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The application of free-form grid shells as protective shelters in archaeological sites

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Abstract

The challenge of preserving archaeological sites by the adoption of grid shells is investigated in this paper. Archaeological remains often require protection from external agents, especially environmental threats. In fact, when covered by soil, they are preserved effectively under certain equilibrium conditions. Nonetheless, when exposed to the outer environment they can easily deteriorate. Therefore, a shelter or enclosure may be provided for protection.

When a large area requires protection, steel structures such as portal frames or two-dimensional trusses are extensively employed. These have a heavyweight character and require deep foundations, the construction of which is substantially limited in archaeological sites, and increases the risk of damage during erection.

Through the development of an extensible free-form grid shell design with a minimum weight, maximum stiffness and constructability approach, the potential application of shelters for archaeological sites is evaluated. This study involves a parametric investigation and considers the worst-case scenario conditions.

Keywords: archaeological sites, conceptual design, dynamic relaxation method, free-form finding, genetic algorithm, optimisation, parametric modelling, steel grid shells

1. Introduction

Archaeological sites are locations with concentrations of remains such as artefacts or structures, which reflect past activity and, subsequently, may be of interest for archaeological studies.

As a result of the excavation, archaeological materials are uncovered after long periods of time in a particular physicochemical equilibrium state with soil which allowed their preservation. Hence, once exposed to new conditions of moisture and temperature, they are at risk of deterioration. In some occasions, the site might offer stable conditions and, therefore, intervention is minimum, yet in most cases, not implementing an appropriate conservation plan may lead to the loss of valuable cultural heritage. While archaeological excavations generally demand significant periods of time, the methods for conservation need to be rapidly determined to avoid the decay or collapse of the recently uncovered remains (Ertosun [3]).

The fundamental objective of a conservation plan is, therefore, to protect the heritage from loss and depletion. Typical protection techniques can be divided into two categories: ex-situ and in-situ. The former consists of transporting the artefacts into other installations, usually museums or workshops, where adequate environmental conditions are easily provided, yet decontextualizing the archaeological authenticity. On the other hand, it may not be possible to convey the materials. Therefore, in-situ methods are required. In some occasions, the remains may be directly altered through structural stabilisation or reassembly; therefore, it is often preferred to offer a cover. Some methods within this group include reburial, wall capping and flashings, fabric sheeting and shelters.

2. Analysis of the problem

2.1. Protective covers in archaeological sites

Protective shelters consist of roof structures placed immediately above the ruins and providing protection against sunlight, rain, snow and hail, amongst others. If an enclosure is implemented, protection against wind and dust may also be provided, as well as predetermined temperature and moisture conditions may be achieved through planned heating, ventilation and air conditioning. This is particularly advantageous for the control of condensation and the growth of vegetation, which is one of the most intricate threats in archaeological conservation. A protective cover must also be lightweight to avoid the implementation of heavy foundations and allow for the ease of construction. Small shallow foundations will minimise the chance to damage the archaeological material and will result rapid installation, which will reduce the exposure periods of the ruins after excavation. Moreover, they will maximise the flexibility of the structure in case of its modification or removal upon new future circumstances or needs.

Usually, it is hard to determine the limits of an archaeological site. Similarly, the unexcavated area that should be protected on a site, is equally hard to determine. Despite the existence of methods to determine whether an area has a potential archaeological value such as trial-trenching, assumptions still need to be made to carry out an excavation. As a result, excessively large or insufficiently short areas may be covered. Consequently, the ideal structure should be able to permit its removal or expansion and offer adaptability and flexibility.

Sustainability should also be promoted by the adoption of low-carbon materials and low energy-demanding construction techniques. It would be preferred, therefore, to use eco-friendly and recyclable materials such as steel rather than concrete or polycarbonate rather than glass. Controlled natural ventilation and lighting should also be encouraged to minimise energy consumption and, subsequently, achieve self-sufficient systems which can offer appropriate environmental conditions for the remains. In social and cultural terms, the structure should allow for future research and on-site examination, as well as visitation.

