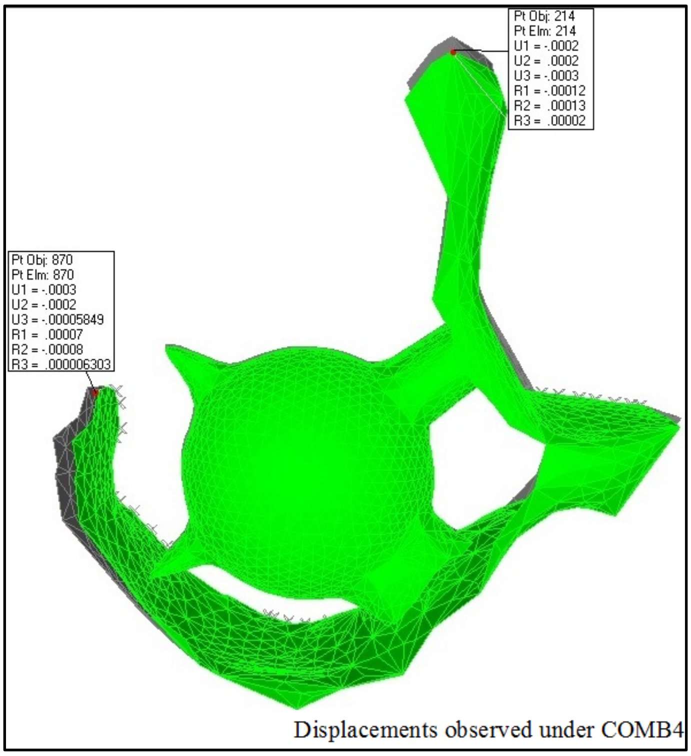
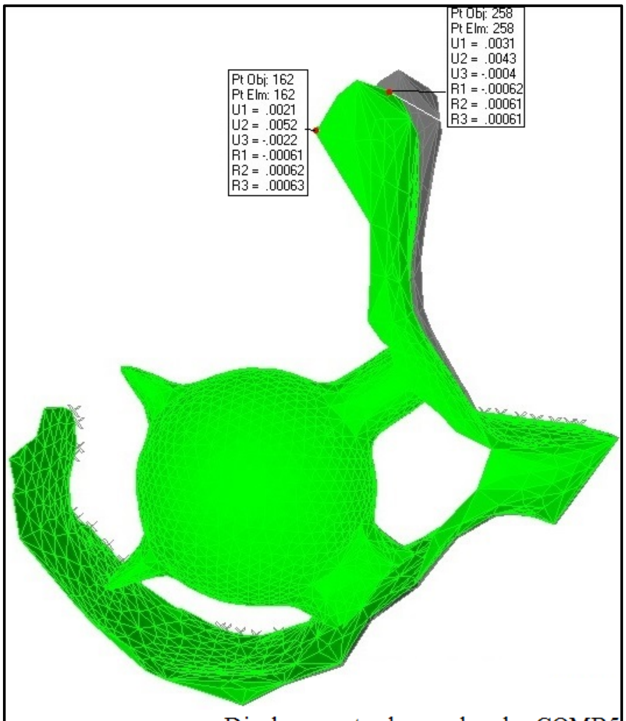
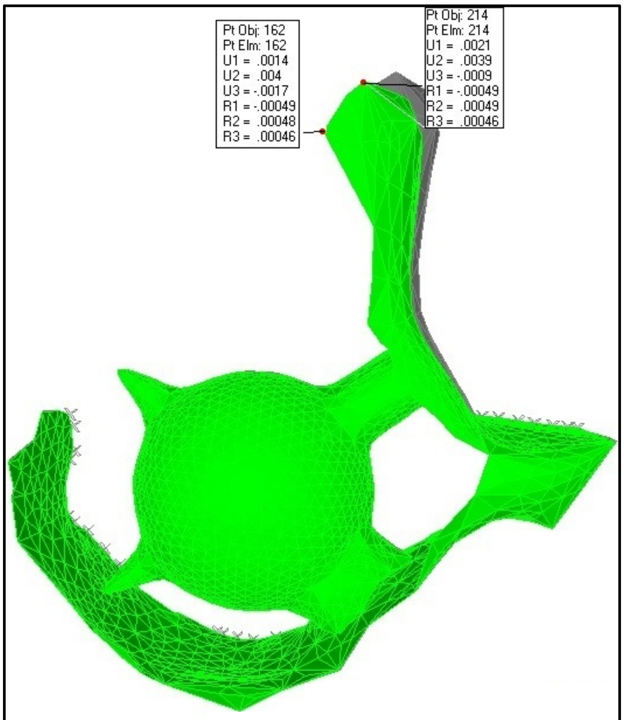


Figure E.1 (continued) : Displacements of North Tower observed for different loading combinations.

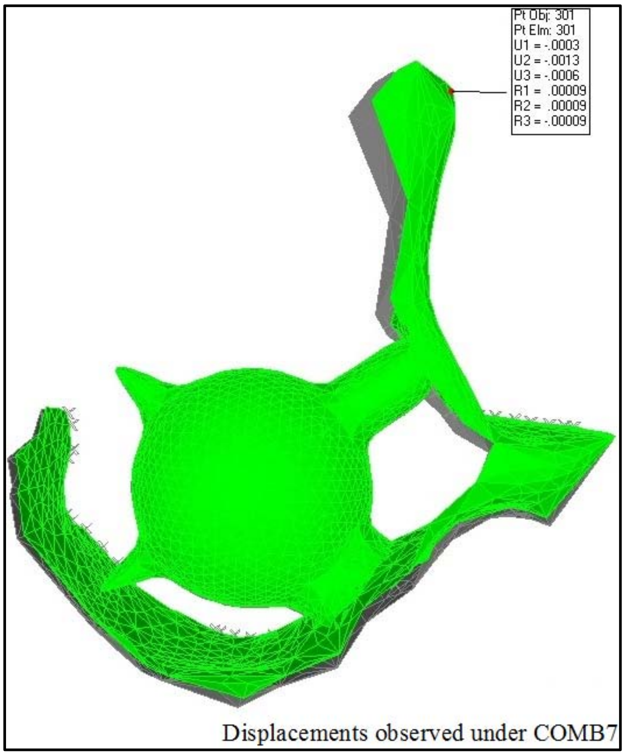


Displacements observed under COMB5



Displacements observed under COMB6

Figure E.1 (continued) : Displacements of North Tower observed for different loading combinations.



