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SAFETY ASSESSMENT OF THE SOUTH OCULUS, CANTERBURY CATHEDRAL (UK)

Paulo B. Lourenço [1], *Marios Filippoupoliti* [2] , *Claudio Corallo* [3], *Nuno Mendes* [4]

ABSTRACT

The South Oculus at Canterbury Cathedral is a wrought iron space frame consisting of two layers (Ferramenta and Grille) connected by tie bars (Pins). It is in very good condition despite its almost 850 years of history. The in situ survey of the Cathedral confirmed that the Ferramenta and the external grille are in general in relative good condition with the exception of some local failures. On the contrary, the pins are the most deteriorated part of the structure. Ambient vibration tests were carried out and the modal response of the structure was identified. In order to assess the safety of the oculus with respect to wind load, a model of the structure was built with the finite element software DIANA and calibrated using the results of the experimental campaign. The non-linear analysis of the existing structure resulted in a safety factor of about ten for the wind load. In addition, parametric studies have highlighted the importance of the external grille for the structure and have provided information of the consequences of further deterioration in terms of the load bearing capacity of the Oculus.

Keywords: *Modal identification, Non-linear analysis, Safety assessment*

1. INTRODUCTION

Oculi are large Romanesque circular windows that are divided into segments by iron armatures and not by stone tracery as happens with the rose windows which replaced the oculi after the mid-13th century [1]. Canterbury Cathedral has two Oculi, one in each of the two transepts. The South Oculus is a wrought iron space frame structure, built between 1178 and 1180. It consists of two layers, one internal (Ferramenta) and one external (Grille), which are connected by small iron ties, the Pins.

The early date of construction, the large scale (4.47m in diameter) and the design of the Ferramenta make it a unique structure. Its construction was so effective that the structure has survived over 800 years exposed to the elements, together with the near collapse of the south gable, bombing, etc.

The Oculus is in very good condition, considering its age, even if it has experienced some decay and localized damage. The aim of this paper is to assess the safety of the South Oculus with respect to wind load and to investigate the influence that deterioration and the Grille have in its load bearing capacity.

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[1] Professor, ISISE, University of Minho, Department of Civil Engineering, pbl@civil.uminho.pt
[2] MSc Student, ISISE, University of Minho, Dep. of Civil Engineering, marios.filippoupolitis@gmail.com
[3] MSc, The Morton Partnership, Claudio.Corallo@themortonpartnership.co.uk
[4] PhD Student, ISISE, University of Minho, Dep. of Civil Engineering, nunomendes@civil.uminho.pt