Removing, adding or modifying features within the archaeology extents may vary the perception of the site (Matero [7]). Besides offering protection against climatological threats and providing adequate and stable environmental conditions to minimise or stop deterioration, the cover should not interfere with the authenticity of the site or the perception of the features and its design must be explicit while in harmony with the site (Rizzi [11]). Therefore, apart from the functional and economic efficiency, the aesthetics and architecture of the solution play an important role in protecting archaeological sites.

2.2. Definition of the problem

Protective covers are often designed as temporary structures with small budgets and a little planning. This is due to the necessity to protect the recently excavated materials under the new environmental conditions. In addition, where an archaeological site is found to be largely valuable, pressures of economic benefits from tourism increase the need to prepare the site for development and visitation in shorter periods (Matero [7]), thus leading to inadequate decisions in the implementation of the solution as observed in Sapinuwa (Figure 1), Saint Nicholas Church (Figure 2) and Heraclea Minoa (Figure 3). These examples clearly fail to meet the important aesthetic constraints, while others, such as the large steel roof above the Akrotiri archaeological site in Santorini (Greece) which collapsed during regular maintenance operations in 2005 and caused the loss of a human life, can also fail mechanically as a result of rapid poor structural design.

Figure 1: A temporary structure becoming permanent in Sapinuwa, Ortaköy, Turkey (Ertosun [3])

Figure 2: Protective cover above Saint Nicholas Church, Demre, Turkey (Ertosun [3])

Figure 3: Before and after at Heraclea Minoa, Sicily (Ertosun [3])

Nevertheless, these structures often become permanent, even if they have been installed with a little planning and promoted as short-term solutions, and they will not be able to provide an effective nor efficient long-term protection. Taking this into account, the development of a generic solution, which can be applied effectively in a range of situations, seems timely. The objective of the current research study is to develop a conceptual design of a structure, which can immediately and efficiently offer all the requirements for a protective cover on an archaeological site in terms of function, aesthetics and cost, as it is summarized in Figure 4. Fostering, in particular, the economic factor that is minimum planning, minimum material usage and a simple erection process.

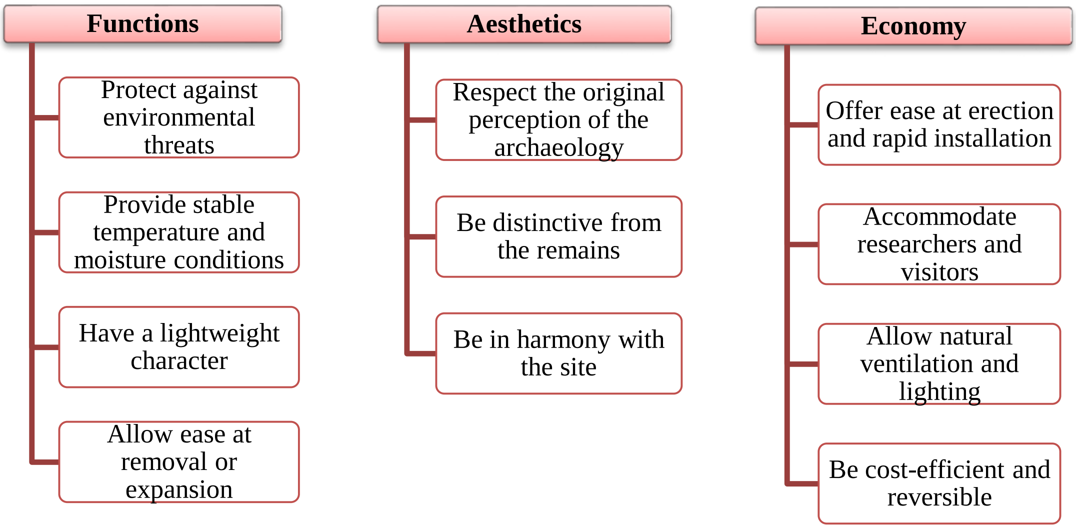

Figure 4: Summary of needs and requirements.

