Dissertation Project

Conservation of stone-roofs

Challenges and the effect of new Techniques

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DECLARATION

I ................................................................. confirm that this work submitted for assessment is my own and is expressed in my own words and designs. Any use made within it of the works of other authors in any form (ideas, text, figures, tables, etc.) are properly acknowledged at the point of their use. A list of the references employed is included as part of the work.

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Abstract

Stone-roofing has a great history which spans many millennia BC which witnessed a lot of development to roofing systems and geometry regarding the area and type of building demands. Therefore, this paper discusses this structural element, presents its history and development as well as highlighting the famous achievements in constructional systems. Also, the study focuses on vault roofs, studies their behaviour as well as the main problems and failures which lead to many types of collapse they had. The structural study intersects with a theoretical review for the conservation achievements and techniques applied to the stone vaults as well as the modern techniques after introducing the computer programs and laboratory experiments to this field. Finally, the study will classify some new techniques which can be applied in order to get rid of common structural problems in stone vaults.
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1 Introduction

1.1 Introduction

Stone-roofs date back to the prehistoric era and were implemented by simple systems at that time, such as stone-slab and corbelled roofs. These systems developed through history and more advanced systems appeared, for example the barrel vaulted roof, domes and crossed vaults, which were a result of those developments. From old Roman passages in 3200 BC to Gothic vaults, we can find great evidence for the fact that stone-roof systems were sufficiently applied and gave the architecture a special character which distinguished it from the others.

Regarding the great value of these monuments, it was crucial to protect them and ensure that they were resistant to all causes of failure. For this reason, all historical attempts in this field were to find new techniques and solutions to the failures, deformations and collapse problems which should be suitable for the problem, historical period and type of stone-roof. In addition, many architects sought to explain the character of the stone-roof and its behaviour under loads to find some constructional aspects which support roof stability.

This study generally reviews the most important stone-roof types and its developments, innovations and main challenges which faced the structural improvements. It searches deeply in crossed vault types, developments as well as main features which added to move from one type to another with justification for adding each feature. Moreover, the paper studies the main differences between two important types - Romanesque and Gothic vaults - and it discusses in detail the natural development and causes which led to the move from the Romanesque type to the Gothic one, with the fundamental changes between the two types. After that, the study is going to be more specific by identifying the Gothic vault’s geometry, structure, main problems and failures which might be related to natural, constructional or material deformation causes.

The paper reviews historical conservation techniques used for vaults, which depended on traditional conservation processes and materials, in addition to the main theories and statements published in terms of the conservation of Gothic vaults. Although the paper goes back in history, it does not ignore the latest years’ innovations, new techniques and materials which entered this field and had their effects on the improvement of the stone vaults conservation process. The computer and new simulation programs are given attention in this
paper by overlaying the program types, uses and significance role in vault remodelling as well as deformation and recording of collapses.

Depending on the theoretical study, the practical work will start with investigating some buildings around Scotland, England and Europe. This investigation will take place in each chosen building by analysing the main deformation and failure which happened. In more advanced analysis, the study will research the main conservation work and techniques which followed in the building, as well as the effects of the conservation work on either the building stability or building character. Furthermore, this paper aspires to find as many techniques as it can which are effective for dealing with many failures and types of deformation. Therefore, the main questions are “what are the main challenges which face the stone-roof (Gothic vaults), what is the role of new materials and techniques in the conservation process and how do they affect the old roof’s character?”

1.2 Research Aim and Objectives

This study mainly aims to benefit from new conservation and architecture techniques in repairing stone-roofs (Gothic vaults) in order to avoid all constraints, problems and failures which face them and preserve the historical building character as it was in the past.

This main aim will be met by realizing the following objectives:

1- Identify the historic stone-roof’s types and their construction in order to understand the development of the stone-roof, the way in which every stone-roof type works, how the loads are applied as well as the roofs’ structure design which increases their resistance.

2- Recognize the main challenges which are faced by the stone- vaults conservation process and define the weaknesses in order to overcome all constraints which hinder the stone vaults conservation.

3- Realize the importance of new materials, techniques and contemporary conservation studies in developing the stone vault’s structure and conservation process, also employing these techniques and materials in solving the latest unanswered research questions in this field.

4- Seek to ascertain the role of computer programs in facilitating discovering and representing the vault’s structure problem with the aim of having quick and clear understanding for the problem.
5- Check the effects of new materials and techniques on the stone vaults conservation process as well as the historic buildings’ character.

1.3 Research Methodology

This study is an attempt to investigate the stone vaults structural behaviour and conservation problems. The study starts by gathering information about the stone-roof types and developments and focusing on the very advanced Gothic vaults. The main structural problems and causes of the damage are then presented. Historical and modern conservation types are discussed, with more investigation into new materials and techniques.

The case studies will be classified initially according to the main damage problem and consequently in terms of the repair technique applied. This classification will address the positive or negative results from the conservation work in the building.

The focus of the theoretical and practical studies will be on the main case study, the barrel vaults in Rosslyn chapel in Edinburgh. This investigation will start with historical and structural background and research on the main conservation work during its history. After that, the study will discuss the main structural problems and damages which occurred to the vaults and their main causes, as also the current conservation programme and materials used.
2 Historical Review and Analysis

2.1 Development of The Architecture, Construction and Structure of Stone-roofs

J. B. Ward-Perkins (1970) discusses the vaulted roof system in old Roman architecture in Italy and refers to the main Roman architectural achievements in Syria, Egypt and the Middle East, where the Roman vaults had been characterized by concrete and rough stone. These were, in addition to their simple and strong form, achieved due to improving the concrete quality. The most important applications for concrete vaults were in Roman baths as it became the inspirational principle of the new current architectural ideas. The Pantheon, figure (2.1), Villa Adriana as well as the Baths of Caracalla and Diocletian were the most famous example of stone vaults in Italy, figure (2.2).

![Figure (2.1): The Pantheon Dome sections and exterior view](image1)

This application was transferred to the south of Syria with a more advanced fine quality of stone vaulting and the presence of domical vaults over the main room. This quality helped the oriental monuments to remain standing until now. Janet Delaine (1997) fosters this perspective and deals with various stone-roofs and techniques used in the baths of Caracalla where they used barrel vaults for some rooms, cross vaults for rectangular spaces, semi-dome vaults for *natatio* part as well as the main dome for *caldarium*, figure (2.3). Also, touches on
the main constructional media and coursing types as the builders used horizontal and radial coursing types which are still valid until now as construction techniques, figure (2.4). (Ward-Perkins 1981) (Adam 1994)

The greatest innovation in Roman architecture and stone roofing was the barrel vault, built with two superimposed rings and radially located one above another. These rings meet at the top formed spandrel, the most critical point in the structure. This technique essentially depends on the strength of the bottom ring - for this reason, the builder courses this ring more carefully than the upper one. All these techniques influenced Middle Eastern architecture, especially in Syria and Egypt. In more detail, West baths, in the southern west of Syria, bear witness to the influence of Roman architecture in Syria. The main space in this building was vaulted by a hemispherical roof of dressed light volcanic stone, figure (2.5).

In Egypt, the Roman influence was different in techniques, materials and vaults profile where a pitched-brick technique which requires a shuttering bar of timber was carried out by builders to erect the barrel vaults and shallow saucer-domes. The best example of this period is the Karanis house, which is built of mud and brick with a distinctive profile and pitched brick vaulting, figure (2.6). (Ward-Perkins 1981; Adam 1994)
According to James H. Acland (1972), after many years of searching for a solution to get rid of stone-roof problems and challenges in Europe, barrel vaults became a more commonly used structural element for roofing in France and Spain than any other type because it was the answer to constraints and problems of earlier types. This system became as an answer for all problems faced the roofing process of rectilinear and longitudinal spaces, especially in the church’s architecture for the choir vault, nave, or the lateral aisles which were added to facilitate prayers movement during the services. This heavy structure was used suitably in the south sunny area, but it was not suitable for rainy, cold and wet areas in the north. Solutions to these demands were developing for three centuries, replacing the Romanesque heavy barrel vaults with much more elegant ones in Gothic architecture. One of these solutions was in increasing shell thickness, but it was not enough to resist the lateral thrust, which actually increased. A solution was to insert timber or metal ties in the span to brace the thrust as it happened in repairing Narthex Chapel in St. Philibert at Tournus, figure (2.7). (Acland 1972)

The main disadvantage was the aesthetic effect on the nave’s character, and for this reason, they did not use it anymore and depended on increasing the shell thickness for some time. The most important requirement was lighting the interior and the shell thickness hindered that. Before 1000 AD, the masons lightened the vaults by adding stone arch rings supported by buttresses, which divided the continuous vaults into equal sections and decreased its thickness facilitating compartments, figure (2.8). This technique was successfully used in Santa Maria de Naranco in Asturias in northern Spain because of the country’s good location at that time between feudal Europe and the Islamic Empire. That allowed masons to benefit from both cultures in creating very important and elegant architecture between the ninth and eleventh century, figure (2.9). (Acland 1972)
In the south of France, the masons tried to deal with thrust by using a pointed profile for the vaults. A further innovation was to open the walls between the buttresses as an answer to climate and lighting requirements, leading to simple and strong structures in the eleventh century. In St. Philibert at Tournus, for example, the nave vaults were held by stone ribs and the builders could open as many windows as they needed because they avoided heavy buttresses, figure (2.10).

Also, because of the desire to increase daylight, masons began to use simple crossing vaults over the aisles. The vaults’ thickness was greatly reduced by adding elegant timber ties and counteracting the barrels to cancel their thrusts, figure (2.11). The response of thirteenth century masons was to create folded shells supported by ribs. This new solution came to make the structure lighter, support using the ribs in intersection areas and as a result of opening the flank’s walls and use the buttresses as a ribs’ supporter and load’s holder. Many experiments were carried out to understand the folded shells’ responses and find an answer for how it can be strengthened. Increasing the shell thickness and the use of pointed profile in Romanesque structures were suitable solutions for the structure stability but they wasted time, effort and money. A more sophisticated solution was taken by introducing folding in the intersection areas which was the fundamental principle to find out the Gothic vaults model. (Acland 1972)
The cross vault was created at an intersection between two semi-circular barrel vaults and the use of stone ribs along the intersections and edges. Acland (1972) also discussed the principle of creating earlier cross vaults and how reducing materials leads to the concentration of the vault’s loads and thrusts upon four main points in order to make the vault behaviour better. For this purpose, the barrel vault with four supporters was diagrammed by compressive and tensile lines and, as a result, the most compressed area was between the supports. A solution which was suggested was to remove the material in that area to channel the loads through four groins. Although the suggestion was implemented, the vault was still unstable and weak at the crown. Therefore, it was essential to support the crown by inserting another barrel vault vertically into the cut-away portion. That leads to channelling the loads down into four groins and leaving the vault stable, figure (2.12).