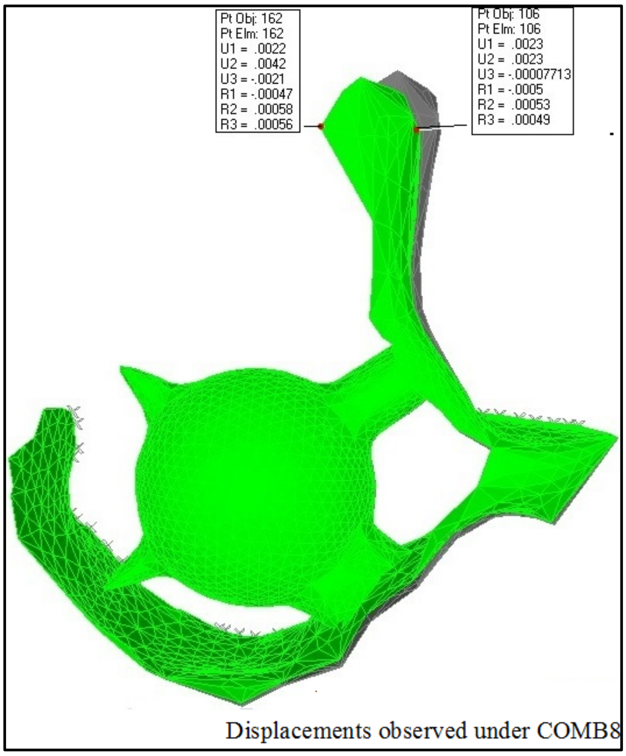
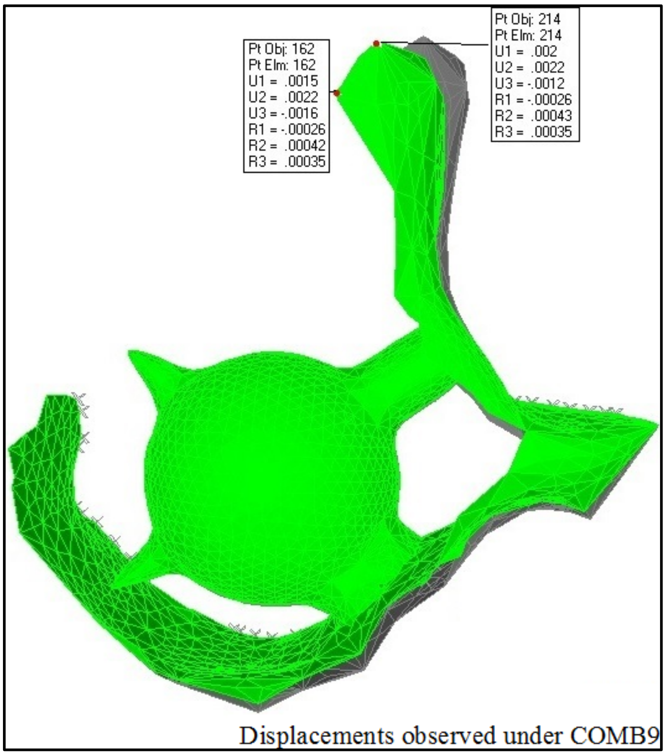


Figure E.1 (continued) : Displacements of North Tower observed for different loading combinations.



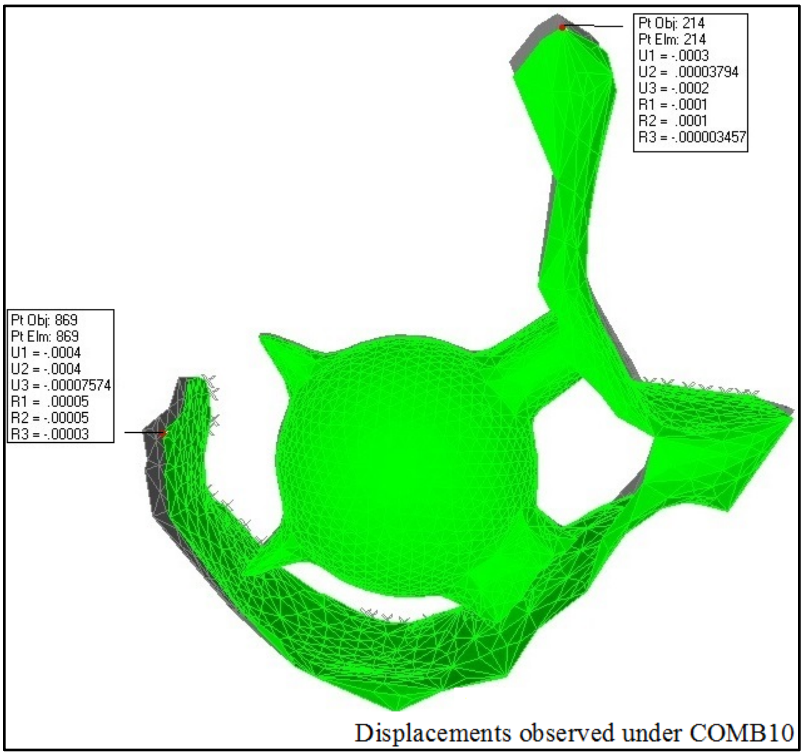
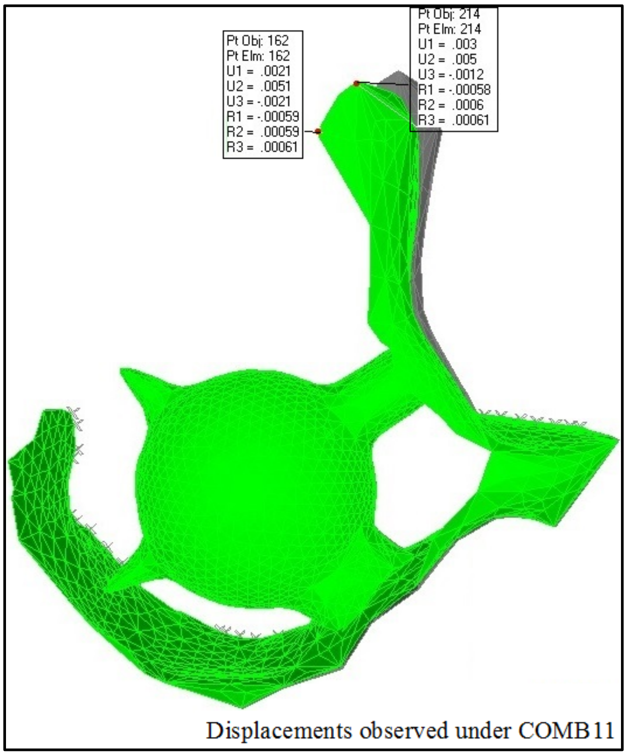


Figure E.1 (continued) : Displacements of North Tower observed for different loading combinations.