3. Grid shells as protection for archaeological sites

3.1. Theoretical overview

Given the characteristics that grid shells offer, their implementation seems to be an ideal solution for protecting archaeological sites. Next, the advantages and limitations are examined and a parametric study is carried out to develop a possible optimised solution.

3.1.1. Advantages

Lightweight, flexibility, reversibility and aesthetics are the main advantages offered by grid shells. Among those, weight is an obvious benefit. Portal frames, being the primary steel structural systems used nowadays as protection for archaeological sites, imply the installation of heavy concrete foundations. These limit the flexibility and reversibility of the solution and are more energy-demanding. The lightweight feature of grid shells also minimises the risk of damage during erection or in the case of the collapse of the structure under exceptional loads.

The existence of fully developed methods for the development of free-form surfaces which can adapt to a range of situations with infinite possibilities allows for the design of an optimum structure while only constrained by the support conditions. Also, the visibility of precise load paths and the presence of large openings, together with the lightness transmittance resulting from the transparency of the glazing, offer an architectural perception of openness, suitable for sites with architectural character. Moreover, the curvilinear shape that is mimicking natural forms induces tranquillity. The structure is modern and aesthetically pleasing, thus being easily differentiable from the actual archaeology but in visual harmony.

1.1.1.Limitations

Lattice shells are extremely lightweight structures, hence they are prone to uplift due to wind loading, especially in open sites. Usually, the solution to overcome wind uplift phenomena is to implement heavier foundations or piles to increase the vertical resistance by either gravity loading or shear. In archaeological sites, however, the installation of bulky foundations should be prevented, as well as that of piles. Moreover, as a result of the curved shape imitating arch behaviour, the structure often transmits not only vertical loads into the foundations but also horizontal. These can lead to overturning or sliding phenomena. While heavier or more extended foundations are often implemented in other applications to increase the shear resistance in pad foundations, only shallow foundations should be employed in archaeological sites.

One of the advantages is the design flexibility of the structure; adaptable to different support conditions and areas to cover as a consequence of the great range of methods to find free-forms. Nonetheless, these methods, while not complex, are not routinely studied. This results in steel framing systems being the most common construction technique nowadays. Subsequently, the cost of design is higher while there are fewer professionals specialised in the design of such unusual structural systems. Furthermore, unforeseen geometrical imperfections and eccentricities in the design or assembly can lead to loss of strength, thus unstable structures. As a result of the lightweight character, such structures are also prone to deformation and vibration due to live loads.

3.2. Parametric study and conceptual design

Since archaeological excavations are slow, protection needs to be provided rapidly. The budget is often limited, and large structures cannot be implemented at first, even if required by the extents of the archaeology. The solution to this problem can be tackled by the development of an extendable modular solution which is gradually implemented as the excavation evolves, as well as the turnover increases resulting from tourism or the augmented importance of the findings. The objective of the current work is to design three solutions which are multiples of a basic 20 m x 20 m module (Figure 5).