Figure (2.10): St. Philibert at Tournus. High transverse barrel vaults with arch rings

Figure (2.11): St. Philibert at Tournus. Cross vaults over aisles

Figure (2.12): the principle of creating a cross vault
In Romanesque architecture, masons installed a new type of roofing for major spans. It was made up of cross vaults formed by an intersection between the surfaces of two barrel vaults. Also, they projected pointed barrel vaults over the naves. Later in Gothic architecture, stone ribs were added to strengthen the shells’ surfaces. The twelfth century saw major progress. Earlier, a vault was built by radial coursing, like the domical vaults used in St. Lazare at Avallon in Burgundy, figure (2.13). Introducing the ribs during the twelfth century changed the mason’s concept, like at St. Serge in Angers, from radial coursing to horizontal intersection at the ribs. Because of the extra thrust by the domical vaults, ring arches were added between each bay as a joint between them aiming to make each bay abut its neighbours, figure (2.14).

Romanesque and early Gothic rubble stone vaults had ribs inserted as a structural skeleton to support them figure (2.15).

In contrast, in the Renaissance, masons carefully cut the stones and used a special way to assemble them together with the aim of creating hidden ribs, figure (2.16). (Acland 1972)
The centring of each part of the skeleton was totally separate from the others. Nonetheless, masons began by projecting the supporting elements and then completing the work by laying the rubble shell over them. This technique continued to be used during the great Gothic architecture period in England and France. In the middle of the same century, improved forms with pointed arches distinguished the Gothic architecture and its simplicity, practicability and suitability made possible a wide range of uses. The famous applications of this form were initially in St. Denis Abbey in Paris, where masons tried to establish a specific design form, giving birth to Gothic architecture. These forms gave new freedom to the construction systems practically to resist loads and structure’s thrust and, logically, a response for lightening and ventilation requirements, figure (2.17). (Acland 1972)

Primarily, to justify the requirement of new systems which were in demand at that time, it was very important to stabilise the walls, masons would analyse forces as they were not aware of structural theory or even the concepts. Masons working on Durham cathedral realized this problem and solved it in 1133 by adding quadrant arch rings under the gallery roof. This solution was quite efficient because it abutted until the higher points of the piers figure (2.18). Also, what happened in St. Denis and earlier in Vézelay was that masons moved up the restraining arches to become exposed flying buttresses, figure (2.19).
Thirteenth century masons and architects benefited from the carpenter’s frame as it was the most useful solution to resist the loads and avoid the structure’s reactions and failures during the building process. Also, they divided each unit into repetitive bays to facilitate erection in isolation of the whole structure and then merged all bays which required ribs to shed the loads between bays and make good use of extra support elements such as buttresses to stabilize the structure. (Acland 1972)

English stone vaults (D. Theodossopoulos 2008, 2010) had a lot of technical achievements and innovations.
Earlier innovations were made in Durham Cathedral by correct application for the pointed arch, use of ribs on a large scale and merging some international decorative forms, figure (2.20). In Lincoln, the main innovation was between 1192 and 1265 by adding and remodelling skewed vaults as a new structural innovation, which helped by their special construction to improve the stability of the structure, creates a special surface and enlarge the span of the vaults which reached 11.65m with a width of 6.5m for each bay, figure (2.21).

Another innovation was in the tierceron vaults at the nave and Angels’ choir which appeared transversely because of adding the lierne decorative ribs. Notre Dame, in Paris, was influencing Gothic architecture as it was an imperial church. Jean Bony (1983) discussed the presence of Gothic type in this building by dressing the building with flying buttresses in 1175, using the pointed arches as well as applying the ribbed vaults instead of the dome, figure (2.22). (Theodossopoulos 2008) (Theodossopoulos 2010)

This building was greatly influenced by the Gothic style, especially after the latest restoration between 1845 and 1853 which was carried out by the Viollet-le-Duc, who always put his own personal interpretation of the Gothic style into all his restoration works. (HENDERSON 2010)
The fourteenth century saw new innovation in the vault’s design field which freed the designer from the eleventh century heavy structure by using an interlacing meshed grid into which to spread the pressure. This concept played an essential role in late Gothic architecture by further lightening the masonry structure, lessening the shell thickness, decreasing the vaults’ thrusts, which are spread over the whole grid surface and, as a result, getting rid of the heavy Romanesque masses and early Gothic buttresses. German masons raced to apply this pattern in their cathedrals which became more elegant and harmonious. The vaults built by Nicolas Eseler in St. Georg at Dinkelsbuhl became shallow spherical shell varied between bays and braced by a decorative ribs pattern, figure (2.24). (Acland 1972)

More decorative ones were in the choir vault of Freiburg Cathedral, where the masons formed a gridded rib pattern which was distributed over two bays or more to fashion as beautiful, big and decorative a grid as they demanded, figure (2.25).
A more progressive pattern appeared later in the fourteenth century when designers thought about more support for the vault’s crown by adding new structural elements called "lierne ribs". These ribs’ function is represented in tying tierceron main ribs together in order to create a meshed crown which diffuses the loads into a stiffened structural crown and decreases the use of the early Gothic bays system by dividing the whole bay into small components which are easy to counter and control. The first use of this structural system was between 1321 and 1349 when John Wysbeck applied it to the Lady Chapel roof design at Ely, figure (2.26). Wysbeck did not aim only to design decorative elements but he took structural and economic issues into account and concentrated on seeking light and inexpensive shells. Furthermore, in the fifteenth century, architects were able to erect interlacing, light and decorative grids with thin shells over Norwich Cathedral’s nave without any need for any additional buttressing works, figure (2.27). (Acland 1972)

These interlacing grid vaults provided with some curved stones are located at the junction points between ribs. These bosses adorned the remodelled Romanesque nave at Winchester, figure (2.28) which was completely recovered with a stellar vault pattern by William Wynford in 1450.

During the fourteenth and fifteenth centuries, architects sought to achieve new vaulting patterns by developing the structural system. This new innovation depended on dissolving the walls into skeletal armature and liberating the ribs from the shell to become flying arch rings supporting the vault, figures (2.29).
Using this pattern was justified when the aisles and nave became at the same height as it happened in the choir vault of Temple Church in London when architects formed narrow transverse vaults by flying arches across the aisle. Many architects consider this type as a development of eleventh century vaults in St. Philibert at Tournus by gathering all ribs into the main piers. This system was applied in the choir vault of St. Mary’s Church in Warwick in the fourteen century where the longitudinal ribs were braced by flying concave modelling arches which rise up from the props, figure (2.30).

With the aim of developing the interlaced ribs before 1377, a major innovation was reached by architects at Gloucester when they built the southern bays with fully developed fan vaults. These vaults are small and detailed but twelve feet wide and the ribs raise the vaults shell by their horizontal hoop system, figure (2.31). (Acland 1972)
Stone vaults have not stopped developing to this day, despite all the problems, failures and challenges they have faced. Because of this, architects, masons and carpenters always seek to find more innovation, techniques and solutions in order to save these types of roof and develop it for more advanced structural functions.

2.2 Behaviour of the Structure

Although during medieval times there was no understanding of the behaviour of Gothic vaults’ structure, masons did not stop searching and finally they approached a satisfactory result when both physicists and historians agreed the significant role of ribs in the vaults. Also, equilibrium was considered to be the first and best approach in vault’s design and safe state which scientifically can be met by correct geometry. Although the arch shape was studied mathematically by Robert Hooke (1635-1703), Gregory (1697) and Poleni (1748) when they discussed the effects of loads and tension forces on the arch, the early masons and their followers’ principle was to design the arch while keeping it in compression. This principle was applied by designing domes and vaults which gave the medieval building architecture its universal reputation. Although the thrust’s line has many position’s to identify stability, to understand the structure behaviour, Heyman supports the seventeenth century statement of Hook and Gregory “if a position of the catenary can be found which lies within the boundaries of the masonry, then the structure is satisfactory”

Heyman (2000, 2006) discusses in detail the Gothic arch behaviour after centring removal and how the thrust’s line works. He illustrates the arch and abutment work and how cracks are formed as a result of the structure’s response to the external environment as well as internal forces between voussoirs when the arch is trying to accommodate, figure (2.32). (Heyman 2000)

![Diagram of internal thrust lines due to weight of the arch itself](Heyman 2006)
Derosa and Galizia (2007) complete Heyman’s investigation in evaluating the pointed arch behaviour under the live loads. The results they obtained confirmed the great ability of the pointed arch to resist loads and how safety and stability were gradually increased by using the equilateral pointed arch regardless of the arch’s span or depth, figure (2.33). Also, Romano and Ochsendirf’s study in 2010 confirmed the fact that the pointed arch has a lower value of thrust than a circular one, that is related to the height given to the crown which increases the load’s capability and equilibrium status. (Galizia 2007)

![Figure (2.33): Forces acting on the generic voussoir, collapse mechanism and line of pressure (De Rosa & Galizia2007).](image)

There were a lot of theories and opinions about Gothic vaults’ structure and behaviour. The most famous theories were written by Robert Willis in 1845, Viollet-le-Duc in 1858-68, Victor Sabouret in 1924, Pol Abraham in 1934 and Jacques Heyman in 1964. In 1845 Robert Willis emphasizes the predominant structural role of ribs in the vaults and divides his observation between mechanical and decorative construction aspects to realize how the ribs are supported or seem to be supported. The visual impression which he depended on allows many experts to criticize his theory. (Huerta 2009) (K. D. Alexander 1977)
From another point of view, Victor Sabouret in 1924 disagreed with Viollet-le-Duc’s theory and he pointed in his book ‘’A Provocation to the Orthodoxy of Gothic’’ to the decorative role of groined ribs, affirming his opinion by noting that the usually small scale of the ribs does not allow them to be as important as constructional elements. Also, another justification he noted was that because of the vault’s movement, in many cases the ribs are separated from the groin. Furthermore, Pol Abraham in 1934 concurred with Sabouret in his opinion about the decorative role of the ribs and had his own observation to study the vaults’ behaviour, the horizontal thrust concept as well as vault’s three dimensional explanations and as a result he totally refuted Viollet’s theory. The reasons he gave were completely convincing to his followers because of deep analysis, numerous explanatory drawings and his excellent experience in structure’s behaviour, despite the fact that not all of his results were totally correct, figure (2.34). (Huerta 2009) (K. D. Alexander 1977)

Jacques Heyman has his own direction in studying the concept of equilibrium for the masonry as well as the loads and forces the structure is suffering from. After a lot of theoretical studies, books and actual application on the masonry, he found that masonry does not have tensile strength, but it has unlimited compressive strength due to the low stresses in it as well as the fact that sliding failure has no opportunity to occur. Also, he noted that the intersection between two shell surfaces develops concentrated stress. This is why, in all his studies, he emphasized the importance of arch’s geometry as the most crucial factor in the structure’s stability. (Huerta 2009) (D. F D’ Ayala 2008)
2.3 The Main Damages, Failures and Challenges which Occur to the Gothic Vault’s Structure

As a result of searching for more advanced structure elements and lighter masonry, many types of failure had a place in the structure either in the support elements or in the lateral elevations. For this reason, all masons, architects and engineers’ efforts were focused on describing the failures, their pattern and causes as well as using new techniques, materials and solutions with the aim of preventing the masonry from falling down. D. Theodossopoulos and B. Sinha (2008) discuss in details the failure moods and Gothic structure safety and classified failure pattern regarding the causes such as lateral instability, design error, the effects of inappropriate intervention or some actions affecting specific areas in the structure, figure (2.35).