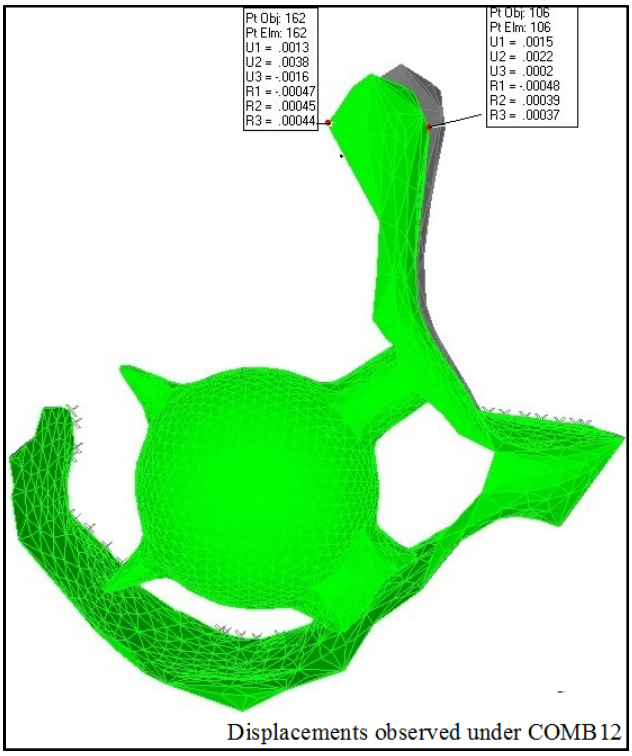


Figure E.1 (continued) : Displacements of North Tower observed for different loading combinations.

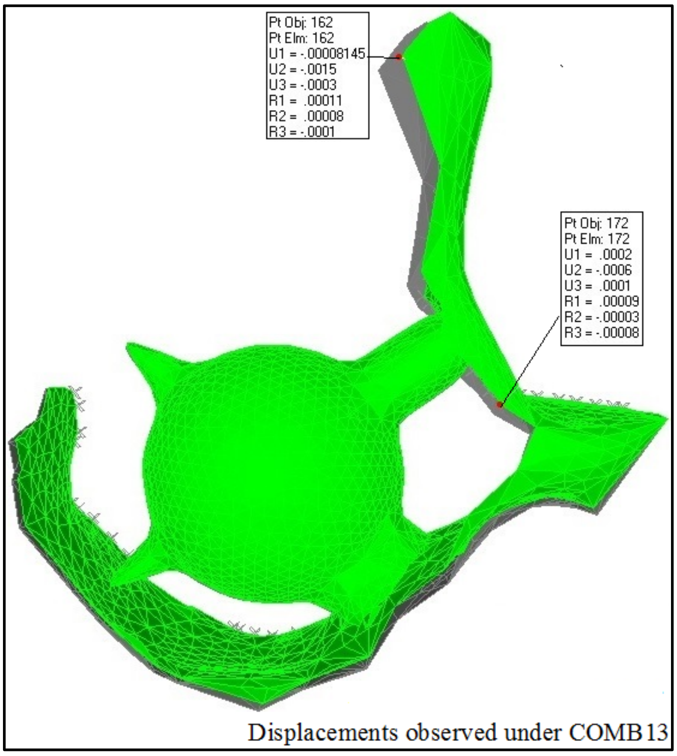
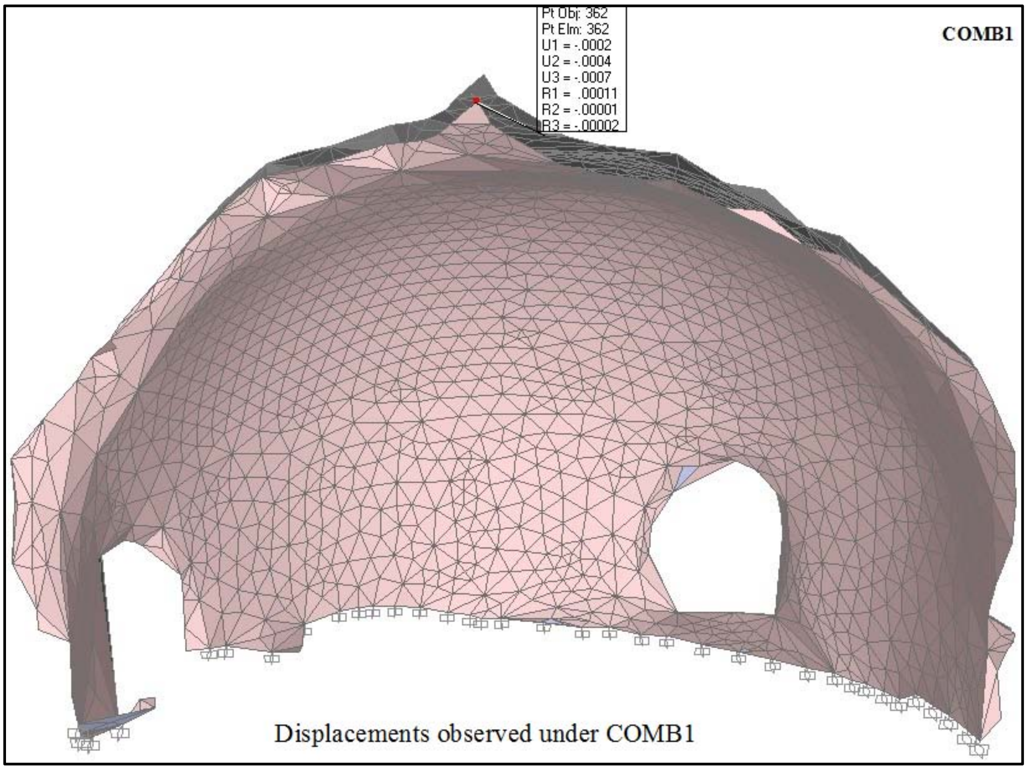


Figure E.1 (continued) : Displacements of North Tower observed for different loading combinations.

APPENDIX F: Displacements of South Tower observed for different loading combinations