2. CANTERBURY CATHEDRAL AND THE OCULUS IN THE SOUTH TRANSEPT

2.1. Review of the history of the Canterbury Cathedral

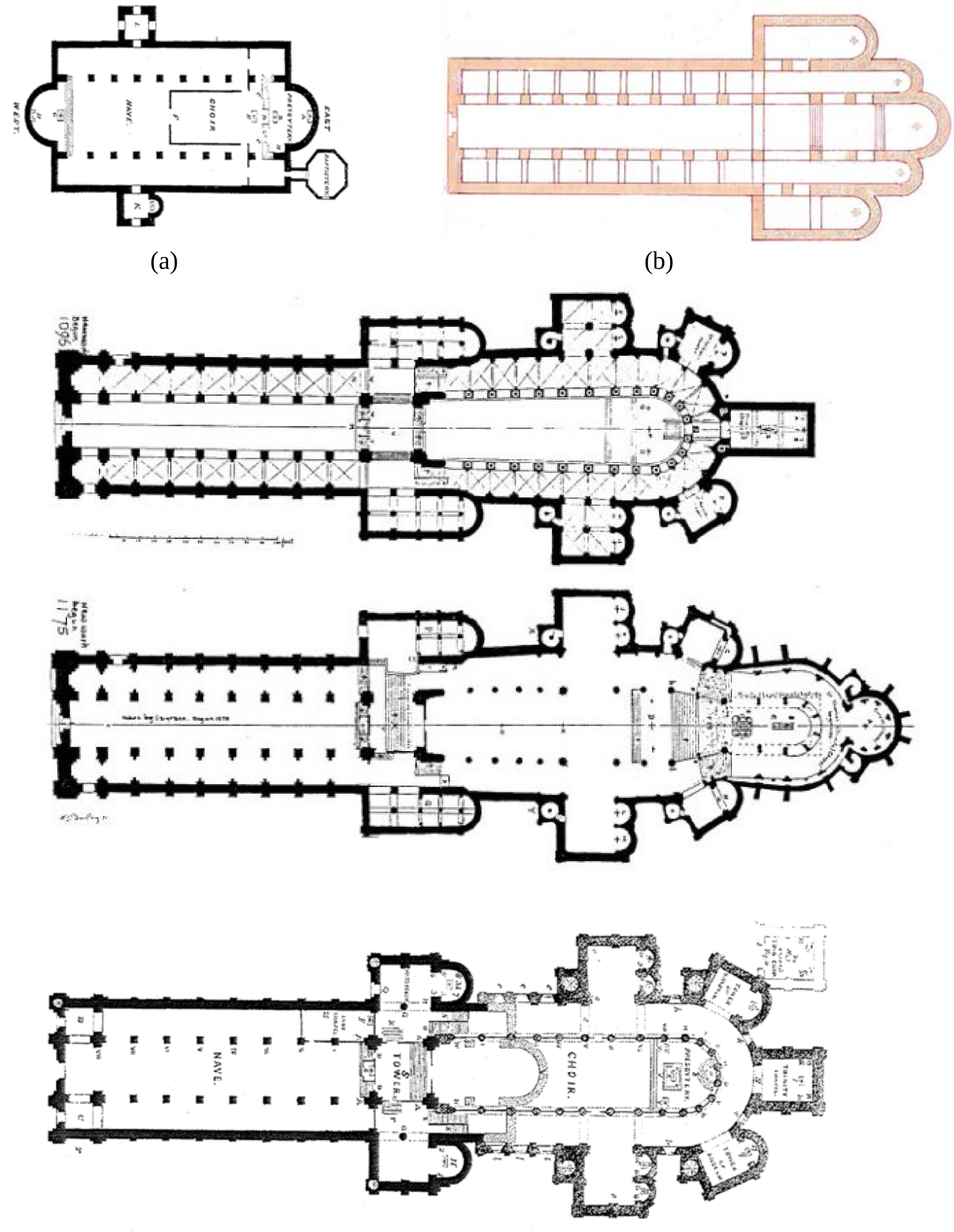
St Augustine, the first Archbishop of Canterbury, arrived as a missionary to England in 597 AD and established the first Cathedral [2]. Until 1070, the construction history of the Cathedral probably consists of four phases, see Fig. 1a: (a) The early church with an apsidal chancel and a simple nave, gradually surrounded on the west, north and south sides by porches; (b) A baptistery church laid within 0.50 m of the southeast corner of the nave, extended in subsequent periods; (c) A massive enlargement in the tenth century involving strengthening of the foundations and incorporating the porches into side-aisles; (d) A final westward extension, and the rebuilding of the west end of the Cathedral, adding a large western apse and towers. The church and most of the monastic buildings were destroyed by a great fire on 6 December 1067. Until 1077, Archbishop Lanfranc rebuilt the Cathedral as a Norman church, see Fig. 1b. The tower was placed at the centre of the church, raised upon four large pillars. On the west of the tower is the nave of the church supported on both sides upon eight pillars and ended by two towers. On the left and right of the central tower, the two transepts of the Cathedral can be found. In the middle of each transept a pillar sustains a vault.

After the death of Lanfranc (1089), Canterbury was without an Archbishop for five years and Anselm was consecrated on 4 December 1093. In 1096, Archbishop Anselm started the reconstruction of Lanfranc’s choir. The new building entirely replaced Lanfranc’s choir and crypt. Whereas Lanfranc’s choir had extended some 21 m east of the crossing, the new choir ran 58 m east, with commensurate extension to the north and to the south. Because of the huge dimensions of the new choir, it was required not only to extent the crypt eastward but to reconstruct it totally. This is the vaulted crypt that exists today. The reconstruction work finished on 1130, see Fig. 1c. The choir of Archbishop Anselm was again destroyed by a fire in 1174 and in the following years William of Sens begun building a third choir. Triforium and clerestory levels were constructed in order to relief the older masonry from the loads of the vaulted stone roof. The new choir had the proportions of the previous one, with the new architecture of the thirteen century. On 1378, Archbishop Sudbury pulled down Lanfranc’s nave, intending to rebuild it, but was prevented by his death in 1381. The nave was reconstructed by the Prior Thomas Chillenden (1390 -1411) who gave to the nave the style of English Gothic that exists today. In 1498, the Bell Harry Tower (the tower between the nave and the choir) was extended and the Cathedral was largely complete as seen today. Finally, the original Norman northwest tower was demolished in the late 18th century due to structural concerns. It was replaced during the 1830’s with a twin of the southwest tower, currently known as the 'Arundel Tower'. This was the last major structural alteration to be made to the Cathedral, see Fig. 2.