Lateral instability takes place in Gothic vaults by the weakness and collapse of buttresses or increasing the trust which may become over the buttresses capability. This failure produces cracks and detachment lines in the vaults’ surfaces and happens because of a design error, incorrect intervention, neglect or slender walls, which accelerate the failure’s occurrence. This type of failure is typically characterized by a longitudinal crack such as the one noticed at the high vaults of Lincoln Cathedral where the cracks started at the intrados of the vaults and longitudinal vertex and were then followed by the extrados cracks above the springs, figure (2.36).

Another example was noticed at Amiens Cathedral, where the cracks occurred in the vault’s surfaces heading for its intrados, figure (2.37). In Durham Cathedral, types of cracks were noticed by the outward lean in the nave which was ascribed to the quadrant buttressing which supports the roofs rather than tying and bracing the high vaults, figure (2.38). (Dimitris Theodossopoulos 2008)
The desire to achieve a modern and light structure drove architects and engineers to use slender structural elements. This design was sometimes inappropriate to the big cathedral and masonry and because of that, many noticeable collapses happened in famous buildings where the engineers preferred slender elements instead of identifying the correct design needed by the building. Classic examples for this failure are Beauvais and Vitoria Cathedrals which suffered from partial collapse in 1284 because of slender piers, figure (2.39).

Despite all the hypotheses of S. Murray and J. Heyman, which tried to attribute the reasons for collapse to the upper structure port-a-faux junction, aisles or the buttresses location, the slender structure and design are still the main considerable reason. In Vitoria Cathedral, a typical deformation happened because of inappropriate containment of the upper thrust and eventually deformation due to the building’s big scale despite all advanced intervention which had taken place before to strengthen the structural elements. Every building with such a problem essentially became under the three levels monitoring in order to avoid the upcoming deformations and deal with their causes, figure (2.40). (Dimitris Theodossopoulos 2008)
Inappropriate interventions in old fabric potentially have their negative effects in addition to the main deformation which happened in the structure and caused some structural failures in the buildings. The roof replacement in Holyrood Abbey Church, Edinburgh, was the main cause of the failure of 1768 when this replacement created a huge increase in thrusts which could not be contained by the buttresses, figure (2.41). (D. Theodossopoulos 2003)

Also, seismic action deeply affects Gothic structure because of the horizontal and vertical pressure applied on the building during it. This pressure leads to the loss of some elements and material which logically impact upon other structural elements as it happened during the collapse documentation for two vaults in St. Francis Basilica in Assisi using 3D FE modelling, figure (2.42). Another example of an earthquake’s effects is the collapse of St. Angelo dei Lombardi during 1980s in Italy which shows the similarity between earthquake and imposed deformation’s effects, figure (2.43). (Dimitris Theodossopoulos 2008)
John Fitchen (1961) emphasizes the importance of centring and points out that it should be made strong enough to avoid any unexpected loads and deformation during the erection process. The main problem was in centring for the high vaults with wide spans, which doubled the effort and expenses. These multiple problems relate to the framework logging as well as timber-work for the centring frame and the main desire is to find a suitable solution which can control the expenses and efforts as well as prevent their doubling. Also, creating the same medieval falsework nowadays faces two main constraints. Firstly, the use of mineral features was limited as much as the builder could. Secondly, they did not understand or use the current universal truss techniques which are complex and mix members between tension and compression assembled together over wide spans in the aim of avoiding triangle deformation. Concerning the lack of timber after the appearance of new methods for iron construction which are faster, more durable and less expensive than timber falsework, it will be difficult to reuse the traditional falsework in modern-day vault centring. Convergence and intersection were clearly pointed out in typical Gothic vaults when it was common to use more than eight half-frames for as many ribs, all converging on common key. It is obvious that leading the stone courses from the side creates a major shift in the stone framework techniques compared with the traditional leading from above. This technique changed directly after using the ribs as feature elements in the Gothic vaulting system. As for the framing, four
Diagrammatic framing and undergirdings were suggested for the Gothic ribbed vault’s centring, figure (2.44). The main problem is in both A’s and B’s patterns, when major loads would be concentrated at the middle of the span during the erection process which requires more support at the vault’s centre and against the lateral thrusts. Patterns C and D came to correct this failure by a successful scheme which concentrates the centring frame by horizontal lower elements and carefully exist for the upper part to solve the design problems of the high-level supporting falsework as well. (Fitchen 1961)

Other sudden effects can be taken into consideration, which can damage the Gothic structure and apply new unexpected loads on the masonry. James H. Acland (1972) discusses the vaults’ failures, especially those which happened to the structures during the two World Wars, which destroyed the harmony and relationship between folded shells, ribs and arches system despite the fact that they work together to ensure the vault’s stability. Gilman (1920) supports this idea by many examples like shells of Reims, Soissons and Noyon Cathedrals. Other different causes attack the shell’s upper part and create direct damage to it which, as a result, affects the stability of lateral supports. A sharp change in the water table and fire damage in Yorkminster are good examples of affecting the upper shell and consequently the rest of the structure.
3 Repair Methodology and Techniques

3.1 Historic Repair Techniques

Repair work’s birth in Rome was as a result of citizens criticizing those who destroyed ancient buildings and monuments. For this reason, Martin V launched the first measure by establishing his court which was responsible for repairing the main buildings that still had a contemporary use, such as churches, aqueducts, bridges and gates. It was necessary during the churches’ restoration to deal with roofs and the desire sometimes to preserve something as in the past led to innovate some techniques to realize that. For example, when the church’s roof was needed to preserve, conservators were erecting beams supported by a machine called a caprae. The support elements were added on both sides in order to identify good stability and correct section for the roofs. Another repair work by Pope Paul II (1464–71) happened in St. Marco’s Church using supporting techniques when the main nave and walls were reinforced by new walls tied to the old ones and supported the lateral aisles’ pillars. After that, a great desire for advanced science and technology dominated during the Enlightenment, during which religion attracted less attention.

The effects of medieval principles on classical architects were very clear in Sir Christopher Wren’s works when he repaired Salisbury Cathedral and the western towers of Westminster Abbey, figure (3.1). The appreciation of Gothic architecture principles was obvious in roofing details after their repair. Major changes in repair principles happened in England by replacing some old stone in perished vaults by more decorative ones. This principle was carried out in Merton College Chapel at Oxford, Durham, and Glasgow Cathedral in the aim of making the interiors more attractive. This conservation approach was criticized because of sometimes losing the old appearance of the building, which has great meaning for the citizens. (Jokilehto 1986)

Figure (3.1): Westminster Abbey, west front after reconstruction of the towers in the 18th century. (Jokilehto 1986)
Moreover, in Arab countries (Syria, Palestine and Lebanon) a lot of repair projects were launched to protect and reconstruct historical buildings. For example, the south of Syria and Lebanon had a lot of conservation projects for basalt stone-slabs as well as corbelled roofs. These roofs had suffered from negligence and decay for many years. All projects worked on reconstructing the demolished roofs, supporting the holding walls as well as covering and repointing the roofs in order to reuse the repaired spaces, figure (3.2).

Furthermore, Palestine especially in Nablus since 1990 had a lot of repair projects to preserve the historic buildings which suffered from many years of destruction and negligence. Many historical baths, inns, public buildings as well as palaces were repaired using simple reconstruction and repointing techniques. The most important project was Al-Kaasem palace where repointing barrel vaults and supporting the structural elements were the main conservation works which happened to the roofs there, figure (3.3). (Cana'an 1932-33)
Another traditional technique was used in vault repair which is still clearly noticed until now, especially in Turkey. Mortar and plaster repair was widespread during the Byzantine, Seljuq and Ottoman periods using gypsum, lime and lime pozzolana as the main materials in the building. In addition, there are some supplementary materials such as river sand, pebbles as well as brick pieces and powder which were used together with horse or goat’s hair. These materials gave the mortar the concrete strength and durability in Ottoman buildings especially the 15th century architecture. In the 18th and 19th centuries, lime mortar was called royal mortar, which was formed of non-hydraulic lime which made it resistant to the water and humidity. For this reason, this technique was developed by combining it with pozzolana which increases its resistance to water, and after that it was known as Horasan concrete in the history. (N. Arıoglu 2005)

Repair works mainly depended on the construction ideas and techniques during medieval period and before. In fact, the masons followed their constructional skills to solve any damage occurring to the building’s structure during its construction or after that. This technique enabled masons to decrease the cost of repair and preserve the building’s character as it was planned. This good preservation is due to the use of the same erecting systems and materials used in the original construction of the building. The best example for that is what happened at Gloucester and Wells in the 14th century when builders tried to distribute the crossing tower loads over the central bays around it instead of erecting stone arches to hold it. In order to realize their aim, they installed pointed arched between props and created a reverse arch ring by connecting a pointed arch upwards. These reverse rings strongly braced the piers. Also, tracered circles were introduced to brace the whole upper piers’ surface and spread the hunching over them. (Acland 1972)

3.2 Conservation Philosophy

The most important architectural conservation theories try to draw two main aspects, which are: to realize the historical building value as well as how to bring these buildings up-to-date during the conservation project. Also, intervention works usually happened in pre-existing fabric during the conserving process such as what had happened in Hera Temple, Olympia, and or special way of transformations of medieval churches in Rome.
In the 1970s, Tafuri adopted the idea of opening construction in historical project which reflects past events in the reading of the current situation of the project. In this case, the main work is to re-describe and reconstruct the project as a shift from the past by some historical innovation which helps to create the historic character rather than apply scientific constructional techniques. He also considers history as a deconstruction and analysis for the historical elements which offer new materials, ideas and means for the new desired appearance. For that, the active history is not determined only by the analysed historical elements, but it also defines the reconstructed and recomposed elements and methods. Moreover, Tafuri emphasises the good understanding of the relationship between the project analysis and tension elements. These elements are considered as the causes of the project’s criticisms. He stresses the importance of multiple principles which urge the historian to think by tangles of phenomena. The core of his interest is the manipulation of architectural forms which usually has an objective more important than the form itself. Therefore, he encourages historians to focus on ideologies which generally work as bundles. He clarifies that the main task of the historian is to investigate many independent histories to find out the antagonisms and interdependencies. Therefore his project depends on an intermittent journey through a maze of tangled paths though the history. (Tafuri, ‘The “Historical” Project’)

All attempts and perceptive efforts were made in the aim of employing a clear attitude towards the historical buildings parallel with emphasising the importance of technology and modern architectural aspects in terms of 19th century conservation processes. These aspects were either as a result of Viollet-le-Duc or a reaction of John Ruskin. In terms of cathedral restoration, a new concept ‘formal unity’ was added by the former’s stylistic approach. This concept is epitomized by an arbitrary re-introduction of styles and idioms. Also, the anthropomorphic approach was widespread between architects and thinkers by the influence of J. Ruskin as he thinks about the historical buildings as organisms with all rights of life and death in their time.