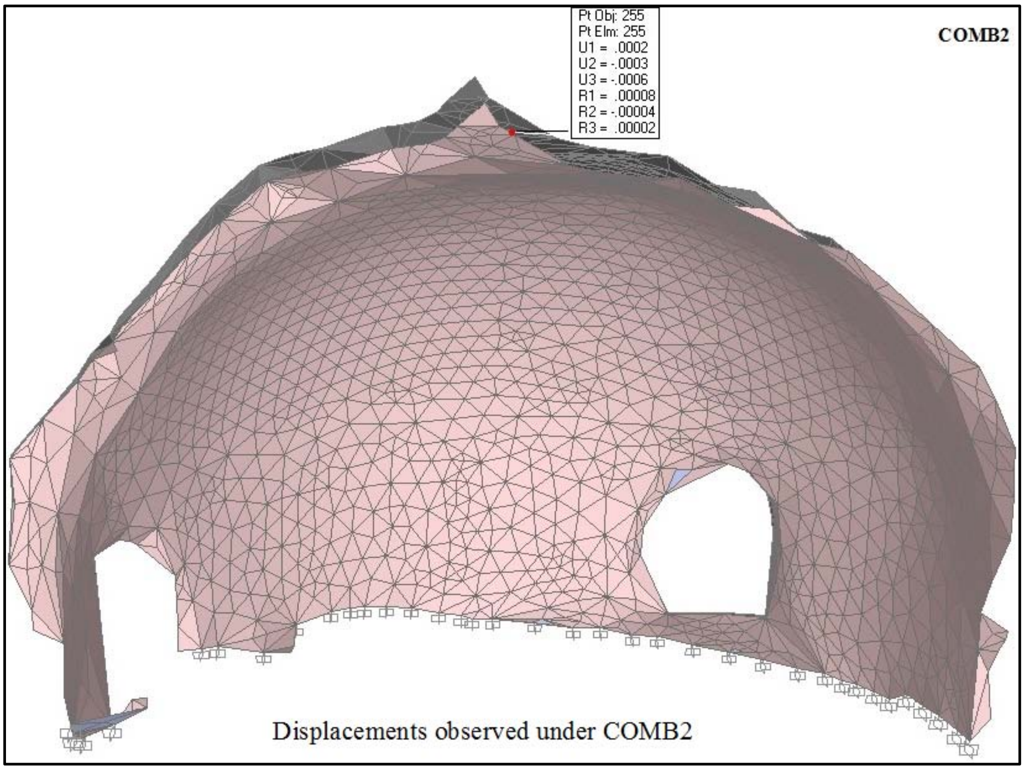
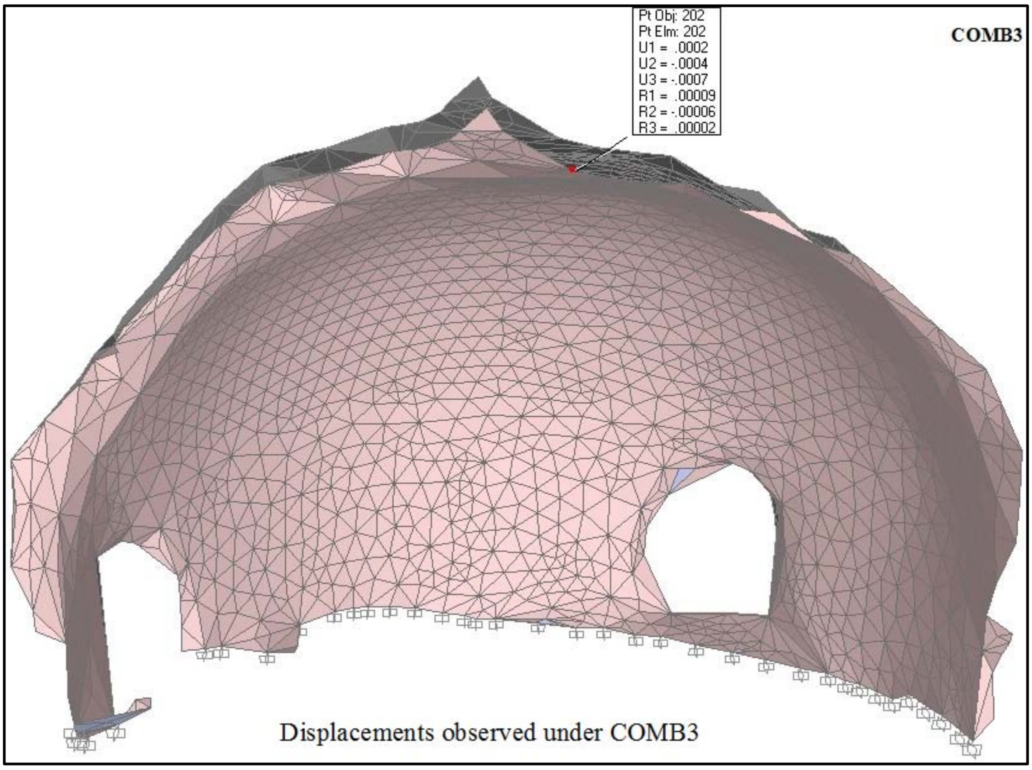


Figure F.1 : Displacements of South Tower observed for different loading combinations.



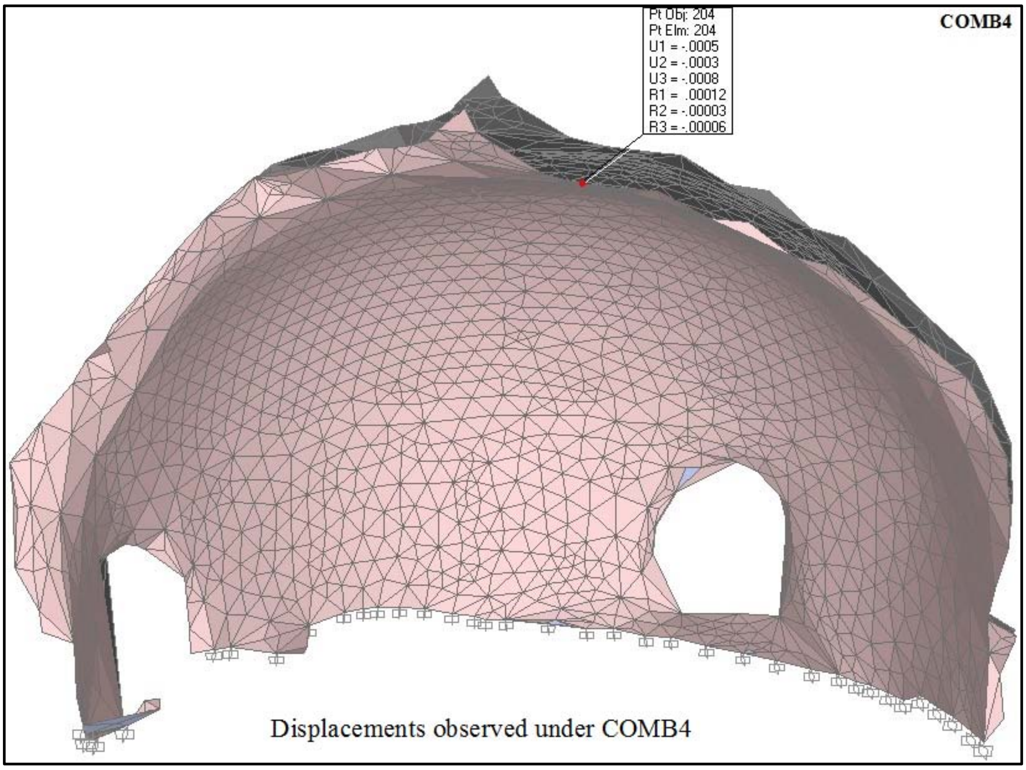
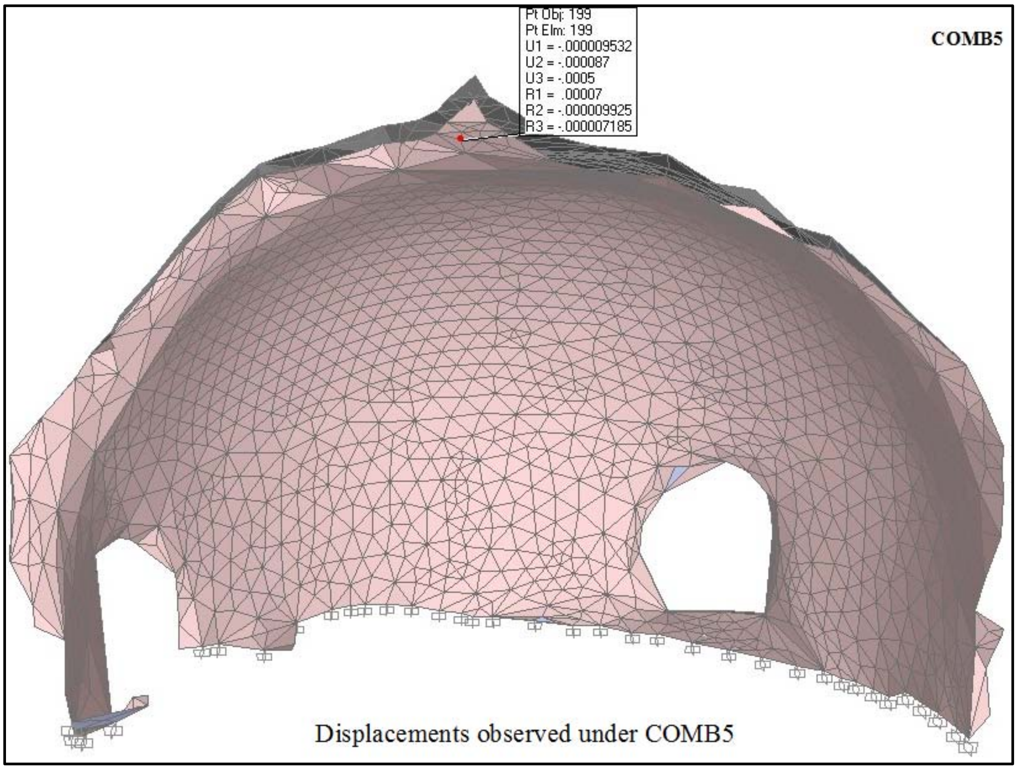