2.2. Recent conservation works

The walls of the Canterbury Cathedral are made of three leaf masonry, made of Caen stone and bond together with long through stones. The intervening gap between these two masonry leaves is filled with a mixture of lime mortar and small fragments of rubble [3]. The large bombing during the Second World War is said to have had the effect of separating the outer layer of the masonry from the wall. This damage could be dangerous for the stability of the building and could be become larger by rain and freezing temperatures [3]. In order to restore the initial condition of the masonry, Harold Anderson (Surveyor to the Fabric from 1946 to 1968) inserted a strong Portland cement grout into the masonry for reinstating the integrity of the wall and increasing its strength. Unfortunately, the use of Portland cement had negative consequences for the soft limestone of the masonry by accelerating its decay at the areas where it was used. Anderson also used Bath stone to repair the masonry of Bell Harry Tower.

In 1968, Peter Marsh became Surveyor to the Fabric and tried to use again stone imported from northern France but it was impossible to obtain Caen stone in the desired quantity or quality since the end of the 19th century. He found another high quality limestone from the southwest of France, known as Lepine, and undertook the following projects: (a) Rebuilding the gable of the southwest transept. A reinforced concrete cantilever beam was used to tie the weight of the gable back into the main structure of the building; (b) Conservation of the south window's glass. The glass was put back into the cathedral in specially made brass frames with a layer of protective glazing on the outside; (c) Large scale repair works at the west end of the cathedral. Rebuilding the oculus and gable and stone replacements at the southwest and northwest towers.



(a) (b)

(c)

Fig. 1 Plan evolution of the Cathedral: (a) The Anglo-Saxon phases; (b) Archbishop Lanfranc; (c) Different versions of choir additions (1096, 1175 and 1411)


(a) (b)

Fig. 2 Images of the cathedral: (a) The last important change (1830); (b) the Cathedral as it is today

In 1991, John Burton became the new Surveyor of the Fabric and his most important projects were: (a) Re-flooring of the Cathedral nave and southwest transept. A new Portland concrete slab floor was laid on a lime screed over an under floor heating system; (b) A cleaning program was applied to the original parts of the cathedral in order to remove the dark crust that increases the stone's decay and change its colour; (c) An environmental monitoring system was installed into Canterbury cathedral to monitor temperature, relative humidity and movements; (d) He found a small quarry near the French city Caen where the extraction of the "Caen - type" limestone had been re-established. The first new Caen stone block was fixed into reconstructed pinnacles on top of the corona chapel in 2009.

2.3. The South oculus

Canterbury Cathedral has two ocular windows, called as "eyes", set in the north and south façades of the transepts, see Fig. 3. The oculi are large Romanesque circular windows divided into segments by iron armatures and not by stone tracery, as happens with rose windows. These oculi are unique due to the early date, large size and the design of the Ferrament. Both oculi of the cathedral are decorated with stained glass panels.

The South Oculus is a space frame made from wrought iron which was built between 1178 and 1180. Despite its age, the iron of the Oculus is in remarkably good condition. The south oculus consists of one internal and one external layer. The internal layer is called Ferramenta and includes all the ironwork required to hold the window in place. The armature is the iron frame required to support the glass, with rectangular cross-section bars joined together with neat mortise joints, see Fig. 4a. On the inside of the armature bars, lugs project so that the glass can be pinned in place – and easily removed – with simple wedges, see Fig. 4b. The external layer, or Grille, consists of vertical and horizontal bars of round section which create an iron grille. The vertical bars are widening at regular intervals so the horizontal bars can pass through them, see Fig. 4c. The horizontal bars are restrained at the intersection with the vertical bars by copper wedges. The joint is then sealed with lead putty, Fig. 4d. The two iron layers of the Oculus are connected to each other by many iron rods, the pins, Fig. 4e. The end of the pin connected to the grille has the form of a circular eye and is fixed to the bars by using copper wedges. Also in this case the joint is sealed with lead putty. The other end of the pin passes through a hole in the armature and then is hammered flat, like a cold rivet [1]. The length of these metal rods varies between 130 and 150 mm, which is also the distance between the two layers of the space frame. The space frame is fixed into the masonry as shown in Fig. 4f. The two-layer structural system of the South Oculus is probably original (around 1180), as scars on the outside of the North Oculus Ferramenta roughly correspond with the rod attachments on the South Oculus, indicating that a similar reinforcement was originally in place on the north side.