Moreover, the main difference between Viollet-le-Duc and Ruskin is that the first one strongly encourages the obvious use of modern material in historical building conservation, whereas Ruskin always demands obsessive authenticity. These two different opinions ignored the great value of the historical fabric as considering the building only by the aim which they are repaired or redesigned for. In addition, the factual documentation for any conservation project is very important and should depend on comprehensive scientific studies such as archaeological, archival and structural research. This importance draws on the large influence
of the monuments historic dimension aspect which had a widespread effect over many national policies. It is noticeable that when history is made up of complex interactions of phases, the limitation of these approaches will clearly come to the fore. Other great approaches, developed into scientific synthesis, were contemporary with the previous once. These new approaches were initially developed by Camillo Boito in 1883, later by G. Giovannoni in 1932 in addition to the influence of archaeological method and Boito’s principles on them, which have their effect on conservation process until now.

Other elements should be considered to realise create artistic, spatial, cultural and even economic values for the project. These criteria are defined by architecture and ability of designing a project which are considered as the fundamental component for any project structure. Also, the aesthetic dimension, art history as well as histories of architecture were developed to become more fundamental in conservation projects. This importance became very great, especially after the two World Wars, when the desire to reconstruct demolished buildings gave an opportunity for designer and conservators to apply new aspects, material and techniques. Therefore, they were able to create a good database by making a lot of experiments and tests on the building structure, new applications and materials. Furthermore, the conservation process is sometimes guided by the desire to restore the national identity to the buildings. That is exactly what happened in the cathedral conservation after the First World War, especially in Reims, Soissons and Frauenkirche Cathedrals, later in 2005 where the desire of representation of the Gothic form was demonstrated on the project. Another example using the Hanseatic instead of Gothic Revival style in Warsaw Cathedral, annihilated in the Second World War, was considered as a better choice to introduce Warsaw’s reborn identity.

The formulation was raised with the artistic emphasis by Cesare Brandi in his “Teoria del Restauro” (1963). His definition has been influential: “Restoration is the methodological moment of the recognition of a work of art as such, in its physical nature and its aesthetic and historic character, in view of its transmittance to the future” (Brandi 1963). After that, planning of the buildings’ “sustainable construction, environmental consideration, like statutory requirements and community engagement” became more influenced by the increasing complexity of the design’s professional role. This complexity drove the conservation theory to suggest a similar range specific to valuable historic buildings which reconciled the monument with its operator. Most conservation works are exposed to public criticism and pressure regarding to the conservation choice. In fact, the main stakeholders are
the architect and the engineers with the difference that their main aim is to make a conservation project relevant to expectations by bringing cultural and technical richness.

3.3 Reviewing The Benefits of New Materials, Techniques, Structural Solutions in Solving Failures and Damages

3.3.1 Strengthen Using FRP (Fiber Reinforced Polymer) Laminated Materials

Using these materials was widespread all over the world due to their properties in upgrading the masonry structure and increasing its safety level. Also, when the structure has suffered from different distribution of the loads, these materials guarantee the structure stability and cohesion as well as encouraging architect’s innovation. This ideal role and diverse application are related to the major advantages produced by using laminated materials. We can summarise these benefits as follows: they offer very low weight, high tensile strength, low thermal expansion coefficient and corrosion immunity. In addition, the application of laminated materials became more and more popular despite their high costs. This popularity is due to the material ability in facilitating the intervention execution in historical buildings in difficult situations and with any type of damage and deformations. Furthermore, these materials greatly help in avoiding the collapse and pursuing the safety conditions when they are used in wrapping structural elements. One criticism which arose was the shortage in specific models and design recommendations for the building’s structure. Also, the deep investigation demanded for some materials’ aspects in the aim of totally understanding for these materials’ behaviour, figure (3.4). (M.R. Valluzzi 2001)

Figure (3.4): Example of a vault with fill in a existing masonry building. (M.R. Valluzzi 2001)
3.3.2 The Thrust Network Approach (TNA) to The Equilibrium Problem of Unreinforced Masonry Vaults

Since Antiquity and throughout history, architects and scientists were attracted by using and investigating the force network models for the stability analysis of the masonry vaults. Also, many attempts were made in this field by O’Dwyer (1999), Fraternali (2001), Fraternali et al. (2002a, b), Block and Ochsendorf (2005, 2007), and Ochsendorf and Block (2009), aiming to find a compressive state of thrust in equilibrium with the applied loads. These attempts concluded with a design of a statically admissible thrust network depending on analytical, graphical and computational methods. Many years after that, the TNA approach had appeared, aiming to find some solutions for the structure equilibrium problems. This approach proposes that the compressive membrane is responsible for resisting the external loads. This membrane, during the stress state, is located through the material surfaces. The approach is applied by using the variational formulation for the problem and polyhedral test function for the thrust surface of membrane stress potential. Moreover, aiming to enforce the no-tension constraint and suitable geometric bounds, a frequency procedure is proposed through geometrical and topological adaption of an initial candidate solution. After many research’s works on hemispherical domes, groin vaults and cloister vaults, numerical results were given to predict the thrust network and crack pattern. These studies obviously showed the ability of TNA in doing actual observation for the crack’s mechanism. (Fraternali 2010)

3.3.3 Reduction The Vault’s Lateral Thrust with FRP (Fiber-Reinforced Polymer) Composites

Regarding what it is referred to before, FRP materials became very important in the field of conservation due to the positive effects they have on the repair process. Thus, it is essential to clarify another importance in resisting the thrust loads which normally result from the vault’s self-weight. The most important situation is when the piers cannot resist the vaults’ thrust and the tie rods are adopted. In this case, to resist and reduce the lateral thrust resulting from the vault itself, an externally bonded FRP sheet can be successfully used to get rid of any potential collapse which might happen. Installing the FRP reinforcement could happen in two ways. It can be either placed at the intrados spanning one central angle at the crown, or at the extrados spanning two angles between abutments and hunches. Moreover, FRP application with intrados produces, which uses to strengthen the four lateral arches in the cross vault, is
very effective in eliminating the thrust transmitted to the piers and, as a result, prevents any collapse potentiality. Effectively, the use of FRP anchor spikes prevents the debonding of an FRP sheet applied at the intrados of a masonry arch. The application of FRP at the intrados can then be regarded as an effective solution. Usually the vault implies removal of floor finishes and spandrel fill, for this reason strengthening of a vault at the extrados is unfeasible or significantly onerous, figure (3.5). (Laura De Lorenzis 2006)

![Figure (3.5): Geometry of edge vaults. (a) Plan of a cross-vault. (b) Plan of an edge vault. (c) An example of edge vault over square plan with semicircular webs. (d) An example of edge vault over rectangular plan with semicircular (long sides) and pointed (short sides) webs. (Laura De Lorenzis 2006)](image)

### 3.3.4 Strengthen The Vaulted Roof by Using SRG Strips and Sheets

This application was as a development of using FRP application with the introduction of the useful performance of the material using the twisted steel wires. It is very important to increase the structure safety as well as develop the structure performance in seismic situation using advanced means such as SRG sheets and strips. The most important example for applying this technique is cloister Portico when it was affected by the Umbria-Marches earthquake in 1997. In this example, introducing the SGR sheets alongside with the arch surface enhanced the arch structure, fixed the masonry as well as supporting the piers. Consequently, after the removal of the filling materials, the horizontal thrust of such arches is going to be resisted by introducing the SGR sheets, figure (3.6). (A. Borri 1996)
Another example of this application was in two masonry vaults of the Jacobilli building in the city of Foligno, Italy. Similarly to all examples before, this technique was applied to save the masonry structure and introduce the most up-to-date techniques and technologies in this field, taking into the account the historical building’s character as well as respecting the cultural significance of the building. Moreover, different applications took place in this building regarding the vaults’ situation and type of deformation. For example, presenting the SGR sheets, anchoring of SGR strips and applying of steel flat plates were the most important works which had taken place in the building, figures (3.7) (3.8) (3.9). (A. Borri 1996)
3.3.5 Retrofitting and Monitoring The Vaults Masonry Using The CFRP Application

Carbon-fiber-reinforced polymer or carbon-fiber-reinforced plastic (CFRP or CRP) is a very strong and light fiber-reinforced polymer which contains carbon fibers. The polymer is most often epoxy, but other polymers, such as polyester, vinyl ester or nylon, are sometimes used. The composite may contain other fibers such as Kevlar, aluminium, glass fibers as well as carbon fiber. This application successfully took place in the historical centre of Foligno, Italy, which suffered from many deformation types due to the modification works through its history. Introducing the CFRP sheets was done to the vaults of the drawing room at the extrados aimed to reduce the effects of probable failure mechanism, figure (3.10). (Filippo Bastianini 2005)

The repair works began by inserting solid clay bricks into the outer wall after removing the filling materials. After that, cleaning the surface with sand and water and levelling the outer surface of the outer vault area had taken place in the preparatory stage before applying (Filippo Bastianini 2005) the technique. The first layer of the CFRP sheet was led over the bedded band with epoxy-resin. Due to the sensitivity of CFRP, good preparation for the surfaces was required to reach a successful application. The conservators cast a small amount of epoxy putty over each lintel after the CFRP sheets were laid that in the aim of fitting the steel plates with the steel wedges, figure (3.11). (Filippo Bastianini 2005)
3.4 The Use of Computer Systems and Programs in Solving Vaults Failures

