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UNREINFORCED MASONRY WITH EMBEDDED IRON TIE-RODS – THE CASE OF PANAGIA FANEROMENI CHURCH, CYPRUS

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UNREINFORCED MASONRY WITH EMBEDDED IRON TIE-RODS – THE CASE OF PANAGIA FANEROMENI CHURCH, CYPRUS

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ABSTRACT

The current research addresses the effectiveness of metallic elements, tie rods, as an auxiliary device in significant Cultural Heritage Monuments. Faneromeni Church was selected in order to accomplish this aim, which considered as the oldest building in Cyprus that has metallic tie rods. Finite Element Method is considered as the most suitable for the analysis of such an important and complicated structure, that allows multiple analyses, in short period of time with accruable results. Abaqus Programme chosen for the analysis, were geometry and mechanical properties of Faneromeni presented as accurate as possible. Three models were made for the analyses. Initially Faneromeni's Church model presented and analysed under dead and dynamical loads. Subsequently, metallic tie rods removed from the structure, in order to consider their contribution to the structure. Finally, first model was analysed, with the absence of the most basic tie rods of the structure.

Process of studying the contribution of tie rods in presented in four main chapters. The first chapter discusses about Monuments around the world that include or included in the past, metallic tie rods as part of the structure. The second chapter presents the decision of Finite Elements Analysis, as the most suitable solution for this process. Next chapter presents geometry and material's mechanical properties of Faneromeni Church. Finally, the fourth chapter demonstrates the three analyses and their results. The overall purpose of the study is comprehension of contribution of tie rods in structures, as well as the way they work.

ΠΕΡΙΛΗΨΗ

Η παρούσα μελέτη πραγματεύεται την αποτελεσματικότητα των μεταλλικών τενόντων ως μια βοηθητική συσκευή σε σημαντικά Μνημεία Πολιστικής Κληρονομιάς. Για να επιτευχθεί αυτός ο στόχος αποφασίστηκε η μελέτη της Εκκλησίας της Φανερωμένης στην Λευκωσία, η οποία θεωρείται η παλαιότερη κατασκευή στην Κύπρο στην οποία τοποθετήθηκαν αυτοι οι μεταλλικοί τένοντες. Η μέθοδος των Πεπεασμένων Στοιχείων κρίθηκε ως η καταλληλότερη για την ανάλυση μιας τόσο σημαντικής και περίπλοκης κατασκευής, δίνοντας την ευκαιρία πολλαπλών αναλύσεων σε σχετικά λίγο χρόνο και παρέχοντας αρκετά ακριβή αποτελέσματα. Η ανάλυση έγινε στο πρόγραμμα ABAQUS, όπου η γεωμετρία και οι μηχανικές ιδιότητες των υλικών της Φανερωμένης αποτυπώθηκαν όσο το δυνατόν πιο κοντά στις πραγματικές. Οι αναλύσεις που έγιναν αφορούσαν τρία βασικά μοντέλα. Αρχικά ένα μοντέλο μελετήθηκε όπως ακριβώς η πραγματική αποτύπωση της Εκκλησίας κάτω από νεκρά και δυναμικά φορτία. Στη συνέχεια αφαιρέθηκαν όλοι οι μεταλλικοί τένοντες της κατασκεύης, κατανοόντας έτσι την συνεισφορά τους στην κατασκευή. Τέλος, το ίδιο μοντέλο με το πρώτο αναλύθηκε, με την μόνη διαφορά την αφαίρεση ενός από τους βασικούς τένοντες της κατασκευής.

Η διαδικασία της μελέτης της συνεισφοράς των μεταλλικών αυτών στοιχείων, πραγματοποιήθηκε σε τέσσερις κύριες ενότητες. Αρχικά, μελετήθηκαν διάφορα Μνημεία ανα το παγκόσμιο στα οποία οι μεταλλικοί τενοντες αποτελούν ή αποτελούσαν μέρος της κατασκευής τους. Στη συνέχεια, γίνεται επεξήγηση της επιλογής της Μεθόδου Πεπερασμένων στοιχείων ως την καταλληλότερη λύση για μια τέτοιου είδους ανάλυση. Ακολουθεί η περιγραφή των γεωμετρικών στοιχείων και των μηχανικών ιδιοτήτων των υλικών του Ναού. Τέλος παρουσιάζονται οι τρείς αναλύσεις καθώς και τα αποτελεσματά τους. Γενικότερος στόχος της παρούσας μελέτης είναι η κατανόηση της συμβολής των μεταλλικών τενόντων στις κατασκευές καθώς και ο τρόπος λειτουργίας τους.

Contents

CHAPTER 1 – INTRODUCTION

Cultural heritage constitutes the history, the memories the wounds and the victories of every civilization around the world. One sight of a monument, church, castle or even a settlement can resuscitate a huge part of a past era and the history of a country. Cultural Heritage Monuments around the world are every culture's legacy, which stand there through the centuries engendering the visitor's admiration. Admiration of the beauty, the magnitude, the detailed work in contrast with the lack of means, knowledge and techniques.

Maintenance of these memories presupposes preservation of these monuments. Restoration of such significant buildings is a task with high complexity and high importance. Stepping into a slightly unknown, in most cases, path of exploring these complexities. Every monument, every "piece of history" must be treated as unique and examined thoroughly before any decision about preservation is taken. Materials used in such cases, hundred years before, are most of the times local, which could be moved easily to the construction site. Every region used its own materials on the contrary of nowadays that engineers know all the mechanical properties of the materials that are used. Another reason that defines their uniqueness are the master builders of that monuments. Different techniques were developed throughout the years from different people serving different purposes. Although, a construction innovation could spread in different country, but these could take years.

Behaviour of ancient structures cannot be defined only by materials and building techniques. Decay throughout the centuries is an essential factor of characterizing stability of monuments. How years past through them. How nature treated them. How human factor affected them. Visitors' safety constitutes primary factor in every structure, and furthermore in monuments that attract thousands of people.

Restoration of cultural heritage monuments can only occur when the existing materials are completely comprehensible. Interaction between all the elements, mechanical properties of the materials, clarification of how the structure is corresponding after thousands of years, and circles of decay. Some materials contributed a significant role at the survival of some of the most important Cultural Heritage Monuments.

Contribution of tie rods is analysed in following chapters and especially in an important Church in Cyprus. Use of tie rods, through the centuries and in different places of the world indicates that these elements used in multiple situations as an auxiliary device, with a very distinctive appearance in structures and without causing an aesthetic disharmony to these monuments.

2. TIE RODS

Tie rod can be defined as a rectangular or circular piece of wood or iron used in construction process from the 12th century until nowadays (Fitchen, 1961). These elements maintained the spacing of the truss beams of a wooden frame or the tilting of two parallel walls, or the thrust of an arch. In some cases, they were hooked into the walls without visibility of the anchorage. Other times hooks pinned to the wall were used, or they were anchored outside the structure. Effectiveness of tie rods contributed to several different situations which are presented in this chapter. Tie rods are separated in three different categories according to their time of use:

2.1. Permanent Tie Rods

2.2 Temporary Tie rods

2.3 Tie rods as a mean of emergency restoration

According to these three categories several examples of Cultural Monuments around the world that used or still using these elements are presenting in following subchapters.

2.1 PERMANENT TIE RODS

2.1.1 MILAN CATHEDRAL - MILAN, ITALY

Milan Cathedral well known as “Duomo di Milano” (Error! Reference source not found.) (Carmelo Gentile, 2017) is one of the most remarkable cultural heritage monuments in Europe. Millions of people every year visit this impressive structure, as it is considered part of the identity of Milano for many centuries. Duomo di Milano’s imposing structure of 108.5 metres height and 157 metres length stands there for over six hundred years, and constructed in an era that knowledge, means and technology were inadequate. Important elements of the structure, which seems to have contributed to the stability of this massive masonry cathedral, are the permanent metallic tie rods that are placed under each arch (**Figure 2**). Tie rods of Milan Cathedral seem to interest many specialists, considering that the

Figure 1 *Milan Cathedral*

Figure 2 *Inner part of the Cathedral with tie-rod view*

comprehension of their behaviour would lead to significant conclusions about the stability of the whole structure and its rehabilitation.

The construction of the Cathedral started in 1396 from the East to West and completed in 1805 with the astonishing façade. Major part of the construction was built in 15th and 16th century, including the transept, the main dome and the tiburio. Remarkable aspect of the construction is the geometry of the bays which included a / (spandrel) over them. Complexity of the bays structure as much as piecemeal construction set the need for a supporting device in order to connect the pieces and help arch bearing later thrusts. These devices are the metallic tie rods which were placed under every arch of the Cathedral. By the end of the structure, 118 iron tie rods were placed in the inner of the Cathedral, and most of them are the originals until today. Based on reports throughout the years only 7 of the original tie rods replaced which 4 of them where under the tiburio. Recent replacement of the old wrought elements with new iron tie-rods allowed researchers to examine broken parts, in order to understand better their behaviour.

Tie rods effectiveness on this structure can be validated through some serious events that the cathedral undertaken throughout the centuries (Vasić, A MULTIDISCIPLINARY APPROACH FOR THE STRUCTURAL ASSESSMENT OF HISTORICAL CONSTRUCTIONS WITH TIE-RODS, 2020). For example, in the 15th century four piers damaged due to the construction of arches in order to support tiburio and dome. These eccentrically load to the piers lead to the break of four iron elements which remained broken for over 500 years. Two of them, broke and fell to the floor of the nave while the other two were discovered broken at a restoration in 1980-1984. All four elements were replaced with contemporary steel tie rods, as well as several columns and 4 piers located under tiburio area. This zone (near tiburio) suffered serious deformation, and rest of the structure affected due to load redistribution.

In 19th and 20th century industrial activities caused soil settlements in the area of Duomo di Milano, negatively affecting parts of the Cathedral. While level of the water reduced about 25m in 200 years, foundation settlement led to severe damages at vaults and arches of structure. Cracks appeared on the arches and piers, incident that aggravate the situation and lead to interventions of 20th century. Serious issue at this soil settlement was redistribution of tensile forces at iron elements and how they were affected. FEM model created for that reason and showed that tensile stresses on tie rods are being affected by soil settlements (Vasić, A MULTIDISCIPLINARY APPROACH FOR THE STRUCTURAL ASSESSMENT OF HISTORICAL CONSTRUCTIONS WITH TIE-RODS, 2020) but these settlements did not cause the break of any iron elements.

Iron elements in Milan Cathedral responded to various challenges throughout the centuries allowing the structure to remain intact. From supporting assistance through construction process, to auxiliary device at soil settlements, tie rods enabled Milan Cathedral to exist in Milan hundreds of years after its construction.

2.1.2 SULEYMANIYE MOSQUE – ISTANBUL, TURKEY / ULU MOSQUE – AKSARAY, TURKEY

Middle East Structures constitute significant part of the worldwide cultural heritage. More specifically, Turkey is a country with plenty outstanding architectural achievements throughout the centuries, standing there for thousands of years proving the intelligence of their creators. Affected by Roman, Byzantine and Ottoman cultural heritage monuments can be samples for many structural engineers taking into consideration the size of these structures, their design and the fact that Turkey is a seismogenic area.

Mosques are religious places of worships for Muslins, and places of great importance in Turkey (Naser Almughrabi, 2015) (O.B. Sadan, 2017). Suleymaniye Mosque in Istanbul was constructed between 1550-1557 by architect Sinan, and this Mosques is his largest structure. Suleymaniye Mosque is an attempt of the architect to compete with Hagia Sophia, another great monument in Istanbul constructed during the Byzantine Empire. Affected by Hagia Sophia structural system Suleymaniye Mosque has an impressive dome, arches and buttresses system and an orientation of tie-rods above arches. Tie rod system was widely used in Turkish structures until 20th century where concrete structures started to build. According to Almughrabi about Suleymaniye Mosque "Historians did not mention that this mosque suffered of any structural difficulties, but on the contrary was described as a mark; excellence and cohesion in the face of natural factors and earthquakes." Important role to the good structural behaviour of mosque played the wrought iron tie rods. Despite the lack of historical evidence about the efficiency of permanent iron ties in Turkey, wide use of them and good condition of the structures where these were used, confirm their vital role in structural behaviour on complex constructions.

On the other hand, insufficient information about the anchorage of that tie rods, may lead to the opposite results. Erroneous example of replacement of the damaged tie rods is Ulu Mosque in Aksaray. Ulu Mosque had tie rods placed under almost every arch of the building, technique similar to other Mosques. Corrosion, strong seismic excitation or soil settlements are some of the reasons that lead to the replacement of some tie rods. As mentioned before, the methods used to anchor the tie rods originally were unknown. Attachment of tie rods around the pillar with bracelets placed incorrectly resulting delayed transfer of the tensile forces to iron ties. This example underlines the need of further study of these elements, in order to avoid situations like Ulu Mosque and possible permanent damage at monuments of great importance.

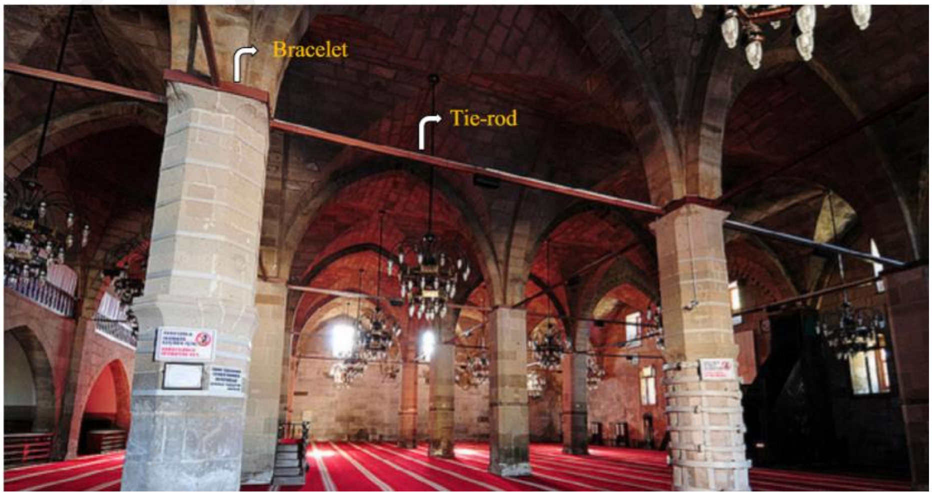


Figure 3 *Ulu Mosque, Faulty replacement of Tie Rods*

2.1.3 CASA ROMEI – FERRARA, ITALY

Casa Romei establishes a great mixture of Gothic and Renaissance components of architecture. Located in Ferrara, a city in north Italy, originally used as a house for a wealthy family in 15th century (Eva Coïsson, 2019). Nowadays, Casa Romei is residence for plenty works of art and sculptures which allow visitors to discover the ancient city of Ferrara that no longer exists. Characteristic of this structure is two row arcades and significant number of tie rods connecting the arches. Throughout the years, several interventions took place, but an earthquake in 2012 made things worse. This construction hosts important pieces of art for the area, that allow people to meet a whole different world. Any lack of understanding the behaviour of the structure could lead to the disaster of an era, in many ways. After this earthquake, several dynamical tests carried out in order to examine the dynamical behaviour of tie rods, and their effectiveness after all these years. Results have shown that some of ancient tie rods do not contribute to the whole static system and do not undertake any stresses. The more prevalent reason of failure of certain iron elements is their faulty anchorage. Replacement of ineffective elements can undertake some stresses of arches and help structure’s behaviour under dynamical and static loads.