(a) (b)

Fig. 3 Images of the oculi: (a) South (before conservation); (b) North (after conservation)

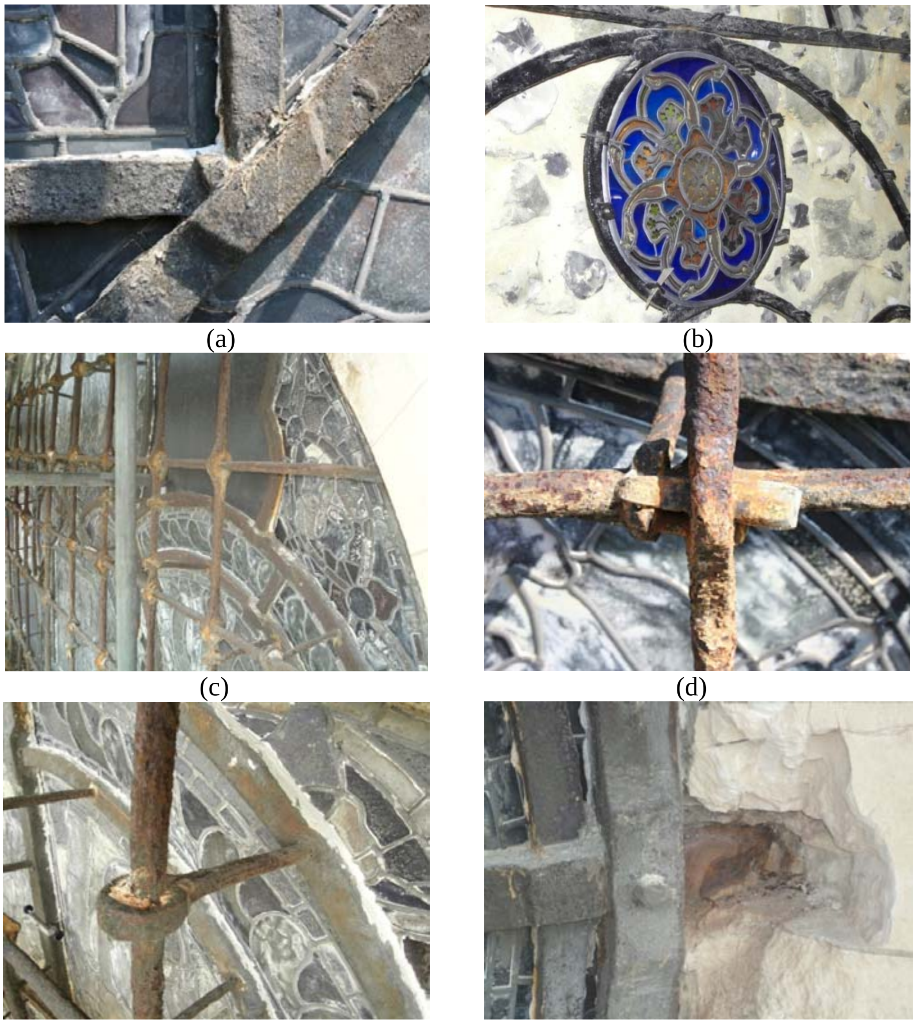

(a) (b) (c) (d) (e) (f)

Fig. 4 Details of the ironwork: (a) Joint detail of the armatures; (b) System for holding the stained glass on the armatures (another window is shown); (c) Iron grille with round bars; (d) Copper wedge in the connections of the grille; (e) Iron pin connecting the two layers, (f) Fixing of the space frame into the masonry