3.4.1 The Use of Elastic Solution ‘’Photoelasticity and FEM Analysis’’

The equilibrium analysis using graphic tools was the early solution suggested to give a fast and concrete answer for some practical solutions in restoration work. This solution was not trusted by engineers and the correct one was in applying elastic solution which were practically used in the nineteenth century masonries. This application was an appropriate solution for equilibrium, materials and compatibility problems. In the 20th century, Robert Mark (1968) began to use photoelastical methods in Gothic cathedrals and followed that by using spatial models with the employment of Finite Element programs in 1970. This approach was in the aim of finding out the Gothic vaults’ behaviour and structure. A better solution was found by simulating the non-tensile strength materials and using non-linear FEM analysis. But due to the sensibility of the equation system and influenced by original boundary conditions and loading history, the system does not give an exact illustration about the state of masonry structure. However, engineers were able to come to interesting results by using non-linear FEM packages in 1991. This achievement was by Barthel when he succeeded in describing the masonry’s behavior and defining the anticipated crack pattern in crossing vaults using the computer in addition to his wide knowledge and practical experience in restoration work. (Huerta 2009)
3.4.2 The Modal Experiments for the Validation of Masonry Vault Models

Concerning the great interest in assessment, preservation and rehabilitation the vaults masonry, it was crucial to depend on advanced analysis techniques with the aim of getting correct and accurate results. The three-dimensional finite element analysis method (FEM) is a very advanced technique for analysing masonry, especially the structures of arches, vaults and buttresses. This technique depends on the accurate entering of the data into the system in order to obtain a correct simulation for the behaviour and mode shapes of the masonry vaults structure. This technique was actually applied over the vaults of Washington National Cathedral where the main aim of applying the technique was to evaluate the vibration characteristics of the floor system, figure (3.12). (Ece Erdogmus 2005)

As for the model, there are several stages the model has to pass in the aim of reaching the final stage of simulation using the ANSYS commercial software. Firstly, geometric modelling produced by using AutoCAD program depending on the actual dimensions of the structure, then use the known points’ coordinates to enter the model into the ANSYS software while the ribs are modelled as three-dimensional solid arches and are meshed with 8-node SOLID45 elements, figure (3.13) illustrates the model of a choir vault of the Washington National Cathedral. After that, experiments took place on the model, which represents the actual situation of the Cathedral’s vaults. This experiment had taken place in many stages beginning with the situation of no constraints and then continuing by adding bracing elements and applying the actual loads, figure (3.14). In this technique, the simulation of actual structure is very helpful to understand the vaults’ behaviour, especially for the cases where information on material properties is available. (Ece Erdogmus 2005)
The Use of 3D-Laser Scanning in Assessing the Safety of Masonry Vaults

Depending on the 3D-laser scanning is a very important procedure in order to have a correct estimate for the vault’s geometry. That is related to the great importance of the vault’s stability which should be strongly considered in any procedure taken in the conservation or restoration works. This simulation method depends on a 3D-point cloud and is very useful in defining the thrust line in the vault’s structure as well as the reaction of the abutments. Also, critical appraisal is given by the application of laser by obtaining the 3D-modelling, gathering the point clouds, structural analysis calculating thrust lines and the consolidation requirements that are obtained. (Luc Schueremans 2008)

This scanning method was mainly used in the modelling of the vault of the main nave of Saint-Jacob’s Church. The vault’s scanning was done by Leica HDS 3000 laser scanner. This scanner is
distinguished by its great guaranteed accuracy which is between 6mm per point up to a range of 50m, figure (3.15).

In this case study and aiming to get rid of any occlusion and shadow, it was necessary to use two scan positions, which are vertical and horizontal scan resolutions. Furthermore, using the Cyclone software was very helpful in identifying the Leica scanner target, and applying the Rapidform software was the most important factor in filtering the cloud points in order to remove the noise, create the mesh and eliminate redundant points. (Luc Schueremans 2008)

The laser scanning process consists of several main stages sequentially arranged to reach the final demand of an electronic file which describes the geometric and structural situation of the vault masonry. Firstly, meshing the model takes place with the aim of creating the model of the vaults by scanning the shell and ribs to determine the structure function of each element as well as the predicted way or transmitting and resisting the loads. After that, it is necessary to define a new coordinate system for the model and project a grid onto the model. Finally, the grid points are transferred into an AutoCAD document which illustrates the 3D-dimension with a vertex in order to use it in any future simulating and virtual loads applications, figure (3.16) (3.17). (Luc Schueremans 2008)
Another example of laser application is the use of 3D Digital Pointcloud Laser in a Heritage Survey in Durham Cathedral. Recently, a detailed metric laser survey was completed for part of the UNESCO World Heritage Site at Durham Cathedral on behalf of Purcell Miller Tritton. The survey was carried out using a Faro Photon120 phased based laser scanner and took approximately 10 days to be finished. The survey process was launched using 250 scans and Faro’s scene software which provided the system with easy ways to attract the targets automatically, record the scenes as well as process and manage this great project. After finishing the scanning process the system had produced two types of documents - one with photos and another without. Hence, all information can be transmitted into AutoCAD where all details, 3D models and 2D elevation can be processed to produce the final scanning results, figure (3.18).

Figure (3.17): Laser scanner data processing (d) final grid points - AutoCAD DWG

Figure (3.18): 3D and 2D models in Durham Cathedral
4 Practical Study

Practical study depends on investigating many case studies in Scotland, England and Europe. The first step is to classify the buildings into groups in terms of problems or techniques. The buildings classification takes into account the following groups:

1- Metal reinforcement techniques: This group includes Glasgow Cathedral, Gadzow Castle and Tantallon Castle.
2- Buttresses and containment of thrusts: This group includes Durham Cathedral, England and Santa Maria Cathedral, Vitoria, Spain
3- Repair and strengthening after a failure: This group includes Holyrood Abbey and Beauvais Cathedral
4- Earthquake damage: This group includes St. Francis, Assisi.
5- Reconstruction: This group includes Soissons Cathedral
6- Repainting and durability: This group includes St. Giles Cathedral and Linlithgow Palace.

4.1 Metal Reinforcement Techniques

4.1.1 Glasgow Cathedral

This cathedral was built before the Reformation from the late 12th century, its history is linked with that of the city, and is allegedly located where the patron saint of Glasgow, Saint Mungo, built his church, figure (4.1). (Elizabeth Williamson 1990)
We can distinguish many types of vault in this, which are: figure (4.2) (4.3)

- Rectangular ribbed vaults cover the aisles surrounding the nave.
- Stellar ribbed vaults (tierceron pattern) in the basement chapels.
- Elaborate pattern vaults in the Blacader aisle which has a particular star-like design.

As regards the repair of the vaults, we can begin with conservation work in proper sequence according to importance, as follows:

The East End of the cathedral, figure (4.4). Specifically the south east corner of the East Chapels and Crypt, has suffered slow long term movement for a considerable period, probably for centuries. At the corner is a holy well, and this may have contributed to the foundations weakening in this area. Externally, considerable distortion is evident in the masonry of tracery in the most south-easterly window bay- so slight movement of the cathedral fabric may always have been a problem in this location. Some vertical cracking is still apparent on the bay, and although the crack is small, it extends to the full height of the bay running from approximately mid-point of the bay from wall-head parapet to the base plinth.
Internally, the ribbing of the two vaults at crypt level and the most south easterly chapel vault are distorted. It would appear that this may be a result of a combination of three factors:

a) Different building periods, setting out anomalies.

b) Trauma caused when the central spire fell in 1400, severely damaging the choir vault.

c) Structural movement due to poor ground bearing capability.

In 2006, Historic Scotland opened up the parapet of the south eastern bay to indent a new gargoyle (the original being decayed and unsafe). Behind the gargoyle, within the wall-head, they found a long wrought iron flat bar (approximately 50 x 12 mm extending most of the bay’s width in length). This had been built into the bed joint of the wall masonry just at the corbel table level. At regular centres wrought iron tie bars of similar dimensions to those of the bed joint bar hooked over the bar and extended into the masonry fill above the vault (as the area was not fully exposed, figure (4.5). the number and length of these bars was not ascertained). From the mortar and degree of corrosion it would seem that this work dated from the early to mid-19th century. No paper records of this intervention have been found.

Subsequently, in the early 20th century, steel beams were installed over the vaults within the attic area of the East Chapels. Rod ties extend at a 45 degree angle from these beams and are embedded within the wall masonry to compress and tie the vault below, figure (4.6). As far as is known, there are no other vault reinforcement measures within the cathedral, though the
cathedral had extensive masonry repairs carried out on it in the mid-19th and 20th century with other types of repair works.

Figure (4.5): Glasgow Cathedral: Repair techniques for the most south-easterly chapel vaults in 19th century.

Figure (4.6): Glasgow Cathedral: Repair techniques for the most south-easterly chapel vaults in the early 20th century.

Another type of repair work took place in the Blacader aisle, which was built in the beginning of 15th century, after the damage which happened to the ribs, shell as well as bosses. For that, lime-washed works began in the early 20th century to reform the interior space of the aisle with the aim of supporting the service activities. The lime-washed vaults were provided with new reformed bosses in different and elegant shapes representing ornaments, saints or coats of arms, figure (4.7).
Parallel with Blacader repairing works, aisle vaults around the nave were repainted white, figure (4.8). Also, some stone replacement works had been done to the basement chapels and chapter house vaults where some damage and deviation occurred to the vaults’ shells and caused stones to fall, figure (4.9). These stones were replaced and new stones attached with cement mortar.
The effects of cement mortar are obviously noticed in many parts inside the cathedral. Many stones were damaged because of the pressure produced between them and the cement mortar hardness which prevents any natural expansion usually happens in the stone, figure (4.10). Moreover, the cement mortar also affect the appearance of the stones matching because it does not have the same matching ability as the other mortar types, lime mortar as an example, figure (4.11).

Figure (4.9): Glasgow Cathedral: stone replacement works in the Basement Chapel and Chapter Houses vaults

Figure (4.10): Glasgow Cathedral: some damages happened to the vaults because of cement mortar
4.1.2 Gadzow Castle

This castle dates back to the 15\textsuperscript{th} century and was built by Sir James Hamilton of Finnart. It became one of the greatest buildings in the 16\textsuperscript{th} century and had a good location of parkland of Hamilton palace. The castle is now roofless except for some remaining vaults and slabs which Historic Scotland demanded to be preserved. The main focus point in this study is the technique suggested to preserve the barrel vault located within the northern west tower, figure (4.12). This vault is dressed by ashlars and the north part has partially collapsed. Therefore, the remaining section stones are badly misaligned and the joints are opened due to the tree roots which have grown through the stones. Also, the unstable bearing in addition to the destruction of the south part increase the danger of collapse in the structure, figure (4.13).

Figure (4.11): Glasgow Cathedral: the effects of cement mortar on the vaults appearance and character.