2.2 TEMPORARY TIE RODS

2.2.1 MALLORCA CATHEDRAL

Santa Maria De Palma de Mallorca is a cathedral constructed over three hundred years ago, located in Spain (Luca Pel à J. B., 2016). Mallorca Cathedral is one of the most characteristic monuments of Gothic style in Mallorca (**Figure 4**).

Figure 4 Cathedral Of Mallorca (Luca Pel à J. B., 2016)

Completion of the whole structure lasted for over a period of three hundred years, from 1306 to 1600. As one of the most emblematic gothic Cathedrals in Mediterranean, Mallorca Cathedral interested many researchers for multiple reasons. Firstly, its long time that took to complete and how this affected the structure and secondly the material behaviour throughout the years like the creep behaviour of the masonry limestone. At the beginning of the construction Cathedral was designed for a more moderate height. About one century after the beginning of the construction alternations at the design decided, and original one nave structure alternated to three nave structure with higher vaults. The central nave has length of 77 metres, and vaults have height 44 metres from the ground to the top of the vaults and free span of 18.7 metres. Later vaults are shorter, with a height of 29.4m and free span of 8.7 m. The whole structure consists of seven bays. Construction of the vaults and arches is a complicated task regarding the construction means of 13th century. Firstly, later naves were built, on two sides of the central nave, and then central nave was built as last step of completion of a bay (**Figure 5**). The process of building that bays was time consuming and unfinished parts undergo significant deformations. As a solution for avoiding these deformations temporary tie rods were placed in order to sustain tensile forces that created. After the finalization of the bay these auxiliary devices where removed. Due to tensile forces remained after the completion of the naves, iron ties were difficult to remove and the use of heat required in order to be cut out. In situ observation led to the conclusion that tie rods where placed in two different heights under vaults, due to remaining hooks and darker spots on the masonry of the cathedral. The rectangular shape of removed tie-rods can be assumed by the dark spots remaining (**Figure 6 Dark spots and remaining hoops of** the removed, temporary tie rods, but dimensions cannot be verified easily. Two remaining tie rods until this day are at the same height as the remaining hoops and the dark spots on the stone masonry, that confirms in a way the position of the rest tie rods that have been removed. Although, it is just an assumption due to the fact that the time period that the remaining two metallic tie rods placed has not been clarified.

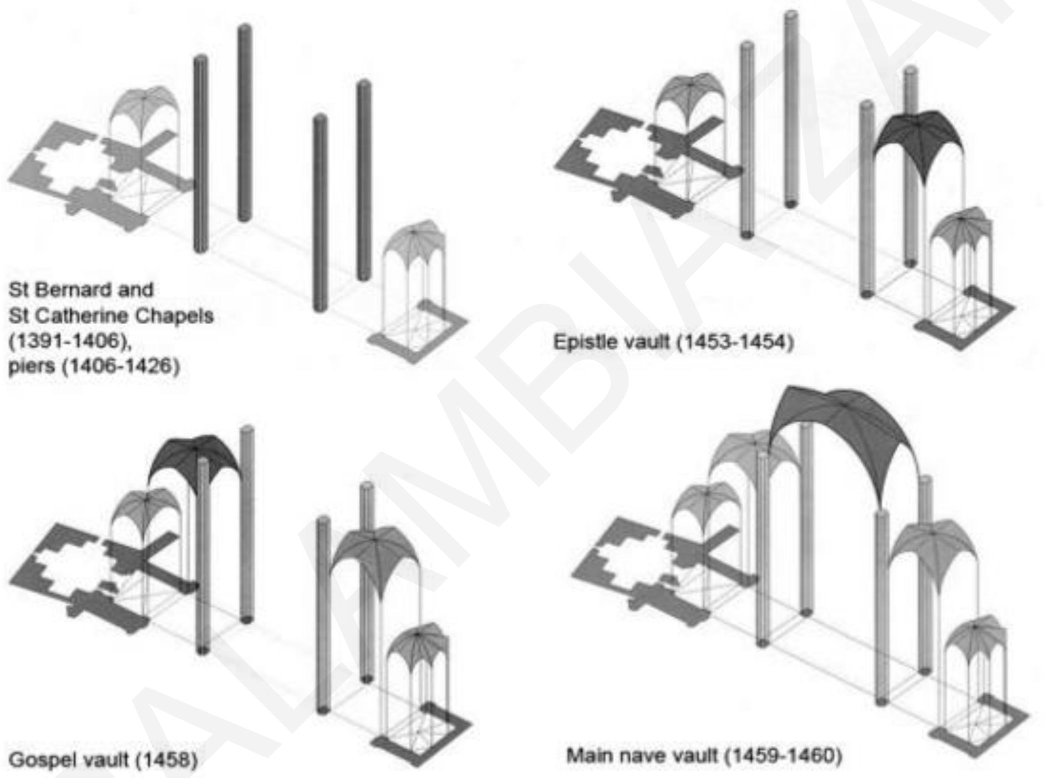


Figure 5 *Constructions process of the fourth bay (Luca Pel à J. B., 2016)*

Figure 6 *Dark spots and remaining hoops of the removed, temporary tie rods (Luca Pel à J. B., 2016)*

A closer and more careful observation at the dark spots shows stone damage around the marks of the tie rods. This damage can be a sign of the concentration of tensile stresses which means that rods indeed helped the stone construction by receiving a significant part of the tensile stresses. Another possible reason of this stone decay is the difficult removal of the tie rods or corrosion of the remaining hoops all these years.

In situ observation can provide several conclusions about place and type of the rods but a more detailed analytical method such as FEM analysis can give a better representation of the stresses and deformations of these stone - tie rods interaction. As FEM analysis allows to make different models in short period of time, in this case three analysis were produced. First model included the lower part of one of the bays that is the lower part of the buttress, the pier, the lateral vault, the lower part of the clerestory wall and the ties. As a second stage the analysis has be done after the completion of the upper part of the bay and as a final step of the analysis is the removal of tie rods. These three analyses adhere to the realistic construction process as it is represented in **Figure 5**.

Analysis showed the positive effect of tie rods during the construction as rods eliminated the lateral deformation of piers and managed to balance the thrust of the later vault. Indeed, there were deformations of the piers due to the expansion of the ties but was significantly limited. Crack patterns were modified due to the existence of tie rods during the construction process. Piers cracks almost disappeared. Cracks at arches and vaults on the other hand, affected negatively due to the metallic elements.

2.2.2 NOTRE DAME OF AMIENS

Notre Dame d'Amiens is a Gothic style Cathedral located in city of Amiens, north of Paris. It is the largest Gothic style Cathedral in France, from 13th century that it is built until nowadays. Construction of Amiens Cathedral started in 1220, as a replacement of a smaller church that had collapsed after a fire. It took around 36 years to complete the nave and the western façade, and about 34 more years to completely constructed. Of course, some additions happened the next centuries, and a restoration work took place in 19th century by the famous French architect Eugene-Emmanuel Vioellet-le-Duc. The Cathedral in its current form do not include any tie rods (**Figure 7** Signs of Wooden tie rods in Amiens Cathedral), but the signs in the nave arcade indicates the presence of wooden tie rods. Furthermore, some sketches from the architect of restoration Vioellet-le-Duc display some wooden tie rods **(Figure 8).** There is no further information about the time period that wooden beams removed, but according to Fitchen (Fitchen, 1961) these beams was an auxiliary mean during construction of the Cathedral of Amiens "as the higher portions of the superstructure came into operation and thus came to supersede the temporary function of the ties".

Figure 7 *Signs of Wooden tie rods in Amiens Cathedral (Media Center of Art History, 2020)*

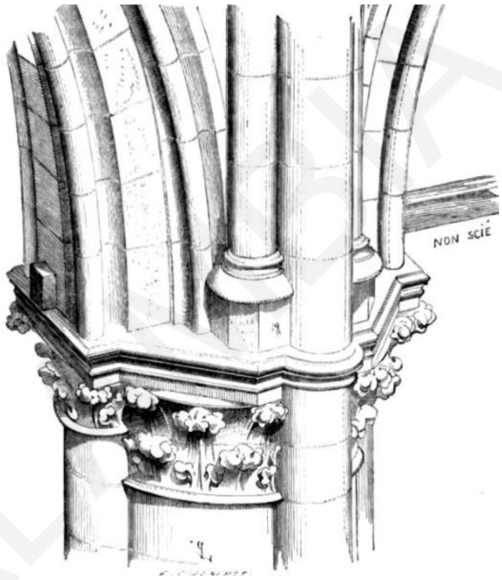


Figure 8 *Sketches of Viollet-le-Duc indicating the existence of Wooden tie rods (Media Center of Art History, 2020)*

2.2.3 WESTMINSTER ABBEY

Westminster Abbey undoubtedly is one of the most important monuments for English people and an important architectural ornament of medieval ages. Westminster Abbey is used for coronations and important ceremonies. Its construction begun in 1245 in the place of the Edward's church, which was demolished except the central nave. The construction of the nave started during the service of King Henry III who was influenced from the great architecture of Gothic Cathedrals mainly in France like Reims, Amiens and Beauvais. Architecture elements of these French cathedrals are the flying buttresses and the high vaults which as mentioned before need some auxiliary devices, tie-rods, to help with the construction of these complicated but very impressive sections.

Although the Westminster builders clearly influenced from the French techniques for accomplishing such complicated designs with that time limited means, they progressed from using wooden ties (NOTRE DAME OF AMIENS) to using iron ties. Use of wooden ties is much cheaper solution and probably attributed to a clearer prospective of French builders of the use of these beams. French builders' intentions were presumably from the beginning to remove these elements after the completion of the construction, which in English buildings is not very explicit (Fitchen, 1961).

In Westminster Abbey two types of tie-rods can be found. Permanent metallic tie-rods that are continuous through the pier and are built into the wall directly which can be found at central nave (**Figure 9**).

Second type of tie rods are placed in The Chapter House and according to Wander (Wander, 1977), these elements were removed at an eighteenth-century restoration of these part of the Westminster. The Chapter House was probably built around 1246-1255. It has an impressing octagonal shape with "an imposing central pillar, fanning out to a vaulted ceiling (**Figure 10**) (https://www.westminster-abbey.org/, 2020) . According to the remaining hooks, Chapter House had eight metallic tie-rods passing from the central stem to the ribs according to Fitchen (Fitchen, 1961). These elements supported the complicated vaulted roof and ensured the safety of the tracery windows that are right below the roof and are considered as pieces of art.

Figure 9 *Westminster Abbey central nave tie rods* (https://www.westminster-abbey.org/, 2020)

Figure 10 *The Chapter House, Westminster Abbey remaining tie rod hooks ((https://www.westminster-abbey.org/, 2020)*

2.3 TIE-RODS AS MEANS OF RESTORATION

2.3.1 SANTA MARGHERITA & BEATA ANTONIA CHURCHES, L'AQUILA

Cultural heritage structures nowadays receive the attention and appreciation that is necessary for this kind of buildings. All of them have a different story to tell about the area, the history and lifestyle of each region and for the architecture generally. Several organizations all over the world took over the difficult part of protecting and conserving the character of these structures. In some cases, although, human power cannot prevent power of nature and in such cases these architectural gems are in danger of destroying entirely. In emergency situations, some energies of restoration can save these buildings from further damages and prevent them from collapsing.

In 2009 L'Aquila region was hit by an earthquake, an especially important area mostly known for its architectural heritage buildings and history (Claudio Modena, 2010). The outcome of this earthquake interpreted to a hit at the cultural heritage of the region, which includes many ancient churches. In an emergency like an earthquake Fire Brigade department is the first to take over action in order to ensure the safety of the region. Although, when this disaster includes such important buildings there are other organizations and experts that are included in the process to achieve the better solution for these monuments. Along with the Fire Brigade, employees from the Cultural Heritage Ministry and researchers from regional Universities arrives at L'Aquila. Combining experience and knowledge from these three departments, an evaluation of the damage and economic quantification was made to take temporary safety measures.

Santa Margherita and Beata Antonia Churches were two examples where metallic tie-rods were used to ensure temporary stability of the buildings. Tie-rods as a mean of restoration is easy to use, economic and can have multiple uses. Complicated structures can develop different failure mechanism in each situation or develop more than one collapse mechanism in one structure. Each problem must confront with a specific way and not use a global intervention for everything. In Santa Margherita case tie rods helped in two ways. Metallic ropes connected two side walls and anchored with an exterior beam, which enabled the structure to react as one part and prevent walls from overturning (**Figure 11**). An intervention where tie-rods used was to connect apse to the masonry which connects central nave with the lateral chapels. In Beata Antonia case, metallic tie rods were used from the beginning of Church construction until a later restoration where these elements were falsely removed. These elements connected the walls of the church. Experts operating the interventions of the earthquake decided to put back the tie-rods to their old places (**Figure 12**).

Figure 11 Santa Margherita restoration with metallic ropes

Figure 12 Beata Antonia tie-rods placed after intervention

CHAPTER 3 - FEM ANALYSIS

Restoration of cultural heritage monuments is considered as a very subtle issue for multiple reasons. Intervention in any way at this kind of buildings must be an outcome of a multidisciplinary approach. In comparison, with the study of new conventional structures of 21st century, monitoring the behaviour of a monument can be quite complicated process and any mistaken decision can be fatal. Main requirements in this kind of operations is reversibility, minimum intervention and re-treatability (Janez Turk, 2019). Reversibility is defined as the actions and interventions that can be reversed if needed in a future stage without causing any permanent or significant damage. Intervening to a cultural heritage structure which defines the local identity of each country and constitutes compelling legacy of past centuries, preventing of its original character is critical. Therefore, minimum intervention means changes must be as limited as it takes, only relaying to necessary actions. Finally, re-treatability means that there are not any unexpected consequences of the intervention, and do not prevent any different treatment at the future.

Finding the most suitable solution is an outcome of a three-phase method. First, identifying the structure, geometry, materials and loads. In that case the physical model is examined as much as possible in order to be closer to the elements of the realistic structure. For monuments constructed hundreds of years before this is not an easy task, having in mind that materials, construction methods and techniques were a lot different then, than nowadays. Furthermore, history of that structure must be considered, as past events can affect structure behaviour or material response.

Subsequently, with the information collected in first phase a mathematical model is created. Mathematical simulation is a representation of the existing construction in a mathematical form. This mathematical model must be the closest version of real structure, but a part of these simulation is based on analyst's hypothesis. Numerical model, of course, is one of many solutions that an analyst has, including architectural, analogical, experimental scale models. Mathematical model constitutes an excellent and common solution in this kind of analysis due to economic reasons, its versatility and capability. Analysis of a monument many times can be quite expensive. The cost can be a deterrent factor for the restoration of a cultural heritage building so analysis expenses have to examined seriously. Inexpensive in situ or laboratory tests cannot always give a representative image of a complicated construction. Therefore, the analytical process must be a compromise between realism and cost. Versatility on mathematical analysis permits many changes and improvements for the best solution to be found. Alternative hypothesis in short period and limited effort allows examiner to find the most representative version of real structure. Capability and diversity of numerical formulations enabled improved models and computer applications in this engineering field of restoration. Easy to use programmes introduced engineers to a new field of analysation and restoration.

Finite elements method is widely used the past years in considerable number of masonry structural analyses, as a sign of effective method approach in such complicated structures. Domes, arches, vaults and embellish facades that most of historical cathedrals and churches have, makes the process and the mathematical model even more complicated. Indicator at this process is the cautious selection of the model. In some situations, the whole structure is analysed in a simpler but still representative form. St. Gemma Church in Gioriano Sicoli (Giuseppe Brando, 2015) after L'Aquila earthquake which affected many structures of the area, was investigated and a FEM model was created in order to establish church vulnerabilities (**Figure 13**). FEM analysis showed many similarities of the existing condition of the church, and conclusions of this search can be used in the future restorations for St. Gemma church and other similar buildings in the area. FEM analysis was developed in two churches in Northern Italy, Sant' Antonia Abate church and San Agostino and Ernesto (Marco Valente, 2017). In 2012 Emilia earthquake affected many masonry structures of the area. Detailed FEM model allowed the identification of the churches' weaknesses and detection of the most vulnerable elements (**Figure 14**). This investigation resulted a better view of how these two churches can be improved in order to gain more effective seismic behaviour in future and avoid a possible collapse.