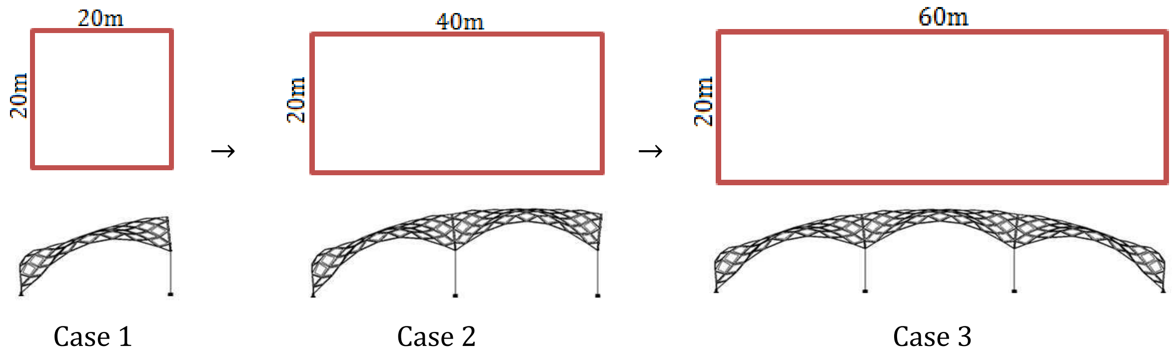

Figure 5: Cases 1, 2 and 3 of the modular solution.

3.2.1. Form-finding and structural optimisation

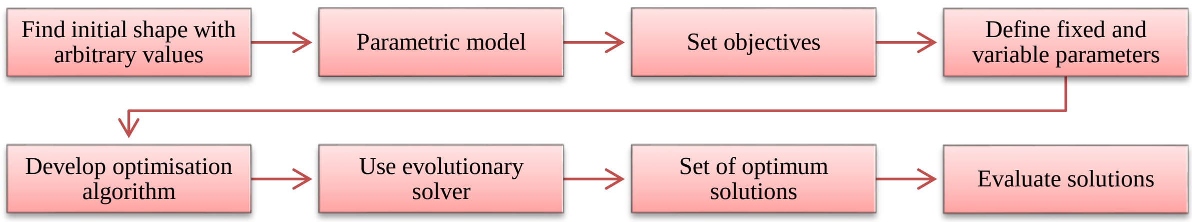

Figure 6: Form-finding and structural optimisation process.

The design process synthetised in Figure 6, consists of applying a free-form finding method in conjunction with an optimisation algorithm: the Dynamic Relaxation Method (DRM) with a Multi-Objective Genetic Algorithm (MOGA). Both processes are undertaken by the use of Grasshopper for Rhinoceros following the pattern presented in Figure 7. A set of optimum solutions is obtained, and their structural performance is evaluated.

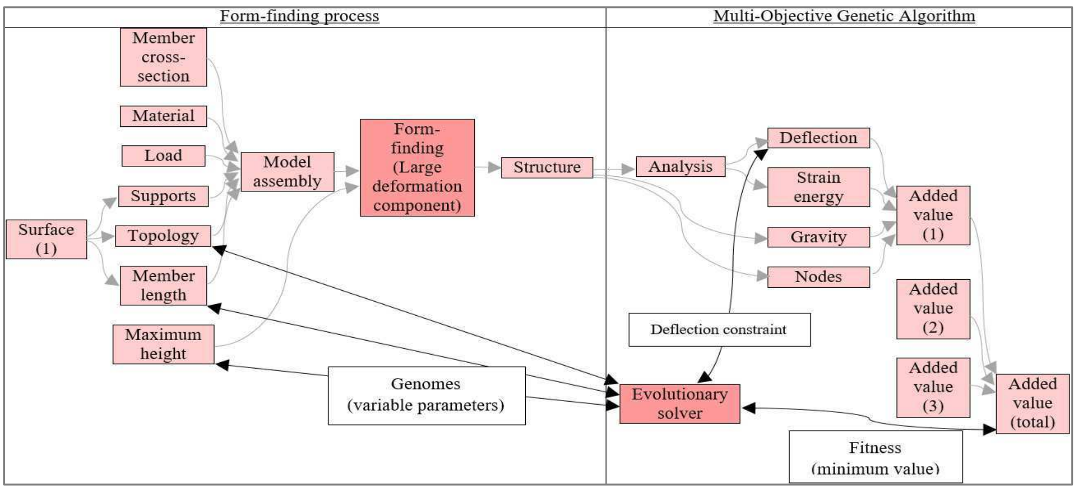

Figure 7: DRM and MOGA processes as followed in Grasshopper.