Figure (4.12): Gadzow Castle plan: illustrates the location of vault.
Aiming to preserve the remaining vault, in 2004 Historic Scotland suggested a conservation technique consisting of three main stages. Firstly, to clean the vault by removing the topsoil and tree roots. After that, to realign the stones and repoint the vault using hydraulic lime mortar. The repainting works should be preceded by metal reinforcement technique to maintain the vault standing. This technique, as it is illustrated in, figure (4.14), depends on scaffolding and works on supporting the vault. Historic Scotland suggested inserting horizontal metal beams under the vault surface, aiming to keep it upright as well as brace the wall behind the vault and prevent its collapse. The horizontal beams are held with metal pillars and provided with counter ballast attached to the ground at the other side to realize their equilibrium. Finally, the vault was covered by a clay waterproof layer to lessen the outer condition effects.

Figure (4.13): Gadzow Castle: photographed in 1997, the unstable vault masonry, now temporarily supported by scaffolding

Figure (4.14): Gadzow Castle: the metal and scaffolding works.
4.1.3 Tantallon Castle

Tantallon castle was built by William Douglas in the mid-14th century to the east of North Berwick, in East Lothian, Scotland, figure (4.15). It was besieged many times, which caused a lot of damage to the building’s structure. The latest one was by Oliver Cromwell’s invasion of Scotland in 1651 which produced several damages around the castle. (John Gifford 1984)

The main remaining vaults in the castle are the springing vault with corbel courses and beam holes erected with buff pink ashlar stones at the 3rd floor as well as the vault fragment on the 4th floors erected with the same pink buff stones, figure (4.16). The vaults were in a bad condition especially at the east side because of the erosion behind the cementitious mortar and the voids created by the wind erosion. (Historic Scotland)

The main repair works to the castle were carried out by Historic Scotland and can be classified as repainting and metal reinforcement works. Firstly, they began with removing the cementitious mortar and repainting the stones by moderate hydraulic lime mortar. After that they applied advanced metal reinforcement technique with the aim of bracing the vault with walls and keeping it upright. This technique, illustrated in figure (4.17), depends on surrounding metal beams assembled around the vault edges. This beam is bound with the vault by three metal tensile ties. The ties as well as the beam brace the vault to the walls and keep it stable. (Historic Scotland)
4.2 Buttresses and Containment of Thrusts

4.2.1 Durham Cathedral, England

Durham Cathedral has been described as one of the great architectural experiences of Europe. It is renowned as a masterpiece of Romanesque (or Norman) architecture. It was begun in 1093 and largely completed within 40 years. It is the only cathedral in England to retain almost all of its Norman craftsmanship, and one of few to preserve the unity and integrity of its original design, figure (4.18).
The vault types in the cathedral vary between the simplest types of crossed vaults to the most advanced one. We can classify the vault types as follows:

- Simple crossed vaults with ribs cover the area of current kitchen and café, figure (4.19).
- Rectangular ribbed vaults which cover the nave and surrounding aisles, figure (4.20).
- Semi-circular ribbed vault in Chapter Houses, figure (4.21).
- Ribbed tierceron vaults under the tower in the crossing area, figure (4.22).
- An elaborated and lofty intersecting rib vault in the form of eight-pointed star in the great Kitchen ‘the books shop now’, figure (4.23).

Figure (4.19): Durham Cathedral: Simple crossed vaults

Figure (4.20): Durham Cathedral: Rectangular ribbed vaults
None of the various vaults in the cathedral church, including those in the north and south transepts and all the various side aisles, have undergone any form of repair or conservation in living memory. They seem generally sound. The repair works which were carried out on the rest of the vaults can be discussed in proper sequence as follows: figure (4.24).
The vaults in the nave was repaired in the late eighteenth century - details unknown - and again early in the 20th century, work having been carried out from around 1915 to sometime in the 1920s. On the latter occasion iron tie-bars were inserted across the roof space immediately above the vault and two orders of stonework were added to the original single order to stiffen each of the quadrant arches which span the triforium galleries above the side aisles. This provided a buttressing effect, and with the tie-bars seems to have halted the previous gradual outward spread arising from inability of the clerestory walls to resist the sideways thrust of the vault. A crack running down the length of the vault was filled in and the plaster on the underside of the vault was renewed in part or wholly, figure (4.25).
The vault running through the choir vault from the crossing into and including the centre bay of the Chapel of Nine Altars was re-lime-washed with some plaster repairs by way of preparation in 1992-3. No structural work was necessary, figure (4.26). The vaults in the arms of the Chapel of Nine altars still show the general state of dilapidation of the decoration and areas of damp damage to the plaster similar to that previously apparent in the choir vault and remain on a 'wish list' for eventual refurbishment. Also, the plaster repair and lime-washed works extended to the appended (supported) space which is now used as a kitchen and café, figure (4.27).

Figure (4.26): Durham Cathedral: lime-wash and plaster works applied to the choir and aisles vaults

Figure (4.27): Durham Cathedral: lime-wash and plaster works applied to the current cafe vaults
The only other vault on this site which has attracted remedial attention is that of the Priory Kitchen - known as the Great Kitchen, erected in 1366-71, which now houses the cathedral book shop. This suffers from damp permeating through its stone roof, which is completely exposed to rainfall (and snow) externally, resulting in gradual deterioration of the internal surface with precipitation of efflorescing salts, lumps of lime mortar and small fragments of stone - not to mention occasional water leakage. This is not only detrimental to the vault itself but also damaging to the bookshop stock and fittings and a distinct safety hazard for staff and customers. The problem was undoubtedly made worse by the removal of the plaster from the vault sometime between the end of the Second World War and the 1970s. To combat this, a lead-covered timber over-roof is currently being constructed. This is intended to prevent the dampness at the source. After the over-roof is complete and the stonework has had several months to dry out, a lime-washed lime plaster will be applied to the underside to reinstate what was removed. figure (4.28) (4.29).
4.2.2 Santa Maria Cathedral, Vitoria, Spain

Santa Maria Cathedral was built in the 13th century and it was important that it was fortified. Therefore, it was built as a fort church. With time, the church became a Gothic Cathedral, which makes it a contradictory building because of the front presence in the Gothic Cathedral interior style as in the French cathedral ‘‘Notre Dame’’, figure (4.30).

The main problems in the building were due to the traditional building materials and the structure, where it was clearly noticed that the materials and the structural elements behave badly toward the tensile forces. Therefore, a conditional survey was carried out in the building over eight years using contemporary computer programs and analysis techniques. The advanced survey mainly aimed to analyse the problems, make a model for the building as well as define the main failure and structural problems on the model. The main problems noticed where the cracks in the South, North and West exterior walls figure (4.31), failures in the transverse arches and inclination in the vaults axis line, especially at the nave, figure (4.32) (4.33).
The loss happened in some materials in the Brazo transept, which contribute to an increase the thrust and concentrate the loads on the effective elements. This led to some failures in vaults, walls as well as piers. Moreover, the walls’ height strongly affected the building structure due to their horizontal movement which produced many cracks created in the walls, separations at corners and, as a result, cracks and failures in the vaults as well as losing the lateral stiffness, figure (4.34).

Many attempts had been made to find a solution for the vaults’ failure, crack extension as well as the bad intervention which had been carried out on the structural elements. The first solution was by adding new arches connecting the walls and the next interior piers, figure (4.35). This solution was installed in order to brace the wall and prevent any movement in them. It successfully braced the wall at the bottom, but because of the wall’s height, new movement was generated at the top part, causing dangerous cracks in the walls and vaults. Therefore, new exterior flying buttresses were added to the building to prevent any anticipated movement and save the remaining structural elements. These buttresses were added and developed in several stages, until they reached their
current shape, due to structural requirements, building material properties as well as aesthetic aspects, figure (4.36) (4.37).

Concerning the huge amount of damage which happened to the structural elements, a comprehensive restoration for the cathedral was carried out over the whole building. The main works related to the roofs were adding tie-rods to brace the arches as well as supporting the piers and the interior arches which braced the walls figure (4.38). Moreover, propping the vault’s ribs by adding metal beams during their repair and banding the walls by using metal anchors inside the walls of the high transept and lateral elevations which was the later repair work done by M. Lorente, figure (4.39) (4.40).

Figure (4.36): Santa Maria Cathedral: historical development of the external buttresses

Figure (4.37): Santa Maria Cathedral: current external buttresses

Figure (4.38): Santa Maria Cathedral: brace the arches by introducing tie-rods

Figure (4.39): Santa Maria Cathedral: (left) propping the vault’s ribs by adding metal beams. (Middle) using metal anchors to strength the walls. (Right) scaffolding system used in the later conservation works by M. Lorente
4.3 Repair and Strengthening After a Failure

4.3.1 Holyrood Abbey

The history of Holyrood Abbey goes back to the 12th century when it was founded by King David I of Scotland in 1125. It has been ruined since the 18th century after being used as a parish church serving the royal palace for a long time until the 17th century. The remaining walls of the abbey lie adjacent to the palace, at the eastern end of Edinburgh’s Royal Mile. The site of the abbey is protected as a listed building, figure (4.41).

In the 13th century, the royal vaults were introduced over the nave and aisles at the same time as the old church was replaced by a new cathedral-sized building enhanced by the new cloister. These vaults caused a lot of stress to the side walls, which led to the introduction of new buttresses in the middle of 15th century to the building’s south side in order to lessen the stress as well as brace the vaults and walls, figure (4.42). During the 18th century, much attention was paid to developing the vaults where the vaults were covered with flags instead of the timber being taken off.

After ten years and as a result of additional weights produced by this solution, the vaults had collapsed, taking down almost all of the nave and north aisle roofs. The destruction spread over the whole building and caused damage to many structural elements such as some other vaults in the nave and south aisle, pillars as well as piers, figure (4.43).
Jane Robertson of Historic Scotland carried out a conditional survey at the cathedral in 2005. She concluded that much decay had happened to the structure due to either the collapse effects or the weather performance at the building, figure (4.44). Thus, the vaults’ condition was described and many solutions for the whole problem were suggested to keep the building upright in good condition.

The main suggested works are to brush off salt deposits, brush off the friable material with a bristled brush, cutting out the stone and indenting with matching stone especially where erosion has compromised the structural integrity or weathering capabilities of a stone, or where erosion significantly detracts from the architectural composition figure (4.45).
The most appropriate work there is to repaint open joints and the joints which lost mortar with lime mortar and which successfully matched between stones and pointed the cracks kept under monitoring for further movement. In addition, to check the state of painting to vault soffits from scaffolding and carry out repainting repairs as necessary and monitoring erosion is very important work, especially in the areas where the water runs off from architectural feature. Furthermore, ending the repair works by removing debris, moss and other biological growth effects to maintain the remained structure elements in good condition.