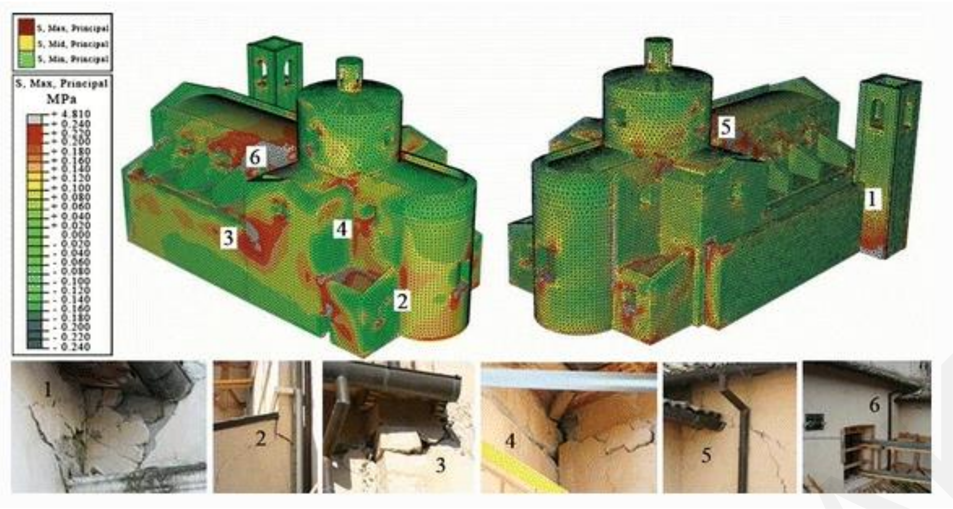
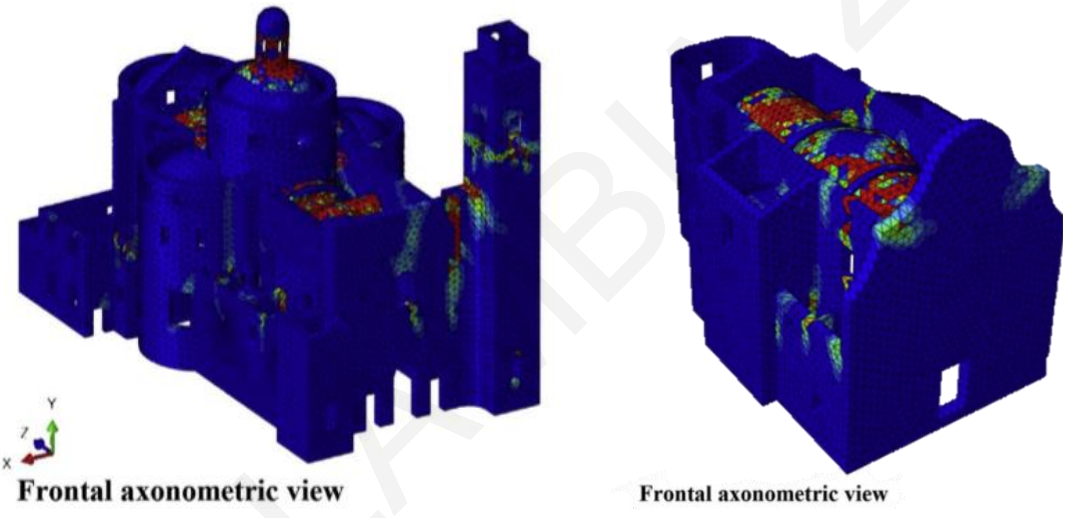


Figure 13 *FEM model of St.Gemma Church and in situ observation (Giuseppe Brando, 2015)*



(a)

(b)

Figure 14 *(a) Sant' Antonio Abate Church (b) San Erasmo and Agostino Church, tensile damage contour plots*

In other situations, parts of the structure considered more important, are isolated and analysed in parts. For example, two FEM models of three arches (**Figure 15**) are demonstrated, one model with and one without timber tie beams, in order to examine the effectiveness of timber tie rods on stone masonry arches under dead loads (Shaher Rababeh, 2013). In Jordan use of tie beams estimate that were used from the late BC century in many structures. Aim of this analysis is the effectiveness of tie-rods in arches, and a better understanding of their behaviour. Conclusions about the help of tie beams in structures were established with the demonstration of a part of structure that was considered the more important, the arches.

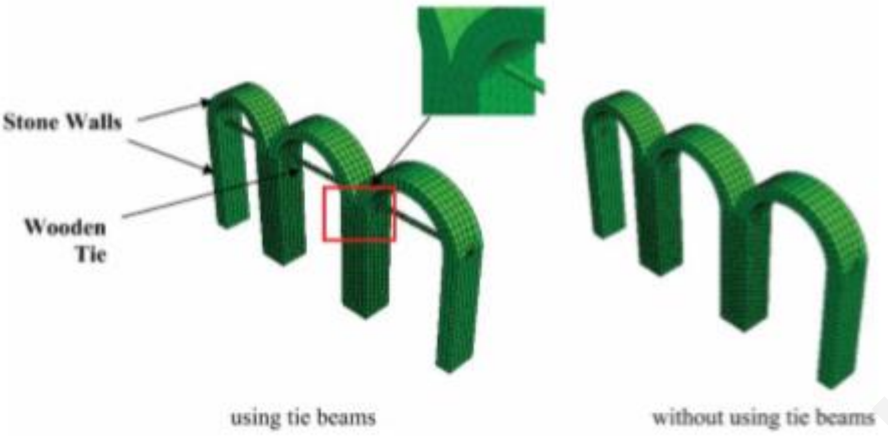


Figure 15 *Three dimensional model of stone masonry arches in Jordan Structure (Shaher Rababeh, 2013)*

As mentioned in Chapter 2, tie-rods used as auxiliary devices during the construction process in order to support arches and connect already built parts with new parts of the structure. This matter interest many researchers who tried through FEM models to observe how these iron elements operate during construction. Milan cathedral and Mallorca Cathedral are two very characteristic monuments where tie rods used, supporting a more complicated system of more than one arches. Computer analysis gave us a reflection about the construction process and the arch – tie rods system behaviour. Both Vasic and Angjeliu (**Figure 16**) demonstrated efficient numerical models of a bay located in Milan Cathedral (Grigor Angjeliu, 2020), (Vasić, A MULTIDISCIPLINARY APPROACH FOR THE STRUCTURAL ASSESSMENT OF HISTORICAL CONSTRUCTIONS WITH TIE-RODS, 2020). According to Vasic "*Numerical analysis showed that making instantaneous analysis may predict significantly different state of the stress in the final configuration of the building with respect to the staged analysis*". Angjeliu analysis outcome showed that numerical modelling can predict the state of

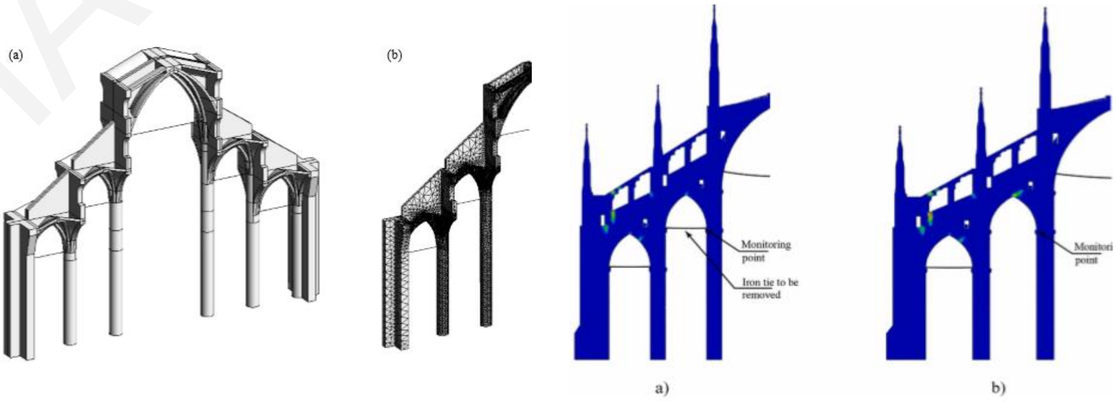


Figure 16 *Part of Milan Cathedral Numerical Model (a) (Vasić, A MULTIDISCIPLINARY APPROACH FOR THE*

iron elements and predict any maintenance or replacement of the elements, due to their internal forces state.

A time-dependent analysis on material and geometrical non-linearity numerical model of Mallorca Cathedral showed the effects of tie rods and their removal on the other elements of the model (**Figure 17**) (Luca Pel à J. B., 2016).

(a) (b)

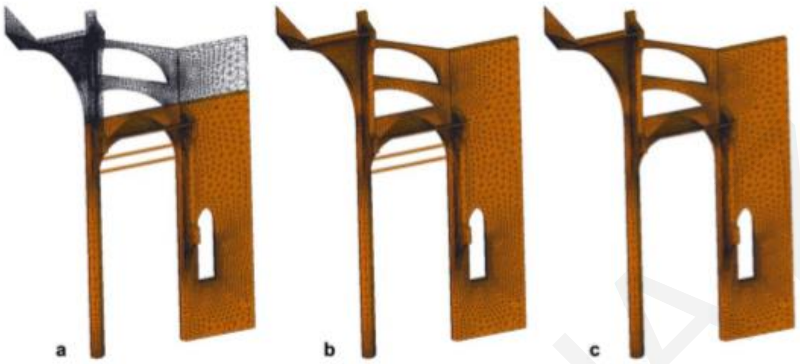


__Figure 17__ Mallorca Cathedral FE analysis of the construction process (Luca Pel à J. B., 2016)

In the third phase of method and after the conscientious research of model, or parts of it, results are investigated. FEM methods used the past years, as mentioned before, are quite accurate, but always results must examined from researchers in order to see any mistaken results or uncertainties. Valuation of the outcome of this analysis is considered as a significant part of the process as can lead to the final decisions of restoration. Computer can make a major part of the process but is on researchers' behalf to examine and control these results in order to lead to reasonable conclusions.

CHAPTER 4- FANEROMENI CHURCH

Church of Panagia Faneromeni (**Figure 18**) is an old masonry building located in Nicosia's, Cyprus' capital, historic centre. It is the biggest church inside the historic Venetian Walls of Nicosia. Initially, in 1222, when first constructed was a women Monastery. In 1561 Cyprus Island was under Ottoman Empire, and the Monastery would have become a mosque, as many other churches in Cyprus. Ottoman gave up their efforts when assigned imams kept losing their lives and the church remained as it was. In 17th Century a big earthquake caused damages in many structures in Nicosia including Faneromeni Church. Faneromeni Church after the earthquake needed to rebuild. Reconstruction of the Church was from 1872 to 1874 and maintains its appearance until today (Cyprus for Travellers, 2020). Until today Faneromeni Church has been a significant structure for the town and one of the most emblematic building in Nicosia. Faneromeni church is a three-aisled dome basilica with cross-shaped vaults, but it has also an influence from gothic style cathedrals. Innovative intervention for the era of its construction are the iron elements connecting the arches of the church called tie-rods. Faneromeni is considered as the first building in Cyprus that these elements where used, and they were placed during construction and not as an addition to a postnatal stage. These kind of iron elements, as mentioned in Chapter 2, were used both in Europe and Middle East countries. Assured assumptions about how this technique came to Cyprus and where the builders learnt about the effectiveness of these elements cannot be made.

Figure 18 *Faneromeni Church, exterior (Big Cyprus, 2020)*

In order to examine the effectiveness of iron tie rods a FEM model of Faneromeni's Church designed in ABAQUS. Design of these model is based on few historic accessible documentations, but many assumptions were made due to lack of information.

4.1 MATERIALS

Faneromeni is built mainly with three leaf Unreinforced Masonry which is consisted of local limestone called "Gerolakkos" (S. Modestou, 2015) and lime mortar. Gerolakkos stone units have a density of about 1600 kg/m^3 due to their relatively high porosity that is estimated around 40%. Therefore, their compressive strength is estimated between 0.5-8 MPa, which is considered as low compressive capacity for a masonry material. Lime mortar strength usually does not exceed the 1 MPa. According to this information masonry capacity was estimated with an EC6 equation,

$$f_k = K \bullet f_b^{0.7} \bullet f_m^{0.3}$$

Equation 1

The compressive strength of the units, fb, was estimated to be around 5.5 MPa and the compressive strength of the mortar, fm, around 1MPa. The constant K was taken equal to 0.45 according to the relevant table defined in EC6. Compressive strength of the masonry is calculated by equation 1 and tensile strength is considered as the 1/10 of compressive strength. Properties of masonry are shown in

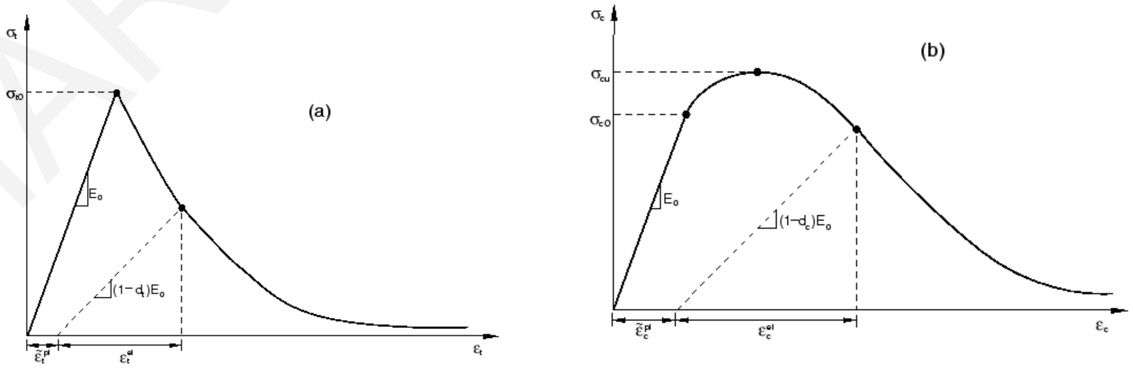


Table 1 and its plasticity is considered as damaged concrete (**Figure 19**), because concrete and limestone are brittle materials and have the same behaviour.

Figure 19 Response of concrete to uniaxial loading in (a) tension and (b) compression (ABAQUS docs, 2020)

Tie rods, elements that have more interest in this analysis, cannot be examined experimentally in order to determine their properties. In some cases, like Milan Cathedral, where these elements needed to be replaced, broken parts were investigated experimentally in order to determine their mechanical properties (Mariagrazia Bellanova, 2015). In this analysis properties of the iron elements that used in Finite Element Model are drawn from literature and are shown in

Table 1. Iron ties were considered having elastic behaviour.

Another material included in the analysis is unreinforced concrete of the bell tower. Bell tower was rebuilt in 1937-1938, and after visual inspection and taking into matter the age bell tower concrete type estimated 15MPa. Mechanical properties of concrete C12/15 were estimated for the FEM model.