Figure F.1 (continued) : Displacements of South Tower observed for different loading combinations.



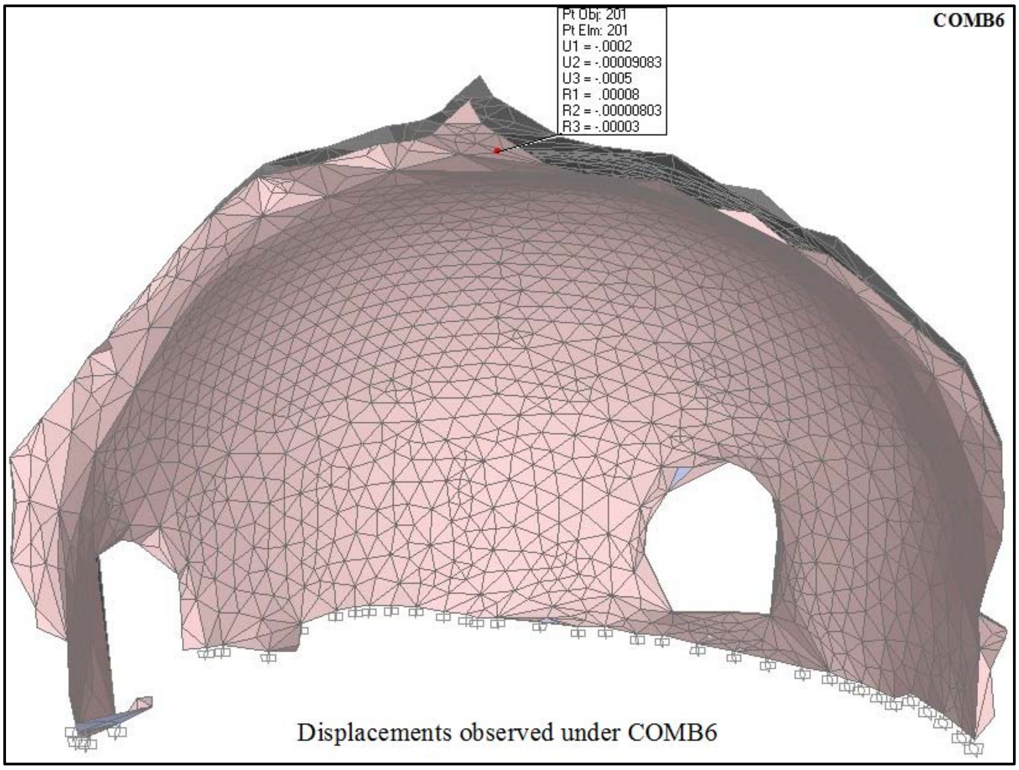
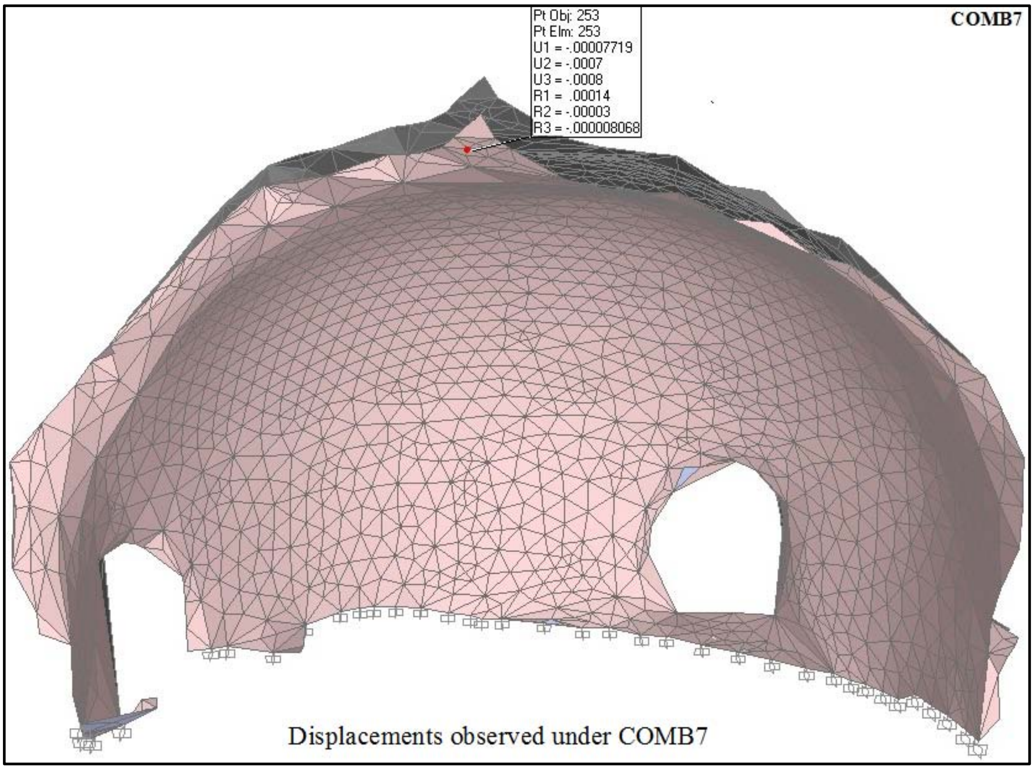


Figure F.1 (continued) : Displacements of South Tower observed for different loading combinations.