4.3.2 Beauvais Cathedral, France

Saint-Pierre Cathedral is located in Beauvais, just north of Paris, and goes back to 13th century when it was rebuilt after the collapse of 1284. The tallest structure in the north of France had its first of repair works during the 14th century, after the collapse by installing the choir vault, but it could not be completed until the 16th century, figure (4.46). The main reasons were the decrease in population and the ruin due to more than one hundred years of war, figure (4.47).

Beauvais Cathedral contains three types of Gothic vaults which are considered as the largest Gothic vaults in Europe. These two types are as follows, figure (4.48):

- Rectangular ribbed vaults with pointed arches over the cathedral aisles
- Tierceron vaults pattern over the choir with six ribs
- Hemicycle vault at the end of main the nave with eight main ribs support it.
- Rectangular tierceron vault at the crossing area.
The great span of the ain vessel was the main reason for having the largest and most important Gothic vaults there. These large vaults are the main cause of collapse because they did not provide the church with the appropriate buttresses system. Because, after the piers and flying buttresses had been damaged, the horizontal thrust could not be taken to the ground anymore. This contributed to producing great thrust to the clerestory walls and, as a result, the vaults had fallen down.

After analysing the cathedral, it was noticed that the main rebuilding works are done by buttresses system reinforcement and changing the vaults of the choir. Moreover, rebuilding the damaged piers and adding new extra piers, done by Viollet-le-Duc, was considered as a substitute for solid detached shafts, figure (4.49). These works can be visibly noticed due to the difference in shape and materials, figure (4.50).
The main analysis work was done by Mark and Wolfe when they made an elastic model to find out the loads distribution over the actual building size. Also, they analysed the building materials and structural elements in order to understand their properties and behaviour. Their study clarified that the piers or colonnettes were unlikely to be faulty, either in their slenderness or the load they could carry.

The later work in the cathedral is represented by the wooden braces which were used in the nave to enhance the structural element because of the great span distance between north and south piers. These braces are considered as interior buttresses in the altar and choir vault with the aim of supporting the original structural elements in the cathedral. Moreover, the designer was aware about the series structure problem in the building. Thus, he created a new and appropriate solution by adding tie-rods to support some interior piers figure (4.51). The reconstruction works were carried out by involving more than one mason and it took a long time to be finished.
4.4 Earthquake Damage

4.4.1 St. Francis, Assisi, Italy

St. Francis’ cathedral was built in the 13\textsuperscript{th} century and had suffered from many earthquakes which occurred in Italy. These serial earthquakes produced large cracks and many examples of permanent damage over all vaults in the building. Also, the main destruction happened to the vaults close to the facade and the transept which were totally demolished. Although the masons there were aware of the historical value of the building, many changes had happened to the building’s character due to the serial repair works which happened to the building over many centuries. That mainly affected the building’s original character.

This building was built of two Basilicas, one above the other, and it was noticed that there are many vertical cracks affecting the side walls near the centre of each bay. These cracks were enlarged by the serial earthquakes which occurred to the building and finally, after all repair works, the cracks reopened when a new earthquake attacked the building in 1997, figure (4.52). Therefore, it was necessary to protect the building against the seismic effects to avoid excessive cracks during the seismic actions, especially at the centre of each bay of the nave and lateral chapels.

Computer modelling programs play a role in understanding structural behaviour during seismic action. For this reason, as mentioned before, 3D FE modelling is used to enhance the analytical investigation in the cathedral. This model gave clear results of the building vibration modes in the seismic situation. Also, it produced numerical results about the stresses and deformations which happened to the vaults in many cases with fill, without fill and the reinforced vaults, figure (4.53) (4.54).

Figure (4.52): St. Francis’ cathedral: plan and diagram illustrate the collapsed zone

Computer modelling programs play a role in understanding structural behaviour during seismic action. For this reason, as mentioned before, 3D FE modelling is used to enhance the analytical investigation in the cathedral. This model gave clear results of the building vibration modes in the seismic situation. Also, it produced numerical results about the stresses and deformations which happened to the vaults in many cases with fill, without fill and the reinforced vaults, figure (4.53) (4.54).
The first intervention in the cathedral was done by adding a chain of steel trussed beams over the cornice, bracing the lateral walls of the upper Basilica by adding beams to work instead of the previous concrete reinforcement as well as connecting between the tympanum and roofs by steel beams. This traditional connection by tie bars is very stiff and potentially it is very dangerous to the roofs as well as the tympanum itself, figure (4.55).

Figure (4.53): St. Francis’ cathedral modelling: (left) One of the modes of vibration of the global model. (Right) Stresses and deformation of the vault with fill. (Croci 1998)

Figure (4.54): St. Francis’ cathedral modelling: (left) Stresses and deformation in the vaults without fill. (Right) Stresses and deformation in the reinforced vaults (Croci 1998)

Figure (4.55): St. Francis’ cathedral: the first intervention by adding metal beams
Steel works continued in the building by horizontally inserting a steel girder above the trussed ribbing and along the Basilica walls between the transept and apse. These steel beams were divided into portions according to the bays and connected stiffly by a couple of STUs behind the pillars to guarantee good behaviour during seismic activity, figure (4.56) (4.57).

Figure (4.56): St. Francis’ cathedral: plan illustrates the steel works system

A new concrete truss was built with the aim of disconnecting the roof structure from the tympanum wall. The main function of the truss was to support the roof beams and transfer the roof loads directly to the transept’s lateral walls. It was connected to the tympanum walls by SMADs spaced 50cm apart.

Figure (4.57): St. Francis’ cathedral: connecting the steel work parts by a couple of STUs.

The main repair work to the vaults, which came after many experiments, was in using composite materials to establish thin ribs following the Gothic vaults extrados pattern and maintaining the original structure visible from the interior. These ribs were manufactured from aramid fibers, light and very strong and less stiff than steel, bedded in epoxy resins around a central timber nucleus, figure (4.58).
They were located on the vault’s surface according to the deformation line with a constant width. The ribs are connected to a system of tie bars, which are anchored to the roof, figure (4.59).

The last stage of vault and structure reinforcement was using a mortar salt-free injection with the frescoes, sufficiently fluid to penetrate and diffuse to all the cracks and microcracks, capable of being injected into dry masonry without using any water. As a result, the structure
had a good level of strength and bond capacity to be continued in use and avoid any danger from the crack as well as during seismic action, figure (4.60).

Figure (4.60): St. Francis’ cathedral: the injection technique using in the later repair work

4.5 Reconstruction

4.5.1 Soissons Cathedral, France

This Gothic cathedral is located in Soissons, France and its construction began in circa 1180. The cathedral was completed in 1479 and nothing happened there until 1799 when the first restoration was started. The successful restoration improved the cathedral’s external and internal elements. This situation did not continue for very long because of the explosion which happened in the two nearby powder factories, which destroyed some of the cathedral’s windows and affected its external buttresses. Therefore, in 1840, Edouard Corroyer supervised new restoration to the damaged elements, including the south transept buttresses. The desire to imitate the architectural design of Notre Dame Cathedral in Paris encouraged the designer to build the Soissons cathedral tower, figure (4.61) (4.62).

Figure (4.61): Soissons Cathedral: the plan illustrates the main repair works location
The First World War caused extensive damage to the cathedral due to the German bombardments which continued for several years. The tower’s upper section and the nave’s first three bays are the main damage which occurred to the building at that time. Consequently, very successful restoration was carried out by Emile Brunet, architect of Historic Monuments, between 1928 and 1937 using advanced methods in historical building reconstruction to restore the tower and nave, figure (4.63).
The main vault types in the cathedral are as follows, figure (4.64):

- Rectangular ribbed vaults pointed arches
- The main rectangular vault at the crossing area
- Hemicycle ribbed vault at the east end with eight ribs
- Hemicycle ribbed vault at the south arm with six ribs (south transept).

The main technique used to reconstruct the broken vaults is centring the wooden framework which is used to accommodate the ribs and which is the first step in reconstruction figure (4.65) (4.66). After that, lighter stones were placed between the ribs over the removable wooden form and covered with a thin layer of concrete. The main function of the ribs is to enhance the role of the concrete in holding the vaulted stone together. As a result of this reconstruction, lighter vaults were established and no more pressure produced against the wall and buttresses. Consequently, this technique provides the reconstruction
field with new advantages where the walls become thinner, taller and have more space for windows and as a result more flexibility was added to the architectural aspects and designs.

4.6 Repointing and Durability

4.6.1 St. Giles Cathedral

St. Giles cathedral was the first cathedral in the royal burgh and was built in 1120 on the same site of the oldest one which had been built in 845. For this reason, the history of the site goes back to the 9th century in the same use as a religious building. The 12th century building was burnt down by the English during the second invasion in 1385. Immediately after the disaster, over the 150 years the cathedral witnessed a lot of repair and reconstruction works and became the most important cathedral in Edinburgh, especially after achieving independence from St. Andrews’s Bishop Jurisdiction, which placed the cathedral directly under the Pope’s control in 1470, figure (4.67).
The building contains three main types of ribbed vaults which are, figure (4.68) (4.69):

- Rectangular ribbed vaults with pointed arches located at most cathedral aisles.
- The main ribbed vault at the crossing area
- Tierceron ribbed vaults with pointed arches

Many repair and restoration works happened to the cathedral during the period from 1500 until 1830 where the most important restoration had been carried out by Burn. During Burn’s restoration, a lot of noticeable alterations were made to the building’s elements. As for the roofs, the whole building was re-roofed after heightening the central nave aisle.

The first condition survey for the roofs was carried out in 1978 in order to record the vaults, discover the problems as well as estimate the whole building’s volume, which is very important in order to estimate the loads on the columns. It was noticed that the shrunken mortar had some fine cracks which do not affect the roof structure but only the appearance of the roof and vaults. Also, some discontinuities in the ribs’ curved profiles which were caused by incorrect construction were noticed. This survey was the fundamental report which guided the later conservation works on the roofs.

The major repair works were done by repointing the stone vaults using lime mortar and some stone replacement work where necessary. The traditional lime plaster work took place in the stone vault above the crossing area and the two southern aisles, figure (4.70) (4.71).
The different repair works affect the interior space of the cathedral because the roof surfaces now have different colours and sometimes the traditional stones appear nearby the lime-washed surfaces which strongly reduce the great significance of the elements there, figure (4.72).