***Figure 20** Interior of Panagia Faneromeni Church (Cyprus for Travellers, 2020)*

Table 1 Material model parameter values

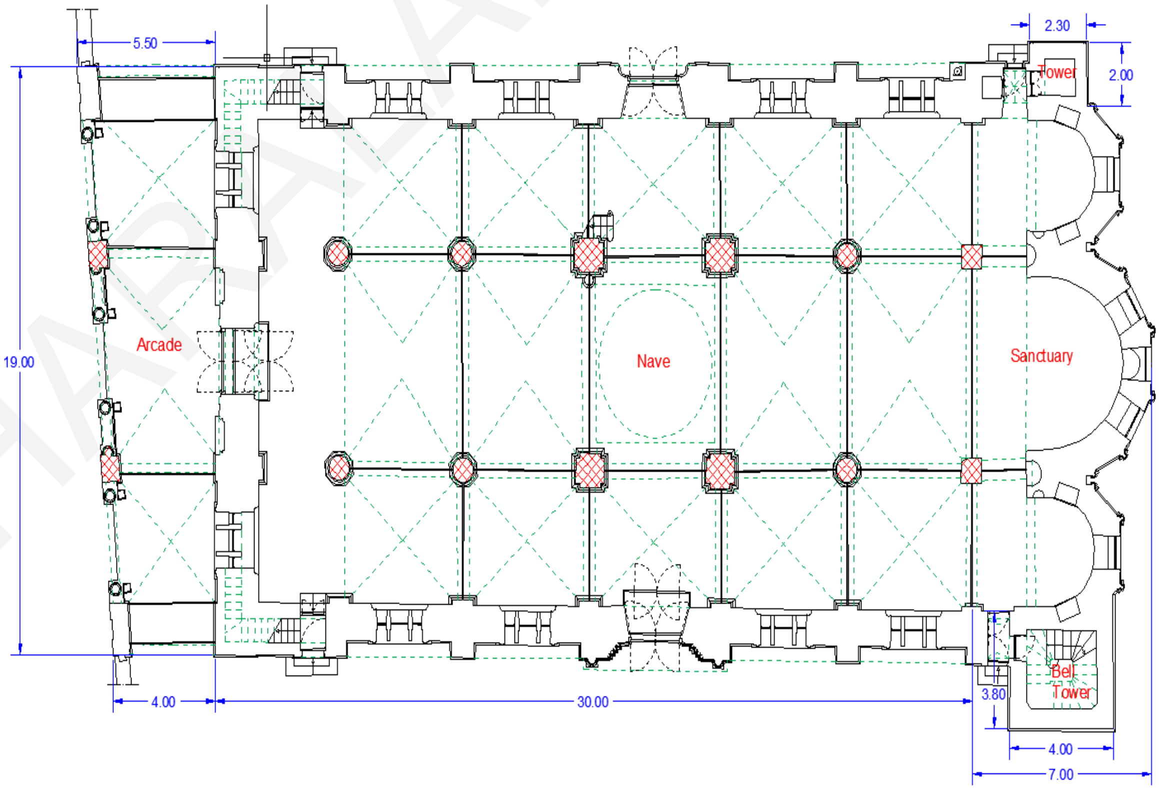
MATERIAL	Density [kg/m^3]	Young Module E (GPa)	Poisson Ratio v (-)	Compressive Strength fc (MPa)	Tensile Strength ft (MPa)	Behaviour
Masonry	1600	0.90	0.25	1.50	0.15	Non-linear
Soft Iron	7850	200	0.20	248	325.50	Linear
Unreinforced concrete C12/15 (EC2)	2400	26	0.30	12	1.60	Non-linear

4.2 GEOMETRY

Faneromeni church has length of 42 metres and width of 22 metres (**Figure 21**). Central nave is 37 metres long, including the nave sanctuary, a small tower and the bell tower. The free span of arches inside the nave is 6.2 metres and the height from the floor to the highest interior vaults in 11.50 metres tall (**Figure 22**) (Philippou).

At the centre of the nave there is a dome with a diameter of 5 metres and a length from the floor till the exterior cupola of the dome of 22 metres. It is the tallest part of the church after the bell tower. At the façade of the church there are vaults of 5 metres span and height of 6.50 metres from the floor till the top of the arcade 6.5 metres. At the back part of the church there is a tower at one side that its height does not exceed the height of the lateral naves. Length and width of this tower is 2.3 and 2.0 metres, respectively. The bell tower, tallest part of the church, has 4 metres length, 3.80 metres width and height up to 26.50 metres.

Buttresses thickness varies from 0.50 to 1.80 metres at the main church and from 0.35 to 0.65 metres to bell tower. Twelve columns of the structure can categorize in three profiles according to their geometry. There are four square columns 1.15x1.15



metres, six circular columns with diameter of 80 centimetres and finally two square columns of 80x80 cm.

Figure 21 Top view of Faneromeni Church (Philippou)

Shape of tie-rods is rectangular with 5*5 cm dimensions. They are pinned into the arches at 6.20 metres from the ground. They are anchored inside the wall, so the anchorage method cannot be defined certainly.

Taking into consideration the description above, a three-dimension model was developed in ABAQUS programme. Since the complexity of such structure cannot be formulated to a numerical model, several assumptions were made. Firstly, elongated elements like masonry and concrete walls were simulated as shell and slender elements, respectively. As beam elements were simulated columns of masonry church and tie-rods.

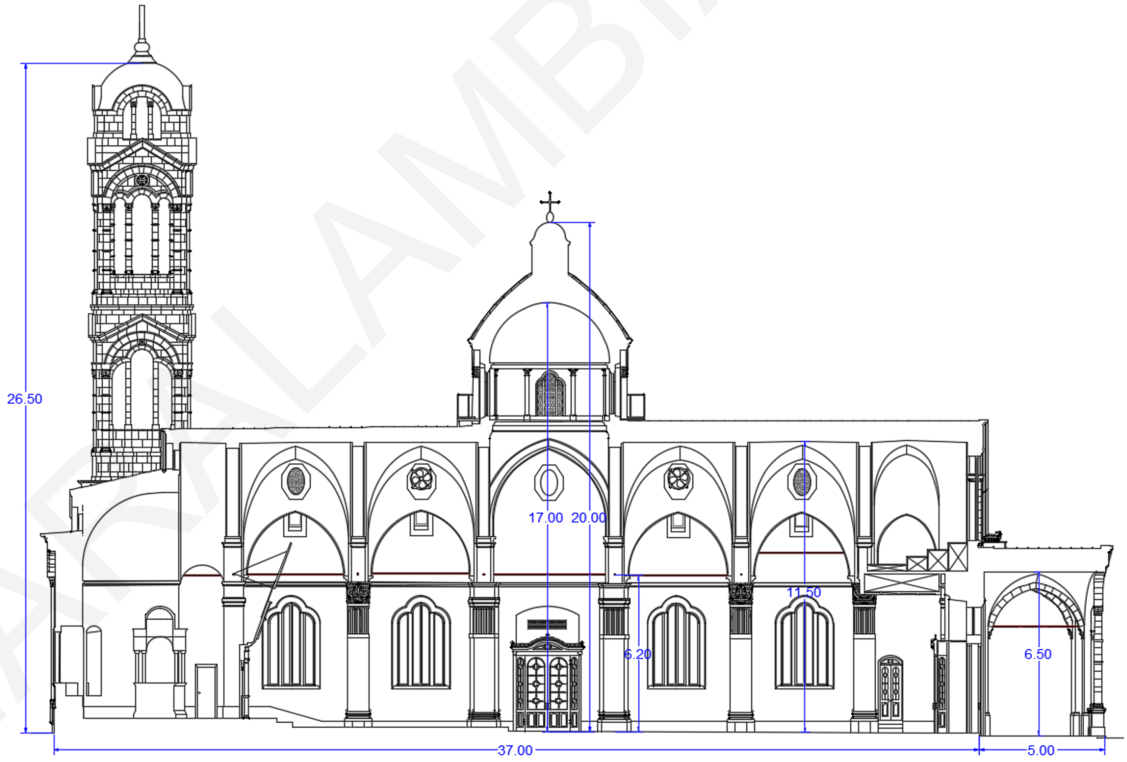


Figure 22 Section and dimensions of Faneromeni Church (Philippou)

Furthermore, the dimensions of the arcade were considered to be symmetrical with a constant span of the vaults equal to 4.5 m. The boundary conditions of the structure considered to be pinned at the base.

CHAPTER 5 – ANALYSIS

In Section 4 Faneromeni's Church description was presented as an aspect for better understanding of the analysis that is developed in this Chapter. As mentioned in previous sections, investigation of a masonry monument that was built hundreds of years before can be a complicated and difficult task as much of the data that were needed, cannot be examined and several assumptions need to be made. Collecting information through literature, previous interventions and in situ observation a model is developed in FEM analysis programme ABAQUS. The model was subjected in nonlinear static analysis under the self-weight and a pressure of 2 KN/m2 applied on the roof, representing the weight of the tiles. Distributed loads 1 KN/m and 2KN/m were applied on the top of the tower, respectively, in replacement of their covers. The model was meshed using 33,410 triangular three-node linear shell elements and 649 two-node beam elements; 34,059 elements in total (**Figure 24**). The number of the nodes created is in total 17,990 and the number of the variables of the problem is 108,028. Main aims of these analysis are the understanding of the existing structure as it really is, and examination of the effectiveness of iron tie-rods. In order to complete these aims three models where developed and corresponding analyses were made. Extensive analysis is described subsequently, as well as results. Three FEM models are:

5.1 Realistic Model with Tie Rods
5.2 Realistic Model of the church Without Tie Rods
5.3 Realistic Model with Removal of one basic Tie rod

Through these three different analyses the basic element that changes is the number of tie-rods of the structure. Chapter 2 showed different kind of monuments through Europe and Middle East, and how the appearance of these elements helped the behaviour of the monument. Faneromeni Church seems to be the first building in Cyprus that these elements were applied and remained until nowadays. Through the following analyses stresses, deformations and decays on the model will be examined for better understanding of the existing structural system and for future interventions to the church if it is required.

5.1 REALISTIC MODEL WITH TIE RODS

First model **(Figure 23)** of FEM analysis was developed just like the existing church and with the description from Chapter 4. Tie rods placed at 6.20 metres from the ground, exactly at the position of the real ones. Tie rods anchorage was considered as perfectly fixed boundary conditions, which means no deformations and rotations.

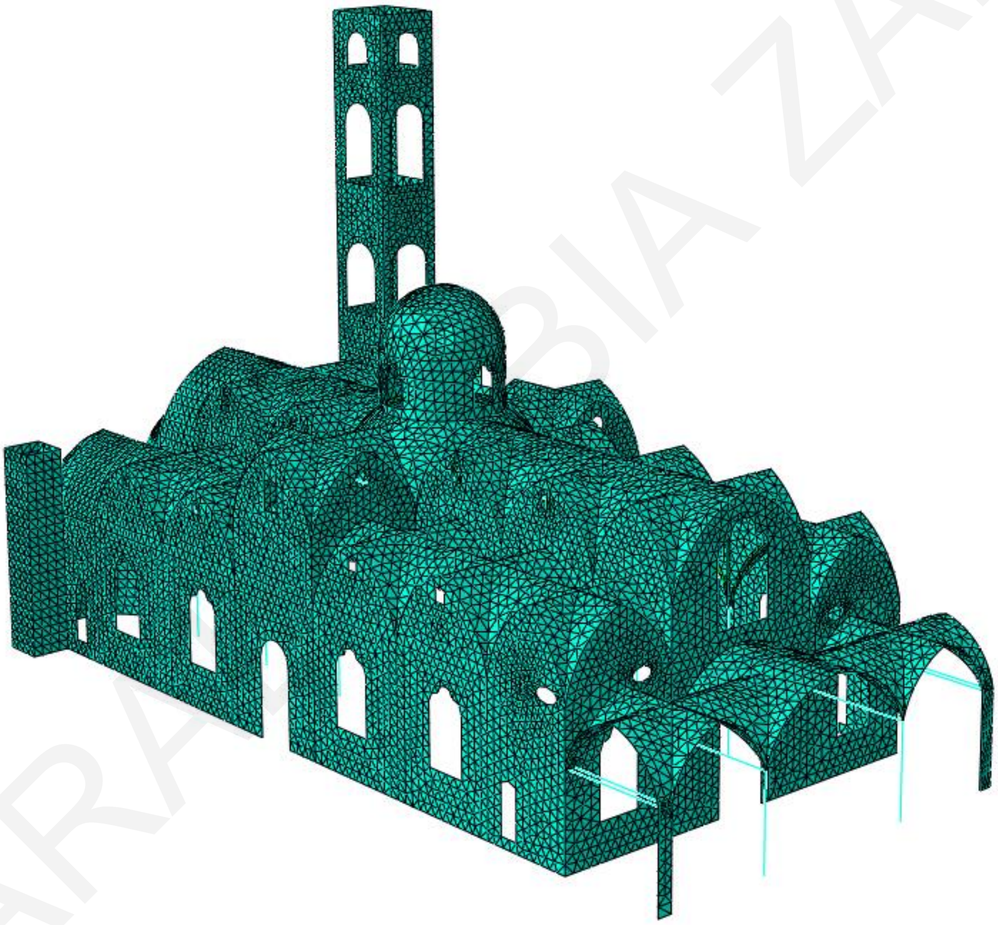


Figure 23 *FEM MODEL*

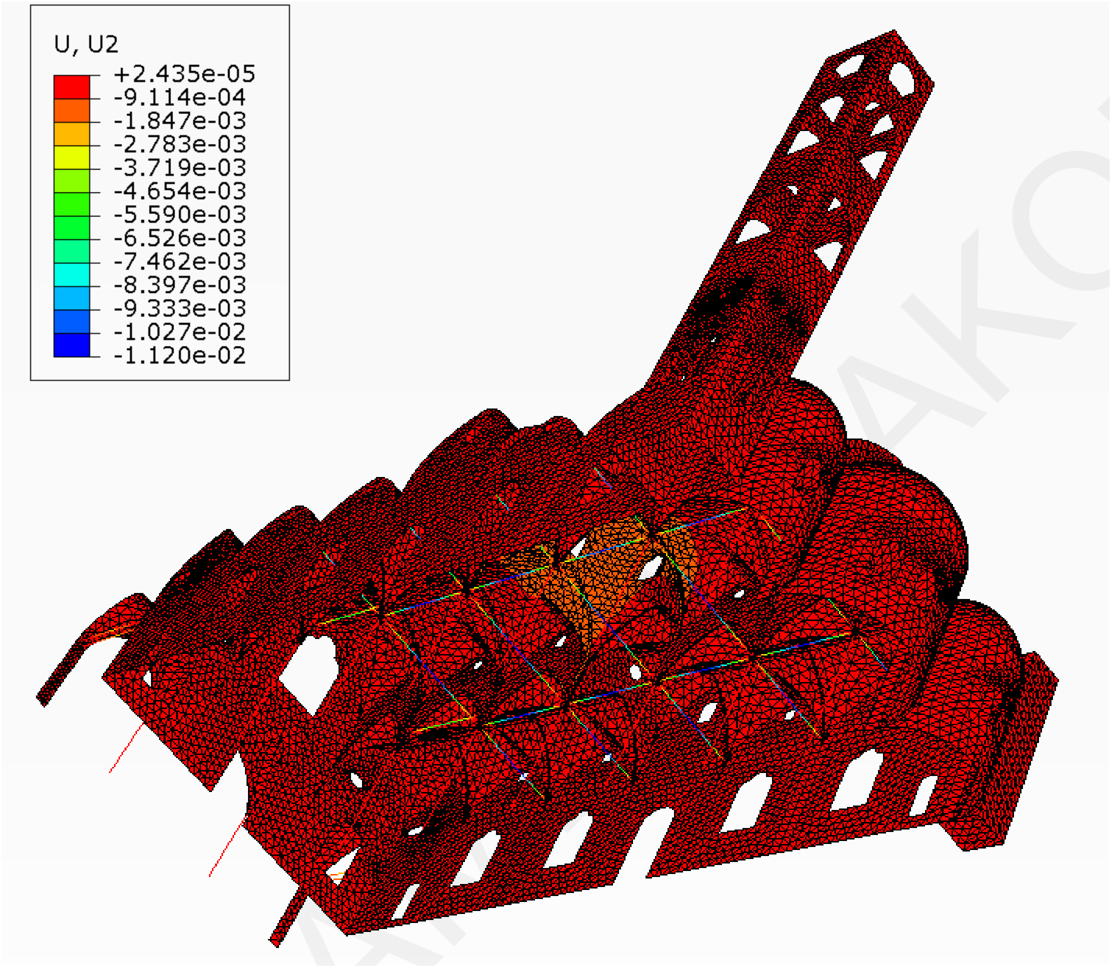


Figure 24 *Realistic model under dead loads - Results of deformation in metres.*

Firstly, with the effect of dead loads of the structure, a major deformation can be seen at the tie rods, and no special deformations are observed at the rest of the model. Specifically, central tie rods that have a spam of 7 metres, have the biggest deformation of the whole construction of 1.12 cm. The results are shown at **Figure 24**, table of contour representation of deformation, are in metres. Tie rods located further from the bell tower, with smaller length than the centrally located, face less deformation. Moreover, a deformation around 2 mm can be noticed at the dome, as the rest of the structure do not face any noticeable deformations.