The objectives and constraints are consisted meeting the needs and requirements of protective covers for archaeological sites. For the MOGA, these can be reduced to cost and constructability. The curve continuity is required to ensure divisibility while maintaining shell behaviour, as well as for maximum stiffness. Thus, the objectives and constraints can be identified as presented in Tables 1 and 2.

Table 1: Constraints for MOGA.

Objectives	Range
Weight	Minimum
Nodes/members	Minimum
Strain energy	Minimum

Table 2: Constraints for MOGA.

Constraints	**Range**
Displacement	Meet SLS design
Shape	Continuity along longitudinal curve

The fixed parameters have been set according to standard practice procedures and as summarised in Table 3, and they are the material, cross-section typology, grid connectivity, support conditions and permanent loads. In the case of the member cross-section, an arbitrary value is employed throughout the process as the topology optimisation produces is much more efficient than the size optimisation (Liang et al. [6]), and the shape is to be found so that it will be virtually optimum (in compression).

The variable parameters considered are as follows: grid topology, member length, maximum height and covered area (Table 4). Regarding grid topology in particular, only typical geometries are considered for the ease of design and structural efficiency. The member length is determined with consideration of the glazing, the dimensions of which are limited to 3.21 m x 6 m – as described in Guidance for European Structural Design of Glass Components [5]. The maximum height of the structure is set within a range that ensures shell behaviour, and simultaneously, does not increases the use of material excessively. The height of the supporting columns is fixed equal to the maximum height of the shell structure. This allows avoiding large tension zones originate along the longitudinal edge curves because of larger convexities at the supports when the curvature of the central axis increases. Nevertheless, in a real case, the actual height of the supporting columns will only depend on the topography of the site. In the current study, the worst-case scenario is considered and large moments at the foundations occur.

Table 3: Fixed parameters.

Fixed	**Value**
Material	Steel grade S355
Element cross-section	Tubular section (CHS139.7x6.3)
Grid connectivity	Rigid
Support conditions	Pinned and fixed
Loads	Structure and glazing (20 mm thick glass) self-weight

Table 4: Variable parameters.

Variable	**Range**
Grid topology	*Squared*, diamond, *triangular, 'Union* Jack.'
Member length	1 to 3.2 metres
Maximum height	4 to 8 metres
Covered area	20x20, 20x40, 20x60 metres

3.2.2. Structural evaluation

According to Bletzinger and Ramm [1], optimisation is often a generator of instabilities and imperfection sensitivities which may lead to proneness buckling or sudden bending failure. Within the set of optimum solutions, tendency lines can be observed in the behaviour of the weight, the deflection and strain energy. However, arbitrary values far out of the trend lines tend to appear in the cases of deflection and strain energy, especially in the squared (Figure 8). It is, therefore, necessary to carefully select the solutions within stable ranges before carrying out a full structural analysis. Once stable optimum solutions are obtained (before selecting the definitive solution), it is necessary to carry out a structural analysis with ultimate and serviceability limit state checks, as well as buckling checks. In this paper, an analysis has been carried out employing the Finite Element Analysis (FEA) software package of Autodesk Robot.