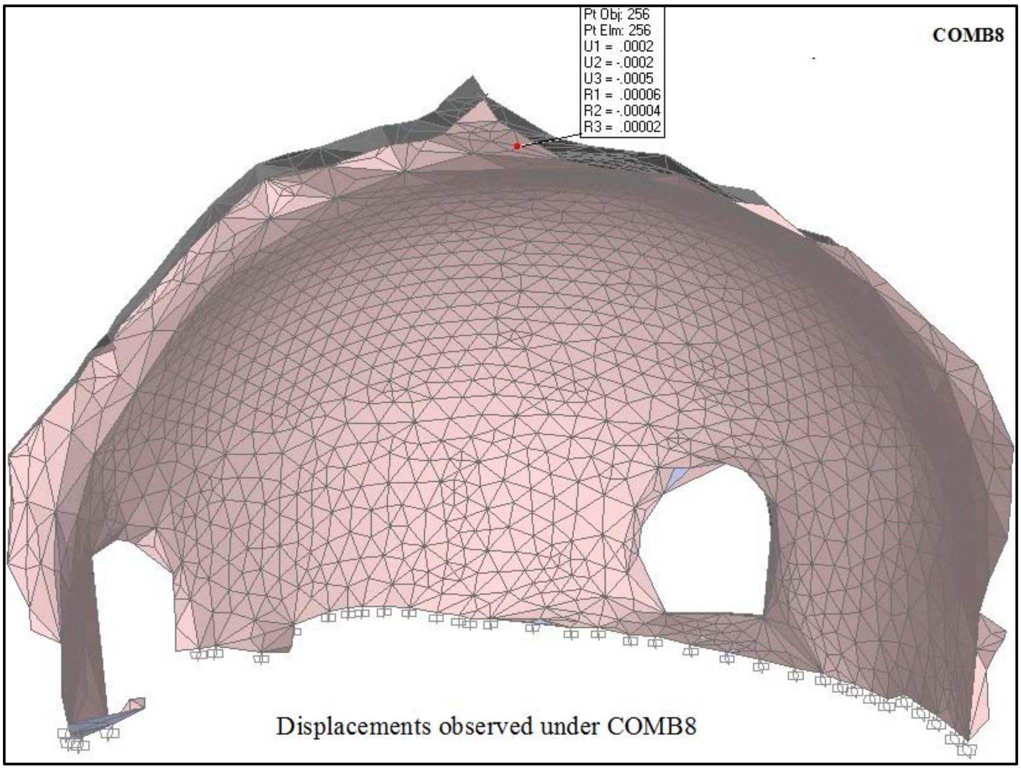
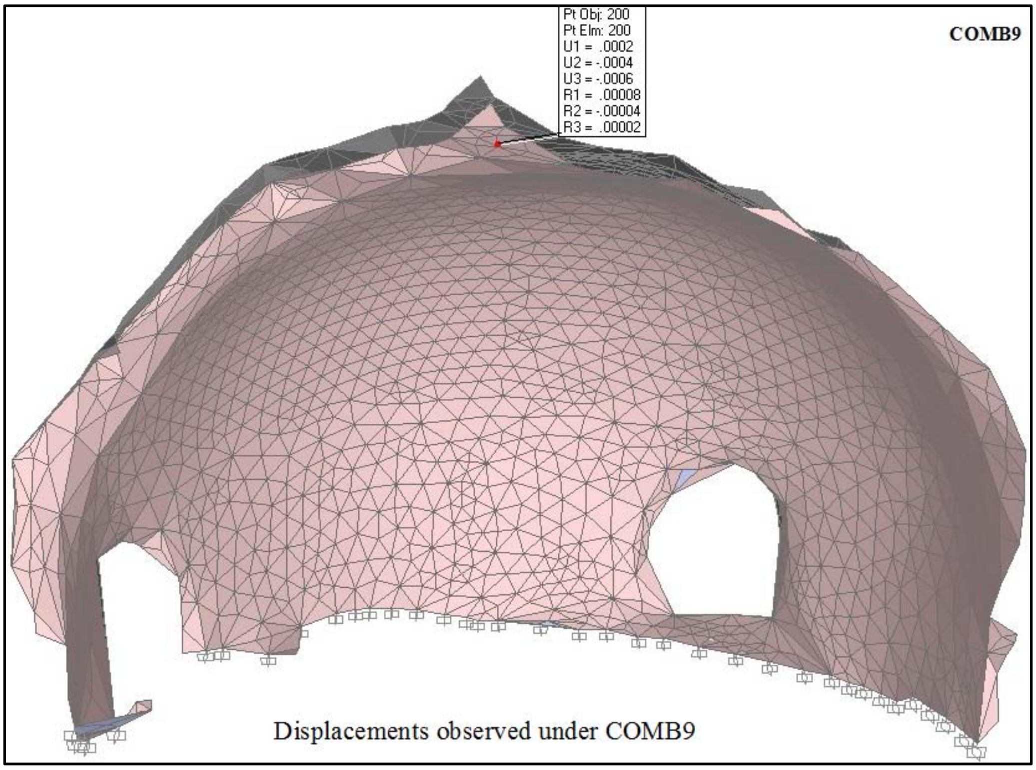
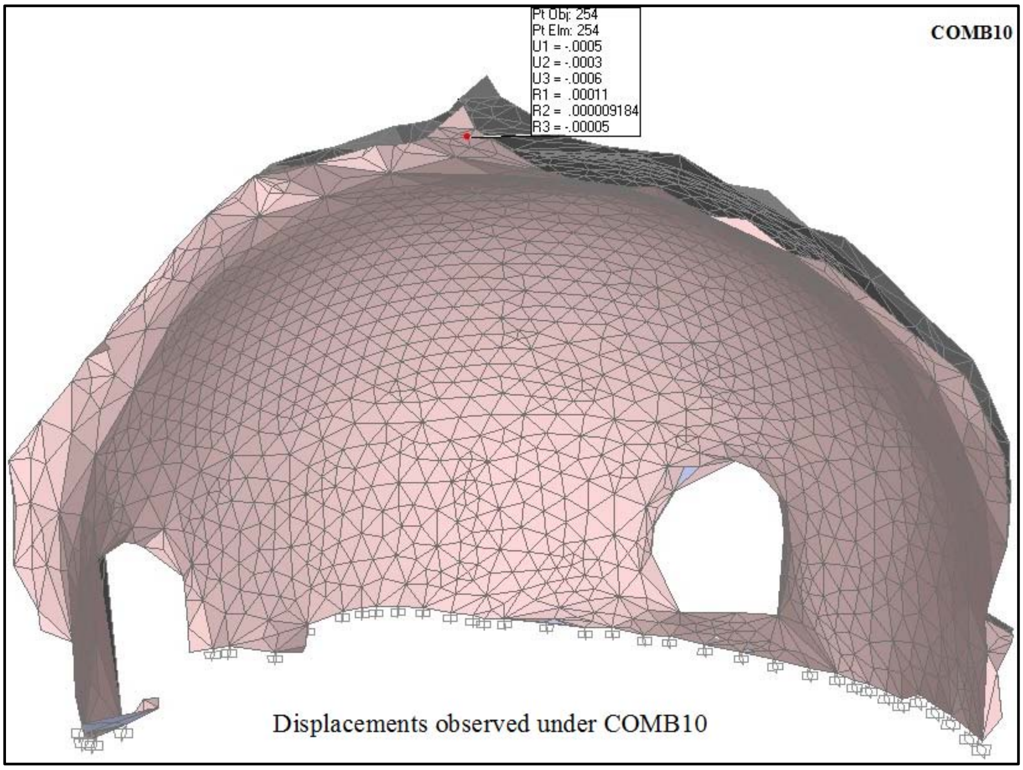