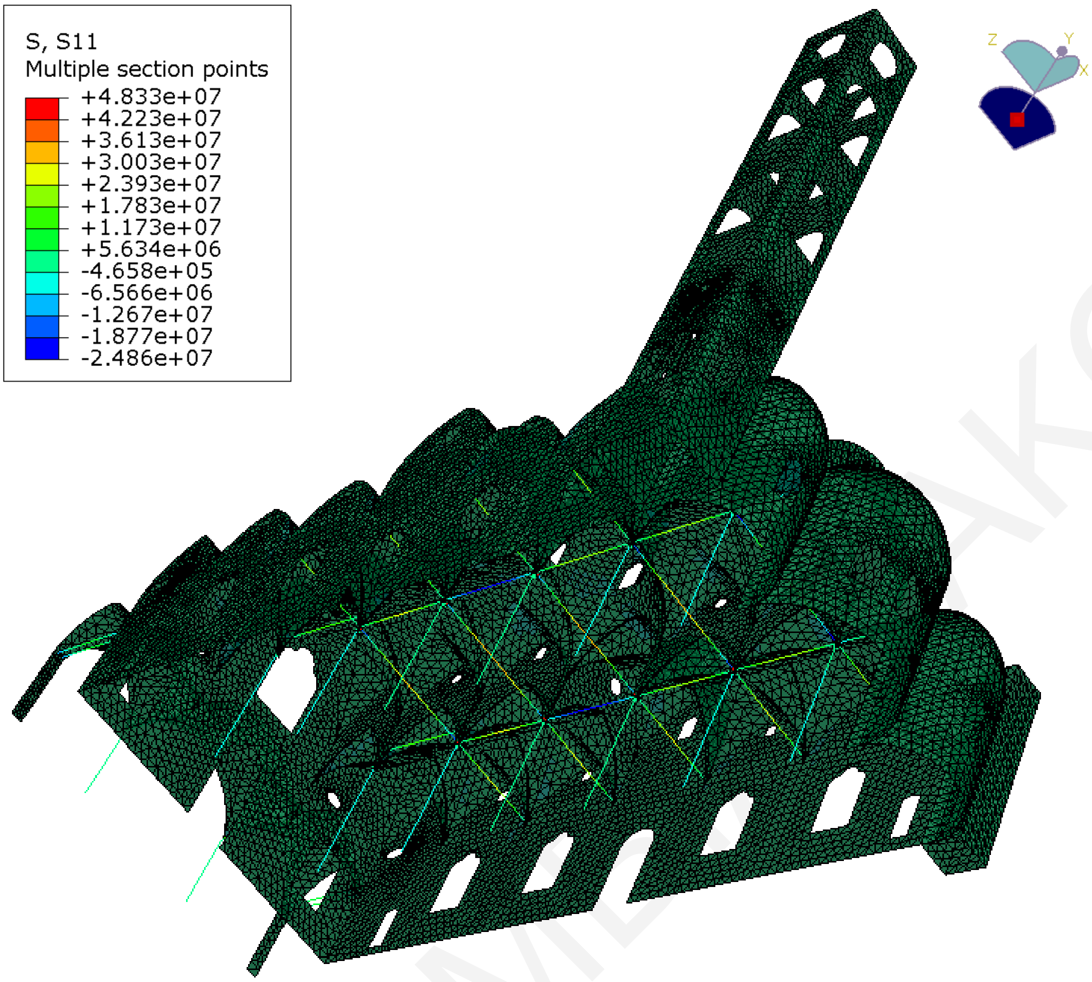


Figure 25 Stresses of model under dead loads. Stresses in (Pa)

According to **Figure 25** that shows stress contouring of the model under dead loads, all tie-rods that hold the walls of the church together, in Z direction, have a tensile stress. That tensile stresses shows that tie rods in that direction tend to hold the walls of the church together. Weight and structure of the dome tend to push walls of the church to open under dead loads. Tie-rod stress at this point, where no important loads are applied at the model, shows that these elements tend to hold the walls together in order to bare the structure of the dome. Tensile stress of about **48 MPA** appears near anchorage of the tie rods at Z direction **(Figure 26,Figure 27).** Masonry stresses according to **Figure 28** appeared low as it was expected.

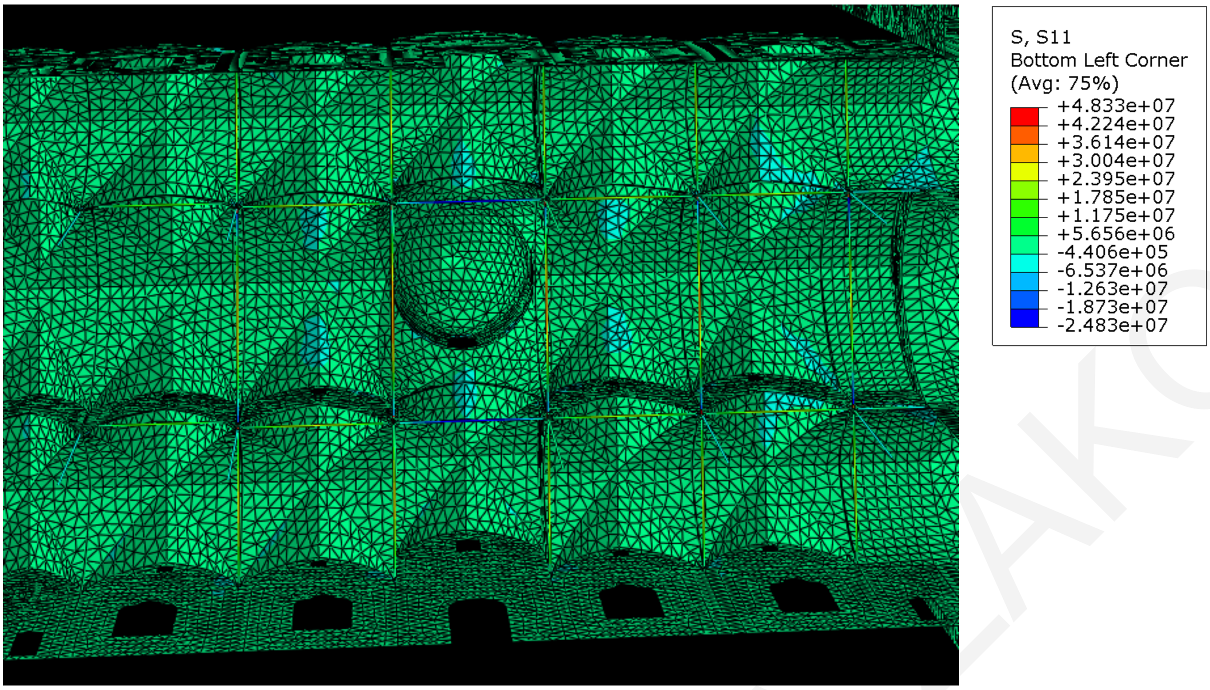


Figure 26 *Stresses of the tie rods top view as* ***Figure 21***

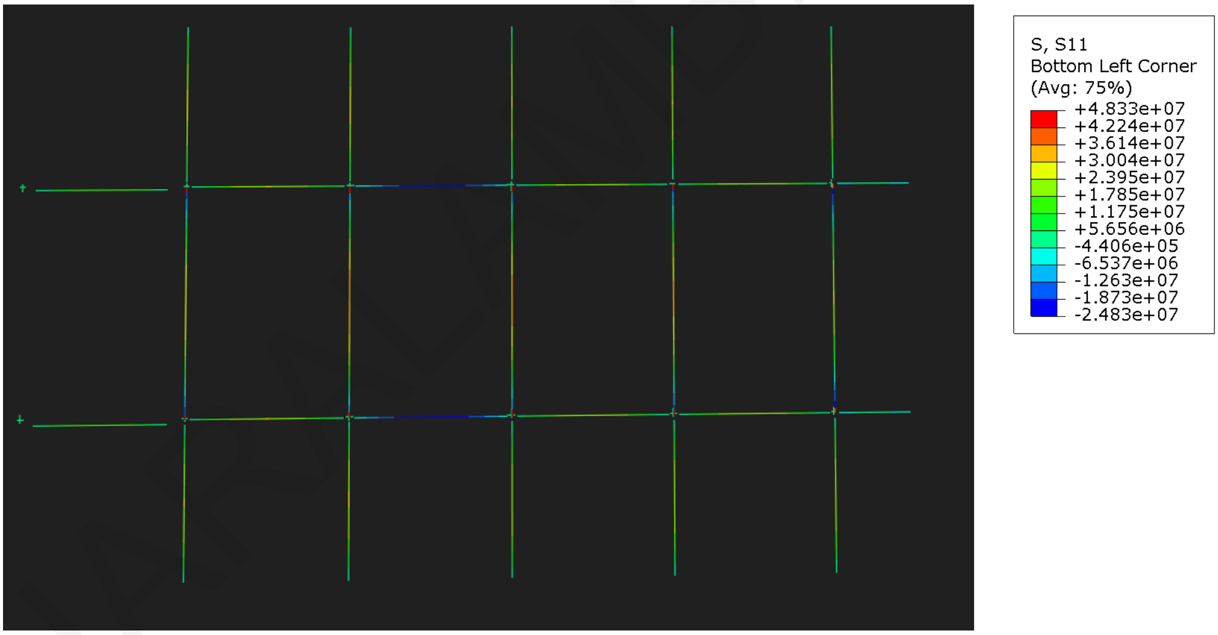


Figure 27 *Stresses of tie rods, Caption from beneath the church (hidden masonry stresses)*

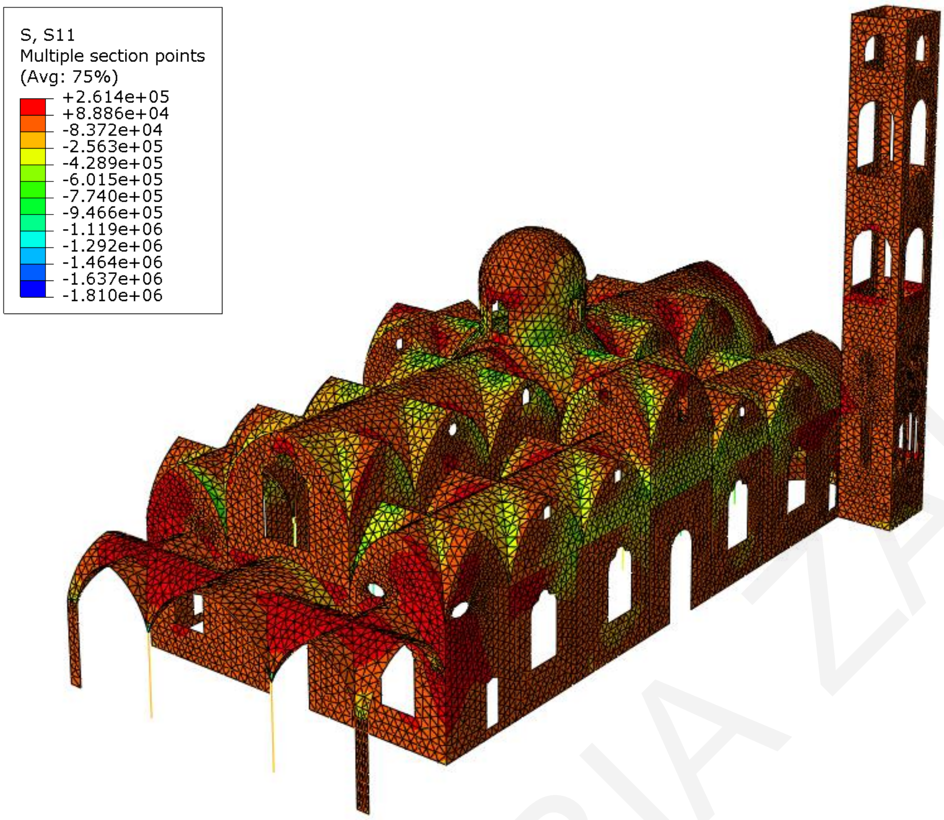


Figure 28 Stresses of the masonry (hidden tie rods results)

Subsequently, the model underwent a time history analysis using real life data of a recorded earthquake which stroke Cyprus on August 11th, 1999. This seismic excitation was selected because of its high magnitude which makes it one of the strongest earthquakes of the last 20 year, in Cyprus. Its surface magnitude (Ms) was 5.6 as calculated by Cyprus Geological Survey Department, and its epicenter was placed in the Limassol area. The Geological Survey Department, also, reports that the excitation was strongly felt across the island and even some buildings in the Limassol area were damaged. Numerous aftershocks continued for months. The excitation lasted for 41.7 s and the maximum longitudinal, traversal and vertical acceleration recorded was 0.1670g, 0.1617g and 0.0961g respectively. The data used for the analysis was provided by Cyprus Geological Survey Department (Geological Survey Department - Earthquakes - Historic Earthquakes, 2017) and is shown in **Figure 29**.

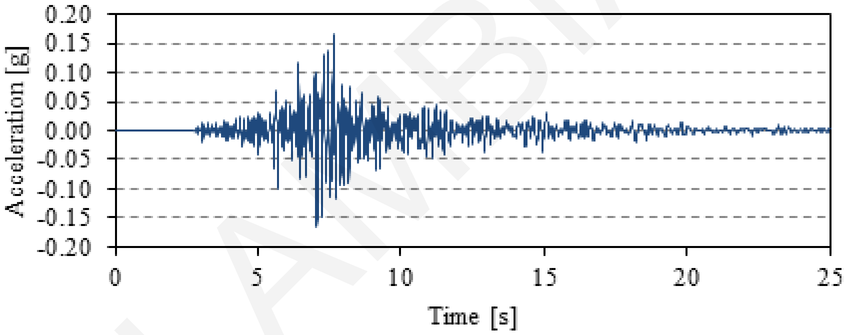


Figure 29 Longitudinal ground acceleration of the earthquake of 11/8/1999 in Limassol area, Cyprus

The earthquake in **Figure 29** is used at the dynamic analysis of the model and firstly was applied in **X direction** (north-south). Response of chosen iron elements ***Table 2*** **Figure 30** show that from the beginning of the earthquake the elements are activated, and axial forces are increasing until 10th sec that are stabilizing. Stresses shown in following ***Table 2***, ***Table 3***, ***Table 4***, ***Table 5*** are taken from the note in the middle of each tie rod.