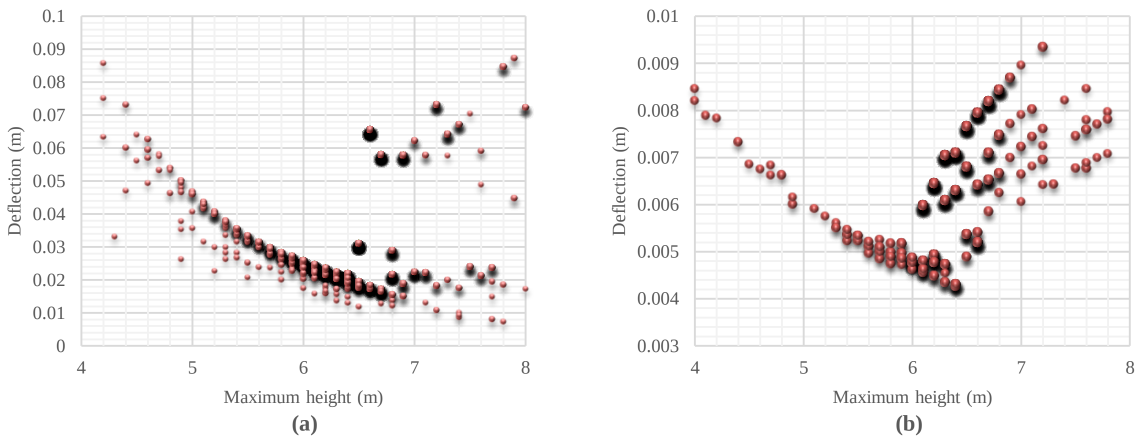

Figure 8: Deflection behaviour with maximum height increase of; a) squared typology, b) diamond topologies.

Extreme environmental action (wind, snow, thermal) are considered for the analysis. Maximum common values for this scenario are obtained and calculated according to Eurocode 1 [8], and the UK National Annex Part 1[10]. Other parameters such as the altitude above sea level or terrain profile have been assigned for the worst case scenarios. A summary with the values introduced can be found in Table 5. For the wind action, the basic wind velocity is introduced into Autodesk Robot, where the simulation acts as a wind tunnel. As a result, the programme automatically generates loads on the structure with eight directions considered, at intervals of 45 degrees.

These loads are combined with the ULS and SLS design criteria, according to Equations 6.10a and 6.14b, respectively, from Eurocode 0 [4]. Regarding buckling failure, the eigenvalue is obtained from the FE analysis. A summary of the performance criteria is depicted in Table 6.

Table 5: Summary of loads on the structure

Loads	Values
Dead loads	*Self-weight*
Imposed loads	$q_k=0.6kN/m^2$
Snow loads	$s_k=0.85kN/m^2$
Wind loads	$v_b=33m/s$
Thermal action	$\Delta T_u=26.5°C$

Table 6: Performance criteria for ULS, SLS and buckling.

Case	Performance criteria
ULS (STR)	$E_d < R_d$
SLS	d < L/200 (UK NA to BS EN1993-1-1 [14])
Buckling	Eigenvalue < 1.0

3.3. Results, implementation and limits

For weight and constructability, the squared tiling option provides the best performance, yet its deflection line behaves arbitrarily once an absolute maximum height – which varies for each case and topology – and it is surpassed as it can be observed in Figure 9. Also, the estimated strain energy is significantly larger than those for the other topologies, which range under 5kJ. This can also be observed by examining the curvature lines along the longitudinal axes of the structure; the curve presents significant convexities at the division lines in both the edges and the centre, and prevent efficient shell behaviour. The solution comes by implementing another topology with more stable performance curves. The diamond, triangular and Union Jack tessellations, instead, provide more stability and continuity in the curve, and consequently

Table 7: Parameters and performance.

	Squared	Diamond
Maximum height (m)	5.8	5.8
Nodes	341	330
Member lengths (m))	2.00-2.16	1.74 – 3.20
Deflection (mm)	26	5
Weight (kN)	259	289
Strain energy	16.6kJ	4.2kJ

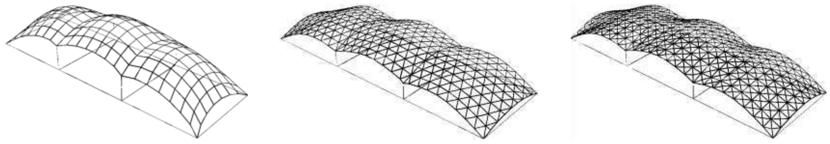

Figure 9: Case 3 with square, triangular and Union Jack tiling (in order).