Figure (4.70): St. Giles Cathedral: the repointed vaults

Figure (4.71): St. Giles Cathedral: the plaster works in the crossing area

Figure (4.72): St. Giles Cathedral: the effects of different materials and colours on the interior space of the cathedral
4.6.2 Linlithgow Palace

The ruins of Linlithgow Palace are situated in the town of Linlithgow, West Lothian, Scotland, 15 miles (24 km) west of Edinburgh. The palace was one of the principal residences of the monarchs of Scotland in the 15th and 16th centuries. Although maintained after Scotland’s monarchs left for England in 1603, the palace was little used, and was burned out in 1746. It is now a visitor attraction in the care of Historic Scotland, figure (4.73).

The palace contains three main vaults which are, figure (4.74):

- Ribbed vault covering the Corner of the North Range
- Barrel vault covering the wedding venue
- The remainder of the barrel vault inside the Great Hall

The palace did not undergo major repair works to the roofs. Only the repainting the roofs of wedding hall, north Range and some rooms in the ground floor in order to keep them stable, preserve them from deformation and accommodate some necessary functions inside them.
5 Main Case Study - Rosslyn Chapel

5.1 Historical Background

Rosslyn chapel, a collegiate chapel, figure (5.1), was built in 1446 by Sir William Sinclair, Earl of Orkney, on a high bank. The location is very close to the castle and overlooks the valley of the river Esk. The construction of this building was delayed from the expected time because of the financial problems which Sir William Sinclair suffered between 1450 and 1460 and continued until 1470 when he lost the majority of his earldom. After the death of Sir William, his son continued the work there by adding a stone vault to the choir vault, but he could not complete his father’s design. The last three decades of the 16th century had many effects on the building’s history, where the provost and prebendaries in 1571 followed the violent confiscation to resign their endowments. Also, in 1592, the altars of Rosslyn chapel were destroyed due to the threat of excommunication which the family was exposed to if the altars stayed standing. The most critical period for the chapel was in the 17th century when the mob spread over Scotland, especially Edinburgh. The chapel was ransacked and ornaments were destroyed without any consideration for their value.

Figure (5.1): Rosslyn Chapel: General view.

5.2 Building Description

The collegiate chapel, figure (5.2), consists of three main parts which date back to different periods. These are the entrance, the main chapel and the sacristy. As for the entrance, it is the newest part in the chapel added in the west end part with two levels. The main chapel consists of the nave, three transepts around the nave as well as the Lady Chapel. All parts are roofed by stone vaults but of different types. The third part, the sacristy, is a long rectangle covered with a

Figure (5.2): Rosslyn Chapel: the chapel’s plan illustrates the main repair work location.
circular barrel vault and located at the south eastern part at a lower level than the two other parts, and can be reached by a stair. The whole building is provided with another two lateral entrances led into the south and north transepts with a segmental arch thrown over each door between buttresses. Flying buttresses were added to the building from three sides - north, east and south - in addition to the main solid wall at the western façade which was considered as the main elevation before adding the new entrance, figure (5.3).

The interior of the chapel is characterized by rich ornamentation where roofs, beams, piers and pillars were carefully carved, especially the pillars located at the east part known as the Apprentice’s Pillar, which is wreathed with ascending spirals of foliage and the Master’s pillar, which has different carvings from the previous one. Also, the vaults of Lady Chapel and the props of the three transepts and the nave are considered the most beautiful ornamented vaults in Scotland, figure (5.4).
5.3 Vault Types

In general, the whole chapel is roofed by stone roofs except the main entrance, which was added later. The stone-roof vault types in the cathedral are as follows, figure (5.5) (5.6):

- Carved barrel vault with pointed arches as a ribs over the main choir (the nave)
- Simple barrel vaults with pointed arches over the three transepts around the nave
- The most carved and ornamented ribbed vaults over the four bays forming the Lady Chapel
- Simple circular barrel vaults over the sacristy

Figure (5.5): Rosslyn Chapel: vault types: (left) carved barrel vaults over the nave. (Right) simple barrel vaults over the aisles.

Figure (5.6): Rosslyn Chapel: vault types: (left) carved ribbed vaults over the Lady’s Chapel. (Right) circular barrel vaults over the sacristy.
5.4 Chronological Sequence of Repair Works and Techniques

During the 18th century, Sir John Clerk encouraged General Sinclair to repair the chapel and promoted its preservation. As a result, General Sinclair carried out the repair work between 1738 and 1742, depending on John Baxter as an architect and carpenter. The repair works concluded by adding a new high sloping roof to the building. This roof was removed in 1770 by the architect William Burn, who was asked by Sir James Alexander Sinclair to return the original appearance and plane of the roof. These developments led to the rededication of the chapel by the Bishop of Edinburgh in 1861. There is no further documentation in the chapel’s preservation history until 1950, when the Ministry of Works undertook major repair work in the chapel. The preservation works undertaken touched all parts of the building, improved the heating system as well as undertaking extensive work on the ornamentation. Moreover, the roof was covered with a thick coating of asphalt in order to stop it leaking. Over time, the crack allowed more water to be let in, and the problem came back again to the barrel vaults. In 1997, a new conservation plan was started by Simpson and Brown architects when the damp problem strongly affected the structural elements, especially the barrel roof as well as the buttresses. Therefore, a new metal structure, a canopy, was erected over the whole building aiming to dry out the roofs naturally, figure (5.7). This idea gives the chapel more importance and it was considered as the finest example of Scottish architecture.

The canopy gave an opportunity to make a detailed survey for the elements without any external weathering effects. After that, the first step of the conservation process was begun by removing the asphaltic layer, figure (5.8), and there were many options suggested for the removal and, after that, protection. Finally, after suggesting five options, the conservators agreed on the last option. This option encouraged the removal of the asphaltic layer by hand without any mechanical tools and then adding a protective layer over the barrel vaults suitable for resisting weathering effects.
as well as in keeping with the historical appearance of the building. The repair process depended on the following outline specification:

- Remove the existing covering coats using manual tools without any force to ensure the integrity of the stone works as well as the roof structure. Then, use lime-based materials to cover and repair the joint between stones after a careful inspection had been carried out by the architects, engineers and stone conservators, figure (5.9).

![Figure (5.9): Rosslyn Chapel: removing the asphalt covering using simple hand tools, without disruption to the stones below. The stone surface was found to be in good condition but requiring 100% renewal of lime-based mortar pointing between joints.](image)

- Install a wooden frame over the stone works which consist of pre-curved timber straps fixed to the joints between stonework and 50 mm high performance rigid insulation boards between the straps. Also, fix new straps laterally across the timber straps to create the opportunity for cross-ventilation.

- Install a leadwork over the whole roof surface, as a waterproof structure for the outer surface, with careful attention to the appropriateness of the historical context of the building as it was recommended in order to reduce the visual impact of the leadwork detailing. This leadwork was fixed over the existing raggle line without more stone cutting. It is noticed that the leadwork formed a continuous ridge and ventilation slots with insect mesh with the aim of avoiding the mid-roof vents, figure (5.10).

![Figure (5.10): Rosslyn Chapel: detailed section illustrates the layers and the technique of the suggested covering leadwork](image)
After finishing all works on the roof, the canopy was removed one year ago and the building returned to be obviously visible with no more effects on its historical appearance.

In March 2009, thermo-graphic Scanning, works by detecting the infrared radiation, was carried out inside the chapel to locate areas where the stone is particularly damp. These are the red area in the images, Figure (5.11). This scanning helped the specialists to locate the dampness through leaks and condensation. Also, the scan can detect the structural decay of materials, identify voids and locate air leaks.

As for the buttresses, the weathering problems had affected them and a lot of damage had occurred. Therefore, the engineers carried out a conditional survey for them in order to find out the whole effects of weathering on the buttresses’ structure and appearance, also whether there is any additional effect on the vaults. As a result of the survey, it was obviously found that there is no structural function for the buttresses. They are only decorative elements and it is possible that they were built as an imitation of the types of cathedrals and churches to be found around Scotland. Also, the engineers found out the strong effects of the weathering factors on the buttresses, figure (5.12).
5.5 The Effects of Repair Works on The Roof’s Characteristics

Comparing the roof’s appearance in 1996 and 2008, we can clearly notice that the ceiling has dried out and most of the mould has disappeared. This result was achieved using a natural drying technique and manual conservation works, figure (5.13).

Figure (5.13): Rosslyn Chapel: the effect of natural drying on the roofs between 1996 and 2008. The most of the mould has disappeared
(Left) the vault in 1998
(Right) the vault in 2008

Thus, there are no effects on the interior appearance of the roof. The exterior surface was covered with leadwork, which is slightly different from the historical fabric of the building, despite the fact that the architects put all their efforts into lessening the impact of the new added materials. In general, the building was successfully conserved and the historical appearance was returned approximately to what it was in the past, figure (5.14).

Figure (5.14): Rosslyn Chapel: general view shows the covering layer of leadwork
6 Findings and Recommendations

- Gothic architecture introduced to the roofing systems many structural elements and features in solid stonework during its development time.
- The traditional repair methods were successful in maintaining the historical building roofs, but they could not consider the extra loads that could be applied to the structure elements and the limited ability to resist the loads. That was because of using their short experience in estimating the whole loads as well as solving the problems with extra safety margins than it is actually needed. Thus, the piers and pillars section sometimes extended to adopt with new structural loads.
- Buttressing concept has wide positive effects in Gothic architecture. These effects divide between the great function in stabilizing the building and the very elegant external appearance added to the building. Also, Gothic architecture developed the buttresses types and produced the most elegant types noticed in almost historical cathedrals all over the world.
- Computer program applications are very useful in understanding the roof’s problems, identifying the main deformation and defining the causes. Therefore, the repair works became more specific and deal with the exact problem.
- New materials and techniques that appeared in the conservation field, help in increasing the strength of structural elements and invent new methods to deal with different damages as well as roof reconstruction.
- New restoration methods are very necessary as they proved to save time and but they are not always less expensive than the traditional methods.
- Understanding the geometry and performance of a stone roof is key in determining the type of repair work, materials as well as the techniques which help in avoiding the failure.
- It is not advised to use the cement mortar in conservation process, because of its hardness which affect the long-term durability of stone along its edges. The most useful alternative is the lime mortar which has proved its good properties and great ability to provide very cohesive and durable bond between the stones, but its long setting times must be considered.
- It is crucial to take into consideration the type of material used in repairing the historical building, which should be compatible with the building fabric and the context. Thus, it can lessen, as much as possible, the adverse impact in the historical
building as a result of introducing new materials and techniques during the conservation process.

- Reconstruction works provide the conservation field with new lighter vaults concept. These vaults lessen the pressure produced against the wall and buttresses as well as contribute to more flexible designs due to the thinner walls could be used.

- Using the injection with mortar is very successful solution to get rid of any possible danger from either the cracks or micro cracks. This solution provides the building with strong bonds and allows completing its function without any problems.
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