At the parallel direction of the earthquake all elements that examined have tension stresses. E3 and E4, the tie-rods under the dome as is shown in **Figure 30**, have the highest values of stresses. Tensile stress of E3 and E4 tie rods is up to 25-30 MPA, value that is far from the yield stress of iron. On the other hand, elements closer to the bell tower, the stiffest part of the church, like E1 have the smallest value of tensile stress in comparison with the other tie rods of that direction. Tie rods on that direction have the same response at nonlinear analysis and are all tensed.

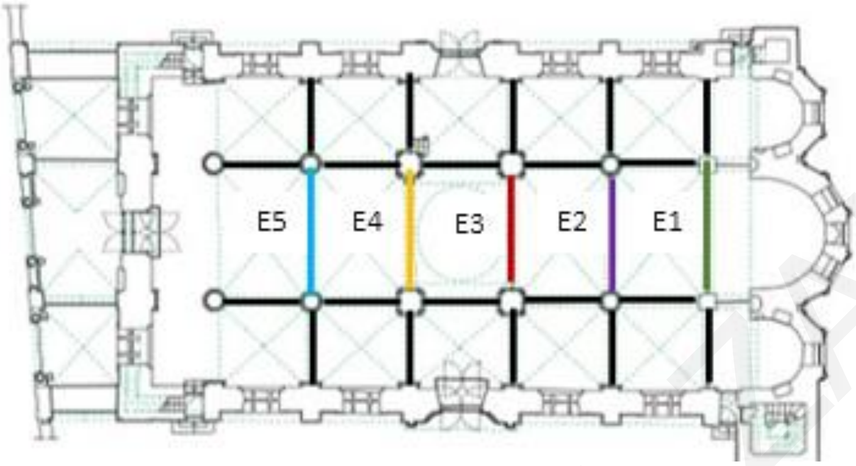


Figure 30 Place of tie rods according to Table 2 & Table 4

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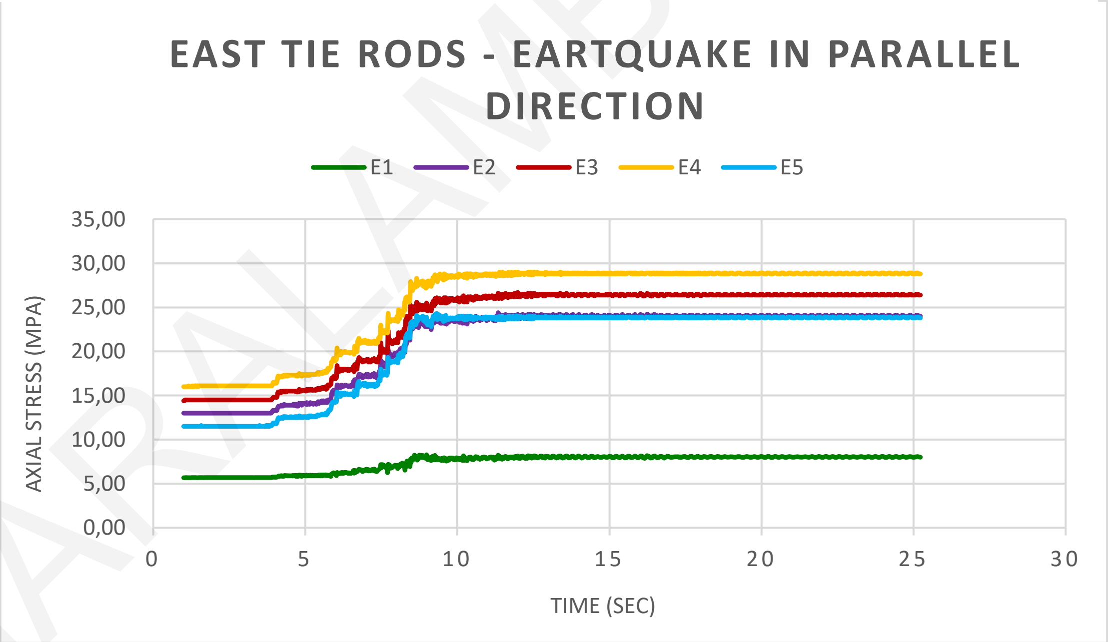
Table 2 Nonlinear time history - East tie rods



On The other direction (west tie-rods), according to ***Table 3*** **Figure 31**, elements W1, W2, W4 are tensed and W2, W5 and W6 are compressed. West direction iron elements have exceptionally low stress values with the highest not exceeding 1.5 MPa. None of the tie rods, on both directions, reach or get close to their yield point. Elements parallel with the earthquake have bigger stresses than elements perpendicular with earthquake.

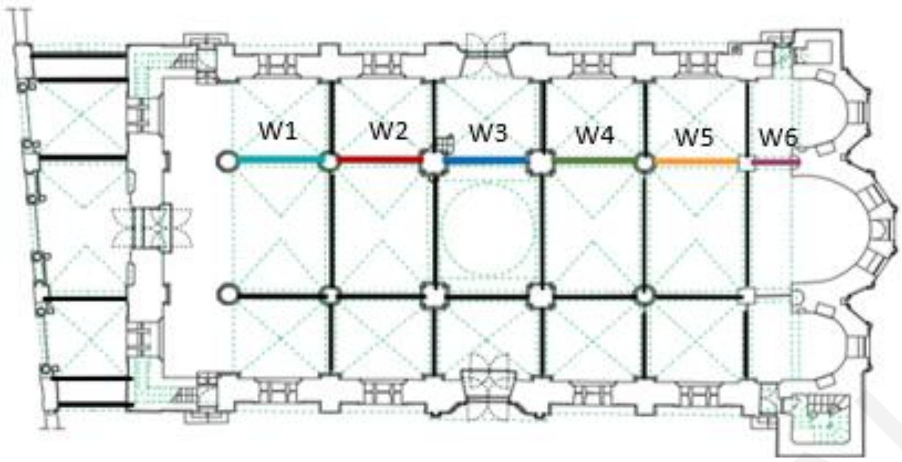
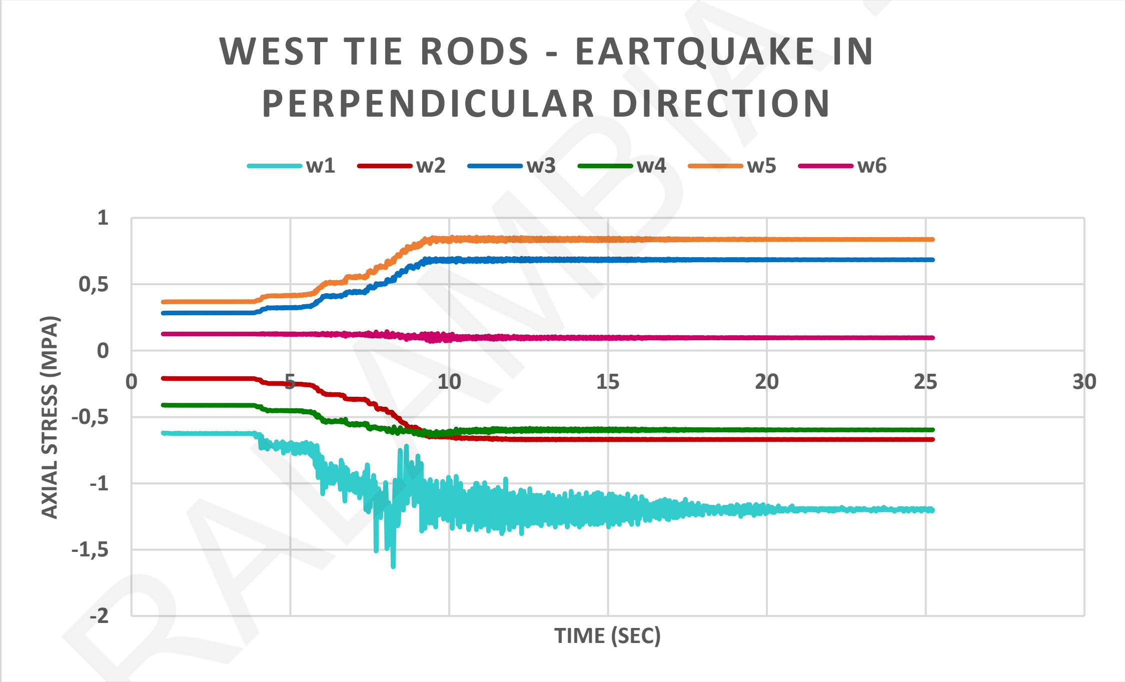


Figure 31 Place of tie rods according to Table 3 & Table 5

Table 3 Nonlinear time history - West tie rods



According to displacement results (**Figure 32**) bell tower, highest part of church, affected from dynamical loads. Upper part of bell tower reaches up to 6mm displacement at the maximum ground acceleration. In addition to this, plastic hinges are appeared on the bell tower at the end of the earthquake revealing possible cracks at the church after the effect of such dynamical loads (**Figure 33**).

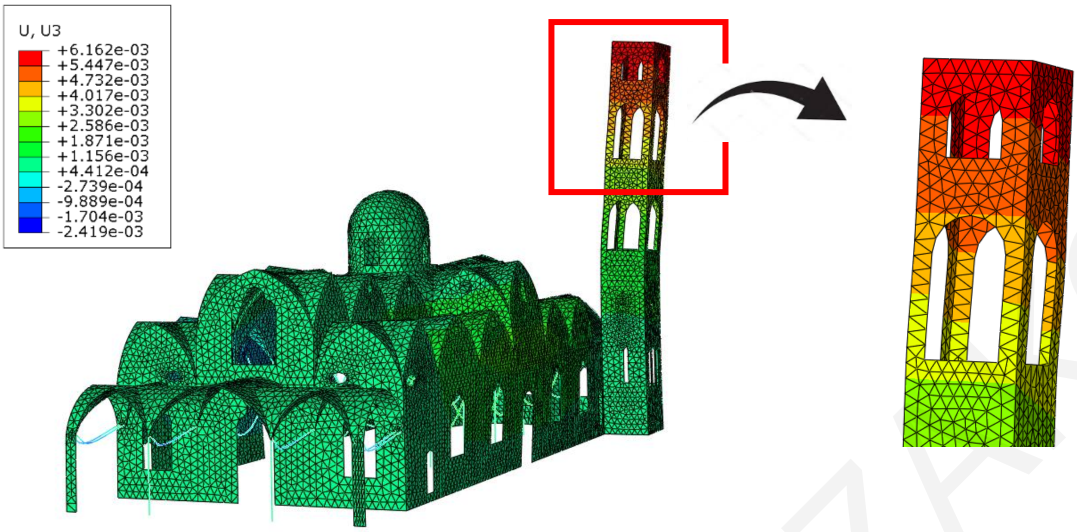


Figure 32 Displacement at 7.6 sec of dynamic loads

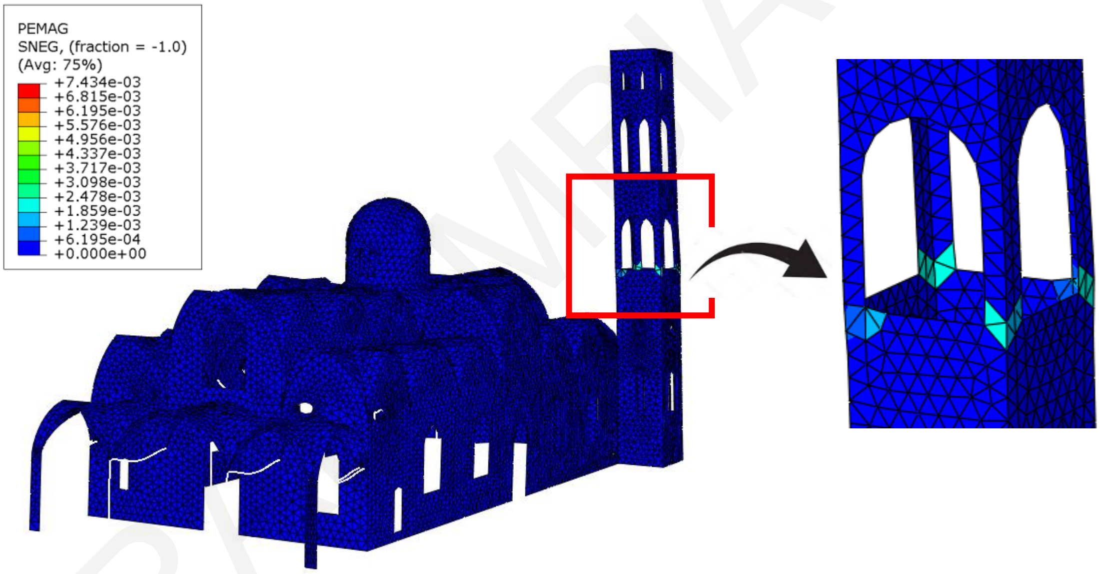


Figure 33 Plastic hinges at the end of earthquake

The same earthquake that applied before (**Figure 29**) at the model, is applied at the structure but at **Z direction**, stiffest direction of the church. Stress values of tie rods examined in ***Table 2*** and ***Table 3***, are calculated with ground acceleration at the other direction. Distribution of axial stresses against time are shown in ***Table 4*** and ***Table 5*** representing the same examined tie rods as **Figure 30**, **Figure 31**.