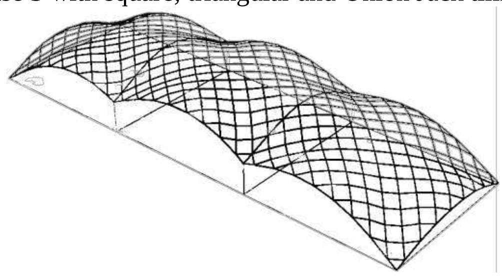

Figure 10: Preferred solution with diamond tiling.

smaller strain energy, yet the first appears to be the most efficient design as the number of nodes, and members are smaller (Figures 9 and 10). Within a range where the structure is stable, the optimum solution for this topology is as presented in Table 7, where the diamond topology is compared with the squared for case 3.

As it was noted, in a pragmatic design the length of the columns would vary depending on the topography of the site. It has been considered herein that the terrain is flat so the columns are all equal. The behaviour of shells is arch-like, thus transferring horizontal and vertical forces at the supports unless defined from the translation or rotation of a semi-circle, i.e., semi-circular barrel vaults and domes. As a result of longer columns and the existence of horizontal forces, the supports on the columns are horizontally displaced in the transverse direction in a way that the SLS criteria is not met while undesired bending stresses also accumulate in the area around the supports – a shell is considered to be well-designed if mostly loaded in compression (Ney and Adriaenssens [1]).

The structural analysis proves that the stability of shells depends considerably upon the support conditions due to their slenderness, as the solutions do not meet the performance criteria. Regardless, when the horizontal movement of the supports is restrained, the performance is ideal. In the case of a typical steel frame construction, bracing systems or reinforced concrete cores are employed. Notwithstanding, neither of these solutions can be implemented in archaeological sites for obvious reasons.

According to Schittich et al. [12], additional features can be added to reduce the liability to instabilities in some occasions. Some of these are the inclusion of trussed elements or cable arrangements, such as the trusses in Shukhov’s Production Hall at Vyksa or the cable spokes at the Museum of History in Hamburg. While the former solution would require re-design, the latter is a flexible addition which does not importantly influence the aesthetical perception while improving the structural performance.

- Protection against environment
- Lightweight character
- Reduced cost
- Allow natural lighting
- Minimum modification of existing structure
- Fast erection

Figure 11: Design constraints for the shell at the Hamburg museum.

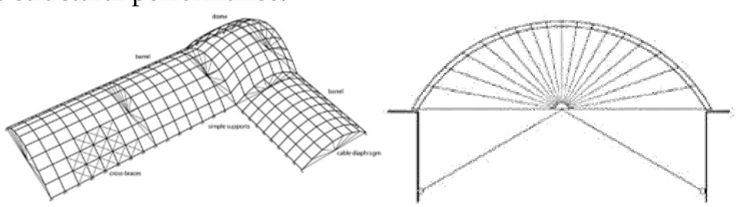

Figure 12: Sketch of the shell and a cable diaphragm (Ermias et al [2]).

For the courtyard roof at the Museum of Hamburg History, Jörg Schlaich designed the shell as a combination of two barrel vaults and a spherical dome with a Union Jack lattice. The constraints for the design were as defined by Ermias et al. [2] and presented in Figure 11. Cable diaphragms at specific sections were implemented to stiffen the structure by redistributing the forces into the cables (Figure 12). As a result, the forces transmitted to the supports at the original building drastically reduced, thus optimising the structure for one of the initial objectives.

By comparing the case of archaeological sites with that of the Hamburg museum, it can be observed that the constraints for design are coincident. Therefore, the implementation of cable systems is effective in this design. With the inclusion of cables acting as horizontal ties, the structural behaviour is stable, and the forces transferred to the foundations are smaller, thus require smaller sections and dimensions – optimise the structure for minimum weight. Tying cables should also be added to tie foundations together so that the horizontal forces transferred into them are smaller and sliding is prevented. An alternative to implementing additional features is to increase the transversal curvature, hence modifying the shape and leading to undesired solutions.