3. INSPECTION

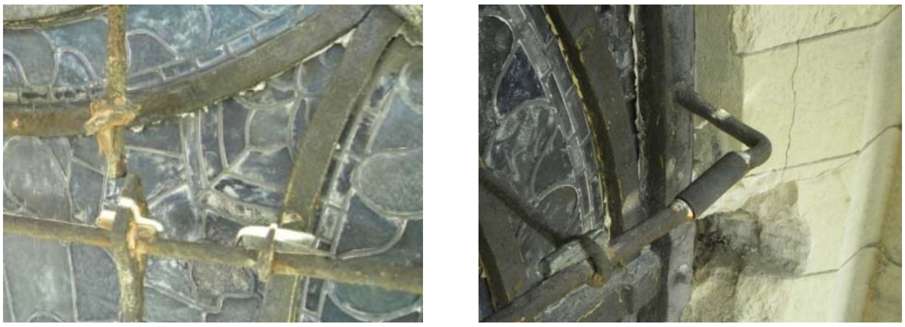
3.1. Visual inspection and geometrical survey

In general, the Ferramenta members were in very good condition despite their 850 years age, as no remarkable change in their initial shape was noticed and damage was limited. Except for one broken section, Fig. 5a, no damage was noticed in the Ferramenta members. There are a number of old repairs but they do not seem to affect the stability of the structure, see Fig. 5b. There is a coating of stabilized corrosion products on the iron's surface and the connections are in very good condition. The sections of the Ferramenta members are of rectangular shape in the range of 3 to 8 cm and were measured using a digital calliper, see [4] for details.

(a) (b)

Fig. 5 Visual inspection of the Ferramenta: (a) Broken section; (b) Old repair

The Grille is more damaged and deformed, without a regular spacing of bars. The third vertical grille bar from the left is broken, see Fig. 6a, whereas some bars were repaired by using tubular sections, see Fig. 6b. These repairs should be removed as they are promoting galvanic corrosion to the iron grille [5]. The shape of the bars is not perfectly circular and the sections of the grille bars were again measured in two orthogonal axes. The average diameter is 24 mm [4].



(a) (b)

Fig. 6 Visual inspection of the Grill: (a) Broken section; (b) Old repair

The majority of the pins connecting the Ferramenta and Grille have a similar shape, with the exception of existing hardly deteriorated pins and pins that were replaced in the past, Fig. 7. The pins are the most deteriorated part of the structure, with a serious reduction of their cross section near the connection with the Ferramenta in most pins. Scars on the Ferramenta reveal that many of the original pins are missing from the structure. Furthermore, the "eye" of many pins is destroyed, making them inactive. This is possibly due to the electrochemical reactions between the wrought iron pins and the wrought iron Grille and Ferramenta. The connections of the pins to the Ferramenta (cold rivets) are in good condition. All Grille - pin joints were inspected and two types of failure were identified, namely a damaged pin "eye" because of the deterioration and the loss of wedges and putty. Nine pins were considered inactive because of this damage, see Fig. 8a. The sections of the pins are not constant and the diameter of each pin was measured at three points along its axis (two ends and central section). Two measurements were taken at each point, one horizontal and one vertical, proving diameters between 9 and 21 mm [4]. Forty-five pin sections (out of total of seventy-one) were measured due to the time available to carry out the survey. According to the results obtained the pins were classified into two groups, Fig. 8b: (a) pins with a diameter greater than 15 mm at the Ferramenta connection, assumed with a constant section given by the average of the readings in the three pin sections; (b) for the other pins, the section is divided in one deteriorated part and a non-deteriorated part [4].

Finally, the connection between with the surrounding masonry revealed that the Oculus is connected into the masonry at 16 anchor points, basically the main diameters (4 points), the diagonals (4 points) and at the third-points between these diameters (8 points) [4]. In general, the masonry is in very good condition except the anchor point at three o'clock where stone detachment can be noticed.


(a) (b)