Table 4 Nonlinear time history - East tie rods – Perpendicular direction earthquake

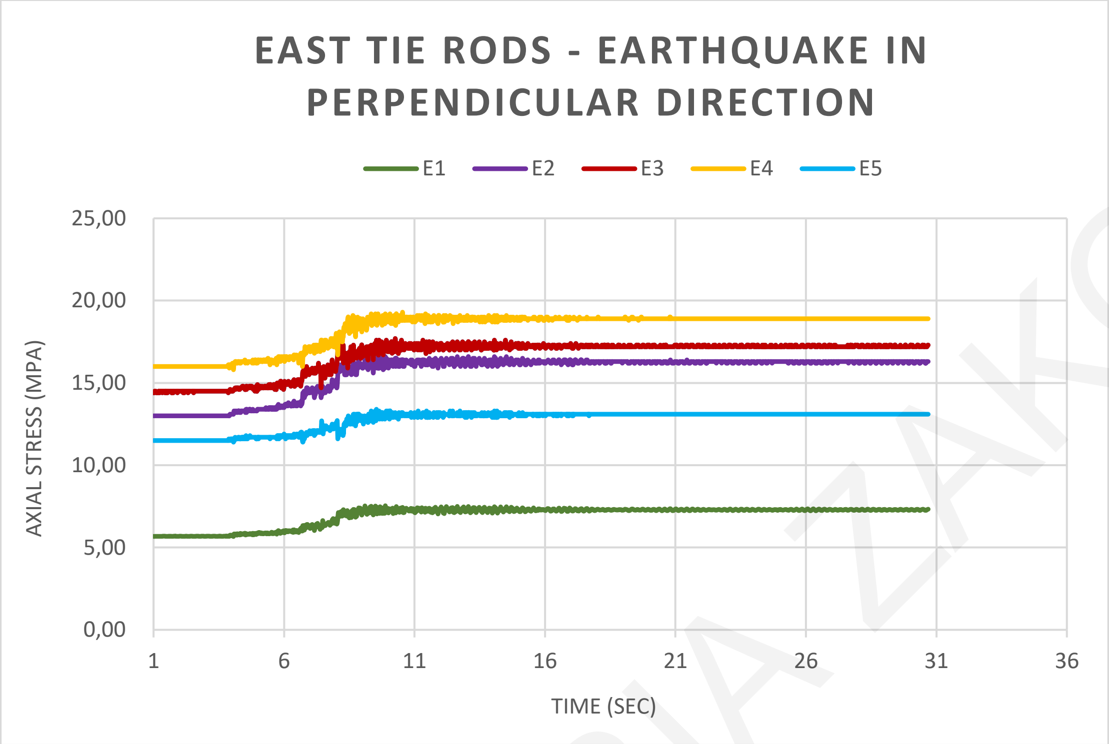
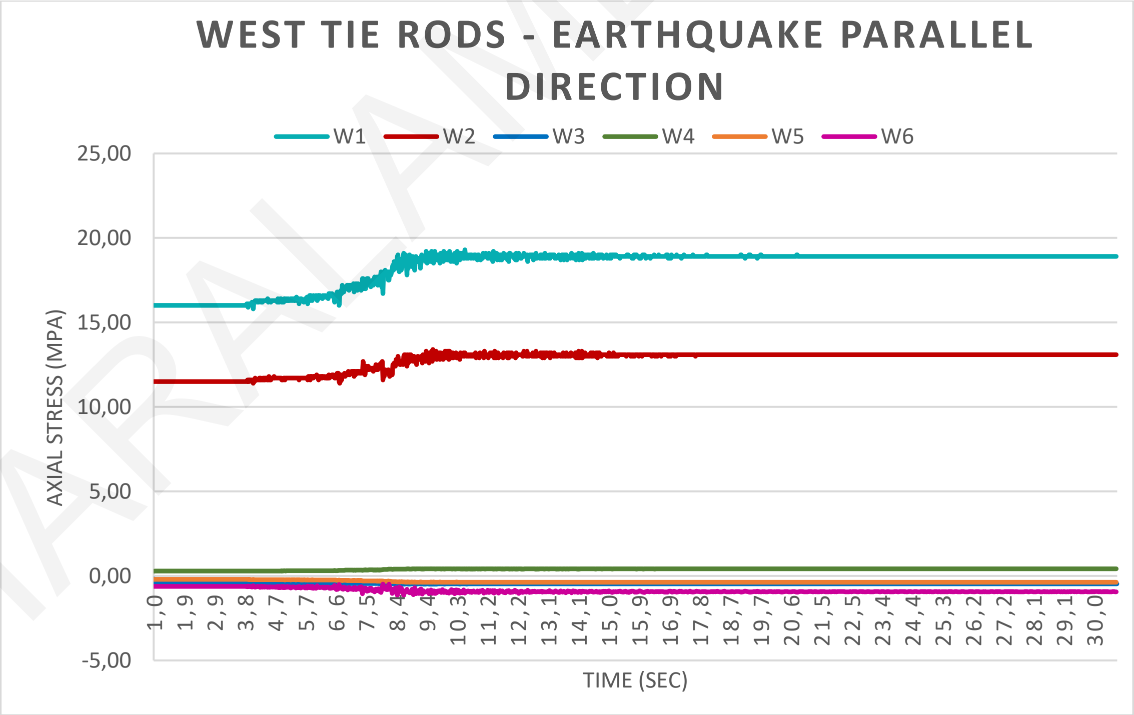


Table 5 Nonlinear time history - West tie rods – Parallel direction earthquake



According to results in ***Table 4***, East tie rods axial stresses seemed to have been reduced by approximately 10MPa compared to the results with the earthquake parallel to them. Regarding ***Table 5***, W3-W5 have extremely low axial stresses during the ground acceleration parallel to them. Remarkable increase of their axial stresses shows W1 and W2, were at earthquake perpendicular to them had compressive stresses near to 1-1.5 MPa. With the earthquake at the other direction W1 and W2 have tensile stresses near to 15-20 MPa. As noted in the previous analysis, nor in this analysis any of the examined iron elements get close to their yield point.

5.2 REALISTIC MODEL OF THE CHURCH WITHOUT TIE RODS

In order to examine the contribution of tie rods on the structure, all iron elements are removed, as the rest of the model remained the same. As it mentioned before, in some structures tie-rods removed after the end of construction and in other remained as auxiliary device for seismic vulnerability of masonry constructions. Aim of this analysis is the observation of the structure without these iron elements and any possible damages that would happen if the builders decided to remove them after the completion of the construction of a church.

A major difference at the results of the model in chapter 5.1 is the deformation of the dome. A deformation increase at the dome of approximately 1 mm appeared after the removal of all the tie rods of the church, under only dead loads from the original deformation at model with tie rods. Under the dome there is a large span of 7m and without having something, like a tie rod, to hold together the walls of the church, dome seems to have a minor deformation that can affect the rest of the construction. Furthermore, the absence of auxiliary tie rods may affect the 'box behaviour' of the whole structure (**Figure 35**, **Figure 36**, **Figure 36**). Tie-rods not only contribute to the seismic behaviour of the model but help the walls to stay together and help the structure operate as one body.

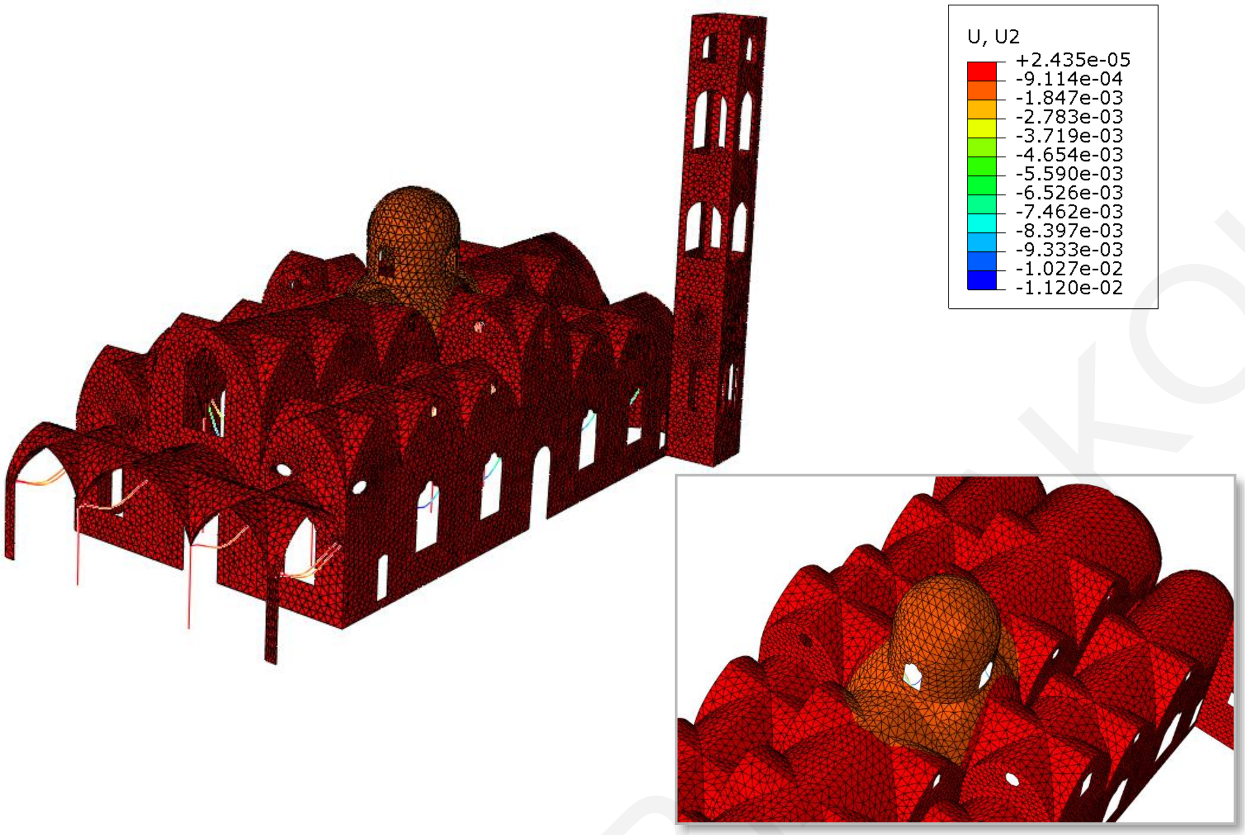


Figure 34 Displacement of realistic model 5.1 under dead loads

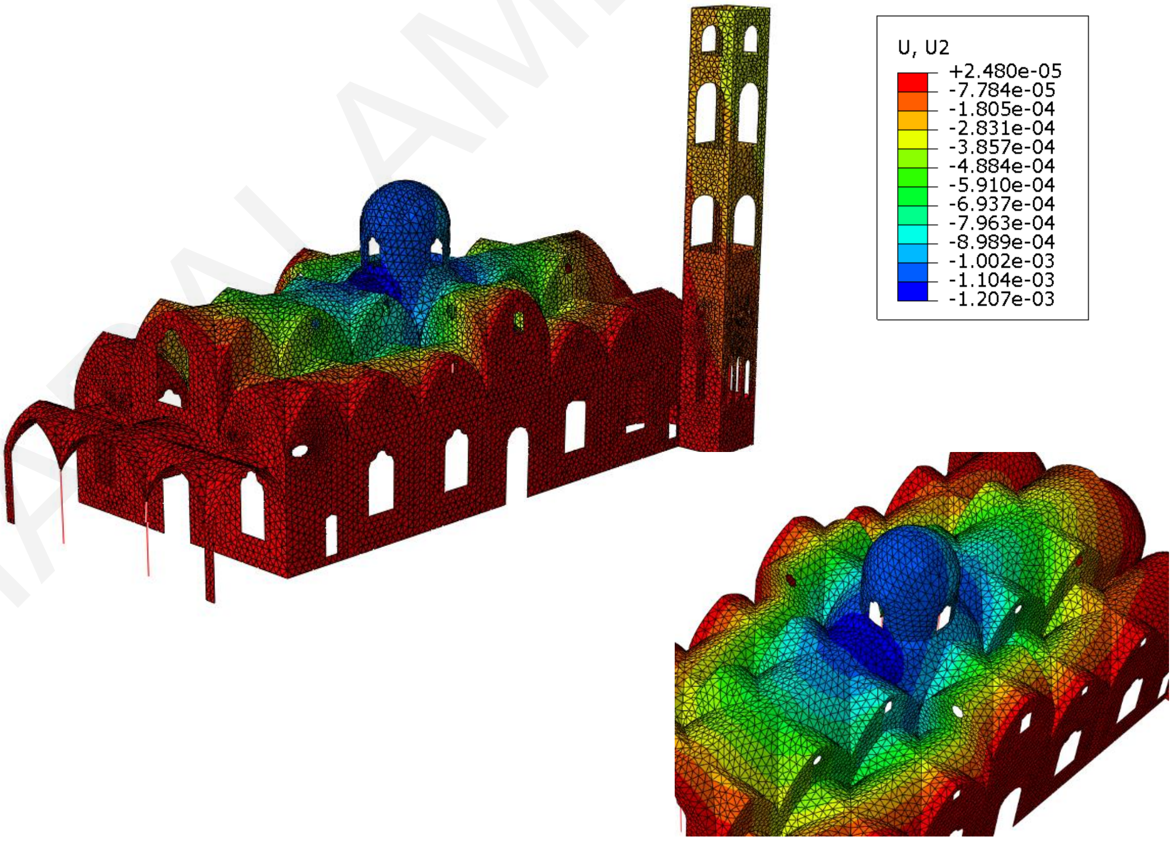


Figure 35 Displacement of NO- tie rod model 5.2 under dead loads

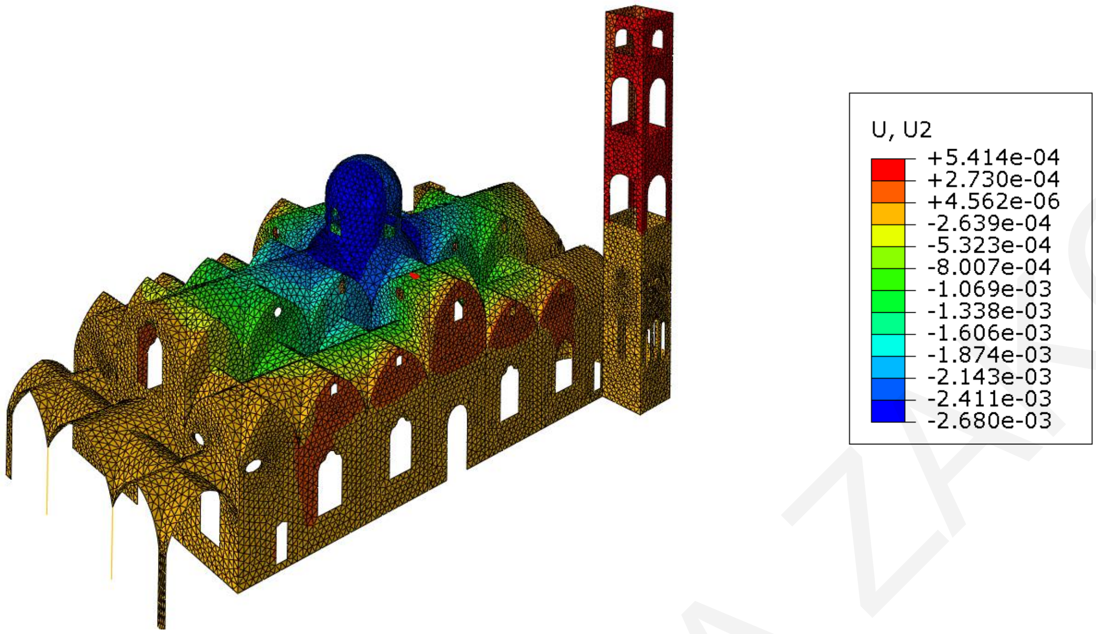


Figure 36 Deformation at model 5.1 after ground acceleration

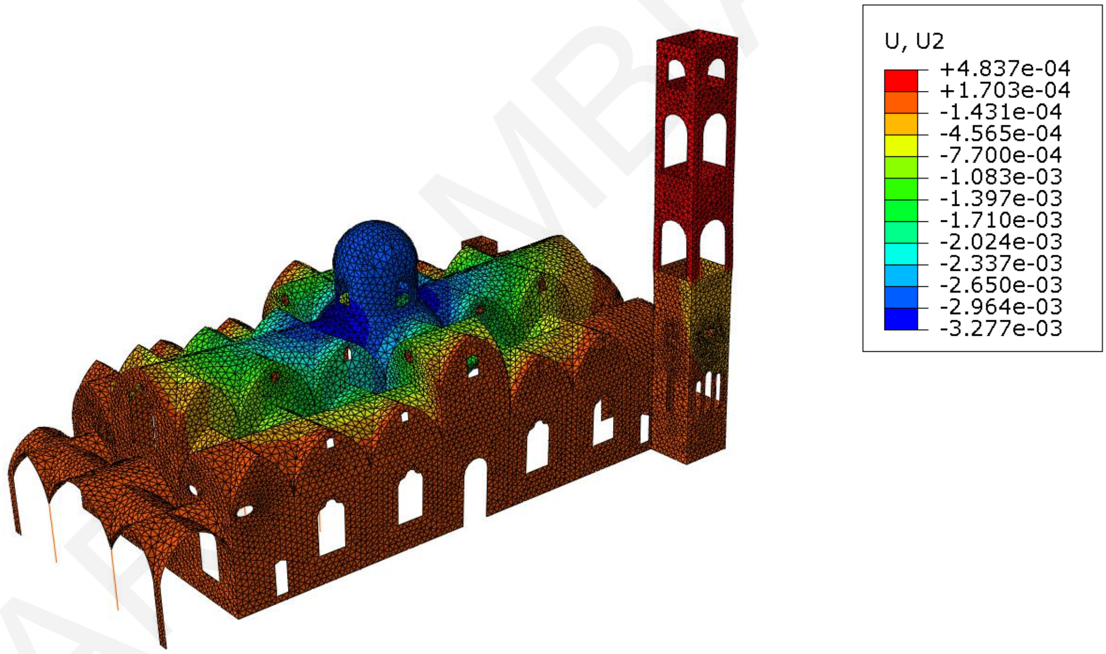


Figure 37 Deformation at model 5.2 NO TIE RODS after ground acceleration

The deformation increase remains at 1mm (between the model with tie rods and the model without) after the dynamical loads as it seen in **Figure 36** & **Figure 37**. At the model 5.1 deformation was approximately 2mm related to the model 5.2 that has a deformation of 3mm after the earthquake.