Figure F.1 (continued) : Displacements of South Tower observed for different loading combinations.





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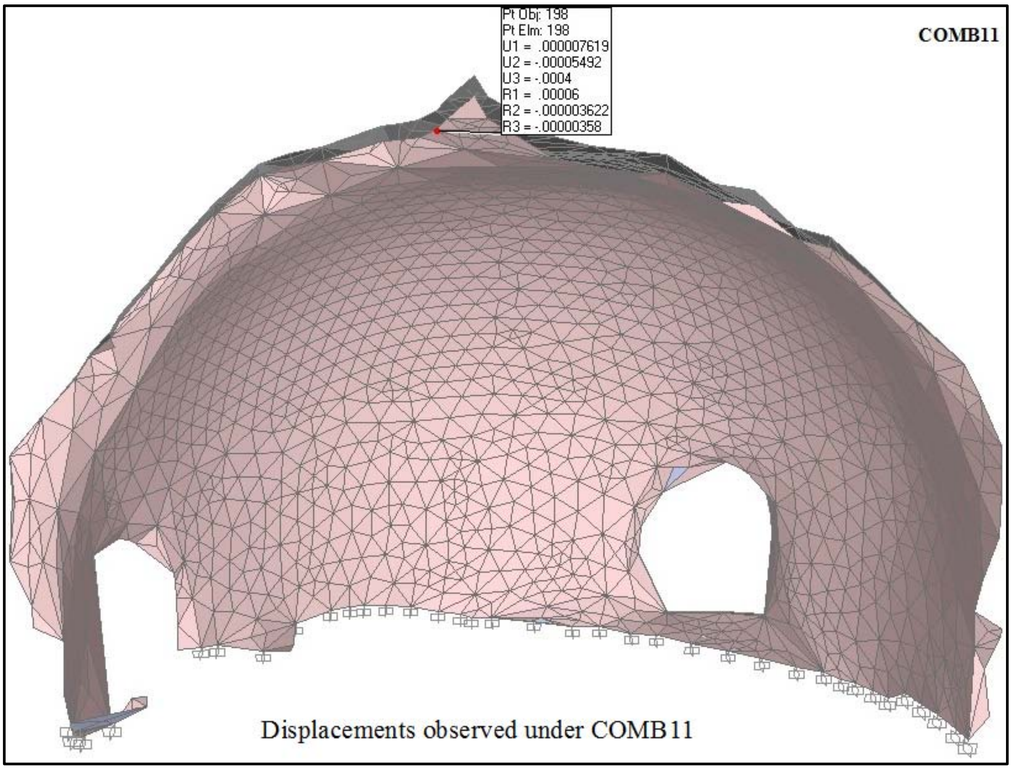

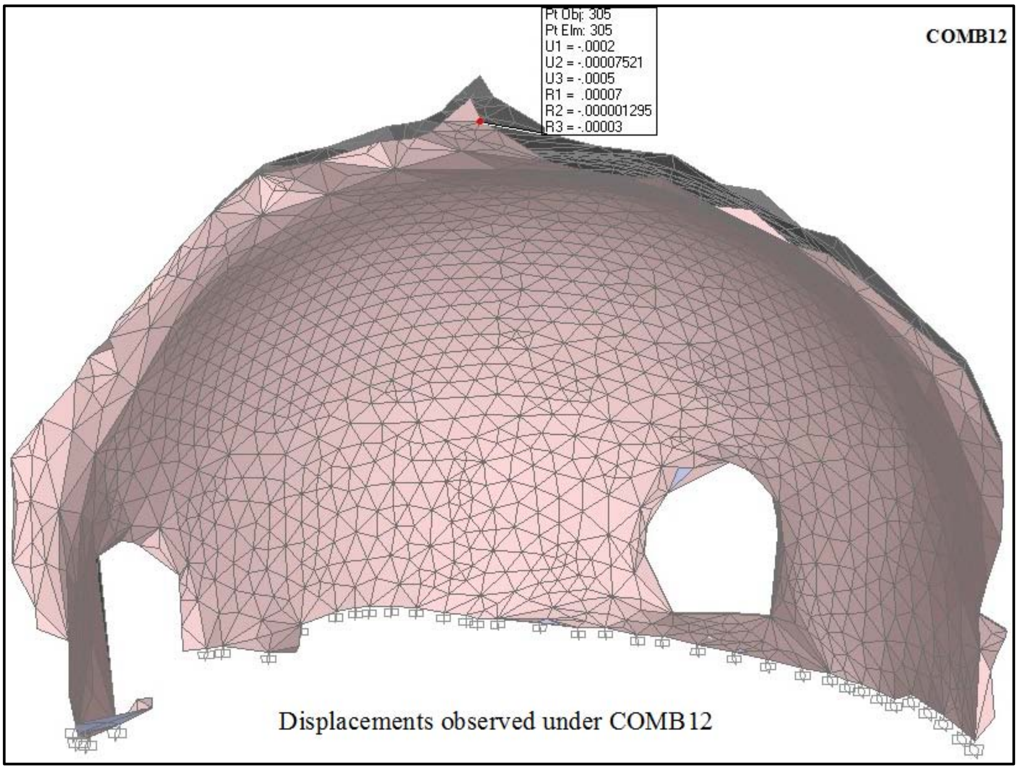

Figure F.1 (continued) : Displacements of South Tower observed for different loading combinations.