Fig. 7 Details of the pins: (a) Recent pint; (b) Original deteriorated pin

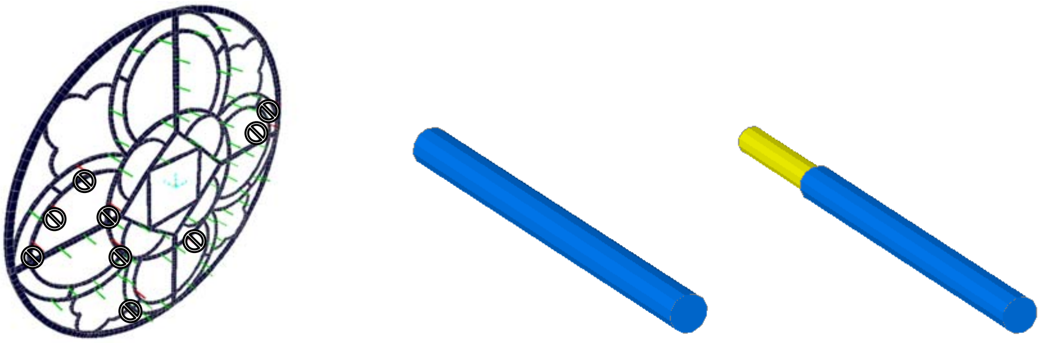
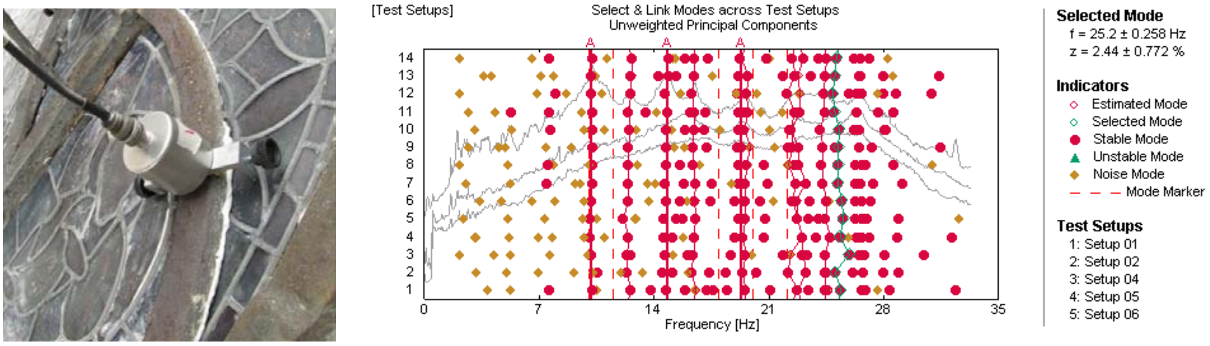

(a) (b)

Fig. 8 Details of the pins: (a) Inactive pins (forbidden sign); (b) Types of pin considered

3.2. Ambient vibration tests

Four piezoelectric accelerometers, with bandwidth ranging from 0.15 to 1000 Hz, dynamic range ± 0.5 g and a sensitivity of 10 V/g, connected to a data acquisition system with 24-bit resolution were used, together with ambient vibration. Eighteen points of the structure were selected for measuring. The accelerometers were fixed on the Ferramenta and Grille, see Fig. 9a, with different data sets (setups) and keeping two points as reference points. Fourteen sequential setups were used, with a sampling frequency of 200 Hz and a total sampling of 10 min. The Unweight Principal Component (UPC) technique, implemented in the software ARTeMIS Extractor Pro [6] was used to estimate the dynamic parameters. This technique operates in the time domain and is based on the Stochastic Sub-space Identification (SSI) method. The maximum amplitude of vibration was lower than 6 mg. Fig. 9b shows four stable modes in the frequency range under 17 Hz, while it is difficult to specify a stable mode over the frequency of 17 Hz. Still, overall, ten modes were estimated with experimental frequencies between 10 and 25 Hz [4]. The first six modes are global with a regular shape and have single or double curvature, while the shape of the higher modes is complex.



(a) (b)

Fig. 9 Modal identification: (a) Accelerometer applied to the Ferramenta; (b) Frequencies measured

4. STRUCTURAL ANALYSIS

4.1. Model updating

Six different models were built in the Finite Element Software, DIANA [7], and the results of the eigenvalue analysis were compared with the experimental data in order to achieve the most realistic finite element model. Different options for the geometry, joint connection and support conditions were tested [4]. Here, only the final model is reported. It includes the bar members of the Ferramenta, Pins and Grille meshed using three-node curved beam elements CL18B. The CL18B element is a three-node, three dimensional beam element based on the so-called Mindlin-Reissner theory which takes shear deformation into account. The model does not contain 2-D elements for the simulation of the stained glass. Springs were used to simulate the semi-rigid connection between Pins-Grille bars and Horizontal-Vertical Grille bars. It was assumed that the Oculus is fixed into the masonry wall at 16 points, with the translational and rotational degrees of freedom restrained. Different cross sections were used for the Ferramenta bars, Grille bars and pins according to the geometrical survey carried out, see Fig 10a for an example. The mechanical and physical properties of the wrought iron used in all the analysis models have been obtained from the literature [8].