Another analysis took place in order to examine dynamic performance of the church under dynamical loads at the structure without tie-rods. Removal of tie rods caused the appearance of plastic hinges around the upper side of the nave after the impact of the earthquake. Plastic hinges appeared to four points around the dome, where none of them appeared at the model with tie rods (**Figure 39**). In addition to this, any absence of tie rods or malfunction of them during the Cyprus earthquake of 1999 may have costed serious damage at the upper body of the building, especially at the dome.

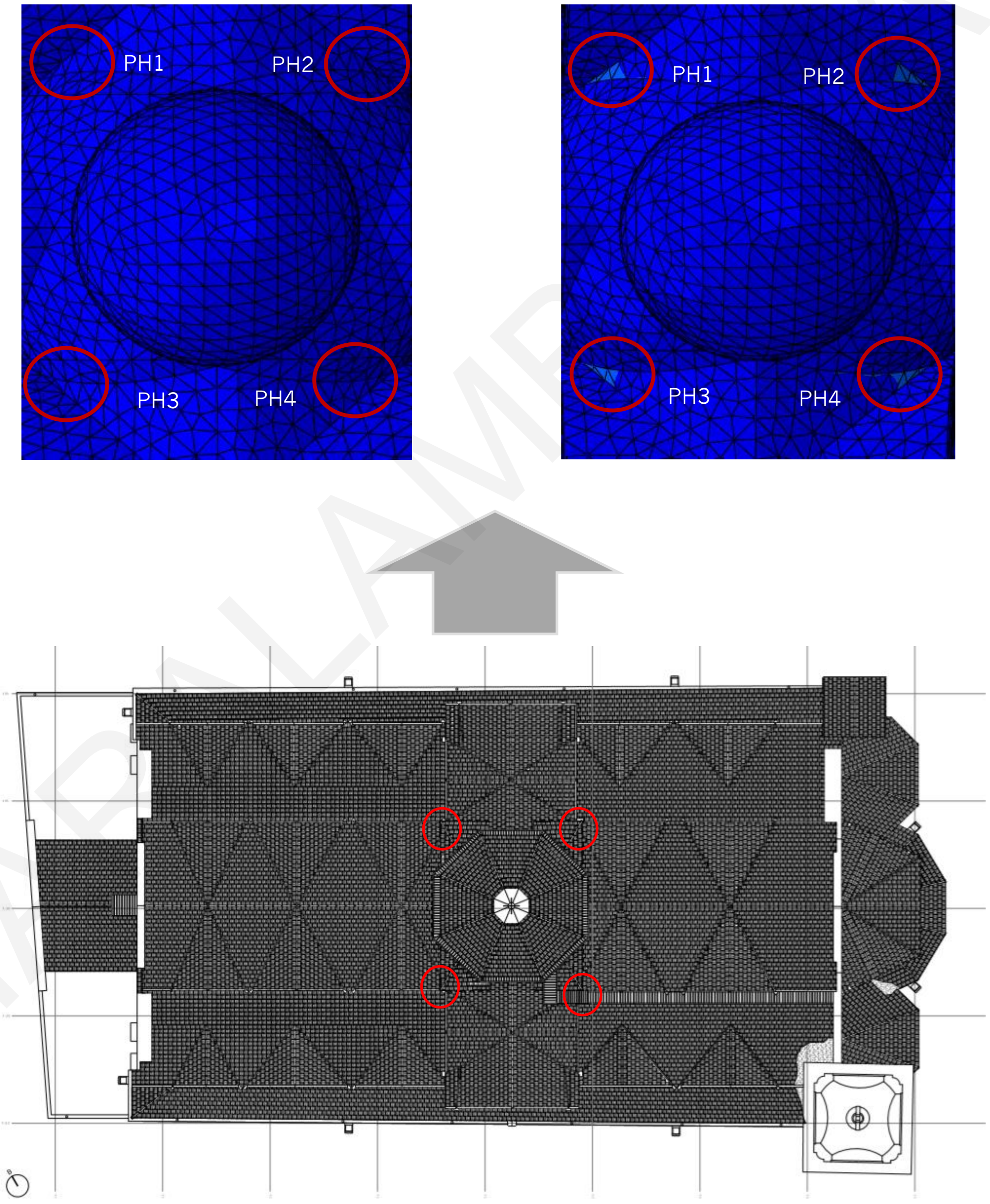
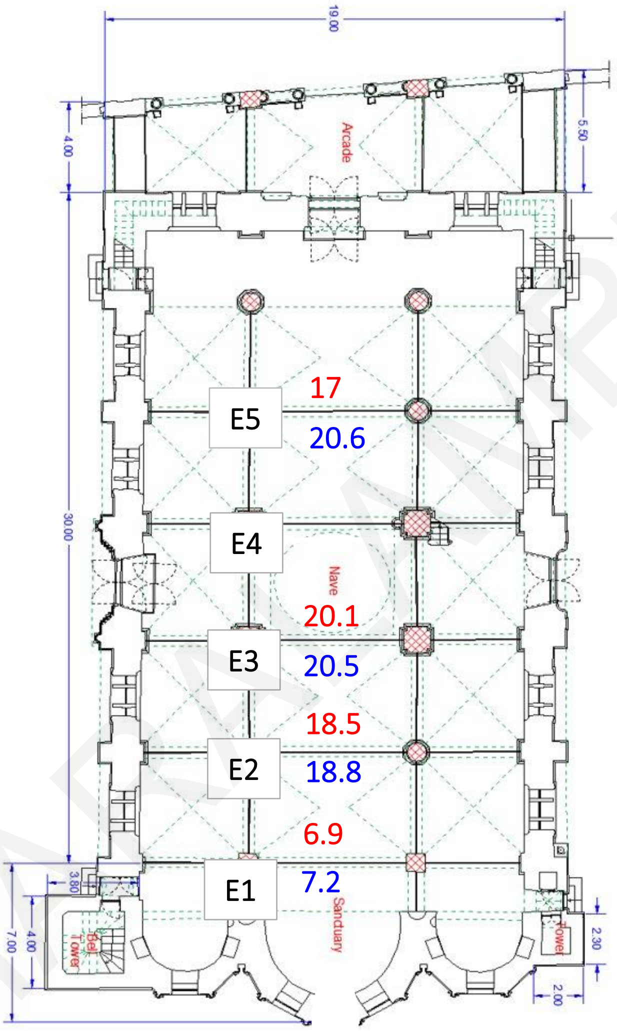


Figure 38 Plastic hinges created at the No tie rod model in comparison with Realistic model – Real roof plan of Faneromeni Church

5.3 REALISTIC MODEL WITH THE REMOVAL OF ONE TIE ROD

Considering the results of section 5.1 tie rod E4, under the dome, takes over the biggest stresses of all tie rods in both directions. Assuming that E4 tie rod is more likely to exceed the yield point or break during dynamic loads a third model created exactly like the realistic model (section 5.1), with earthquake at parallel direction of east elements, but without tie-rod E4. In this way, it can be seen how the construction will react if one of the major tie rods removed and do not be replaced in time.



— TIE RODS STRESSES AT REALISTIC MODEL 5.1

— TIE RODS STRESSES AFTER THE REMOVAL OF E4,5.3

Figure 39 *Redistribution of stresses (MPa) in Realistic - No E4 tie rod Models*

Compared to the realistic model stress values, the removal of E4 has led to redistribution of the tension stresses to the remaining iron elements (**Figure 40**). Comparison of stresses happens at 7.6 sec of the seismic load, exactly the moment that the maximum ground acceleration is reached in both models. The rest four elements on that direction face inconsiderable increase of tension stress, which leads to the conclusion that the rest elements undertake the stresses of tie-rod E4. Deactivation of only one element in the church can lead to increase of tension stress up to 3 MPa to the other tie -rods and more specific to nearby elements. Tie-rods who are further from the E4 face less increment of stresses. For example, E1 face least increment at stress values due to the distance from the E4 and due to its position, near the stiffest part of the construction, the bell tower. Although, increase of tensile forces is insignificant, according to yield point of elements, a more intensive earthquake could have shown the impact of element E4 in the structure.

CHAPTER 6 – CONCLUSIONS

6.1 CONCLUSIONS

In the current study, analysis about the uses and efficiency of metallic tie rods in Faneromeni church have been conducted. In an early stage an investigation about properties and applications of these elements throughout the centuries and around the world developed. Therefore, acknowledgment about what these elements could do to a structure was clarified, a basic Finite Element Model of Faneromeni Church was made. Three different FEM models were produced with common feature the Faneromeni Church but different number of tie rod elements. First one was an original model of Faneromeni as it is today, under dead and dynamical loads. Second model was Faneromeni Church exactly like the first model but without any tie rod. Same process was followed and changes in the model were observed. Third and final model of the analysis was Faneromeni Church as stage one but with the absence of one tie rod which was considered as the most beneficial. Dead and dynamical loads were used again in order to examine the results and compare with the first model. Results were presented through figures and tables in Chapter 5.

Cultural Heritage Monuments require a special treatment and further investigation than modern buildings. Materials that are used have not specific and, most of the times, standard mechanical properties. Building techniques were based on each builder's knowledge and evidence about the construction process are not very straightforward or does not exist. Architectural Monuments around the world appear to have these elements, tie rods, until today or some of them have signs which testify that in some stage of their construction history have had tie rods. Tie rods were used temporarily in many cases as an auxiliary device for construction process. Churches, cathedrals and naves are constructions with complicated structure and generally large spans, arches and flying buttresses that could take decades or centuries to complete. As arches and buttresses were build these elements were used to undertake the tensile forces until the whole construction was completed. In some cases, tie rods were wooden which indicates the builder's intention from the beginning to remove them, and wood was easy to cut off afterwards. Permanent tie rods are displayed in most times at seismogenic countries or regions like Italy, Greece and Middle East. Metallic elements were used also in construction process but remained afterwards for two basic reasons. First, tie rods holding two parts of the structure together can ensure that the structure behaves as one piece and the walls will not overturn. Second, under dynamical loads, in an earthquake situation, tie rods will undertake some serious stresses and help the rest of the construction. In both cases, tie rods can contribute to the load distribution of the structure and relieve some more complicated parts like the arches and domes.

Capabilities of tie rods investigated through literature and Finite Element Method with the help of Abaqus was considered as the most effective solution for this stage of analysis. FEM model was created with essential information collected about the existing structure. First model created as Faneromeni church is nowadays, and mechanical properties of the materials were taken from past experiments and literature. From the beginning of the analysis, tie rods appear to take part at the response of the whole structure when only dead loads were applied. Tensile forces developed at the metallic elements indicating the role of them at keeping parts of the church together. Assistance provided from the tie rods to the walls of the church in order to keep them from overturning is more obvious at the tie rod under the dome where this seven-metre metallic element have the biggest tensile force. Walls around the dome face significant forces from the dome’s dead loads which tend to diverge them, and tie rods hold them together. Dynamical loads applied at the model subsequently. One of the most intense earthquakes that happened in Cyprus of maximum ground acceleration of 0.167g, added at the model. Although it is considered as one of the biggest earthquakes in Cyprus, generally is not a strong earthquake. In a future analysis would be interesting to see how a bigger earthquake affects the structure, but as for these analyses a more realistic approach, with Cyprus data, was developed. Earthquake at north south direction showed that the elements in parallel direction with the earthquake developed biggest stresses than the elements in the other direction. Tie rods under the dome faced the biggest tensile forces, around 25-30 MPa, values that indeed does not approach yield point of iron. Ground acceleration was applied at the stiffest side of the church in the next analysis to monitor the differences. As expected, tensile stresses at east side dropped about 10MPa from previous analysis. Significant increase of tensile forces of 10-15 MPa happened, at west tie rods, especially at W1, W2 elements. Stress values of tie rods did not approach Yield point of iron in this analysis either. Tie rods activated during the dynamical loads but with the specific ground acceleration does not seem to affect them in a way of reaching their yield point or break them.

Effectiveness of tie rods can be estimated from the above conclusions although an interesting analysis was structure's reaction at the total removal of all metallic elements tied at the Church. Results of this analysis displayed the way that the church reacts without tie rods, and what would have happened in the case that these elements were removed after the completion of the construction process. Another reason for this analysis to be carried out was presenting the causes of removal these elements in a restoration in the future. Dead loads of the structure seem to cause a deformation of the dome of about 1mm. Deformations that does not happened before are observed to the walls near the dome. Without the tie rods holding together the walls of the structure, dome's dead loads seem to overbalance the walls. Addition of dynamical loads demonstrated another influence of the removal of tie rods at the dome. Plastic hinges developed around the dome after the effect of dynamical forces at the construction. Removal of tie rods appear to have mainly effects at the dome which seems to affect the most.

Even though tie rods at first analysis does not reach or come close to the yield point of iron a third analysis took place investigating the situation of removing the most basic metallic rod. In case of Milan Cathedral some tie rods broke through the years and they were replaced on a restoration. In a similar situation, where the element E4 which takes over the biggest stresses in previous analyses removed. In a dynamical analysis at the parallel direction of East rods showed that the remaining elements seem to have increased tension stresses of only 3 MPa and under from the first analysis. A future removal of these tie rods will not cause significant consequences at then rest of the structure and its replacement will be unnecessary.

Faneromeni Church is one of the most emblematic structure of Cyprus, indicating the great techniques that master builders developed at the island years ago.

Analysis of this Cultural Heritage Monument investigating the effectiveness of metallic elements applied at the structure from the construction showed that these builders recognized the benefits of these elements at such delicate and complicated structures centuries ago. Through a three phase analysis advantages of tie rods proved to be more than removing them or not using them at all. Analysis confirms that tie rods help structure's behaviour under dynamical loads, that is significant at a seismogenic region as Cyprus. Tie rods allow the structure to perform as one body, prevent walls from overturning and take over part of tensile stresses in order to relief rest of the construction.

6.2 FUTURE RESEARCH

Effectiveness and behaviour of such important elements as tie rods is an interesting project for future research. Fields and aspects that this research did not reach would be interesting to be studied extensively in the future.

Different dynamical loads or higher excitation applied at the model would show how Faneromeni reacts and how tie rods response in such situation. Another issue for future research could be the anchorage of tie rods. As it seems data about the anchorage of these elements throughout the centuries are limited. Anchorage although is crucial about the performance of the whole structure and determines whether tie rods will help the structure or do not activate at all. Faults in anchorage in past, affected negatively the construction's behaviour. Faneromeni Church is a significant structure, and a building of great importance in Cyprus. Further investigation about its elements and especially about the bell tower would be interesting. Bell tower affected other elements behaviour in the model as it shown in some of the results of this research. Bell tower is also a sensitive element for this kind of structures and its worth investigation.

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