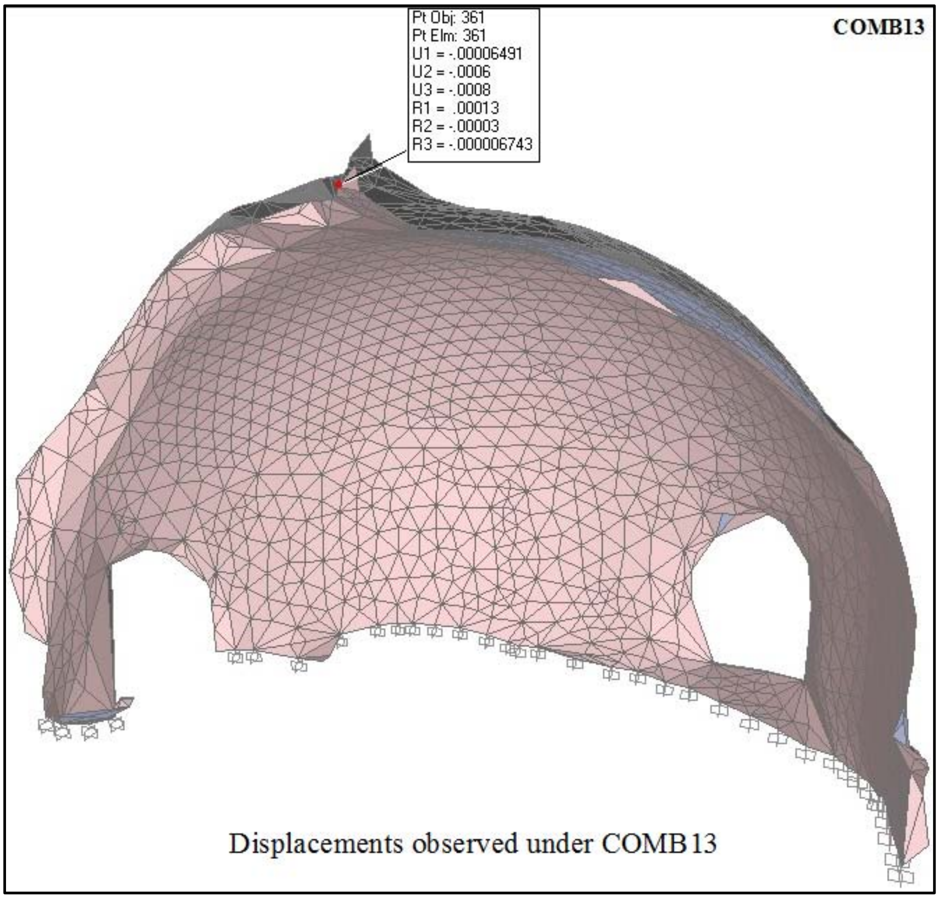

Figure F.1 (continued) : Displacements of South Tower observed for different loading combinations.

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TINCEL Foundation Scholarship (2010)

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TUBITAK National Scholarship for PhD Students (2007-2013.)

List of Publications and Patents:

PUBLICATIONS/PRESENTATIONS ON THE THESIS

*Tekdal-Emniyeti, E., Haefele, K. H. and Isele, J. (2010). Preliminary Results of Semantic 3D Modelling of Seddülbahir Fortress Using Laser Scanning Data, *International Conference on Cultural Heritage and New Technologies*, Vienna, Austria.

*Tekdal-Emniyeti, E., Haefele, K. H., Isele, J. and Celik, R. N. (2011). 3D documentation of historical sites and buildings for interdisciplinary works, *SPIE Optical Metrology*, Munich, Germany.

*Tekdal-Emniyeti, E., Celik, R. N. Haefele, K. H., and Isele, J. (2011). CityGML Model of Seddülbahir Fortress for Protection and Documentation, *WCCE ECCE TCCE Joint Conference 2 Seismic Protection of Cultural Heritage*, Antalya, Turkey

*Tekdal-Emniyeti, E. and Çelik, R. N. (2011). Integration of Different Geodetic Techniques for Renovation and Restoration of Cultural Heritage, *16th Conference on Cultural Heritage and New Technologies*, Vienna, Austria

*Tekdal-Emniyeti, E. and Çelik, R. N. (2011). Tarihi Taşınmaz Kültürel Mirasın Jeodezik Yöntemlerle Dokümantasyonu, *Cumhuriyet Üniversitesi Geomatik Mühendisliği Bölümü Açılış Sempozyumu*, Cumhuriyet Üniversitesi, Sivas

*Tekdal-Emniyeti, E. (2012). 3D Modelling of Seddülbahir Fortress Using Laser Scanning Data, *International Summer Academy: Constructing Heritage in the Light of Sustainable Development (ISAC)*, Cottbus, Germany

*Tekdal, E. and Çelik, R. N. (2013).Tarihi yapılar için jeodezik tabanlı yapı bilgi modeli tasarımı ve uygulaması, Harita Teknolojileri Elektronik Dergisi, cilt 5, sayı 3

International Conference Publications:

*Özludemir, M. T., Ayan, T., Deniz, E. Arslan, Çelik, R. N. , Denli, H. H. , Özşamlı, C., Erol, S., Akyılmaz, O., Acar, M., Mercan, H. and Tekdal, E. (2006). Remeasurement of İstanbul GPS Network, Fifth International Symposium, Turkish-German Joint Days, Berlin, Germany, March 28-31, 2006

*Tekdal, E., Özarpacı, S. and Çelik, R. N.(2006). Continuously Operating Reference Stations and the Current Situation in Turkey Fifth International Symposium, Turkish-German Joint Days, Berlin, Germany, March 28-31, 2006

*Çelik, R. N., Tekdal, E. and Avcı, Ö. (2006). What is the CORS Situation in Turkey? Shaping the Change XXIII FIG Congress Munich, Germany, October 8-13, 2006

*Tekdal, E., Çelik, R. N., and Ayan, T. (2007). Structural deformation determinations for strong motions, IUGG XXIV General Assembly, Perugia, Italy 2-13 July, 2007 (Abstract)

*Tekdal-Emniyeti, E., Çelik, R. N. and T. Ayan, (2008). Structural deformation monitoring analysis using geodetic techniques after the earthquake at Bolu pass of Transport European Motorway, Measuring the changes, 13th FIG Symposium on Deformation Measurement and Analysis, 4th IAG Symposium on Geodesy for Geotechnical and Structural Engineering, Lisbon, Portugal, 12-15 May, 2008

National Conference Publications:

*Tekdal-Emniyeti, E., Çelik, R. N. and T. Ayan. (2008). Bolu Geçişinde Deprem Sebebiyle Meydana Gelen Deformasyonların Koordinat Dönüşümleriyle Belirlenmesi, Türkiye Ulusal Jeodezi Komisyonu Çalıştayı, Koordinat sistemleri-Prof. Dr. Ahmet Aksoy'un Jeodeziye katkıları, 19-21 Kasım

*Özludemir, M. T., Ayan, T., Deniz, R., Arslan, E., Çelik, R. N. , Denli, H. H. , Akyılmaz, O., Özşamlı, C., Güney, C., Erol, S., Erol, B., Acar, M., Mercan, H. and Tekdal, E. (2012) Türkiye yükseklik sistemi ve uygulamada karşılaşılan sorunlar", 2012, TUJK 2012-Türkiye Ulusal Yükseklik Sisteminin Modernizasyonu, Zonguldak, 28-30 Mart