The finite element mesh contains 2278 nodes and 1648 elements of which 381 are the spring elements that connect the pins-Grille bars and the horizontal-vertical Grille bars. The finite element model has a range of the first ten frequencies from 9 Hz to 29 Hz, which is close to the experimental range. For the first three frequencies the average error is 12%, with a Modal Assurance Criteria (MAC) value of 0.94, 0.66 and 0.61, see also Fig. 10b,c.

4.2. Safety assessment

The Oculus of Canterbury Cathedral was subsequently assessed with respect to the wind load. The results of the non-linear analysis were compared with the design values of the Eurocode 1 and the safety factor of the structure was calculated. Parametric studies were made in order to investigate the influence of the Grille, the damage and the future deterioration on the safety of the structure. The net wind pressure on the Oculus was calculated to be 1.19 kN/m^2. For the wrought iron, a linear elastic, perfectly plastic stress-strain relation was adopted with a yield value of 180 MPa, a lower end value from [8]. Fig. 11 presents the variation of the horizontal displacement of the central point of the Ferramenta, as function of the load factor. The structure enters into plasticity for load factor of 12.1, i.e. for a wind load equal to 12.1 kN/m^2. This value, compared with the characteristic value that EC1 proposes for the wind load, gives a safety factor of 10.2, which is rather large. Note that very large displacements are found at ultimate stage. Figure 12a presents the deformed mesh of the structure at failure. The red colour here corresponds to the sections were the yield strength is reached. Yielding appears in the Grille bars (vertical and horizontal) and also in the deteriorated part of some pins.

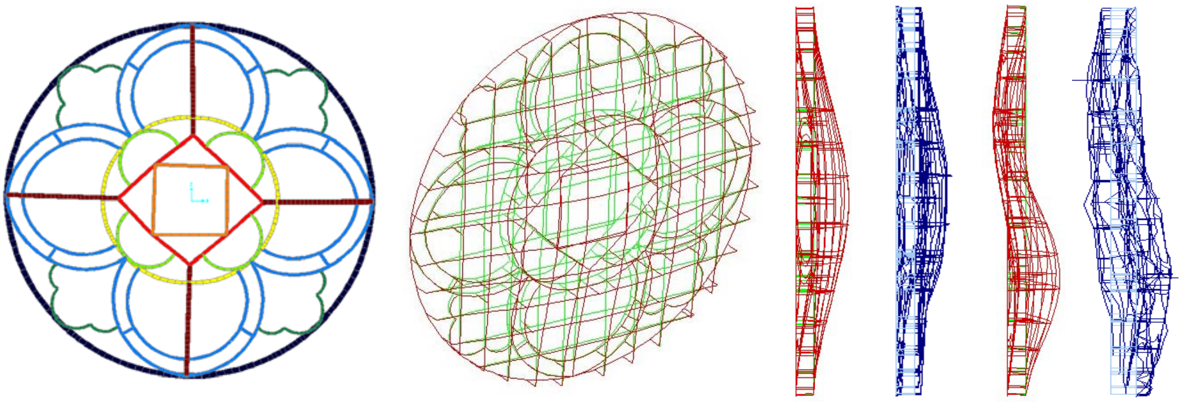

(a) (b) (c)

Fig. 10 Finite element model: (a) Different bar sections of Ferramenta; (b) First numerical mode; (c) First experimental vs. numerical modes, for single and double curvature