Considering the foundation design, it can be observed that these are subject to significant bending stresses and tension forces with unfavourable wind action. Due to the nature of the structure, the uplift pressures are enormous. As a result, the foundations are liable to overturning or sliding failure. For example, in a medium stiff clay, the dimensions of a concrete pad foundation should be 2.5 m x 2.5 m x 1.8 m approximately for overturning not to occur as calculated following Eurocode 7: Geotechnical design – Part 1 [9]. The implementation of an anchorage system with cables appears to be the most feasible option, yet this would be largely limited by the type of remains and the delimitation of the site since the anchors should be placed outside the extents of the excavation.

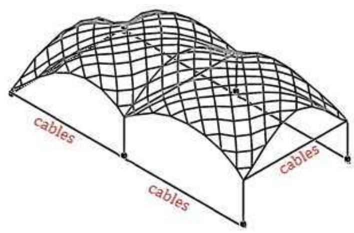

Figure 13: Sketch with tying cables.

When considering cases 1 and 2, the same problem applies. In both cases, the uplift pressures are larger than in case 3. When the wind direction is 'against the opening', the SLS criteria is not met, and liability to overturning becomes larger as the wind penetrates more easily. Nevertheless, when two 'end' modules are joined such as in case 4, the behaviour against wind action remains similar to that of case 3, as the wind penetration is reduced.

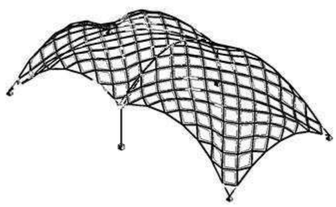
Figure 14: Two 'end' modules (case 4).

4. Conclusions, remarks and recommendations

Grid shells have potential as protective shelters for archaeological sites. Through the development of this conceptual design solution analysed for worst-case scenarios and by exploring further the requirements and constraints of this application, it has been proved that the proposed solution is still limited and depends largely upon the site characteristics. The biggest problem encountered throughout the design process has been the uplift loading provoked by wind forces in extreme conditions. Hence, this type of structures is proved to be effective in locations where the wind action is not as severe as that considered in the current study.

Nevertheless, further development could be done for the structure to function even in harsh conditions. For resistance against the wind, the gravity load or the shear resistance need to be increased when anchorage is not provided. Since implementing bulky foundations is not feasible and the possibility of applying anchorage systems relies heavily on the site, not-permanent massive bodies such as sandbags or water containers could be used. These would increase the gravity load while still being reversible solutions. However, various tests should be undertaken before applying them.

The addition of cable systems has been demonstrated to be effective in this application. Such cables are flexible and can be installed easily, while improving the structural performance largely by minimising the horizontal forces transferred to the supports. Despite their beneficial characteristics, the application will depend on the shape and height of the archaeological remains. In the case that cables cannot be implemented, analytically described shapes such as semi-circular barrel vaults or domes should be employed instead. Combinations between the two could also be effective.

In the particular study, when considering case 1 and 2, it has been observed that the performance against wind uplift is poorer than that of case 3 and 4, where the uplift pressure is not too intensive. Where anchorage or alternative measures for increasing the resistance cannot be implemented, the application of temporary textile-membranes in the openings could be an option to reduce the wind penetration and, therefore, the proneness to overturning, as well as to improve the performance for SLS criteria. An alternative is the design of such shell grid structures as enclosures so that the wind pressures are restrained by the outer surfaces. An example of this is the protecting structure of the Roman villa 'La Olmeda' in Palencia, Spain; the roof structure is supported on more than a hundred pilasters and based on barrel vaults.

A flat rectangular site has been considered in this study. The developed structure can be widely implemented in a broad range of sites as the length of the columns supporting the middle foundations can be modified without affecting the overall performance of the structure resulting from the addition of tying cables. Nevertheless, it is highly recommended to develop a process similar to that followed in this project, as the possible support locations can vary broadly from one site to another, and the optimum shape may change as well.

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