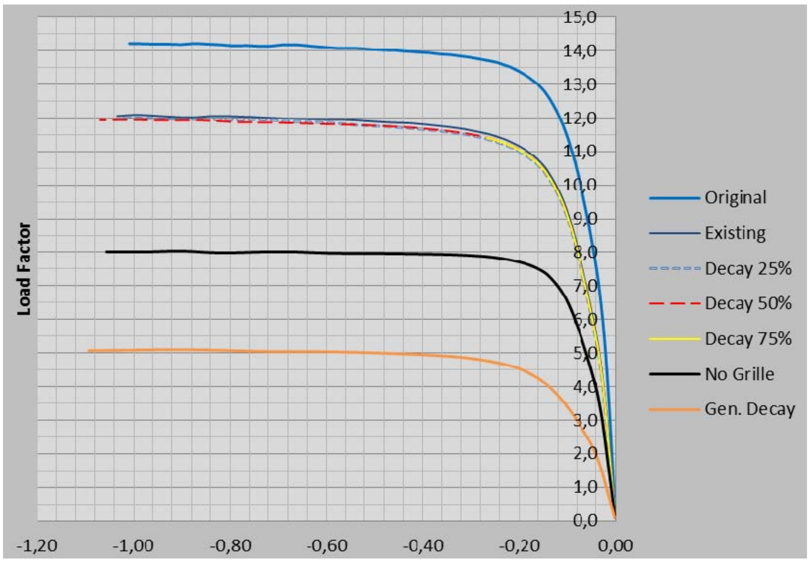


Fig. 11 Load-displacement diagrams for different simulations

Subsequently, a parametric analysis was carried out with different assumptions. Firstly, the “original” structure is considered as the structure just after its construction with no damage or deterioration. Fig. 11 shows that the load factor is now 14.2 (+17%), which indicates a moderate effect of deterioration. Secondly, the Grille and the pins were removed from the finite element model, in order to assess the behaviour of the existing Ferramenta only. The load factor is now 8.04 (–34%), which demonstrates the importance of the Grille for the safety of the structure. Thirdly, the influence of further decay of the condition of the structure is investigated, with a 50% reduction of the already deteriorated sections and 25% of the sections in good condition. The load factor is now 5.01 (–59%). The safety factor is moderate (4.2) but still above the value required by the codes. Finally, the assumption that decay will progress only to the parts of the structure that are already deteriorated was tested. Three cases were studied with 25, 50 and 75% reduction of the pins cross section respectively. It is observed that the deteriorated pins have minor influence on the safety of the structure.

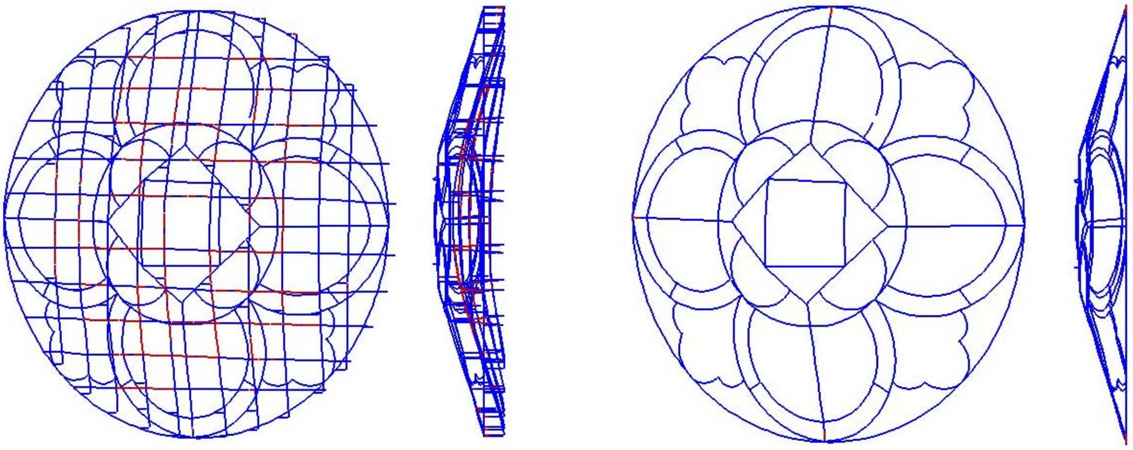

(a) (b)

Fig. 12 Failure modes: (a) Structure in present condition (red colour indicates yielding); (b) Ferramenta only

5. CONCLUSIONS

The conclusions arising from this work are as following: (a) The South Oculus is a wrought iron space frame, consisting of two layers and pins; (b) The internal Ferramenta and the external Grille are in good condition, whereas the pins partly are deteriorated, with breakage, replacement and reduction in cross-section; (c) The safety factor for the wind load in current condition is about ten and the deterioration affected the structure condition only marginally; (d) The Grille is important for the safety of the structure, since the safety factor is reduced by about one third if the grille is removed; (e) Severe further deterioration of the presently decayed parts would have very a small impact on the safety of the structure, given the redundancy of these.

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